(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
31 July 2008 (31.07.2008)

PCT

(10) International Publication Number
WO 2008/091293 A2

(51) International Patent Classification:
H01L 35/32 (2006.01)

(21) International Application Number: PCT/US2007/016873

(22) International Filing Date: 27 July 2007 (27.07.2007)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/834,006 28 July 2006 (28.07.2006) US

(71) Applicant *(for all designated States except US)*: **BSST LLC** [US/US]; 5426 Irwindale Avenue, Irwindale, CA 91706 (US).

(72) Inventors: **BELL, Lon, E.**; 1819 N. Grand Oaks, Altadena, CA 91001 (US). **CRANE, Douglas, Todd**; 259 N. Holliston Avenue, #13, Pasadena, California 91106 (US).

(74) Agent: **SIMPSON, Andrew, H.**; Knobbe, Martens, Olson & Bear, Llp, 2040 Main Street, 14th Floor, Irvine, CA 92614 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

(54) Title: THERMOELECTRIC POWER GENERATING SYSTEMS UTILIZING SEGMENTED THERMOELECTRIC ELEMENTS

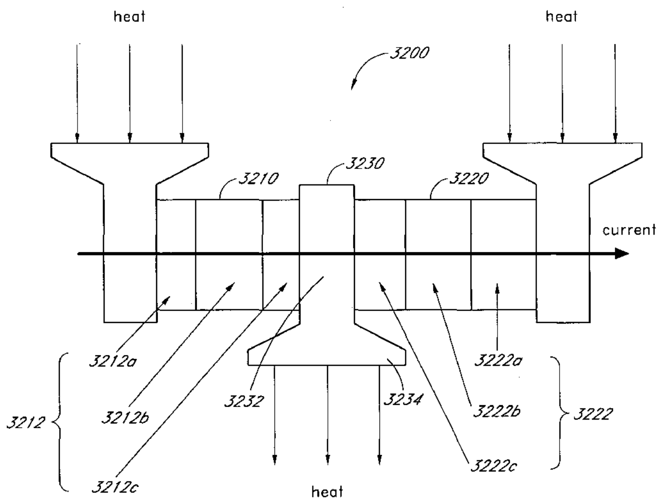


FIG. 32

(57) Abstract: A thermoelectric system includes a first thermoelectric element including a first plurality of segments in electrical communication with one another. The thermoelectric system further includes a second thermoelectric element including a second plurality of segments in electrical communication with one another. The thermoelectric system further includes a heat transfer device including at least a first portion and a second portion. The first portion is sandwiched between the first thermoelectric element and the second thermoelectric element. The second portion projects away from the first portion and configured to be in thermal communication with a working medium.

WO 2008/091293 A2

THERMOELECTRIC POWER GENERATING SYSTEMS UTILIZING SEGMENTED THERMOELECTRIC ELEMENTS

Continuing Application Data

[0001] This application is a continuation-in-part of U.S. Patent Application No. 11/136,334, filed May 24, 2005 and incorporated in its entirety by reference herein, which is a continuation of U.S. Patent No. 6,959,555, filed August 18, 2003 and incorporated in its entirety by reference herein, which is a continuation-in-part of U.S. Patent No. 7,231,772, filed August 23, 2002 and incorporated in its entirety by reference herein, and which is a continuation-in-part of U.S. Patent No. 7,111,465, filed March 31, 2003 and incorporated in its entirety by reference herein, which is a continuation of U.S. Patent No. 6,539,725, filed April 27, 2001 and incorporated in its entirety by reference herein, which is related to and claims the benefit of U.S. Provisional Patent Application No. 60/267,657 filed February 9, 2001 and incorporated in its entirety by reference herein. This application also claims the benefit of U.S. Provisional Patent Application No. 60/834,006, filed July 28, 2006, which is incorporated in its entireties by reference herein.

Background of the Invention

Field of the Invention

[0002] This disclosure relates to improved configurations for solid-state cooling, heating and power generation systems.

Description of the Related Art

[0003] Thermoelectric devices (TEs) utilize the properties of certain materials to develop a temperature gradient across the material in the presence of current flow. Conventional thermoelectric devices utilize P-type and N-type semiconductors as the thermoelectric material within the device. These are physically and electrically configured in such a manner that the desired function of heating or cooling is obtained.

[0004] The most common configuration used in thermoelectric devices today is illustrated in Figure 1A. Generally, P-type and N-type thermoelectric elements 102 are arrayed in a rectangular assembly 100 between two substrates 104. A current, I, passes through both element types. The elements are connected in series via copper shunts 106 saddled to the ends of the elements 102. A DC voltage 108, when applied, creates a temperature gradient across the TE elements. TEs are commonly used to cool liquids, gases and solid objects.

[0005] Solid-state cooling, heating and power generation (SSCHP) systems have been in use since the 1960's for military and aerospace instrumentation, temperature control and power generation applications. Commercial usage has been limited because such systems have been too costly for the function performed, and have low power density so SSCHP systems are larger, more costly, less efficient and heavier than has been commercially acceptable.

[0006] Recent material improvements offer the promise of increased efficiency and power densities up to one hundred times those of present systems. However, Thermoelectric (TE) device usage has been limited by low efficiency, low power density and high cost.

[0007] It is well-known from TE design guides (Melcor Corporation "Thermoelectric Handbook" 1995 pp. 16-17) that in today's TE materials, the cooling power at peak efficiency produced by a module with ZT = 0.9 is about 22% of the maximum cooling power. Thus, to achieve the highest possible efficiency, several TE modules are required compared to the number required for operation at maximum cooling. As a result, the cost of TE modules for efficient operation is significantly higher and the resulting systems are substantially larger.

[0008] It is known from the literature (for example, see Goldsmid, H.J. "Electronic Refrigeration" 1986, p. 9) that the maximum thermal cooling power can be written as:

(1) $q_{COPT} = I_{OPT}\alpha_C - \frac{1}{2}I^2{}_{OPT}R - K\Delta T$,

where:

q_{COPT} is the optimum cooling thermal power;
I_{OPT} is the optimum current;
α is the Seebeck Coefficient;
R is the system electrical resistance;
K is the system thermal conductance;
ΔT is the difference between the hot and cold side temperatures; and
T_C is the cold side temperature.

Further, from Goldsmid's:

$$(2)\quad I_{OPT} = \frac{\alpha}{R}\frac{1}{\left(\sqrt{ZT_{AVE}} - 1\right)} = \frac{\alpha}{R(M-1)},$$

where:

Z is the material thermoelectric figure of merit;

T_{AVE} is the average of the hot and cold side temperatures; and

$M = \sqrt{ZT_{AVE} + 1}$.

Substitution Equation (2) into (1) yields:

$$(3)\quad q_{OPT} = \left[\frac{ZT_C}{(M-1)}\left(\frac{\Delta T}{T_C} - \frac{1}{2(M-1)}\right) - \Delta T\right]K.$$

[0009] The term on the right side of Equation (3) in brackets is independent of the size (or dimensions) of the TE system, and so the amount of cooling q_{OPT} is only a function of material properties and K. For the geometry of Figure 1, K can be written as:

$$(4)\quad K = \frac{\lambda \mathrm{A_C}}{\mathrm{L_C}},$$

where λ is the average thermal conductivity of the N & P materials; A_C is the area of the elements; and L is the length of each element.

[0010] Since α is an intrinsic material property, as long as the ratio Lc/Ac is fixed, the optimum thermal power q_{OPT} will be the same. For current equal to I_{OPT}, the resistance is:

$$(5)\quad R_C = R_{OC} + R_{PC} = \frac{\rho_{TE} L_C}{A_C} + R_{PC},$$

where ρ_{TE} is the intrinsic average resistivity of the TE elements; R_{OC} is the TE material resistance; and R_{PC} is parasitic resistances.

[0011] For the moment, assume R_{P} is zero, then R is constant. I_{OPT} is constant if L_C/A_C is fixed. Only if the ratio Lc/Ac changes, does K and hence, q_{COPT} and R_{OC} and hence, I_{OPT} changes.

[0012] Generally, it is advantageous to make a device smaller for the same cooling output. An important limitation in thermoelectric systems is that as, for example, the length L_C is decreased for fixed A_C, the ratio of the parasitic resistive losses to TE material losses, ϕ_C becomes relatively large:

(6) $$\phi_C = \frac{R_{PC}}{R_{OC}}.$$

[0013] This can be seen by referring to Figure 1C, which depicts a typical TE couple. While several parasitic losses occur, one of the largest for a well-designed TE is that from shunt 106. The resistance of shunt 106 per TE element 102 is approximately,

(7) $$R_{PC} \approx \left(\frac{B_C + G_C}{W_C T_C} \right) P_{SC} ,$$

where G_C is the gap between the TE elements; B_C is the TE element and shunt breadth; W_C is the TE element and shunt width; T_C is the shunt thickness; and P_{SC} is the shunt resistivity.

[0014] For the geometry of Figure 1, the resistance for a TE element is:

(8) $$R_{OC} = \frac{P_{TE} L_C}{B_C W_C},$$

where L_c is the TE element length.

Thus, using Equations (7) and (8) in (6):

(9) $$\phi_C \approx B_C \left(\frac{B_C + G_C}{T_C L_C} \right) \left(\frac{P_{SC}}{P_{TE}} \right).$$

Summary of the Invention

[0015] In certain embodiments, a thermoelectric system is provided. The thermoelectric system comprises a first thermoelectric element comprising a first plurality of segments in electrical communication with one another. The thermoelectric system further comprises a second thermoelectric element comprising a second plurality of segments in electrical communication with one another. The thermoelectric system further comprises a heat transfer device comprising at least a first portion and a second portion. The first portion is sandwiched between the first thermoelectric element and the second thermoelectric element. The second portion projects away from the first portion and configured to be in thermal communication with a working medium.

[0016] In certain embodiments, a thermoelectric system is provided. The thermoelectric system comprises a plurality of thermoelectric elements, at least some of the thermoelectric elements comprising a plurality of segments. The thermoelectric system further comprises a plurality of heat transfer devices, at least some of the heat transfer devices comprising at least a first portion and a second portion. The first portion is sandwiched between at least two thermoelectric elements of the plurality of thermoelectric elements so as to form at least one stack of thermoelectric elements and heat transfer devices. The second portion projects away from the stack and configured to be in thermal communication with a working medium.

[0017] In certain embodiments, a method of fabricating a thermoelectric system is provided. The method comprises providing a plurality of thermoelectric elements, at least some of the thermoelectric elements comprising a plurality of segments. The method further comprises providing a plurality of heat transfer devices, at least some of the heat transfer devices comprising at least a first portion and a second portion. The method further comprises assembling the plurality of thermoelectric elements and the plurality of heat transfer devices to form at least one stack of alternating thermoelectric elements and heat transfer devices. The first portions of the heat transfer devices are sandwiched between at least two neighboring thermoelectric elements. The second portions of the heat transfer devices project away from the stack and configured to be in thermal communication with a working medium.

[0018] These and other aspects of the disclosure will be apparent from the figures and the following more detailed description.

Brief Description of the Drawings

[0019] Figure 1A-1B depicts a conventional TE module.

[0020] Figure 1C depicts a conventional TE couple.

[0021] Figure 2 depicts a general arrangement of a SSCHP system with thermal isolation and counter flow movement of its working media.

[0022] Figure 3 depicts the temperature changes that occur in the media, as the working media progress through the system.

[0023] Figures 4A – 4B depict a system with three TE modules, four fin heat exchangers, and liquid-working media.

[0024] Figures 5A – 5B depict a system with two TE modules, a segmented heat exchanger to achieve a degree of thermal isolation with a single heat exchanger, and counter flow of the liquid media,

[0025] Figure 6 depicts and gaseous media system with two TE modules and ducted fans to control fluid flow.

[0026] Figures 7A – 7D depict a solid media system with counter flow to further enhance performance. The TE elements utilize a high length to thickness ratio to achieve added thermal isolation.

[0027] Figure 8 depicts a system with TE elements arranged so that current passes directly through the array and thereby lowers cost, weight and size while providing improved performance.

[0028] Figure 9 depicts a system with TE elements, heat pipes and heat exchangers that is simple and low cost. The hot side and cold side are separated by thermal transport through heat pipes.

[0029] Figure 10 depicts a fluid system in which the fluid is pumped through the heat exchanger and TE module array so as to achieve a low temperature at one end to condense moisture out of a gas or a precipitate from a liquid or gas. The system has provisions to shunt working fluid flow to improve efficiency by lowering the temperature differential across portions of the array.

[0030] Figure 11 depicts an array in which working fluid enters and exits at a variety of locations, and in which part of the system operates in counter flow and part in parallel flow modes.

[0031] Figure 12 depicts a stack TE system with reduced parasitic electrical resistive losses.

[0032] Figure 13A depicts details of a TE element and heat exchange member in a preferred embodiment for a stack system.

[0033] Figure 13B depicts a section of a stack system constructed from elements shown in Figure 13A.

[0034] Figure 14 depicts another TE element and heat exchanger configuration.

[0035] Figure 15 depicts yet another TE element and heat exchanger configuration.

[0036] Figure 16 depicts a stack configuration with two vertical rows of TE elements electrically in parallel.

[0037] Figure 17 depicts a cooling/heating assembly with two rows of TE elements electrically in parallel.

[0038] Figure 18 depicts another configuration with two TE elements electrically in parallel.

[0039] Figure 19 depicts a heat exchanger element with one portion electrically isolated from another portion.

[0040] Figure 20 depicts another configuration of a heat exchanger element with one portion electrically isolated from another portion.

[0041] Figure 21 depicts yet another configuration of a heat exchanger with one portion electrically isolated from another portion.

[0042] Figure 22 depicts a heat exchanger segment configured in an array of electrically and thermally isolated portions.

[0043] Figure 23 depicts a cooler/heater constructed in accordance with the concepts of Figure 22.

[0044] Figure 24A depicts a heat exchange segment with TE elements aligned in the direction of fluid flow.

[0045] Figure 24B depicts segments of Figure 24A configured as an isolated element heat exchanger array in which electrical current flows generally parallel to working medium flow.

[0046] Figure 25A depicts segments of a design configured as an isolated element heat exchanger array in which electrical current flows generally perpendicular to the direction of current flow.

[0047] Figure 25B depicts a plan view of the assembly in Figure 25A.

[0048] Figure 26A depicts a TE heat exchanger module with reduced parasitic electrical resistance, which operates at relatively high voltage.

[0049] Figure 26B depicts a plan view of a heat exchanger array that uses TE modules of Figure 26A.

[0050] Figure 27 depicts an isolated element and stack configuration with heat transfer to moving solid members.

[0051] Figure 28 depicts an isolated element stack array with heat transfer between a liquid and a gas.

[0052] Figure 29 depicts a heat exchanger module with low parasitic electrical resistance for use in the stack array of Figure 28.

[0053] Figure 30 depicts a segment of an isolated element heat exchanger with solid heat sink and moving gaseous working fluid.

[0054] Figure 31A depicts a heat exchanger element with TE elements generally in the center to about double heat transfer from the element.

[0055] Figure 31B depicts another heat transfer element generally for liquids with the TE element generally in the center.

[0056] Figure 31C depicts yet another heat exchanger with the TE element generally in the center.

[0057] Figure 32 schematically illustrates a portion of an example thermoelectric system in accordance with certain embodiments described herein.

[0058] Figures 33A and 33B show the figures of merit (ZT) as functions of temperature for various P-type and N-type thermoelectric materials, respectively, compatible with certain embodiments described herein.

[0059] Figure 34 depicts the figure of merit, ZT, as a function of temperature for three different compositions of lead telluride doped with various levels of iodine.

[0060] Figure 35 shows the power curve compatibility conflict among three TE elements constructed in series in the direction of flow.

[0061] Figure 36 shows the power curves among three TE elements with varying aspect ratios in accordance with certain embodiments described herein.

[0062] Figure 37 schematically depicts a pair of segmented TE elements in a conventional configuration.

[0063] Figure 38 shows the average efficiencies for three different configurations simulated using a model calculation.

[0064] Figure 39 shows an example of a model analysis of a thermoelectric system where the parameter being varied is the TE thickness.

[0065] Figure 40 shows an example prototype system built using six Bi_2Te_3 TE elements sandwiched between seven copper heat transfer devices.

[0066] Figure 41 is a graph showing power generation curves for the six individual Bi_2Te_3 elements of Figure 40.

[0067] Figure 42 shows experimental results for initial testing of segmented TE elements.

Detailed Description of the Preferred Embodiment

[0068] In the context of this description, the terms thermoelectric module and TE module are used in the broad sense of their ordinary and accustomed meaning, which is (1) conventional thermoelectric modules, such as those produced by Hi Z Technologies, Inc. of San Diego, California, (2) quantum tunneling converters, (3) thermionic modules, (4) magneto caloric modules, (5) elements utilizing one, or any combination of thermoelectric, magneto caloric, quantum, tunneling and thermionic effects, (6) any combination, array, assembly and other structure of (1) through (6) above. The term thermoelectric element, is more specific to indicate an individual element that operates using thermoelectric, thermionic, quantum, tunneling, and any combination of these effects.

[0069] In the following descriptions, thermoelectric or SSCHP systems are described by way of example. Nevertheless, it is intended that such technology and descriptions encompass all SSCHP systems.

[0070] Accordingly, the invention is introduced by using examples in particular embodiments for descriptive and illustrative purposes. A variety of examples described below illustrate various configurations and may be employed to achieve the desired improvements. In accordance with the present description, the particular embodiments and examples are only illustrative and not intended in any way to restrict the inventions presented. In addition, it should be understood that the terms cooling side, heating side, cold side, hot side, cooler side and hotter side and the like, do not indicate any particular temperature, but are relative terms. For example, the "hot," side of a thermoelectric element or array or module may be at ambient temperature with the "cold," side at a cooler temperature than the ambient. The converse may also be true. Thus, the terms are relative to each other to indicate that one side of the thermoelectric is at a higher or lower temperature than the counter-designated temperature side.

[0071] Efficiency gains for geometries described in U.S. Patent No. 6,539,735, entitled Improved Efficiency Thermoelectrics Utilizing Thermal Isolation, yield an additional 50% to 100% improvement for many important applications. Combined with the material improvements being made, system efficiency gains of a factor of four or more appear possible in the near future. The prospects of these substantial improvements have lead to renewed interest in the technology and the effort to develop SSCHP systems for new applications.

[0072] In general, this disclosure describes a new family of SSCHP configurations. These configurations achieve compact, high-efficiency energy conversion and can be relatively low cost. Generally, several embodiments are disclosed wherein TE elements or modules (collectively called elements in this text) are sandwiched between heat exchangers. The TE elements are advantageously oriented such that for any two elements sandwiching a heat exchanger, the same temperature type side faces the heat exchanger. For example, the cooler side of each of the TE elements sandwiching a heat exchanger face the same heat exchanger or shunt, and thus each other. In a group of configurations, at least one working medium is passed sequentially through at least two heat exchangers so that the cooling or heating provided is additive on the working medium. This configuration has the added benefit that it utilizes the advantages of thermal isolation, as described in U.S. Patent No. 6,539,725, in manufactureable systems that exhibit high system efficiency and power density as noted in the references above. As explained in that patent, in general, a TE device achieves increased or improved efficiency by subdividing the overall assembly of TE elements into thermally isolated subassemblies or sections. For example, the heat exchangers may be subdivided so as to provide thermal isolation in the direction of working medium flow. For example, a TE system has a plurality of TE elements forming a TE array with a cooling side and a heating side, wherein the plurality of TE elements are substantially isolated from each other in at least one direction across the array. Preferably, the thermal isolation is in the direction of the working media flow. This thermal isolation can be provided by having a heat exchanger configured in sections such that the heat exchanger has portions which are thermally isolated in the direction of working fluid flow.

[0073] In the present disclosure, having sequential use of heat exchangers of the same temperature type for the working fluid provides a type of thermal isolation in itself. In addition, the heat exchangers or the TE elements, or TE modules or any combination may be configured to provide thermal isolation in the direction of the working fluid flow over and above the thermal isolation provided by having a series or sequence of heat exchangers through which at least one working fluid passes in sequence.

[0074] The principles disclosed for cooling and/or heating applications, are equally applicable to power generation applications, and any configuration, design detail, and analogous part that may be combined in any way to produce an assembly for power generation, is also applicable. The system may be tuned in a manner to maximize the efficiency for the given application, but the general principles apply.

[0075] The embodiments described in this application lower the construction complexity and cost of SSCHP devices while still maintaining or improving efficiency gains from thermal isolation.

[0076] Also disclosed are several embodiments for reducing cost by using less TE material and facilitating operation closer to peak efficiency. Many embodiments achieve a substantial reduction in parasitic losses (see, e.g., Figures 12-31).

[0077] One aspect of the disclosed embodiments involves a thermoelectric system having a plurality of N-type thermoelectric elements and a plurality of P-type thermoelectric elements. Preferably, a plurality of first shunts and a plurality of second shunts are provided. At least some of the first shunts are sandwiched between at least one N-type thermoelectric element and at least one P-type thermoelectric element, and at least some of the second shunts sandwiched between at least one P-type thermoelectric element and at least one N-type thermoelectric elements, so as to form a stack of thermoelectric elements, with alternating first and second shunts, wherein at least some of the first shunts and at least some of the second shunts project away from the stack in differing directions.

[0078] Preferably, the thermoelectric elements are constructed to be quite thin, such as from 5 microns, to 1.2 mm, from 20 microns to 200 microns for superlattice and heterostructure thermoelectric designs, and in another embodiment from 100 to 600 microns. These designs provide for significant reduction in the usage of thermoelectric material.

[0079] In one embodiment, the thermoelectric system further comprises a current source electrically coupled to the stack, the drive current traversing through the heat transfer devices and thermoelectric elements in series. In another embodiment, the heat transfer devices thermally isolate at least some of the P-type thermoelectric elements from at least some of the N-type thermoelectric elements.

[0080] In one embodiment, the heat transfer devices accept a working fluid to flow through them in a defined direction. Preferably, the heat transfer devices are heat exchangers and may have a housing with one or more heat exchanger elements inside.

[0081] In another embodiment, at least some of the first shunts are constructed of a first electrode portion electrically isolated from and thermally coupled to a second shunt portion.

[0082] Figure 2 illustrates a first generalized embodiment of an advantageous arrangement for a thermoelectric array 200. The array 200 has a plurality of TE modules 201, 211, 212, 213, 218 in good thermal communication with a plurality of first side heat exchangers 202, 203, 205 and a plurality of second side heat exchangers 206, 207 209. The designation first side heat exchanger and second side heat exchanger does not implicate or suggest that the heat exchangers are on one side or the other side of the entire SSCHP system, but merely that they are in thermal communication with either the colder side or the hotter side of the thermoelectric modules. This is apparent from the figure in that the heat exchangers are actually sandwiched between thermoelectric modules. In that sense, they are in thermal communication with a first side or a second side of the thermoelectric modules. The colder side of a first TE module 201 is in thermal contact with a first side heat exchanger 205 and the hot side of the TE module 201 is in thermal contact with an inlet second side heat exchanger 206. A second working media 215, such as a fluid, enters the array 200 in the upper right hand corner of Figure 2 through the inlet second side heat exchange 206, and exits near the lower left from a final or outlet second side heat exchanger 209. A first working media 216 enters at the upper left through an inlet first side heat exchanger 202 and exits near the lower right from a final or outlet first side heat exchanger 205. Electrical wires 210 (and similarly for other TE Modules) connected to a power supply, not shown, connect to each TE module 201. First conduits 208, represented as lines on Figure 2, convey the second working media 215 and second conduits 204 convey the first working media 216 sequentially through various heat exchangers 202, 203, 205, 206, 207 and 209 as depicted.

[0083] In operation, the second working media 215 absorbs heat from the TE module 201 as it passes downward through the inlet second side heat exchanger 206. The second working media 215 passes through conduit 208 and upwards into and through the second side heat exchanger 207. In good thermal communication with the heat exchanger 207 are the hotter sides of the TE modules 211 and 212, which have been configured so that their respective hotter sides face toward one another to sandwich the second side heat exchanger 207. The second side working media 215, is further heated as it passes through the second side heat exchanger 207. The second side working media 215 next passes through the second side heat exchanger 209, where again, the hotter sides of the TE modules 213 and 218 sandwich and transfer heat to the second side heat exchanger 209, further heating the second side working media 215. From the heat exchanger 209, the second working media 215 exits the array 200 from the outlet or final second side heat exchange 209.

[0084] Similarly, the first working media 216 enters the inlet first side heat exchanger 202 at the upper left corner of Figure 2. This heat exchanger 202 is in good thermal communication with the colder side of the TE module 218. The first working media 216 is cooled as it passes through the inlet first side heat exchanger 202, on through another first side exchanger 203 and finally through the outlet first side heat exchanger 205, where it exits as colder working media 217.

[0085] The thermoelectric cooling and heating is provided by electrical power through wiring 210 into TE module 218, and similarly into all the other TE modules.

[0086] Thus, in sum, working media is placed in good thermal contact with the cold side of the TE module at the left hand side of the array, so that heat is extracted from the media. The media then contacts a second and third TE module where additional heat is extracted, further cooling the media. The process of incremental cooling continues, as the media progresses to the right through the desired number of stages. The media exits at the right, after being cooled the appropriate amount. Concurrently, a second media enters the system at the far right and is incrementally heated as it passes through the first stage. It then enters the next stage where it is further heated, and so on. The heat input at a stage is the resultant of the heat extracted from the adjacent TE modules' cold sides, and the electrical power into those modules. The hot side media is progressively heated as it moves in a general right to left direction.

[0087] In addition to the geometry described above, the system provides benefit if both media enter at the same temperature and progressively get hotter and colder. Similarly, the media can be removed from or added to the cool or hot side at any location within the array. The arrays can be of any useful number of segments such as 5, 7, 35, 64 and larger numbers of segments.

[0088] The system can also be operated by reversing the process with hot and cold media in contact with TE modules, and with the hot and cold media moving from opposite ends (as in Figure 2 but with the hot media entering as media 216 and the cold media entering as media 215). The temperature gradient so induced across the TE modules produces an electric current and voltage, thus converting thermal power to electrical power. All of these modes of operation and those described in the text that follows are part of the inventions.

[0089] As illustrated in Figure 2, the separation of the heat exchanger into a sequence of stages provides thermal isolation in the direction of flow of the working media from TE module to TE module. U.S. Patent No. 6,539,725, entitled First Improved Efficiency Thermoelectrics Utilizing Thermal Isolation, filed April 27, 2001 describes in detail the principles of thermal isolation which are exhibited throughout this description with various specific and practical examples for easy manufacturing. This patent application is hereby incorporated by reference in its entirety.

[0090] As described in U.S. Patent No. 6,539,725, the progressive heating and cooling of media in a counter flow configuration as described in Figure 2, can produce higher thermodynamic efficiency than under the same conditions in a single TE module without the benefit of the thermal isolation. The configuration shown in Figure 2, thus presents an SSCHP system 200 that obtains thermal isolation through the segments or stages of heat exchangers sandwiched between thermoelectric modules in a compact easily producible design.

[0091] In addition to the features mentioned above, the thermoelectric modules themselves may be constructed to provide thermal isolation in the direction of media flow and each heat exchanger or some of the heat exchangers may be configured to provide thermal isolation in a individual heat exchanger through a configuration as will be described further in Figure 5 or other appropriate configurations. In general, the heat exchanger could be segmented in the direction of flow to provide increased thermal isolation along the flow of a single TE module such as the TE module 218 and the inlet heat exchanger 202.

[0092] Figure 3 depicts an array 300 of the same general design as in Figure 2, consisting of a plurality of TE modules 301 and colder side heat exchangers 302, 305, and 307 connected so that a first working medium 315 follows the sequential heat exchanger to heat exchanger path shown. Similarly, a plurality of hot side heat exchangers 309, 311 and 313 convey a hotter side working medium 317 in a sequential or staged manner in the direction shown by the arrows. The TE modules 301 are arranged and electrically powered as in the description of Figure 2.

[0093] The lower half of Figure 3 depicts the cold side temperatures or temperature changes 303, 304, 306, 308 of the colder side working medium and hot side temperatures 310, 312, 314 of the hotter side working medium.

[0094] The colder side working medium 315 enters and passes through an inlet colder side heat exchanger 302. The working medium's temperature drop 303 in passing through the inlet colder side heat exchanger 302 is indicated by the drop 303 in the cold side temperature curve Tc. The colder side working medium 315 is further cooled as it passes through the next stage colder side heat exchanger 305, as indicated by a temperature drop 304 and again as it passes through a third colder side heat exchanger 307, with an accompanying temperature drop 306. The colder side working medium 315 exits as colder fluids 316 at temperature 308. Similarly, the hotter side working medium 317 enters a first or inlet hotter side heat exchanger 309 and exits at a first temperature 310 as indicated by the hotter side temperature curve T_H in the Figure 3. The hotter side working medium progresses through the array 300 in stages as noted in Figure 2, getting progressively hotter, finally exiting after passing through outlet hotter side heat exchanger 313 as hotter working fluid at 318 and at a hotter temperature 314. It is readily seen that by increasing the number of stages (that is TE modules and heat exchangers) the amount of cooling and heating power can be increased, the temperature change produced by each heat exchanger can be reduced, and/or the amount of media passing through the array increased. As taught in the U.S. Patent No. 6,539,725, efficiency also can increase with more stages, albeit at a diminishing rate.

[0095] Experiments and the descriptions referenced above, show that thermal isolation and the progressive heating and cooling achievable with the configuration of Figures 2 and 3 can result in significant efficiency gains, and are therefore important. With such systems, gains of over 100% have been achieved in laboratory tests.

[0096] Figure 4A depicts an array 400 with three TE modules 402, four heat exchangers 403 and two conduits 405 configured as described in Figures 2 and 3. Colder and hotter side working fluids enters at a colder side inlet 404 and a hotter side inlet 407, respectively and exit respectively at a colder side exit 406 and a hotter side exit 408. Figure 4B is a more detailed view of one embodiment of a heat exchanger 403. It is shown as a type suitable for fluid media. The heat exchanger assembly 403, has consists of an outer housing 412 with an inlet 410 and an exit 411, heat exchanger fins 414, and fluid distribution manifolds 413. The operation of array 400 is essentially the same as described in Figures 2 and 3. The number of the TE modules 402 is three in Figure 4, but could be any number. Advantageously, the housing 412 is thermally conductive, being made from a suitable material such as corrosion protected copper or aluminum. In one embodiment, heat exchanger fins 414 advantageously are folded copper, or aluminum soldered or braised to the housing 412, so as to achieve good thermal conductivity across the interface to the TE Module. The Fins 414 can be of any form, but preferably of a design well suited to achieve the heat transfer properties desired for the system. Detailed design guidelines can be found in "Compact Heat Exchangers", Third Edition by W. M. Kays and A. L. London. Alternatively, any other suitable heat exchangers can be used, such as perforated fins, parallel plates, louvered fins, wire mesh and the like. Such configurations are known to the art, and can be used in any of the configurations in any of Figures 2 through 11.

[0097] Figure 5A depicts an alternative configuration to that of Figure 4 for the conduit connections to provide flow from heat exchanger stage to heat exchanger. The array 500 has first and second TE modules 501 and 510, three heat exchangers 502, 503 and 506, and a conduit 504. Of course, as with previous embodiments and configurations, the particular number of two first side heat exchangers 502, 503 and one second side heat exchanger 506 is not restrictive and other numbers could be provided.

[0098] Figure 5B illustrates an enlarged view of a preferred embodiment for the heat exchangers 502, 503, 506. This heat exchanger configuration as shown in Figure 5B would be appropriate for the other embodiments and can be used in any of the configuration in Figures 2-8 and Figure 11. This advantageous embodiment for one or more of the heat exchangers in such configurations has an outer housing 516 with segmented heat exchanger fins 511 separated by gaps 513. Working fluid enters through an inlet 505 and exits through exit 508. As an alternative to gaps, the heat exchanger could be made so that it is anisotropic such that it is thermally conductive for a section and non-thermally conductive for another section rather than having actual physical gaps between heat exchanger fins. The point is for thermal isolation to be obtained between stages of an individual heat exchanger segment and another individual heat exchanger segment in the direction of flow. This would be thermal isolation provided in addition to the thermal isolation provided by having stages of heat exchangers in the embodiments described in Figures 2-5.

[0099] Advantageously, a first working fluid 507 which, for example is to be heated, enters an inlet 505 and passes downward through an inlet or first heat exchanger 502 in thermal communication with a first TE module 501. The working fluid 507 exits at the bottom and is conducted to subsequent heat exchanger 503 through conduit 504, where it again passes in a downward direction past a second TE module 510 and exits through as a hotter working 508. Preferably, a second working fluid 517 enters from the bottom of Figure 5A through inlet 518 and travels upward through a third heat exchanger 506 past the colder sides (in the present example) of TE modules 501 and 510. The heat exchanger 506 is in good thermal communication with the colder sides of the TE modules 501 and 510. By this arrangement, the working fluids 507 and 517 form a counter flow system in accordance with the teaching of U.S. Patent No. 6,539,725 referenced above.

[0100] Preferably, the heat exchangers 502, 503 and 506, shown in detail in Figure 5B, are constructed to have high thermal conductivity from the faces of the TE modules 501, 510, 510, through the housing 516 and to the heat exchanger fins 511 (depicted in four isolated segments). However, it is desirable to have low thermal conductivity in the direction of flow, so as to thermally isolate each heat exchanger segment from the others. If the isolation is significant, and TE modules 501 and 510 do not exhibit high internal thermal conductivity in their vertical direction (direction of working fluid flow), the array 500 benefits from the thermal isolation and can operate at higher efficiency. In effect, the array 500 can respond as if it were an array constructed of more TE Modules and more heat exchangers.

[0101] Figure 6 depicts yet another heater/cooler system 600 that is designed to operate beneficially with working gases. The heater/cooler 600 has TE modules 601, 602 in good thermal communication with first side heat exchangers 603, 605 and second side heat exchangers 604. A first working fluid, such as air or other gases 606, is contained by ducts 607, 708, 610 and a second working fluid 616 is contained by ducts 615, 613. Fans or pumps 609, 614 are mounted within ducts 608, 615.

[0102] The first working fluid 606 enters the system 600 through an inlet duct 607. The working fluid 606 passes through a first heat exchanger 603 where, for example, it is heated (or cooled). The working fluid 606 then passes through the fan 609 which acts to pump the working fluid 606 through the duct 608, and through the second heat exchanger 605, where it is further heated (or cooled), and out an exit duct 610. Similarly, a working fluid, such as air or another gas, enters through an inlet duct 615. It is pushed by a second fan or pump 614 through a third heat exchanger 604 where, in this example, it is cooled (or heated). The cooled (or heated) working fluid 616 exits through an exit duct 613.

[0103] The system 600 can have multiple segments consisting of additional TE modules and heat exchangers and isolated, segmented heat exchangers as described in Figure 5B. It can also have multiple fans or pumps to provide additional pumping force. In addition, one duct, for example 607, 608, can have one fluid and the other duct 613, 615 a second type of gas. Alternately, one side may have a liquid working fluid and the other a gas. Thus, the system is not restricted to whether a working medium is a fluid or a liquid. Additionally, it should be noted that the exit duct 613 could be routed around the fan duct 609.

[0104] Figure 7A depicts a heating and cooling system 700 for beneficial use with a fluid. The assembly has a plurality of TE modules 701 with a plurality of first side working media 703 and a plurality of second side working media 704. In the present example, both the first side working media 703 and the second side working media 704 form disks. The first side working media 703 are attached to a first side shaft 709, and the second side working media 704 are attached to a second side shaft 708. The shafts 708, 709 are in turn attached to first side motor 706 and second side motor 705, respectively, and to corresponding bearings 707. The preferred direction of motor rotation is indicated by arrows 710 and 711.

[0105] A separator 717 both divides the array into two portions and positions the TE modules 701. The TE modules 701, held in position by the separator 717, are spaced so as to alternately sandwich a first side working medium 703 and a second side working medium 704. For any two TE modules 701, the modules are oriented such that their cold sides and hot sides face each other as in the previous embodiments. The working media 703, 704 are in good thermal communication with the TE elements 701. Thermal grease or the like is advantageously provided at the interface between the thermoelectric element 701 and the working media 703, 704. The purpose of the grease becomes apparent in the discussion below regarding the operation of the working media 703, 704. A first side housing section 714 and second side housing section 715 contain fluid conditioned by the system 700. Electrical wires 712, 713 connect to the TE modules 701 to provide drive current for the TE modules.

[0106] Figure 7B is a cross sectional view 7B-7B through a portion of the system 700 of Figure 7A. A first fluid 721 and a second fluid 723 are represented along with their direction of flow by arrows 721 and 723. The first fluid exits as represented by the arrow 722 and a second exits as represented by the arrow 724. The system 700 operates by passing current through electrical wires 712 and 713 to TE modules 701. The TE modules 701 have their cold and hot sides facing each other, arranged in the fashion as described in Figures 2 and 3. For example, their adjacent cold sides both face the first side working media 703 and their hot sides face the second side working media 704. The Separator 717 serves the dual function of positioning the TE modules 701 and separating the hot side from the cooled side of the array 700.

[0107] For an understanding of operation, assume, for example, that a second fluid 723 is to be cooled. The cooling occurs by thermal exchange with second side media 704. As the second side media 704 rotate, the portion of their surface in contact with the colder side of the TE modules 701 at any given time is cooled. As that portion rotates away from the TE modules 701 through the action of the second motor 705, the second media 704 cool the second side fluid that then exits at exit 724. The second fluid is confined within the array 700 by the housing section 715 and the separator 717.

[0108] Similarly, the first fluid 721 is heated by the first side media 703 in thermal contact with the hotter side of the TE modules 701. Rotation (indicated by arrow 711) moves the heated portion of first media 703 to where the first fluid 721 can pass through them and be heated via thermal contact. The first fluid 721 is contained between the housing 714 and the separator 717 and exits at exit 722.

[0109] As mentioned above, thermally conductive grease or liquid metal such as mercury, can be used to provide good thermal contact between the TE modules 701 and the media 703, 704 at the region of contact.

[0110] As mentioned above, the configuration of Figure 7A and 7B may also be advantageously used to cool or heat external components such as microprocessors, laser diodes and the like. In such instances, the disks would contact the part using the thermal grease or liquid metal or the like to transfer the heat to or from the part.

[0111] Figure 7C depicts a modified version of the system 700 in which the TE modules 701 are segmented to achieve thermal isolation. Figure 7C shows a detailed view of the portion of array 700 in which TE modules 701 and 702 transfer thermal power to heat moving media 704 and 703 (the rotating discs in this example). The moving media 704 and 703 rotate about axes 733 and 734, respectively.

[0112] In one embodiment, advantageously, the working media 704 and 703 rotate in opposite directions as indicated by arrows 710 and 711. As moving media 704, 703 rotate, heat transfer from different sections of TE modules 701 and 702 come into thermal contact with them and incrementally change the temperature of the moving media 704, 703. For example, a first TE module 726 heats moving medium 704 at a particular location. The material of the moving media 704 at that location moves into contact with a second TE module 725 as moving medium 704 rotates counter clockwise. The same portion of moving medium 704 then moves on to additional TE module segments 701. The opposite action occurs as moving medium 703 rotates counterclockwise and engages TE modules 701 and then subsequently TE modules 725 and 726.

[0113] Advantageously, moving media 704, 703 have good thermal conductivity in the radial and axial directions, and poor thermal conductivity in their angular direction, that is, the direction of motion. With this characteristic, the heat transfer from one TE module 725 to another TE module 726 by conductivity through the moving media 704 and 708 is minimized, thereby achieving effective thermal isolation.

[0114] As an alternative to TE modules or segments 701, 725, 726, a single TE element or several TE element segments may be substituted. In this case, if the TE elements 701 are very thin compared to their length in the direction of motion of moving media 704, 703, and have relatively poor thermal conductivity in that direction, they will exhibit effective thermal isolation over their length. They will conduct heat and thus respond thermally as if they were constructed of separate TE modules 701. This characteristic in combination with low thermal conductivity in the direction of motion within the moving media 704, 703 can achieve effective thermal isolation and thereby provides performance enhancements.

[0115] Figure 7D depicts an alternative configuration for moving media 704, 703 in which the media are constructed in the shape of wheels 729 and 732 with spokes 727 and 731. In the spaces between spokes 727 and 731 and in good thermal contact with them, are heat exchanger material 728 and 730.

[0116] The system 700 can operate in yet another mode that is depicted in Figure 7D. In this configuration, working fluid (not shown) moves axially along the axes of the array 700 passing through moving media 704, 703 sequentially from one medium 704 to the next moving medium 704, and so on in an axial direction until it passes through the last medium 704 and exits. Similarly, a separate working fluid, not shown, passes through individual moving medium 703 axially through array 700. In this configuration, the ducts 714 and 715 and separator 717 are shaped to form a continuous ring surrounding moving media 704, 703 and separating medium 704 from medium 703.

[0117] As the working fluid flows axially, thermal power is transferred to the working fluid through heat exchanger material 728 and 730. Advantageously, the hot side working fluid, for example, passes through heat exchanger 728, moves through the array 700 in the opposite direction of the working fluid moving through heat exchanger 730. In this mode of operation, the array 700 acts as a counterflow heat exchanger, and a succession of sequential heat exchangers 728 and 730 incrementally heat and cool the respective working fluids that pass through them. As described for Figure 7C, the thermally active components can be TE modules 701 that can be constructed so as to have effective thermal isolation in the direction of motion of the moving media 704, 703. Alternatively, the TE modules 701 and 702 can be segments as described in Figure 7C. In the latter case, it is further advantageous for the thermal conductivity of the moving media 704, 703 to be low in the direction of motion so as to thermally isolate portions of the outer discs 729 and 732 of the moving media 704, 703.

[0118] Alternately, the design could be further contain radial slots (not shown) in the sections 729 and 732 that are subject to heat transfer from TE modules 701 and 702 to achieve thermal isolation in the direction of motion.

[0119] Figure 8 depicts another embodiment of a thermoelectric system an 800 having a plurality of TE elements 801 (hatched) and 802 (unhatched) between first side heat exchangers 803 and second side heat exchangers 808. A power supply 805 provides current 804 and is connected to heat exchangers 808 via wires 806, 807. The system 800 has conduits and pumps or fans (not shown) to move hot and cold side working media through the array 800 as described, for example, in Figures 2, 3, 4, 5, 6 and 7.

[0120] In this design, the TE modules (having many TE elements) are replaced by TE elements 801 and 802. For example, hatched TE elements 801 may be N-type TE elements and unhatched TE elements 802 may be P-type TE elements. For this design, it is advantageous to configure heat exchangers 803 and 808 so that they have very high electrical conductivity. For example, the housing of the heat exchangers 803, 808 and their internal fins or other types of heat exchanger members can be made of copper or other highly thermal and electrical conductive material. Alternately, the heat exchangers 803 and 808 can be in very good thermal communication with the TE elements 801 and 802, but electrically isolated. In which case, electrical shunts (not shown) can be connected to the faces of TE elements 801 and 802 to electrically connect them in a fashion similar to that shown in Figure 1, but with the shunts looped past heat exchangers 803 and 808.

[0121] Regardless of the configuration, DC current 804 passing from N-type 801 to P-type TE elements 802 will, for example, cool the first side heat exchanger 803 sandwiched between them, and current 804 passing from P-type TE elements 802 to N-type TE elements 801 will then heat the second side heat exchanger 808 sandwiched between them.

[0122] The Array 800 can exhibit minimal size and thermal losses since the shunts, substrates and multiple electric connector wires of standard TE modules can be eliminated or reduced. Further, TE elements 801 and 802 can be heterostructures that accommodate high currents if the components are designed to have high electrical conductivity and capacity. In such a configuration, the array 800 can produce high thermal power densities.

[0123] Figure 9 depicts a thermoelectric system 900 of the same general type as described in Figure 8, with P-type TE elements 901 and N-type TE elements 902 between, and in good thermal contact with first side heat transfer members 903 and second side heat transfer members 905. In this configuration, the heat transfer members 903 and 905 have the form of thermally conductive rods or heat pipes. Attached to, and in good thermal communication with the heat transfer members 903 and 905 are heat exchanger fins 904, 906, or the like. A first conduit 907 confines the flow of a first working medium 908 and 909 and a second conduit 914 confines the flow of a second working fluid 910 and 911. Electrical connectors 912 and 913 conduct current to the stack of alternating P-type and N-type TE elements 901, 902, as described in Figure 8.

[0124] In operation, by way of example, current enters the array 900 through the first connector 912, passes through the alternating P-type TE elements 901 (hatched) and N-type TE elements 902 (unhatched) and exits through the second electrical connector 913. In the process, the first working media 908 becomes progressively hotter as it is heated by conduction from heat transfer fins 904, which in turn have been heated by conduction through the first heat transfer members 903. The first conduit 907 surrounds and confines a first working media 908 so it exits at a changed temperature as working fluid 909. Portions of the first conduit 907 thermally insulate the TE elements 901 and 902 and the second side heat transfer members 905 from the first (hot in this case) working media 908 and 909. Similarly, the second working media 910 enters through the second conduit 914, is cooled (in this example) as it passes through the second side heat exchangers 906 and exits as cooled fluid 911. The TE elements 901, 902 provide cooling to the second side heat transfer members 905 and hence, to heat exchanger fins 906. The second side conduit 914 acts to confine the second (cooled in this example) working media 910, and to insulate it from other parts of array 900.

[0125] Although described for individual TE elements in the embodiments of Figures 8- 9, TE modules may be substituted for the TE elements 901, 902. In addition, in certain circumstances, it may be advantageous to electrically isolate TE elements 901, 902 from the heat transfer members 903, 905, and pass current through shunts (not shown). Also, the heat exchangers 904, 906 can be of any design that is advantageous to the function of the system. As with the other embodiments, it is seen that the configurations of Figures 8 and 9 provide a relatively easily manufacturable system that also provides enhanced efficiency from thermal isolation. For example, in Figure 8, the heat exchangers 808, 803 which alternate between P-type and N-type thermal electric elements, will either be of the colder or hotter heat exchanger type, but will be reasonably thermally isolated from each other and cause the thermoelectric elements of the P and N type to be reasonably thermally isolated from one another.

[0126] Figure 10 depicts another thermoelectric array system (1000) that provides thermal isolation. Advantageously, this configuration may perform the function of a system that utilizes cooling and heating of the same medium to dehumidify, or remove precipitates, mist, condensable vapors, reaction products and the like and return the medium to somewhat above its original temperature.

[0127] The system 1000 consists of a stack of alternating P-type TE elements 1001 and N-type TE elements 1002 with interspersed cold side heat transfer elements 1003 and hot side heat transfer elements 1004. In the depicted embodiment, heat exchanger fins 1005, 1006 are provided for both the colder side heat transfer elements 1003 and the hotter side heat transfer elements 1004. A colder side conduit 1018 and a hotter side conduit 1019 direct working fluid 1007, 1008 and 1009 within the array 1000. A fan 1010 pulls the working fluid 1007, 1008 and 1009 through the array 1000. Preferably, colder side insulation 1012 thermally isolates the working fluid 1007 while travelling through the colder side from the TE element stack and hotter side insulation 1020 preferably isolates the working fluid while travelling through the hotter side from the TE element stack. A baffle 1010 or the like separates the colder and hotter sides. In one preferred embodiment, the baffle 1010 has passages 1010 for working fluids 1021 to pass through. Similarly, in one embodiment, fluid passages 1017 allow fluid 1016 to enter the hot side flow passage.

[0128] A screen 1011 or other porous working fluid flow restrictor separates the colder from the hotter side of array 1000. Condensate, solid precipitate, liquids and the like 1013 accumulate at the bottom of the array 1000, and can pass through a valve 1014 and out a spout 1015.

[0129] Current flow (not shown) through TE elements 1001 and 1002, cools colder side heat transfer elements 1003 and heats hotter side heat transfer elements 1004, as discussed in the description of Figure 9. In operation, as the working fluid 1007 passes down the colder side, precipitate, moisture or other condensate 1013 from the working fluid 1007 can collect at the bottom of the array 1000. As required, the valve 1014 can be opened and the precipitate, moisture or condensate 1013 can be removed through the spout 1015 or extracted by any other suitable means.

[0130] Advantageously, some of the working fluid 1021 can be passed from the colder to the hotter side through bypass passages 1020. With this design, not all of the colder side fluid 1007 passes through the flow restrictor 1011, but instead can be used to reduce locally the temperature of the hotter side working fluid, and thereby improve the thermodynamic efficiency of the array 1000 under some circumstances. Proper proportioning of flow between bypass passages 1020 and flow restrictor 1011, is achieved by suitable design of the flow properties of the system. For example, valves can be incorporated to control flow and specific passages can be opened or shut off. In some uses, the flow restrictor 1011 may also act as a filter to remove precipitates from liquid or gaseous working fluids 1008, or mist or fog from gaseous working fluids 1008.

[0131] Advantageously, additional hotter side coolant 1016 can enter array 1000 through side passages 1017, also for the purpose of reducing the hotter side working fluid temperature or increasing array 1000 efficiency.

[0132] This configuration can produce very cold conditions at the flow restrictor 1011, so that working fluid 1008 can have substantial amounts of precipitate, condensate or moisture removal capability. In an alternative mode of operation, power to the fan 1010 can be reversed and the system operated so as to heat the working fluid and return it to a cool state. This can be advantageous for removing reaction products, precipitates, condensates, moisture and the like that is formed by the heating process. In one advantageous embodiment, flow restrictor 1011, and/or heat exchangers 1005 and 1006 can have catalytic properties to enhance, modify, enable, prevent or otherwise affect processes that could occur in the system. For liquid working fluids, one or more pumps can replace fan/motor 1010 to achieve advantageous performance.

[0133] Figure 11 depicts a thermoelectric array 1100 similar in design to that of Figures 2 and 3, but in which working media has alternate paths through the system. The array 1100 has TE modules 1101 interdispersed between heat exchangers 1102. A plurality of inlet ports 1103, 1105 and 1107 conduct working media through the array 1100. A plurality of exit ports 1104, 1106 and 1108 conduct working media from the array 1100.

[0134] In operation, by way of example, working media to be cooled enters at a first inlet port 1103 and passes through several of the heat exchangers 1102, thereby progressively cooling (in this example), and exits through a first exit port 1104. A portion of the working media that removes heat from array 1100 enters through a second inlet port 1105, passes through heat exchangers 1102, is progressively heated in the process, and exits through a second exit port 1106.

[0135] A second portion of working media to remove heat enters a third inlet port 1107, is heated as it passes through some of the heat exchangers 1102 and exits through a third exit port 1108.

[0136] This design allows the cool side working media which passes from the first inlet port 1103 to the first exit port 1104 to be efficiently cooled, since the hot side working media enters at two locations in this example, and the resultant temperature differential across the TE modules 1101 can be on average lower than if working media entered at a single port. If the average temperature gradient is lower on average, then under most circumstances, the resultant system efficiency will be higher. The relative flow rates through the second and third inlet port 1105 and 1107 can be adjusted to achieve desired performance or to respond to changing external conditions. By way of example, higher flow rates through the third inlet port 1107, and most effectively, a reversal of the direction of flow through that portion so that third exit port 1108 is the inlet, can produce colder outlet temperatures in the cold side working media that exits at first exit port 1104.

[0137] The basic underlying connections for a conventional thermoelectric 100 are shown in additional detail in Figure 1C. As mentioned above, a *P*-type element 110 and an *N*-type element 112 are of the type well known to the art. Shunts 106 are attached to, and in good electrical connection with, *P*-type and *N*-type TE elements 110 and 112. Generally, large numbers of such TE elements and shunts are connected together to form a TE module, as shown in Figure 1A.

[0138] The length of TE elements 110, 112 in the direction of current flow is L_C 116; their breadth is B_C 117; their width is W_C 118, and their distance apart is G_C 120. The thickness of shunts 106 is T_C 109.

[0139] The dimensions B_C, W_C, and L_C, along with the TE material's figure of merit, Z, the current 122 and the operating temperatures determine the amount of cooling, heating or electrical power produced, as is well known to the art (See Angrist, S.W. "Direct Energy Conversion" 3rd Ed. 1977 Ch. 4, for example).

[0140] The design depicted in Figure 12 alters the conventional construction of Figure 1 in a manner to reduce the amount of thermoelectric material required, and the magnitude of the parasitic resistance in the shunts 106. A TE configuration 1200 has a plurality of first side TE elements 1201, 1202 of alternating conductivity types sandwiched in series between shunts 1203 and a plurality of second side shunts 1204, so that a current 1209 passes perpendicular to the breadth B_B and width W_B of the shunts rather than generally parallel to the breadth as in Figure 1C. For the design of Figure 12, the ratio, ϕ_B of R_{PB} to R_{OB} is:

(10) $$\phi_B \approx \frac{R_{PB}}{R_{OB}}$$

Where;

(11) $$R_{PB} \frac{P_{SB} T_B}{B_B W_B}$$

(12) $$R_{OB} = \frac{P_{TE} L_B}{B_B W_B}$$

so,

(13) $$\phi_B \approx \left(\frac{T_B}{B_B}\right)\left(\frac{P_{SB}}{P_{TE}}\right)$$

Where

T_B is the shunt thickness

L_B is the TE element length

ρ_{SB} is the shunt resistivity

B_B is the TE element and shunt active breadth

W_B is the TE elements and shunt active width

[0141] If ϕ_C is set equal to ϕ_B, then the parasitic electrical resistance losses will have the same proportional effect on the performance of the configurations of Figure 1C and Figure 12. For comparative purposes, assume material properties of the two configurations are identical, then;

(14) $\phi_C = \phi_B$

or using Equations (9 and 12) in B;

(15) $\frac{L_C}{L_B} \approx B_C \left(\frac{B_C + G_C}{T_C T_B} \right)$

[0142] For today's typical thermoelectric modules;

$B_C \approx 1.6$ mm.

$W_C \approx 1.6$ mm.

$G_C \approx 1.6$ mm.

$T_C \approx 0.4$ mm.

and assume;

$T_B \approx 2$ mm.

$P_{SB} = P_{SC}$

then,

(16) $\frac{L_c}{L_B} \approx 6.4$

[0143] Thus the length L_B can be $1/6.4$ that of L_C and the resulting resistive losses of the design in Figure 12 do not exceed those of a conventional TE module. If this is the case, and all other losses are negligible or decrease proportionally, a TE system utilizing the configuration of Figure 12 would have the same operating efficiency as that of Figure 1C, but with $L_B = L_C/6.4$.

[0144] The volume of the new configuration can be compared to that of Figure 1C. For the same q_{OPT}, the area ratio must remain the same, so;

(17) $\frac{L_B}{A_B} = \frac{L_C}{A_C}$

and since;

(18) $$\frac{L_B}{L_C} = \frac{1}{6.4}$$

(19) $$A_C = 6.4 A_B.$$

[0145] The volume ratio of thermoelectric material of the two is;

(20) $$V_C = A_C L_C$$

(21) $$V_B = A_B L_B$$

and;

(22) $$\frac{V_B}{V_C} = \left(\frac{A_B}{A_C}\right)\left(\frac{L_B}{L_C}\right)$$

(23) $$\approx \frac{1}{6.4^2} \approx \frac{1}{41}$$

[0146] Therefore with these assumptions, $\frac{1}{41}$ as much TE material is required. This substantial potential reduction, while it may not be fully realized because of the exactitude of assumptions made, nevertheless can be very beneficial in reducing the amount of TE material used and hence, cost and size as well.

[0147] The TE stack configuration 1200 of Figure 12 has *P*-type TE elements 1201 and *N*-type TE elements 1202 of length L_B 1205. The direction of current flow is indicated by the arrow 1209. The TE elements have a breadth B_B and a width W_B. Between *P*-type TE elements 1201 and *N*-type TE elements 1202, in the direction of current flow, are the second side shunts 1204 ("PN shunts"). Between *N*-type 1202 and *P*-type 1201 elements, in the direction of current flow, are the first side shunts 1203 ("NP shunts"). The PN shunts 1204 extend generally in the opposite direction from the stack 1200 than the NP shunts 1203. Angles other than 180° are also advantageous.

[0148] If an appropriate current 1209 is passed in the direction indicated, NP shunts 1203 are cooled and PN shunts 1204 are heated. Through this configuration, the parasitic electrical resistance losses for the configuration 1200 are lower typically than for the conventional configuration 100 of Figure 1 for the same TE element dimensions. Thus, if the TE length L_B 1205 is reduced to equate the ratio of parasitic electrical losses in the two configurations, the TE length L_B 1205 will be smaller, and the configuration of Figure 12 advantageously can operate at higher power density than that of Figure 1. As a result, the configuration 1200 of Figure 12 also uses less thermoelectric material, and can be more compact than in the conventional design of Figure 1.

[0149] The shunts 1203, 1204 can serve the dual function of transmitting thermal power away from the TE elements 1201, 1202 and exchange thermal power with an external object or medium, such as a working fluid.

[0150] An illustration of a preferred embodiment 1300 of a shunt combined to form a heat exchanger 1302 is depicted in Figure 13A. Preferably, at least one TE element 1301 is electrically connected, such as with solder, to a raised electrode surface 1303 of a heat exchange shunt 1302. Advantageously, the shunt 1302 can be constructed primarily of a good thermal conductor, such as aluminum, and have integral clad overlay material 1304, 1305, made of a high-electrical conductivity material, such as copper, to facilitate TE element 1301 attachment and current flow at low resistance.

[0151] Figure 13B depicts a detailed side view of a portion of a stack thermoelectric assembly 1310 made up of the thermoelectric shunts 1302 and TE elements 1301 of Figure 13A. A plurality of shunts 1302 with raised electrode surfaces 1303 are electrically connected in series to TE elements 1301 of alternating conductivity types.

[0152] The shunts 1302 will be alternately heated and cooled when an appropriate current is applied. The thermal power produced is transported away from the TE elements 1301 by the shunts 1302. Advantageously, the raised electrodes 1303 facilitate reliable, low-cost, stable surfaces to which to attach the TE elements 1301. In practice, a stack of a plurality of these assemblies 1310 may be provided. An array of stacks could also be used which also further facilitates thermal isolation.

[0153] The electrodes 1303 advantageously can be shaped to prevent solder from shorting out the TE elements 1301. Also, the electrodes 1303 advantageously can be shaped to control the contact area and hence, current density, through the TE elements 1301.

[0154] An example of a portion of a shunt heat exchanger 1400 is depicted in Figure 14. This portion 1400 has increased surface area to aid heat transfer. A TE element 1401 is attached to a shunt 1402, preferably constructed as depicted in Figure 13A, or as in other embodiments in this application. Heat exchangers 1403, 1404, such as fins, are attached with good thermal contact, such as by brazing, to the shunt 1402. In this embodiment, a working fluid 1405 passes through the heat exchangers 1403, 1404.

[0155] Advantageously, the shunt portion 1400 is configured so that as the working fluid 1405 passes through the heat exchangers 1403, 1404, thermal power is transferred efficiently. Further, the size of materials and proportions of the shunt 1402 and heat exchangers 1403, 1404 are designed to optimize operating efficiency when combined into a stack such as described in Figures 12 and 13B. Advantageously, the heat exchangers 1403, 1404 can be louvered, porous or be replaced by any other heat exchanger design that accomplishes the stated purposes such as those described in "Compact Heat Exchangers", Third Edition, by W. M. Kays and A. L. London. The heat exchangers 1403, 1404 can be attached to the shunt 1402 by epoxy, solder, braze, weld or any other attachment method that provides good thermal contact.

[0156] Another example of a shunt segment 1500 is depicted in Figure 15. The shunt segment 1500 is constructed of multiple shunt elements 1501, 1502, 1503 and 1504. The shunt elements 1501, 1502, 1503 and 1504 may be folded over, brazed, riveted to each other or connected in any other way that provides a low electrical resistance path for a current 1507 to pass and to provide low thermal resistance from a TE element 1506 to the shunts 1501, 1502, 1503 and 1504. The TE element 1506 is advantageously attached to segment 1500 at or near a base portion 1505.

[0157] The shunt segment 1500 depicts a design alternative to the shunt segment 1400 of Figure 14, and can be configured in stacks as depicted in Figures 12 and 13, and then in arrays of stacks if desired. Both the configurations in Figures 14 and 15 can be automatically assembled to lower the labor cost of the TE systems made from these designs.

[0158] Shunt segments can also be formed into stack assemblies 1600 as depicted in Figure 16. Center shunts 1602 have first side TE elements 1601 of the same conductivity type at each end on a first side and second side TE elements 1605 of the opposite conductivity type at each end of the opposite side of the center shunts 1602. Between each center shunt 1602 to form a stack of shunts 1602 is placed a right shunt 1603 and a left shunt 1604, as depicted in Figure 16. The right shunts 1603 are placed such that the left end is sandwiched between, the TE elements 1601, 1605 in good thermal and electrical contact. Similarly, the left side shunts 1604 are positioned such that the right end is sandwiched between TE elements 1601, 1605, and are in good thermal and electrical contact. The shunts 1602, 1603 and 1604 are alternately stacked and electrically connected to form a shunt stack 1600. A first working fluid 1607 and a second working fluid 1608 pass through the assembly 1600. Of course, for the embodiments shown in Figure 16 and of the stack configurations described herein, the stack may be, and likely will, consist of many additional shunt elements in the stack. The small portions of a stack assembly 1600 are merely depicted to provide the reader with an understanding. Further replication of such stacks is clear from the figures. In addition, additional stacks, thermally isolated in a direction of working fluid flow could be provided.

[0159] When a suitable current is applied in the one direction through the TE elements 1601, shunts 1605, 1604, the center shunts 1602 will be cooled and the left and right shunts 1604 and 1606 will be heated. As a result, the first working fluid 1607 passing through the center shunts 1602 will be cooled and the second working fluid 1608 passing through the right and left shunts 1603, 1604 will be heated. The stack assembly 1600 forms a solid-state heat pump for conditioning fluids. It is important to note that the stack 1600 can have few or many segments and can thereby operate at different power levels, depending on the amount of current and voltage applied, component dimensions and the number of segments incorporated into the assembly. Arrays of such stacks may also be advantageous. In a situation where arrays of such stacks 1600 are used, it would be preferable to provide thermal isolation in the direction of fluid flow as described in U.S. Patent No. 6,539,725 for improved efficiency.

[0160] It should also be understood that the shunts 1602, 1603, 1604 can be replaced by other shapes such as, but not limited to, those depicted in Figures 14 and 15, to improve performance.

[0161] A variation to the stack assembly 1600 depicted in Figure 16 is illustrated in Figure 17. For this configuration, a TE assembly 1700 is constructed of right side shunts 1703 and left side shunts 1704 to form a generally circular shape. The right side shunts 1703 are advantageously configured to form a partial circle as are the left side shunts 1704. In a preferred embodiment, the shunts which become cold during operation may be either larger or smaller than the shunts that become hot, depending on the particular goals of the device. It should be noted that the substantially circular configuration is not necessary, and other configurations of the shunt segments shown in Figure 17 to create a center flow portion could be used. For example, the right side shunts could be half rectangles or half squares, and the left side shunts 1704 could be half rectangles or squares. Similarly, one side could be multi-sided and one side could be arcuate. The particular shape of the shunts are changeable. The TE elements 1701 and 1702, of alternating conductivity type, as discussed for Figure 16, are electrically connected in series in the stack assembly 1700. Preferably, a fluid 1712 passes into the central region formed by the shunts 1703, 1704. A first portion 1707 of the fluid 1712 passes between the right side shunts 1703 and a second portion 1706 of the working fluid 1712 passes between the left side shunts 1704. A power supply 1708 is electrically connected to the TE elements by wires 1712, 1713 that are connected to the stack at connections 1710 and 1711. A fan 1709 may be attached to one (or both) ends of the stack. A pump, blower, or the like could be used as well.

[0162] When power is applied to the fan 1709, it pumps the working fluid 1712 through the assembly 1700. When current is supplied with a polarity such that the right shunts 1703 are cooled, the first fluid portion 1707 of working fluid 1712 is cooled as it passes through them. Similarly, the second portion 1706 of working fluid is heated as it passes through heated left side shunts 1704. The assembly 1700 forms a simple, compact cooler/heater with a capacity and overall size that can be adjusted by the number of shunts 1703, 1704 utilized in its construction. It is apparent that the shunts 1703, 1704 could be angular, oval or of any other advantageous shape. Further, the shunts can be of the designs depicted in Figures 14, 15 or any other useful configuration.

[0163] In one embodiment of the thermoelectric system of Figures 12, 14, 15, 16 and 17, more than one TE element can be used in one or more portions of an array as is depicted in Figure 18. In this example, TE elements 1801, 1804 are connected to raised electrode surfaces 1804 on each side of shunts 1802, 1803.

[0164] A number of TE elements 1801, electrically in parallel, can increase mechanical stability, better distribute thermal power and add electrical redundancy to the system. More than two TE elements 1801 can be used in parallel.

[0165] In certain applications, it is desirable to have exposed portions of shunts in accordance with Figures 12-13 electrically isolated from an electrode portion. One example of such a shunt is depicted in Figure 19. In this embodiment, an electrical insulation 1905 isolates an electrode portion 1903 of a shunt 1900 from a heat exchange portion 1904 of the shunt 1900. TE elements 1901, 1902 are preferably mounted on the electrode portion 1903.

[0166] In operation, electrical potential is applied between TE elements 1901, 1902 of opposite conductivity types, through, advantageously, the electrode portion, 1903 made of a high electrical and thermal conductivity material, such as copper. Thermal power produced by the TE elements 1901, 1902 is conducted along the shunt electrode 1903, through the electrical insulation 1905, and into the heat exchange portion 1904 of the shunt 1900. Advantageously, the electrical insulation 1905 is a very good thermal conductor such as alumina, thermally conductive epoxy or the like. As shown, the interface shape formed by electrical insulation 1905 is a shallow "V" shape to minimize thermal resistance. Any other shape and material combination that has suitably low interfacial thermal resistance can be used as well. A stack of such shunts 1900 can be used as described previously.

[0167] An alternate form of electrical isolation is shown in another shunt segment 2000 assembly depicted in top view in Figure 20. First TE elements 2001 are connected to a left shunt 2003 of shunt segment array 2000, and second TE elements 2002 are connected to a right shunt 2004 of shunt segment array 2000. Electrical insulation 2005 is positioned between left side shunt segments 2003 and right side shunt segments 2004.

[0168] The configuration depicted in Figure 20 provides electrical isolation between TE elements 2001 and 2002 while retaining mechanical integrity of the overall shunt 2000. In this configuration as drawn, the electrical insulation 2005 need not provide particularly good thermal conductivity since the sources of thermal power, the TE elements 2001 and 2002, can cool or heat the left and right shunt segments 2003, 2004, at different levels, provided electrical insulation 2005 is on average centered between the TE elements 2001 and 2002. It should be noted that although two TE elements 2001 and two second TE elements 2002 are depicted, a larger TE element or a larger number of TE elements on each side could be utilized. Two first TE elements 2001 and two second TE elements 2002 are merely selected for illustration of a good stable mechanical structure. It should also be noted that depending on the desired route for current, the first TE element 2001 and the second TE elements 2002 need not be, but may be, of differing conductivity types.

[0169] An alternate method of achieving electrical isolation within a shunt 2100 is depicted in Figure 21. A shunt portion 2103 with two first TE elements 2101 is mechanically attached to a second shunt portion 2104 with two second TE elements 2102. Electrical insulation 2106 mechanically attaches shunt portions 2103 and 2104, which are also separated from one another by a gap 2105.

[0170] In cases where mechanical attachment 2106 is approximately centered between the TE elements 2101 and 2102, and the TE elements 2101 and 2102 produce about equal thermal power, the electrical insulation 2106 need not be a good thermal conductor. The TE elements 2101 and 2102 each provide thermal power to the respective shunt portions 2103 and 2104. Electrical insulation 2106 can be adhesive-backed Kapton tape, injection molded plastic, hot melt adhesive or any other suitable material. As shown in plan view in Figure 21, the shunt portions 2103 2104 do not overlap to form a lap joint. Such a joint, with epoxy or other electrically insulating bonding agent could also be used.

[0171] Another shunt segment array 2200, depicted in top view in Figure 22, has electrically isolated shunt segments in a rectangular TE array 2200. First TE elements 2201 are thermally connected to first shunt portions 2202, and second TE elements 2203 are thermally connected to second shunt portions 2204. Each shunt portion is separated electrically from the other shunt portions by gaps 2210, 2211. Electrical insulation 2208 at the left side of the assembly, insulation 2207 in the middle and insulation 2209 on the right side are preferably provided. An arrow 2212 indicates working fluid flow direction. This configuration can be operated at higher voltage and lower current than a similar array without electrical isolation. As noted for Figure 20, first TE elements 2201 and second TE elements 2203 need not, but may be, of differing conductivity types. This will depend on the direction of desired current flow. The TE elements 2202, 2203 may, however, be at different potentials.

[0172] The gaps 2210 serve to effectively thermally isolate first shunt portions 2202 from each other, and second shunt portions 2204 from each other. Similarly, the side insulation 2208, 2209 provide both thermal and electrical isolation while mechanically attaching the shunts together. Center insulation 2207 provides electrical insulation and thermal isolation along its length. Thus, array 2200 is constructed to produce thermal isolation in the direction of arrow 2212 as described in U.S. Patent No. 6,539,725. This configuration can be operated at higher voltage and lower current than a similar array without electrical isolation.

[0173] A cooling system 2300 that employs shunt segment arrays generally of the type described in Figure 22, is depicted in Figure 23. The cooling system 2300 has inner shunt segments 2301, 2302 connected mechanically by electrically insulating material 2320 such as tape. The inner shunt segments 2302 are mechanically connected by electrically and thermally insulating material 2321. Similarly, the inner segments 2301 are mechanically connected by electrically and thermally insulating material 2307. The inner shunt segments 2301, 2302 separately are connected to TE elements at the ends (not shown) in a manner described for Figure 22. The TEs are sandwiched in the stack between inner shunt segments 2301, 2302 and respective outer shunt segments 2303, 2305. The center shunt segments 2301 separately are connected to outer left shunt segments 2305, and the inner shunt segments 2302 are connected to right outer shunt segments 2303. Preferably, the right outer shunt segments 2303 are similarly mechanically connected by electrically and thermally insulating material 2322 which is similar to electrically insulating material 2321 connecting the inner shunt segments 2302. The left outer shunt segments 2305 are similarly mechanically connected. A housing 2311 holds a stack array of shunt segments and TEs. Terminal posts 2312 and 2314 are electrically connected to inner segments 2301. Similarly, terminals 2315 and 2316 connect to inner shunt segments 2302. Preferably, thermally and electrically insulating spacers 2309, 2310 are positioned between each inner and outer segment.

[0174] A first working fluid 2317 passes through the inner region and a second working fluid 2318, 2319 passes through the outer regions. When voltages of the proper polarities and magnitude are applied between terminals 2312 and 2314, 2315 and 2316, the inner shunt segments 2301, 2302 are cooled. Also, the outer shunt segments 2303, 2305 are heated. Thus, the working fluid 2317 passing through the inner region is cooled, and the working fluid 2318, 2319 passing through the outer shunt segments 2303, 2305 is heated. The housing 2311 and the insulators 2309, 2310 contain and separate the cooled fluid 2317 from the heated fluid 2318, 2319.

[0175] The electrical connections to energize each stack in the system 2300 can be in series to operate at high voltage, in series/parallel to operate at about half the voltage or in parallel to operate at about ¼ the voltage. Polarity could be reversed to heat the inner working fluid 2317 and cool the outer working fluids 2318, 2319. More segments could be utilized in the direction of working fluids 2317, 2318, 2319 flow to operate at even higher voltage and to achieve higher efficiency from the resultant more effective thermal isolation.

[0176] Another compact design that achieves enhanced performance from thermal isolation uses combined shunt and heat transfer segments 2400 as depicted in Figure 24A and 24B. This design is very similar to that of Figure 14, but with TE elements 2401, 2402 aligned in the general direction of fluid flow. The TE elements 2401, 2402 of opposite conductivity type are connected to an extension 2403 of a shunt 2404. Preferably, heat exchangers 2405, 2406, such as fins, are in good thermal contact with the shunt 2404. A working fluid 2409 is heated or cooled as it passes through heat exchanger fins 2405, and 2406, depending on the direction of current flow.

[0177] Figure 24B depicts a portion of a stack 2410 consisting of TE shunt segments 2400 as shown in Figure 24A. Current 2417 flows in the direction indicated by the arrow. A plurality of first side shunts 2400 and a plurality of second side shunts 2400a are connected to TE elements 2411. A first working fluid 2418 flows along the lower portion of stack 2410 through the heat exchangers on the second side shunts 2400a in Figure 24a, and a working fluid 2419 flows advantageously in the opposite direction through the heat exchangers of first side shunts 2400.

[0178] When suitable current 2417 is applied, the upper portion of the stack 2410 progressively cools fluid 2419 as it passes from one segment to the next, and the lower portion progressively heats fluid 2418 as it passes from one shunt 2400a to the next.

[0179] An alternative TE stack configuration 2500 is depicted in Figure 25A. This TE stack achieves the benefits of thermal isolation with a working fluid 2513 flowing generally perpendicular to the direction of current flow 2512. A first shunt 2502 is connected electrically to a first TE element 2501 and is in good thermal contact with heat exchangers 2503, 2504. A second first side shunt 2506 is similarly in good thermal contact with its heat exchangers 2508, and a third first side shunt 2505 is in good thermal contact with its heat exchangers 2507. Interspersed between each first side shunt 2502, 2506 and 2505 are TE elements 2501 of alternating type and second side shunts 2509, 2510 and 2511 projecting generally in the opposite direction, as with Figure 12. Second side shunts 2509, 2510 and 2511, not fully depicted, are generally of the same shape and bear the same spatial relationship as first side shunts 2502, 2506 and 2505. A working fluid 2513 passes through the stack assembly in the direction indicated by the arrow. When suitable current is applied vertically through the TE elements, first side shunts 2502, 2505 and 2506 are heated and second side shunts 2509, 2510 and 2511 are cooled. As the working fluid 2513 passes first through heat exchanger 2507, then through the heat exchanger 2508 and finally through the heat exchanger 2503, it is progressively heated. A full stack assembly has repeated sections of the array 2500, in the direction of current flow, assembled so that the top of heat exchanger 2503 would be spaced closely to the bottom of the next sequential heat exchanger 2504 of another array portion. The thermal isolation in the direction of working fluid 2513 flow is readily apparent.

[0180] Figure 25B is a plan view of the array portion 2500 depicted in Figure 25A. The cooling of a plurality of TE elements 2501, alternating in conductivity type, are interspersed with the plurality of first side shunts 2502, 2506, 2505, and a plurality of second side shunts 2511, 2509 and 2510, so that the first side shunts 2502, 2506 and 2505 alternate with the second side shunts 2511, 2509 and 2510. The shunts are separated by gaps 2534 and are in good thermal contact with heat exchangers for each shunt. A first working fluid 2531 passes along the upper section from right to left and a working fluid 2532 passes advantageously from left to right along the lower section. Thermal and electrical insulation 2533 is preferably provided between each pair of shunts, except where the electrical current flows through the TEs and shunts.

[0181] When suitable current passes through the array 2500, for example, the working fluid 2531 is progressively heated and the working fluid 2532 is progressively cooled. The insulation 2533 prevents unnecessary thermal losses and also prevents the working fluids 2531, 2532 from mixing. The array 2500, as shown, operates in counter flow mode, and employs thermal isolation to enhance performance. The same array 2500, can operate with the working fluids 2531, 2532 moving in the same direction in parallel flow mode, and still have the benefits of thermal isolation to enhance performance. In either case, advantageously, the TE elements 2521 are not all of the same resistance, but have resistances that vary depending on the temperature and power differentials between individual TE elements, as described in U.S. Patent No. 6,539,735.

[0182] Another TE module 2600 is depicted in Figure 26A, that uses the principles discussed in the present description to achieve operation at higher voltages and possible other benefits such as higher power density, compact size, ruggedness, higher efficiency. A first TE element 2601 is sandwiched between a first end shunt 2603 and a second shunt 2604. A second TE element 2602, of opposite conductivity type is sandwiched between the second shunt 2604 and a third shunt 2605. This pattern is continued to final end shunt 2606. A current 2607 flows into final end shunt 2606, through the TE modules and out the first end shunt 2603, as indicated by arrows 2608 and 2609. Gaps 2611 prevent electrical conduction and reduce thermal conduction between adjacent shunts. In one embodiment, the first end shunt 2603 and the final end shunt 2606 have an electrode surface 2612. The other shunts have shunt surfaces 2614 that are thermally conductive but electrically insulating from the body of the shunts.

[0183] In operation, suitable current 2608 passes through the TE module 2600 heating the upper surface and cooling the lower surface (or vice versa). The TE module 2600 depicted in Figure 26A consists of five TE elements and six shunts. Advantageously, any odd number of TE elements can be employed, spaced alternately with shunts as depicted. Further, more than one TE element (of the same type as explained for Figure 18) may be connected in parallel between each pair of shunts. To achieve alternative functionality, an even number of TEs can be used, such as to have electrical power confined to electrically isolated portions of one surface.

[0184] An array 2620 of TE modules 2600 is depicted in Figure 26B. Figure 26B depicts two TE modules 2600, of the type shown in Figure 26A, stacked on top of each other with a center heat transfer member 2635 sandwiched between first side shunts 2604. Outer heat transfer members 2632 and 2636 are thermally coupled to second side shunts 2605. The shunt and heat transfer members can also be of any other suitable types, for example, the types presented in Figures 14 and 15. A first end shunt 2603 of a first TE module is electrically connected to the outer heat transfer members 2632. Similarly, the other end shunt 2606 of the first or upper TE module is electrically connected to the center heat transfer member 2635. Similarly, a second end shunt 2606a of the second TE module is electrically coupled to the center heat transfer member 2635 and the first end shunt 2603a of the second TE module is electrically coupled to the outer heat transfer member 2636 on the bottom of Figure 26B. Other than the end shunts, 2603, 2606, 2606a and 2603a, the other shunts 2604, 2605 have electrical insulation 2612 that is thermally conductive. In addition, as in the arrangement of Figure 26A, the shunts have gaps 2611 to electrically isolate them from one another. Current flow is indicated by the arrows 2628, 2629, 2630, 2631 and 2637. As depicted, the TE elements 2601, 2602 alternate in conductivity type.

[0185] When suitable current is passed through the array 2620, second side shunts 2605 and the outer heat transfer members 2632 and 2636 are heated. The first side shunts 2604 and center heat transfer member 2635 are cooled. The opposite is true for reversed current. The operating current can be adjusted along with the corresponding voltage by adjusting the dimensions and number of TE elements 2601, 2602. Similarly, power density can be adjusted. It should be noted that a larger number of shunts and TE elements could be used, which would widen the configuration shown in Figure 26B. In addition, further TE modules 2600 could be stacked in a vertical direction. In addition, an array of such stacks into or out of the plane of Figure 26B could be provided or any combination of the above could be utilized. In a suitable array, thermal isolation principles in the direction of heat transfer or working fluid flow could be utilized in accordance with the description in U.S. Patent No. 6,539, 725.

[0186] An alternative embodiment of a TE module 2700, similar in type to the TE module 2600 of Figure 26A, is illustrated in Figure 27. End shunts 2705, 2704 are electrically connected to a power source 2720 and ground 2709. TE elements 2701, 2702 are electrically connected to between the series of shunts 2703, 2704, 2705, 2706. In this embodiment, all shunts 2703, 2704, 2705, 2706 are electrically isolated by insulation 2711 from first and second heat transfer members 2707, 2708. The shunts are in good thermal contact with the heat transfer members 2707, 2708. First side heat transfer member 2708 moves in the direction indicated by an arrow 2712. Advantageously, the second side heat transfer member 2707 moves in the opposite direction, as indicated by an arrow 2710.

[0187] When suitable current is applied to the TE module 2700, the second side heat transfer member 2707 is cooled and the first side heat transfer member 2708 is heated. Operation is similar to that associated with the description of Figure 7A, 7B, 7C, and 7D. It should be noted that the first and second heat transfer members 2707, 2708, need not be rectangular in shape as might be inferred from Figure 27, but may be disk shaped or any other advantageous shape, such as those discussed in Figure 7A. With effective design, the TE module 2700 can also achieve the performance benefits associated with thermal isolation as discussed in U.S. Patent No. 6,539,725.

[0188] In an alternative embodiment, heat transfer components 2707 and 2708 do not move. In that configuration, the TE module 2700 is similar to a standard module as depicted in Figure 1, but can operate with a high power density and utilize relative thin TE elements 2701, 2702. Advantageously, the TE module 2700 induces low shear stresses on the TE elements 2701, 2702 that are produced by thermal expansion differences between the first side and second side shunts, for example. Because shear is generated in the TE module 2700 by the temperature differential across TE elements 2701, 2702, and is proportional to the width dimension, it can be much less than the shear in a standard TE module, in which the shear is proportional to the overall module width. The differences can be seen from a comparison of Figure 12 with a standard module depicted in Figure 1. Standard modules with more than two TE elements of the same dimensions as those in the configuration of

Figure 12 will exhibit disadvantageously high shear stresses. Such stresses limit thermal cycling durability and module size.

[0189] Figure 27 also provides a good illustration to describe how the embodiments described in this specification can be used for power generation as well. In such a configuration, the terminals 2709, 2720 are connected to a load rather than a power source in order to provide power to a load. The heat transfer members 2708, 2707 provide thermal power in the form of a temperature gradient. The temperature gradient between the first heat transfer member 2708 and second heat transfer member 2707 causes the thermoelectric system 2700 to generate a current at terminals 2709, 2720, which in turn would connect to a load or a power storage system. Thus, the system 2700 could operate as a power generator. The other configurations depicted in this description could also be coupled in similar manners to provide a power generation system by applying a temperature gradient and deriving a current.

[0190] A TE heat transfer system 2800 is depicted in Figure 28 that uses a gas working fluid 2810, and a liquid working fluid 2806. In this embodiment, first side shunt heat exchangers 2803 are of construction depicted in Figure 24A and Figure 24B. The shunt heat exchangers 2803 transfer thermal power with the gaseous working media 2810. In this embodiment, second side shunts heat exchanger 2804, 2805 transfer thermal power with liquid working media 2806. A plurality of TE elements 2801 of opposite conductivity types are sandwiched between second side shunts 2804, 2805 and the shunt heat exchanger 2803. The second side shunt heat exchangers 2804, 2805 are similarly sandwiched between TE elements 2801 of alternating conductivity type. A current 2812, 2813 passes through the system 2800 as represented by the arrows 2812, 2813. In this embodiment, tubes 2814, 2815 pass the liquid working media 2806 from one shunt heat exchanger 2804, 2805 to the next one.

[0191] Operation of the TE heat transfer system 2800 is similar to that of the description of Figure 24B, with one working fluid 2810 being gaseous and the other 2806 being liquid. The benefits of thermal isolation as described in U.S. Patent No. 6,539,725 are also achieved with the design depicted in system 2800.

[0192] Figure 29 depicts details of a shunt heat exchanger 2900. The assembly advantageously has a container 2901 constructed of very good thermally conductive material, an electrode 2902 constructed of very good electrically conductive material, and heat transfer fins 2905 and 2906 in good thermal contact with the top and bottom surfaces of container 2901. In one embodiment, the container 2901 and the electrode 2902 are constructed of a single material, and could be unitary in construction. Advantageously, an interface 2904 between the bottom surface of container 2901 and electrode 2902 has very low electrical resistance. Fluid 2909 passes through the shunt heat exchanger 2900.

[0193] In operation, TE elements, not shown, are electrically connected to the top and bottom portions of the electrode 2902. When suitable current is applied through the TEs and the electrode 2902, the container 2901 and the fins 2905, 2906 are heated or cooled. The working fluid 2909 passing through the shunt heat exchanger 2900 is heated or cooled by the heat exchange 2900. Advantageously, the shunt heat exchanger 2900 is of sufficiently good electrical conductivity that it does not contribute significantly to parasitic losses. Such losses can be made smaller by minimizing the current path length through electrode 2902, maximizing electrical conductivity throughout the current path, and increasing electrode 2902 cross sectional area.

[0194] The container 2901 top and bottom surfaces, and fins 2905 and 2906 provide sufficient electrical conductivity in the direction of current flow, that the solid electrode body 2902 can be reduced in cross sectional area or completely eliminated as shown in the embodiment in Figure 4B.

[0195] A heat sink and fluid system 3000 is depicted in Figure 30. TE elements 3001 of alternating conductivity types are interspersed between fluid heat exchanges 3004, each having shunt portions 3003, and shunts 3002 and 3005. Current 3006, 3007 flows through the shunt portions 3003, the shunts 3002 and 3005 and the TE elements 3001. A working fluid 3009 flows as indicated by the arrow. Heat sinks 3010, 3011 are in good thermal contact with and electrically insulated from the shunts 3002, 3005. In embodiments with metallic or otherwise electrically conductive heat sinks 3010, 3011 electrical insulation 3008, 3012 that advantageously has good thermal conductance confines the current flow 3001, 3007 to the circuit path indicated.

[0196] When suitable current 3006, 3007 is applied, thermal power is transferred to the heat sinks 3010, 3011 and from the working fluid 3009. The shunt heat transfer members 3004 are thermally isolated from one another so that performance gains from thermal isolation are achieved with this embodiment.

[0197] An alternative shunt heat exchanger embodiment 3100 is depicted in Figure 31A. A shunt portion 3101 has electrodes 3102 for connection to TE elements (not shown) and heat transfer extensions 3108 in good thermal contact with heat exchangers 3103, such as fins. A fluid 3107 passes through the heat exchangers 3103.

[0198] The shunt heat exchanger 3100 preferably has electrodes 3102 located generally centered between heat transfer extensions 3108. In this embodiment, thermal power can flow into and out of the TE assemblies in two directions, and thus can increase heat transfer capacity by about a factor of two per TE element in comparison to the embodiment depicted in Figure 24A. The shunt side may have increased heat transfer characteristics such as by incorporation heat pipes, convective heat flow, or by utilizing any other method of enhancing heat transfer.

[0199] Figure 31B depicts a heat transfer shunt assembly 3110 with a shunt 3111, electrodes 3112 and influent fluid ports 3113, 3114, and effluent fluid ports 3115, 3116. The heat transfer shunt assembly 3110 can have increased heat transfer capacity per TE element and more fluid transport capacity than the system depicted in Figure 29.

[0200] Figure 31C depicts a shunt assembly 3120 with shunt member 3121, electrodes 3122 and heat exchange surfaces 3123, 3124. The shunt assembly 3120 can have approximately two times the heat transfer capacity per TE assembly as the embodiment depicted in Figures 26A and 26B. However, in contrast to the usage described in Figures 26 A and 26B, stacks of shunt assemblies 3120 would alternate at approximately right angles to one another and the surfaces 3123, 3124 opposite one another would both be heated, for example, and the next pair of surfaces in the stack at about a right angle to the heated pair, would be cooled. Alternatively the surfaces 3123, 3214 could be at other angles such as 120° and be interdispersed with shunts 2604 as depicted in Figure 26. Any combination of multisided shunts is part of the inventions.

[0201] It should be noted that the reduction in thermoelectric material can be quite dramatic. For example, the thermoelectric elements discussed herein may be as thin as 5 microns to 1.2 mm in one general embodiment. For superlattice and heterostructure configurations, such as could be accomplished using the embodiments of Figures 31A-C, 26A-B, and 27, thermoelectric elements may be between 20 microns and 300 microns thick, more preferably from 20 microns to 200 microns, and even from 20 microns to 100 microns. In another embodiment, the thickness of the thermoelectric elements is between 100 microns and 600 microns. These thicknesses for the thermoelectric elements are substantially thinner than conventional thermoelectric systems.

[0202] It should be noted that the configurations described do not necessarily require the TE elements to be assembled into arrays or modules. For some applications, TE elements are advantageously attached directly to heat transfer members, thereby reducing system complexity and cost. It should also be noted that the features described above may be combined in any advantageous way without departing from the invention. In addition, it should be noted that although the TE elements are shown in the various figures to appear to be of similar sizes, the TE elements could vary in size across the array or stack, the end type TE elements could be of different size and shape than the P-type TE elements, some TE elements could be hetero structures while others could be non-hetero structure in design.

[0203] In general, the systems described in these figures do operate in both cooling/heating and power generation modes. Advantageously, specific changes can be implemented to optimize performance for cooling, heating or power generation. For example, large temperature differentials (200 to 2000° F) are desirable to achieve high-efficiency in power generation as is well know in the art, while small temperature differentials (10 to 60° F) are characteristic of cooling and heating systems. Large temperature differentials require different construction materials and possibly TE modules and elements of different design dimensions and materials. Nevertheless, the basic concept remains the same for the different modes of operation. The designs described in Figures 5, 8 and 9 are advantageous for power generation because they offer the potential to fabricate simple, rugged, low-cost designs. However, all of the above mentioned designs can have merit for specific power generation applications and cannot be excluded.

Thermoelectric Power Generating Systems

[0204] Certain embodiments described herein provide a novel thermoelectric power generator (TPG) system which incorporates state of the art material technology with optimized thermal management. Results from a numerical model of certain embodiments described herein can simulate the operation of the system and facilitates its design. Advanced multi-parameter, gradient-based optimization techniques can also be used to better understand the interactions between various design variables and parameters in order to progress towards an optimal TPG system design in accordance with certain embodiments described herein.

[0205] In certain embodiments described herein, the system comprises a series of segmented thermoelectric (TE) elements (e.g., each TE element comprising up to three different materials). Certain embodiments advantageously combine thermal isolation in the direction of flow of a working fluid with high power density TE materials integrated directly into the heat transfer device. Electrical current runs parallel to the heat source and sink surfaces in certain embodiments, advantageously allowing integration of the TE material with multiple geometric degrees of freedom. In certain embodiments in which this design attribute is combined with a thermal isolation thermodynamic cycle, the system advantageously allows each TE element of the system to be optimized semi-independently. In certain embodiments, each P- and N-type TE element can have a different aspect ratio selected so that the TE material layers of each TE element have sufficiently high (e.g., the highest possible or high enough to provide the desired efficiency) values for a figure of merit (ZT) in the temperature ranges applied to the TE layers during operation. The increased design flexibility of certain embodiments described herein advantageously helps address TE material compatibility issues associated with segmented TE elements and fluid flow that ordinarily degrade performance. Eliminating the impact of thermal expansion mismatch while still maintaining excellent thermal and electrical contacts is also advantageously achieved by certain embodiments described herein. Additional design considerations, including electrical and thermal connector design and minimizing interfacial resistances, are also selected in certain embodiments described herein to optimize the design of the TE system. The system of certain embodiments is suitable for both waste heat recovery and primary power applications.

[0206] The potential of using thermoelectrics to generate power usefully has increased significantly in recent years. Advancements in new higher temperature materials with figures of merit (ZT) substantially greater than unity are under development at places such as Michigan State University (see, e.g., K.F. Hsu *et al.*, "Cubic $AgPb_mSbTe_{2+m}$: Bulk Thermoelectric Materials with High Figure of Merit," *Science*, Vol. 303, Feb. 6, 2004, pp. 818-821) and Lincoln Laboratory at Massachusetts Institute of Technology (MIT) (see, e.g., T.C. Harman *et al.*, "Quantum Dot Superlattice Thermoelectric Materials and Devices," *Science*, Vol. 297,(2002), pp. 2229-2232). In addition, Jet Propulsion Laboratory (JPL) has had considerable success in developing material segmentation concepts (see, e.g., T. Caillat *et al.*, "Development of High Efficiency Segmented Thermoelectric Unicouples," *20th Int'l Conf. on Thermoelectrics,* Beijing, China, 2001, pp. 282-285).

[0207] Meanwhile, BSST, Inc. has demonstrated the benefits of thermal isolation in the direction of flow (see, e.g., L.E. Bell, "Use of Thermal Isolation to Improve Thermoelectric System Operating Efficiency," *21st Int'l Conf. on Thermoelectrics,* Long Beach, California, 2002, pp. 477-487; and R.W. Diller *et al.*, "Experimental Results Confirming Improved Performance of Systems Using Thermal Isolation," *21st Int'l Conf. on Thermoelectrics,* Long Beach, California, 2002, pp. 548-550). These benefits can include improved HVAC coefficients of performance (COP), as well as high power density designs that require about $1/6^{th}$ the TE material usage of conventional TE-based power generator designs (see, e.g., L.E. Bell, "High Power Density Thermoelectric Systems," *23rd Int'l Conf. on Thermoelectrics,* Adelaide, Australia, 2004).

[0208] Certain embodiments described herein build upon these developments and utilize additional design innovations to further increase the amount of power that can be extracted from a heat source using thermoelectrics. Certain embodiments are advantageously combined with high power density concepts (see, e.g., L.E. Bell, "Alternate Thermoelectric Thermodynamic Cycles with Improved Power Generation Efficiencies," *22nd Int'l Conf. on Thermoelectrics,* Hérault, France, 2003).

[0209] Figure 32 schematically illustrates a portion of an example thermoelectric system 3200 in accordance with certain embodiments described herein. In certain embodiments, the configuration schematically illustrated by Figure 32 advantageously provides various benefits, as discussed more fully below. In certain embodiments, the configuration schematically illustrated by Figure 32 more readily accommodates TE elements of different thicknesses, areas, and thermal expansion coefficients. This configuration also accommodates the use of high power density materials, TE elements sized to provide high pwer density operation, and thermal isolation in the direction of working fluid flow.

[0210] The thermoelectric system 3200 comprises a first thermoelectric element 3210 comprising a first plurality of segments 3212 in electrical communication with one another. The thermoelectric system 3200 further comprises a second thermoelectric element 3220 comprising a second plurality of segments 3222 in electrical communication with one another. The thermoelectric system 3200 further comprises a heat transfer device 3230 comprising at least a first portion 3232 and a second portion 3234. The first portion 3232 is sandwiched between the first thermoelectric element 3210 and the second thermoelectric element 3220. The second portion 3234 projects away from the first portion 3232 and is configured to be in thermal communication with a working medium (not shown).

[0211] In certain embodiments, at least some of the first plurality of segments 3212 are in series electrical communication with one another and at least some of the second plurality of segments 3222 are in series electrical communication with one another. In certain embodiments, at least some of the first plurality of segments 3212 are in series/parallel electrical communication with one another and at least some of the second plurality of segments 3222 are in series/parallel electrical communication with one another.

[0212] Figure 32 schematically illustrates an example stack comprising three heat transfer devices 3230 separated by the first TE element 3210 and the second TE element 3220. Certain other embodiments comprise at least one stack comprising a plurality of TE elements (alternating P-type and N-type TE elements) and heat transfer devices, with the heat transfer devices sandwiched between at least two TE elements of the plurality of TE elements.

[0213] The heat transfer devices 3230 of certain embodiments provide an electrical path from the first TE element 3210 to the second TE element 3220, thereby completing a TE p-n couple, such that current from a current source traverses the first TE element 3210, the heat transfer device 3230, and the second TE element 3220 in series. In certain such embodiments, the current traverses the first plurality of segments 3212 in series and the current traverses the second plurality of segments 3222 in series.

[0214] The heat transfer devices 3230 of certain embodiments also provide a thermal path from the working fluid to the TE elements 3210, 3220. Electrical current flows parallel to the heat source and sink surfaces in the configuration schematically illustrated by Figure 32, thereby allowing the integration of the TE material with multiple geometric degrees of freedom. In certain embodiments, the heat transfer devices 3230 thermally isolate at least some of the TE elements from at least some other of the TE elements. The plurality of heat transfer devices 3230 are arranged in certain embodiments to provide thermal isolation in a direction of a working medium flow.

[0215] In certain embodiments, the second portion 3234 of the heat transfer device 3230 is wider than the first portion 3232 of the heat transfer device 3230 in at least one direction (e.g, in a direction generally along a direction of working medium movement). In certain embodiments, the second portion 3234 has a generally flat surface configured to be in thermal communication with the working medium.

[0216] In certain embodiments, the stack comprises a plurality of first heat transfer devices and a plurality of second heat transfer devices, with the first and second heat transfer devices alternating along the stack. The first heat transfer devices project in a first direction and the second heat transfer devices project in a second direction different from the first direction. The second direction in certain embodiments is generally opposite to the first direction, as schematically illustrated by Figure 32. In certain embodiments, the first heat transfer devices are configured to be in thermal communication with a first working medium (e.g., a flowing first working fluid) and the second heat transfer devices are configured to be in thermal communication with a second working medium (e.g., a flowing second working fluid).

[0217] The heat transfer device 3230 having a first portion 3232 and a second portion 3234 projecting away from the first portion 3232 in certain embodiments provides one or more benefits over rectangular-shaped heat transfer devices. To reduce electrical resistance and weight of the heat transfer device 3230, the thickness of the first portion 3232 in the direction of electrical current flow can advantageously be minimized. Furthermore, the dimensions of the first portion 3232 in a plane generally perpendicular to the direction of electrical current flow can advantageously be optimized to provide sufficient electrical and thermal conductivity to the TE elements 3210, 3220. The surface area and/or the thickness of the second portion 3234 along the direction of working fluid flow can advantageously be increased to provide a larger thermal conduit between the heat source or heat sink and the first portion 3232 of the heat transfer device 3230, thereby avoiding a large thermal resistance. It is also advantageous for the second portion 3234 to be wide in a direction generally along the stack and short in a direction generally perpendicular to the stack. Keeping the second portion 3234 short in a direction generally perpendicular to the stack advantageously reduces the thermal resistance from the heat source or heat sink to the surface of the TE element. Weight, structural stability, TE surface area, and temperature gradients at interfaces can each be considered in designing the final dimensions of the heat transfer device 3230.

[0218] In certain embodiments, the first plurality of segments 3212 comprises two, three, four, or more different thermoelectric materials. In certain embodiments, the second plurality of segments 3222 comprises two, three, four, or more different thermoelectric materials. For example, as shown in Figure 32, the first plurality of segments 3212 has three P-type segments 3212a, 3212b, 3212c comprising different TE materials (e.g., p-$CeFe_3RuSb_{12}$, p-TAGS, and p-Bi_2Te_3, respectively) and the second plurality of segments 3222 has three N-type segments 3222a, 3222b, 3222c (e.g., n-$CoSb_3$, n-PbTe, n-Bi_2Te_3, respectively). In Figure 32, the first TE element 3210 is exposed to a horizontal temperature gradient with the hot end at the left, and the second TE element 3220 is exposed to a horizontal temperature gradient with the hot end at the right. As described more fully below, by segmenting the TE materials, the TE elements of certain embodiments can be designed to better achieve a higher average ZT over the temperature range at which the TE elements are intended to operate by matching the properties of the materials of each TE element across the TE elements to the operating temperature gradients or temperature profile across the TE elements.

[0219] The energy conversion efficiency of a TE element generally increases strongly as the average dimensionless figure of merit, ZT, of the TE element increases. Figures 33A and 33B show the figures of merit (ZT) as functions of temperature for various P-type and N-type thermoelectric materials, respectively, compatible with certain embodiments described herein. A material can have a set of one or more thermoelectric properties which determine the efficiency of the material's performance at a given temperature, and the figure of merit is an example parameter characteristic of the set of one or more thermoelectric properties.

[0220] For example, for low temperatures (e.g., less than 150°C), Bi_2Te_3 has the highest ZT for both P-type and N-type TE materials. For intermediate temperatures, (e.g., 150-500°C), TAGS is an optimal P-type material, and Zn_4Sb_3 is another option for this approximate temperature range. PbTe has a high ZT for this same approximate temperature range for N-type materials. For higher temperature ranges (e.g., 500-700°C), skutterudite (e.g., p-$CeFe_4Sb_{12}$, n-$CoSb_3$) has a high ZT. Certain embodiments described herein utilize TE elements in which the materials and/or material combinations provide sufficiently high (e.g., the highest possible or high enough to provide the desired efficiency) average ZT over the temperature range of use.

[0221] As an example of TE material properties, Figure 34 depicts the figure of merit, ZT, as a function of temperature for three different compositions of lead telluride (denoted by M_1, M_2, and M_3) doped with various levels of iodine. Figure 34 shows that no one material has the highest ZT over the full range of temperatures from 100°C to 570°C. Composition M_1 has the highest ZT for temperatures from about 100°C to about 335°C, composition M_2 has the highest ZT for temperatures from about 335°C to about 455°C, and composition M_3 has the highest ZT for temperatures from about 455°C to about 570°C. If TE elements are fabricated from any single composition over the 100°C to 570°C temperature range, the average ZT will be substantially lower than that of an element fabricated from all three compositions suitably configured so that each composition or TE segment is subjected to temperatures in the range in which it has the highest ZT of the three compositions. While Figure 34 corresponds to various compositions of lead telluride doped with iodine, other TE materials and dopants are also compatible with various embodiments described herein (see, e.g., Figures 33A and 33B).

[0222] In certain embodiments, one of the first and second TE elements 3210, 3220 comprises P-type TE materials and the other of the first and second TE elements 3210, 3220 comprises N-type TE materials. In certain such embodiments, the different P-type and N-type TE materials of the segments of the first and second TE elements 3210, 3220 are selected to provide a sufficiently high (e.g., the highest possible or high enough to provide the desired efficiency) average ZT for the temperature ranges over which the segments of the first and second TE elements 3210, 3220 are intended to operate.

[0223] For example, the first plurality of segments 3212 comprises at least a first TE segment and a second TE segment comprising different materials. The thermoelectric system 3200 can be configured in certain embodiments to be operated such that the first TE segment is exposed to a first temperature range and the second TE segment is exposed to a second temperature range. The first TE segment operates more efficiently in the first temperature range than in the second temperature range. The second TE segment operates more efficiently in the second temperature range than in the first temperature range.

[0224] Referring to the system 3200 of Figure 32, in certain embodiments, the first TE element 3210 comprises three TE segments 3212a, 3212b, 3212c of different materials. The system 3200 is configured to be operated such that the first TE segment 3212a is exposed to a first temperature range, the second TE segment 3212b is exposed to a second temperature range, and the third TE segment 3212c is exposed to a third temperature range. The first TE segment 3212a operates more efficiently in the first temperature range than in either the second or third temperature ranges. The second TE segment 3212b operates more efficiently in the second temperature range than in either the first or third temperature ranges. The third TE segment 3212c operates more efficiently in the third temperature range than in either the second or third temperature ranges.

[0225] Similarly, in certain embodiments, the second plurality of segments 3222 comprises at least a first TE segment exposed to a first temperature range and a second TE segment exposed to a second temperature range, the first and second TE segments comprising different materials. The first TE segment operates more efficiently in the first temperature range than in the second temperature range. The second TE segment operates more efficiently in the second temperature range than in the first temperature range. Referring to Figure 32, in certain embodiments, the second TE element 3220 comprises three TE segments 3222a, 3222b, 3222c of different materials and is configured to be operated such that the first TE segment 3222a is exposed to a first temperature range, the second TE segment 3222b is exposed to a second temperature range, and the third TE segment 3222c is exposed to a third temperature range. The first TE segment 3222a operates more efficiently in the first temperature range than in either the second or third temperature ranges. The second TE segment 3222b operates more efficiently in the second temperature range than in either the first or third temperature ranges. The third TE segment 3222c operates more efficiently in the third temperature range than in either the second or third temperature ranges.

[0226] In certain embodiments, various other factors may also be considered in selecting the TE materials to be used as a function of operating temperature, including but not limited to, thermal stability, mechanical stability, and cost. As described more fully below, another factor in designing TE elements compatible with certain embodiments described herein is the impact of compatibility mismatch on optimum power output when the efficiencies for different element segments occur at significantly different current densities (e.g., compatibility factor), (see, e.g., J.G. Snyder, "Thermoelectric Power Generation: Efficiency and Compatibility," *Thermoelectrics Handbook, Macro to Nano,* Edited by D.M. Rowe, Ph.D., D.Sc. (2006)).

[0227] Power curves for TE materials are generally parabolic with increasing current. For segmented TE elements in which different TE materials are used together, the power curves of the TE elements and/or the segments can have their optimum power outputs occurring at significantly different current densities. These differences in power curves can reduce the overall efficiency of a segmented TE element.

[0228] In certain embodiments in which the temperatures across the TE elements differ (e.g., having a series of TE elements assembled in the direction of working fluid flow), the effects of such power curve compatibility conflicts can be significant. Figure 35 shows the power curve compatibility conflict among three TE elements constructed in series in the direction of flow where the hot side temperature T_h is declining from 700K to 500K. A first TE element is exposed to a hot side temperature T_h = 700K, a second TE element is exposed to a hot side temperature T_h = 600K, and a third TE element is exposed to a hot side temperature T_h = 500K. The cold side temperature T_c for each of these three TE elements remains constant for this example at 300K. Ideally, each TE element would operate at a current that produces peak power output. However, since the three TE elements are electrically connected in series, they each are run using the same current. While the first TE element has its maximum power at 130A, the other two TE elements have output powers that are suboptimal (e.g., less than their corresponding maximum powers) at this current. In particular, the third element operating between 500K and 300K has zero output power at 130A. The total peak power output for this example is 7.69W, considerably below the individual peak power outputs of the individual TE elements. In other examples, the output power of the third TE element can be negative at the optimal current of the first TE element, such that the third TE element subtracts power from the other two TE elements.

[0229] In certain embodiments, the form factors or shapes of the TE elements are advantageously selected so that the power produced by each TE element operates at a current which provides peak power or peak efficiency. In certain such embodiments, the aspect ratios of the TE elements are changed in the direction of flow, thereby advantageously reducing the effects of TE compatibility conflicts among the TE elements. For example, referring to Figure 32, in certain embodiments, the first TE element 3210 has a first thickness along a first direction (e.g., the direction of current flow through the first TE element 3210) and a first cross-sectional area in a plane generally perpendicular to the first direction. The second TE element 3220 has a second thickness along a second direction (e.g., the direction of current flow through the second TE element 3220) and a second cross-sectional area in a plane generally perpendicular to the second direction. In certain embodiments, the second thickness is greater than the first thickness. In certain other embodiments, the first TE element 3210 has a first aspect ratio equal to the first cross-sectional area divided by the first thickness, and the second TE element 3220 has a second aspect ratio equal to the second cross-sectional area divided by the second thickness. In certain such embodiments, the second aspect ratio is different than the first aspect ratio. For example, the first aspect ratio and the second aspect ratio can be selected such that under operating conditions the first TE element 3210 and the second TE element 3220 both operate at optimal efficiency.

[0230] Figure 36 shows the power curves among three TE elements with varying aspect ratios for an example device in accordance with certain embodiments described herein. As for Figure 35, the three TE elements of Figure 36 are constructed in series in the direction of flow where the hot side temperatures T_h of the three TE elements are 700K, 600K, and 500K, respectively, and the cold side temperature T_c for each TE element is 300K. Each of the three TE elements of Figure 35 had a thickness of 1 mm. For Figure 36, the first TE element had a thickness of 1 mm, the second TE element had a thickness of 0.77 mm, and the third TE element had a thickness of 0.5 mm. As shown by Figure 36, changing the aspect ratio of the second and third TE elements in the series advantageously aligns the currents at which the TE elements achieve their maximum power, thereby increasing the total power density of the device. The total peak power output for the example device of Figure 36 is 11.51W, a 50% improvement over the power output of the example device of Figure 35.

[0231] Figure 37 schematically depicts a pair of segmented TE elements in a conventional configuration 3700. The conventional configuration 3700 has a first TE segmented TE element 3710 and a second TE element 3720. Each of the first and second TE elements 3710, 3720 are coupled to one surface of an electrically conductive and thermally conductive coupler 3730. The first TE element 3710 has three P-type segments 3712a, 3712b, 3712c (e.g., p-$CeFe_3RuSb_{12}$, p-TAGS, and p-Bi_2Te_3, respectively) and the second TE element 3720 has three N-type segments 3722a, 3722b, 3722c (e.g., n-$CoSb_3$, n-PbTe, n-Bi_2Te_3, respectively). In Figure 37, the temperature gradient is vertical with the hot end at the top.

[0232] In conventional TE configurations, as shown schematically in Figure 37, the TE elements 3710, 3720 are integrated in a TE module such that each TE element 3710, 3720 has the same thickness along the direction of current flow. Such conventional TE configurations 3700 do not lend themselves easily to the use of TE elements having different thicknesses, areas, or aspect ratios. In addition, such conventional TE configurations 3700 are difficult to control if the TE elements are of the same thickness but have different thermal expansion coefficients in a direction generally parallel to the direction of current flow through the TE element. Such thermal expansion mismatches can be particularly problematic in power generation systems in which operating temperatures can be quite high. In contrast, in certain embodiments described herein (e.g., the configuration schematically illustrated by Figure 32) in which the heat transfer devices 3230 are sandwiched between two TE elements 3210, 3220, TE elements of different thicknesses, areas, and/or aspect ratios are advantageously easily incorporated in the system. Furthermore, such configurations advantageously reduce or avoid problems associated with differing thermal expansion coefficients among the TE elements.

[0233] In certain embodiments in which the temperatures across the segments of a TE element differ from one another (e.g., having the TE element between a heat source and a heat sink), the effects of power curve compatibility conflicts among the segments on the overall power output and/or efficiency can be significant. In certain embodiments, such incompatibilities between the segments can be at least partially counteracted by advantageously selecting a different aspect ratio (e.g., cross-sectional area divided by the thickness) for each segment of the TE element. In certain embodiments, the aspect ratio is changed among the different segments of a TE element by maintaining a substantially uniform cross-sectional area and varying the thickness of each segment to better match the current for optimal power output. In certain other embodiments, the aspect ratios of the segments can be optimized by constructing a segmented TE element with non-uniform cross-sectional areas among the segments.

[0234] For example, referring to the example system 3200 of Figure 32, in certain embodiments, each segment of the first plurality of segments 3212 has a thickness along the direction of current flow through the first TE element 3210 different from the thicknesses of the other segments of the first plurality of segments 3212. In certain such embodiments, each segment of the second plurality of segments 3222 has a thickness along the direction of current flow through the second TE element 3220 different from the thicknesses of the other segments of the second plurality of segments 3222. In certain embodiments, each segment of the first plurality of segments 3212 has an aspect ratio equal to a thickness of the segment divided by a cross-sectional area of the segment, and the aspect ratios of the segments of the first plurality of segments 3212 are different from one another. In certain such embodiments, each segment of the second plurality of segments 3222 has an aspect ratio equal to a thickness of the segment divided by a cross-sectional area of the segment, and the aspect ratios of the segments of the second plurality of segments 3222 are different from one another. The aspect ratios of the segments of the first plurality of segments 3212 and the aspect ratios of the segments of the second plurality of segments 3222 are selected in certain embodiments such that under operating conditions the first thermoelectric element 3210 and the second thermoelectric element 3220 both operate at optimal efficiency.

[0235] Figure 38 shows the average efficiencies for three different configurations simulated using a model calculation. The model simulated the performance of three different configurations of a stack of three TE elements and two heat transfer devices which thermally isolated the TE elements from one another along the direction of flow of a working fluid, in accordance with certain embodiments described herein. The hot side temperatures of the TE elements varied from 700°C to 300°C while the cold side temperatures varied from 100°C to 150°C, such that the temperature differences across the three TE elements were 550°C, 375°C, and 200°C, respectively.

[0236] In a first configuration (labelled "uniform non-segmentation & aspect ratio" in Figure 38), all three of the TE elements were made of a single material (non-segmented), the material of each of the TE elements was the same as the others (with two doped to be N-type, and one doped to be P-type), and each TE element had the same aspect ratio. In a second configuration (labelled "uniform segmentation & aspect ratio" in Figure 38), the TE elements were segmented to better take advantage of the optimal ZT over each TE element's operating temperature range, the two N-type TE elements were segmented in the same way, and all three TE elements had the same aspect ratio. In a third configuration (labelled "non-uniform segmentation & aspect ratio" in Figure 38), the two N-type TE elements were segmented differently for each TE element's particular temperature range, and the aspect ratio of each TE element varied advantageously. In all three configurations, the TE elements were connected electrically in series such that the same current traversed each TE element.

[0237] Figure 38 shows that the TE material compatibility as well as TE element compatibility in the direction of flow causes the first configuration to be 35% less efficient than the second configuration, while the second configuration is 15% less efficient than the third configuration. These differences become more dramatic with more thermally isolated TE elements along the direction of flow. Figure 38 illustrates the advantages provided by certain embodiments described herein which combine non-uniform segmentation of the TE elements with optimization of the aspect ratios in the direction of flow.

[0238] In certain embodiments utilizing the configuration schematically illustrated by Figure 32, each TE element can be optimized semi-independently of the other TE elements. For example, each P-type and N-type TE element can have a different cross-sectional area and/or thickness with each segment of each TE element having a sufficiently high ZT at each particular temperature range.

[0239] In certain embodiments, thermal expansion mismatch can advantageously be considered when selecting a material to join the heat transfer devices and the TE elements to assemble a thermoelectric system for high temperature power generation applications. Certain embodiments described herein utilize non-rigid connections to at least partially relieve thermal stresses due to thermal expansion mismatch between different portions of the thermoelectric system. In certain embodiments, the non-rigid connection advantageously prevents complications caused by thermal expansion mismatch between the heat transfer device and the TE element. In certain embodiments, the non-rigid connection also advantageously protects against the mismatch of expansion between the hot and cold sides of segmented TE elements.

[0240] In certain such embodiments, the thermoelectric system comprises one or more liquid metal joints between at least one TE element and at least one neighboring heat transfer devices to provide at least one non-rigid thermally and electrically conductive connections. For example, the thermoelectric system 3200 schematically illustrated by Figure 32 can comprise a first liquid metal joint in thermal and electrical communication with the first TE element 3210 and the heat transfer device 3230, and a second liquid metal joint in thermal and electrical communication with the heat transfer device 3230 and the second TE element 3220. This joint can either be liquid at room temperature or can melt at a temperature lower than the temperature applied to the joint during operation of the system. For example, standard SnPb solder can be used on a hot side of a TE element with operating temperatures that far exceed the solder's melting point.

[0241] Utilizing one or more liquid metal joints can introduce several complications in the fabrication of the thermoelectric system. In certain embodiments, additional structure may be used to provide structural integrity. This additional structure can advantageously be thermally insulating. In certain embodiments, the at least one stack is under compression generally along the stack. In addition, some level of control can advantageously be provided in certain embodiments to prevent the liquid metal from flowing out of the joint area and shorting out the device. In certain embodiments, proper material combinations can advantageously be used to prevent accelerated corrosion or undesired alloying (e.g., resulting in brittleness of the bonds or reduced thermal or electrical conductivity) at the interface due to maintaining a liquid metal at high temperatures.

[0242] In certain embodiments, non-rigid joints are advantageously used to reduce or eliminate the buildup of thermal stresses at the interfaces between the heat transfer devices and the heat sources or heat sinks. The second portion 3232 of the heat transfer device 3230 can result in thermal stress buildup in the x-plane between heat transfer devices, particularly on the hot side. Thermal expansion coefficients for the TE materials between the heat transfer devices can be difficult to match to the thermal expansion coefficient of the heat source. Thus, in certain embodiments, the heat transfer devices are advantageously connected to the heat source using a liquid metal. In certain embodiments, the liquid metal at this interface is constrained so as to make avoid creating an electrical short between two heat transfer devices. The liquid metal can be advantageously contained to the immediate joint area. In certain embodiments, the heat transfer devices are joined to the heat sink (e.g., less than 400°C) using thermal grease. In certain embodiments, the thermoelectric system is placed in compression in order to hold everything in place without the use of a rigid structural connector. This compression in certain embodiments can also improve thermal contact in the y-plane and thermal and electrical contact in the x-plane.

[0243] In certain embodiments, molybdenum can be used to provide a thermally and electrically conductive joint. For example, the thermoelectric system 3200 schematically illustrated by Figure 32 can comprises a molybdenum layer between the first TE element 3210 and the heat transfer device 3230 and a molybdenum layer between the heat transfer device 3230 and the second TE element 3220. Molybdenum, despite having one third the electrical and thermal conductivity of copper and being slightly more dense than copper, can be used as the connector material for the hot side. As a refractory metal, molybdenum does not corrode as easily as copper with many liquid metals, and it has a very low thermal expansion coefficient as compared to copper. These attributes are advantageous when joining the heat transfer device to an electrical isolation layer (e.g., a ceramic with very low thermal expansion coefficient). In certain embodiments, a high thermal and non-electrical conductivity aluminum nitride can be used for the barrier between the heat transfer device and the heat source. Electrical isolation is advantageously used between the heat transfer devices and the heat sources or heat sinks to prevent electrical current from flowing through the working fluids. Electrical current flowing in some working fluids can greatly accelerate the fouling of the heat transfer device. Suitable ceramic layers on copper will crack at high operating temperatures due to the large thermal expansion mismatch. However, in certain embodiments, molybdenum can provide a good compromise. Molybdenum does have its complications. For example, molybdenum is not wet very well by many liquid metals, thereby increasing the electrical and thermal interfacial resistance. To improve molybdenum wettability, in certain embodiments, the molybdenum can be plated with a thin layer of nickel followed by a gold flash, and the outer metallization of the TE elements can be a similar nickel/gold combination.

[0244] In certain embodiments, a method of fabricating a thermoelectric system is provided. The method comprises providing a plurality of thermoelectric elements, with at least some of the thermoelectric elements comprising a plurality of segments. The method further comprises providing a plurality of heat transfer devices, with at least some of the heat transfer devices comprising at least a first portion and a second portion. The method further comprises assembling the plurality of thermoelectric elements and the plurality of heat transfer devices to form at least one stack of alternating thermoelectric elements and heat transfer devices. The first portions of the heat transfer devices are sandwiched between at least two neighboring thermoelectric elements. The second portions of the heat transfer devices project away from the stack and are configured to be in thermal communication with a working medium.

[0245] In certain embodiments, assembling the plurality of thermoelectric elements and the plurality of heat transfer devices comprises placing a liquid metal joint between at least one thermoelectric element and at least one neighboring heat transfer device to place the at least one thermoelectric element and the at least one neighboring heat transfer device in thermal communication and in series electrical communication with one another.

[0246] In certain embodiments, the at least some of the thermoelectric elements have aspect ratios, with the aspect ratio of a thermoelectric element equal to a cross-sectional area of the thermoelectric element in a plane generally perpendicular to the stack divided by a thickness of the thermoelectric element in a direction generally parallel to the stack. The aspect ratios for the at least some of the thermoelectric elements vary from one another along the stack. In certain such embodiments, the aspect ratios are selected such that under operating conditions the at least some of the thermoelectric elements operate at optimal efficiency.

[0247] In certain embodiments, each segment of the plurality of segments of a thermoelectric element has an aspect ratio equal to a cross-sectional area of the segment in a plane generally perpendicular to the stack divided by a thickness of the segment in a direction generally parallel to the stack. The aspect ratios of the segments can vary from one another along the thermoelectric element. In certain such embodiments, the aspect ratios are selected such that under operating conditions the segments of the plurality of segments operate at optimal efficiency.

[0248] Certain embodiments described herein have been modeled using a MATLAB-based numerical, steady-state model based in part on previous work (see, e.g., D.T. Crane, "*Optimizing Thermoelectric Waste Heat Recovery from an Automotive Cooling System*", PhD Dissertation, University of Maryland, College Park, 2003). The model used simultaneously solved, non-linear, energy balance equations which simulate certain embodiments of the high power density TE assemblies discussed herein. The principles used in the current model were also used in a previous TE model developed by BSST (see, D.T. Crane, "Modeling High-Power Density Thermoelectric Assemblies Which Use Thermal

Isolation," *23rd International Conference on Thermoelectrics,* Adelaide, AU. 2004. This previous TE model was validated for heating and cooling applications and was previously shown to be accurate to within 7% for four different outputs. The average error for each of these simulated values was less than 3%.

[0249] The TE segmented material information of certain embodiments was incorporated into the model using algorithms and equations described by G.J. Snyder, "Thermoelectric Power Generation: Efficiency and Compatibility," in Thermoelectrics Handbook Macro To Nano, Rowe, D. M., Editor. CRC Press (Boca Raton, FL, 2006), pp. 9-1 - 9-26). The model can be used to automatically solve for the optimal TE segmentation for a given set of hot and cold side temperatures. The thicknesses of the material segments and the material layers themselves can be allowed to vary to determine optimal performance for a given electrical load resistance. The model can also solve for off-nominal solutions by fixing the material layer thicknesses.

[0250] Using the model, various design variables in certain embodiments were identified and varied to analyze the trade-offs involved in improving efficiency. Advanced multi-parameter, gradient-based optimization studies were used to better understand the interactions between various design variables, parameters, and constraints and to develop an optimal thermoelectric power generation (TPG) design in accordance with certain embodiments described herein.

[0251] Optimization analysis of certain embodiments can also include parametric analyses. Figure 39 shows an example of such an analysis of a thermoelectric system where the parameter being varied is the TE thickness. Figure 39 shows the tradeoffs between high power density and high efficiency. Changing the TE thickness has a more dramatic effect on TE power density than on total heat exchanger power density, which remains relatively unchanged. Using such a parametric analysis, certain embodiments described herein can be designed for a particular application. For example, in automotive waste heat recovery applications, it is very desirable to have as high an efficiency as possible, but having a high power density is also desirable.

[0252] Initial modeling for certain embodiments described herein was completed, and building and testing some fractional prototype devices was also performed to fully validate the model. The model can then be used more extensively to complete the analysis of particular device designs in accordance with certain embodiments described herein.

[0253] Figure 40 shows an example prototype system built using six Bi_2Te_3 TE elements sandwiched between seven copper heat transfer devices. The Bi_2Te_3 TE elements were used because the tests were conducted at lower temperatures with materials that have well-defined properties. These tests were conducted to better isolate problem areas in the integration of TE materials into a system. Copper heat transfer devices were used on the hot side of this system because the temperatures were lower than those seen in higher temperature applications. In certain embodiments for use at higher temperatures, molybdenum heat transfer devices can replace the copper heat transfer devices on the hot side of the system.

[0254] For assembly simplicity, the system shown in Figure 40 used rectangular TE heat transfer devices rather than heat transfer devices having a second portion wider than the first portion as used in certain embodiments described herein. The copper heat transfer devices were placed on an aluminum tube, which served as the heat sink for the system. The aluminum tube was anodized to provide electrical isolation from the copper heat transfer devices. A layer of thermal grease covered the anodized layer to help minimize thermal resistance. Two 100W cartridge heaters provided the heat source for the system, and were enclosed in an anodized aluminum housing. For assembly simplicity, thermal grease was used at low temperatures (e.g., less than 400°C) as the thermal interface material between the aluminum housing and the heat transfer devices. For certain embodiments to be used at higher temperatures, liquid metal can be used instead. A prototype test fixture was constructed to test the fractional build described above.

[0255] Figure 41 is a graph showing power generation curves for the six individual Bi_2Te_3 elements of Figure 40. Using the known temperature-dependent Seebeck coefficient for Bi_2Te_3, the temperature difference across the TE element could be derived from the measured open circuit voltage and compared to the temperature difference measured with thermocouples. The difference between hot and cold side temperature measurements and those calculated at zero current were then applied as an offset for the temperatures at all currents.

[0256] Using the known temperature-dependent electrical resistivity property for Bi_2Te_3, the electrical resistivity followed by the electrical resistance was calculated at the new adjusted temperatures. The bulk joint resistance could be calculated by subtracting the measured voltage at a particular current from the calculated open circuit voltage at the measured temperature difference at the particular current, and dividing by the measured current. This bulk resistance included the resistance of the TE element as well as the contact resistances created by the solder and the TE element plating. The resistance of the copper heat transfer devices was considered negligible when compared to the resistances of the TE element and the interfacial resistances. Subtracting the calculated TE element resistance from this bulk joint resistance revealed the contact resistance for the joints on both sides of the TE element. With the known surface area of the TE element, the electrical interfacial resistivity could then be calculated for each TE element.

[0257] Using these calculated temperature-independent electrical interfacial resistivities along with the current-independent temperature offsets, the power generation curves shown in Figure 41 were calculated using standard thermoelectric equations. The dotted lines in Figure 41 represent the calculated power curves compared to the measured power curves represented by the solid lines. It can be seen from Figure 41 that this method of estimation can be very accurate for all six elements.

[0258] With matched power curves, the hot and cold side surface temperatures as well as the electrical interfacial resistivities could be accepted and analyzed for their absolute values and their consistency between TE elements. The estimated electrical interfacial resistivities can be compared to those described in the literature (see, e.g., G.S. Nolas *et al.*, "Thermoelectrics - Basic Principles and New Materials Developments," Springer-Verlag (Berlin Heidelberg, 2001)). Figure 41 shows that all six TE elements had interfacial resistivities less than 10 $\mu\Omega cm^2$, which can be considered to be a reasonable value. These tests were conducted to see how low this interfacial resistance could be and how consistently it could be achieved across each TE element. In the test shown in Figure 41, the four middle TE elements have relatively low and consistent interfacial resistivities. The two end TE elements have two to three times the interfacial resistance of the inner TE elements. This effect could be due to additional stress put on these TE elements due to being on the ends of the assembly.

[0259] The results of these tests for Bi_2Te_3 elements can be carried over to the tests and device design for higher temperature materials in accordance with certain embodiments described herein. Interfacial resistivities and temperature drops across the interfaces can be similar for these TE elements.

[0260] Figure 42 shows experimental results for initial testing of segmented TE elements. Two N-type TE elements having the dimensions and materials listed in Figure 42 were tested. The same prototype fixture and system configuration to those described above with regard to Figures 40 and 41 were used for this test as well. Temperatures of the cold side bath, heater settings, and the measured TE surface temperatures are also listed in Figure 42. The curves of Figure 42 are different due to the designed difference in the TE element and layer thicknesses as well as the slightly different temperature drops. Figure 42 shows that the amount of power recovered increases with increasing hot side temperature. Optimal current also increases slightly with increasing temperature. Element 1 produced the maximum power at 8A at a hot side temperature of 172°C and at 11.3A at 366°C. Further testing and analysis on these and other similar P- and N-type segmented elements can be used to determine the same level of predictability as the tests on the Bi_2Te_3.

[0261] Certain embodiments described herein significantly improve the ability of thermoelectric power generation to achieve higher power outputs and efficiencies. Certain embodiments described herein address the issues of TE compatibility mismatch not only within an element, but also with respect to elements in the direction of flow to greatly improve TE system performance for many applications. In certain embodiments, the use of heat transfer devices with a second portion extending from a first portion sandwiched between two TE elements with the second portion wider than the first portion advantageously helps incorporate thermal isolation in the direction of flow and non-uniform high power density elements in a usable system. Certain such embodiments advantageously reduce the effects of thermal expansion mismatch, which would otherwise make it more difficult to construct a TE device with elements of differing thickness. Certain embodiments described herein use liquid metal joints to reduce the effects of thermal expansion mismatch to advantageously aid in the construction of a system that will hold together under high operating temperatures.

[0262] The advanced modeling and optimization techniques described herein advantageously help optimize the design concepts of certain embodiments to progress towards maximizing the performance of a TPG system. Prototype builds and tests also help validate the design concepts and the models. A full-scale TPG system in accordance with certain embodiments described herein can be used to recover waste heat from automotive exhaust, for primary power applications, or many other different waste heat recovery applications, including those associated with integrating a TE system into a fuel cell.

[0263] It should also be noted that the disclosures in this patent present designs, configurations and applications of this invention. While the discussion above is analyzed in terms of the properties in cooling, similar results hold for heating and power generation, and lead to similar conclusions. Some systems, in particular those of the thermionic and heterostructure type, may be intrinsically of high power density, in which case this invention can be more suitable to accommodate the properties and possible high power densities of such systems.

[0264] Although several examples have been illustrated, and discussed above, the descriptions are merely illustrative of broad concepts of the inventions, which are set forth in the attached claims. In the claims, all terms are attributed to their ordinary and accustomed meaning and the description above does not restrict the terms to any special or specifically defined means unless specifically articulated.

WHAT IS CLAIMED IS:

1. A thermoelectric system comprising:

a first thermoelectric element comprising a first plurality of segments in electrical communication with one another;

a second thermoelectric element comprising a second plurality of segments in electrical communication with one another; and

a heat transfer device comprising at least a first portion and a second portion, the first portion sandwiched between the first thermoelectric element and the second thermoelectric element, the second portion projecting away from the first portion and configured to be in thermal communication with a working medium.

2. The thermoelectric system of Claim 1, wherein the first thermoelectric element has a first thickness along a first direction, the second thermoelectric element has a second thickness along a second direction, and the second thickness is greater than the first thickness.

3. The thermoelectric system of Claim 1, wherein the first thermoelectric element has a first thickness along a first direction, a first cross-sectional area in a plane generally perpendicular to the first direction, and a first aspect ratio equal to the first cross-sectional area divided by the first thickness, the second thermoelectric element has a second thickness along a second direction, a second cross-sectional area in a plane generally perpendicular to the second direction, and a second aspect ratio equal to the second cross-sectional area divided by the second thickness, wherein the second aspect ratio is different than the first aspect ratio.

4. The thermoelectric system of Claim 3, wherein the first aspect ratio and the second aspect ratio are selected such that under operating conditions the first thermoelectric element and the second thermoelectric element both operate at optimal efficiency.

5. The thermoelectric system of Claim 1, wherein each segment of the first plurality of segments has a thickness different from the thickness of other segments of the first plurality of segments.

6. The thermoelectric system of Claim 5, wherein each segment of the second plurality of segments has a thickness different from the thickness of other segments of the second plurality of segments.

7. The thermoelectric system of Claim 1, wherein each segment of the first plurality of segments has an aspect ratio equal to a thickness of the segment divided by a cross-sectional area of the segment, wherein the aspect ratios of the segments of the first plurality of segments are different from one another.

8. The thermoelectric system of Claim 7, wherein each segment of the second plurality of segments has an aspect ratio equal to a thickness of the segment divided by a cross-sectional area of the segment, wherein the aspect ratios of the segments of the segment plurality of segments are different from one another.

9. The thermoelectric system of Claim 8, wherein the aspect ratios of the segments of the first plurality of segments and the aspect ratios of the segments of the second plurality of segments are selected such that under operating conditions the first thermoelectric element and the second thermoelectric element both operate at optimal efficiency.

10. The thermoelectric system of Claim 1, wherein the first plurality of segments comprises at least a first thermoelectric segment and a second thermoelectric segment, the first and second thermoelectric segments comprising different materials.

11. The thermoelectric system of Claim 10, wherein the thermoelectric system is configured to be operated such that the first thermoelectric segment is exposed to a first temperature range and the second thermoelectric segment is exposed to a second temperature range, wherein the first thermoelectric segment operates more efficiently in the first temperature range than in the second temperature range and the second thermoelectric segment operates more efficiently in the second temperature range than in the first temperature range.

12. The thermoelectric system of Claim 11, wherein the first plurality of segments comprises a third thermoelectric segment, wherein the thermoelectric system is configured to be operated such that the third thermoelectric segment is exposed to a third temperature range, wherein the third thermoelectric segment operates more efficiently in the third temperature range than in either the second temperature range or the first temperature range.

13. The thermoelectric system of Claim 10, wherein the second plurality of segments comprises at least a first thermoelectric segment and a second thermoelectric segment, the first and second thermoelectric segments comprising different materials.

14. The thermoelectric system of Claim 13, wherein the thermoelectric system is configured to be operated such that the first thermoelectric segment is exposed to a first temperature range and the second thermoelectric segment is exposed to a second temperature range, wherein the first thermoelectric segment operates more efficiently in the first temperature range than in the second temperature range and the second thermoelectric segment operates more efficiently in the second temperature range than in the first temperature range.

15. The thermoelectric system of Claim 14, wherein the first plurality of segments comprises a third thermoelectric segment, wherein the thermoelectric system is configured to be operated such that the third thermoelectric segment is exposed to a third temperature range, wherein the third thermoelectric segment operates more efficiently in the third temperature range than in either the second temperature range or the first temperature range.

16. The thermoelectric system of Claim 1, wherein at least some of the first plurality of segments are in series electrical communication with one another and at least some of the second plurality of segments are in series electrical communication with one another.

17. The thermoelectric system of Claim 1, wherein at least some of the first plurality of segments are in series/parallel electrical communication with one another and at least some of the second plurality of segments are in series/parallel electrical communication with one another.

18. The thermoelectric system of Claim 1, wherein the second portion is wider than the first portion in at least one direction.

19. The thermoelectric system of Claim 18, wherein the second portion is wider than the first portion in a direction generally along a direction of working medium movement.

20. The thermoelectric system of Claim 18, wherein the second portion has a generally flat surface configured to be in thermal communication with the working medium.

21. The thermoelectric system of Claim 1, further comprising a current source in electrical communication with the first thermoelectric element, the heat transfer device, and the second thermoelectric element, such that a current from the current source traverses the first thermoelectric element, the heat transfer device, and the second thermoelectric element in series.

22. The thermoelectric system of Claim 21, wherein the current traverses the first plurality of segments in series and the current traverses the second plurality of segments in series.

23. The thermoelectric system of Claim 1, further comprising a first liquid metal joint in thermal and electrical communication with the first thermoelectric element and the heat transfer device and a second liquid metal joint in thermal and electrical communication with the heat transfer device and the second thermoelectric element.

24. The thermoelectric system of Claim 23, wherein the first liquid metal joint and the second liquid metal joint comprise SnPb solder.

25. The thermoelectric system of Claim 1, further comprising a molybdenum layer between the first thermoelectric element and the heat transfer device and a second molybdenum layer between the heat transfer device and the second thermoelectric element.

26. A thermoelectric system comprising:

a plurality of thermoelectric elements, at least some of the thermoelectric elements comprising a plurality of segments; and

a plurality of heat transfer devices, at least some of the heat transfer devices comprising at least a first portion and a second portion, the first portion sandwiched between at least two thermoelectric elements of the plurality of thermoelectric elements so as to form at least one stack of thermoelectric elements and heat transfer devices, the second portion projecting away from the stack and configured to be in thermal communication with a working medium.

27. The thermoelectric system of Claim 26, wherein the heat transfer devices thermally isolate at least some of the thermoelectric elements from at least some other of the thermoelectric elements.

28. The thermoelectric system of Claim 26, wherein the plurality of heat transfer devices are arranged to provide thermal isolation in a direction of a working medium flow.

29. The thermoelectric system of Claim 26, wherein the thermoelectric elements comprise alternating P-type and N-type thermoelectric elements.

30. The thermoelectric system of Claim 26, wherein the plurality of heat transfer devices comprise a plurality of first heat transfer devices and a plurality of second heat transfer devices, the stack comprising alternating first and second heat transfer devices, wherein the second portions of the first heat transfer devices project in a first direction and the second portions of the second heat transfer devices project in a second direction, the second direction different from the first direction.

31. The thermoelectric system of Claim 30, wherein the second direction is generally opposite to the first direction.

32. The thermoelectric system of Claim 30, wherein the first heat transfer devices are configured to be in thermal communication with a first working medium and the second heat transfer devices are configured to be in thermal communication with a second working medium.

33. The thermoelectric system of Claim 26, further comprising at least one liquid metal joint between at least one thermoelectric element and at least one neighboring heat transfer device, and the at least one stack is under compression generally along the stack.

34. The thermoelectric system of Claim 26, wherein at least some of the thermoelectric elements are sized to provide high power density operation.

35. The thermoelectric system of Claim 26, further comprising a current source in electrical communication with the stack, such that a current from the current source traverses the thermoelectric elements and the heat transfer devices in series.

36. The thermoelectric system of Claim 35, wherein the current traverses the plurality of segments of the at least some of the thermoelectric elements in series.

37. A method of fabricating a thermoelectric system, the method comprising:

providing a plurality of thermoelectric elements, at least some of the thermoelectric elements comprising a plurality of segments;

providing a plurality of heat transfer devices, at least some of the heat transfer devices comprising at least a first portion and a second portion; and

assembling the plurality of thermoelectric elements and the plurality of heat transfer devices to form at least one stack of alternating thermoelectric elements and heat transfer devices, wherein the first portions of the heat transfer devices are sandwiched between at least two neighboring thermoelectric elements, the second portions of the heat transfer devices projecting away from the stack and configured to be in thermal communication with a working medium.

38. The method of Claim 37, wherein assembling the plurality of thermoelectric elements and the plurality of heat transfer devices comprises placing a liquid metal joint between at least one thermoelectric element and at least one neighboring heat transfer device to place the at least one thermoelectric element and the at least one neighboring heat transfer device in thermal communication and in series electrical communication with one another.

39. The method of Claim 37, wherein the at least some of the thermoelectric elements have aspect ratios, the aspect ratio of a thermoelectric element equal to a cross-sectional area of the thermoelectric element in a plane generally perpendicular to the stack divided by a thickness of the thermoelectric element in a direction generally parallel to the stack, wherein the aspect ratios for the at least some of the thermoelectric elements vary from one another along the stack.

40. The method of Claim 39, wherein the aspect ratios are selected such that under operating conditions the at least some of the thermoelectric elements operate at optimal efficiency.

41. The method of Claim 37, wherein each segment of the plurality of segments of a thermoelectric element has an aspect ratio equal to a cross-sectional area of the segment in a plane generally perpendicular to the stack divided by a thickness of the segment in a direction generally parallel to the stack, wherein the aspect ratios of the segments vary from one another along the thermoelectric element.

42. The method of Claim 41, wherein the aspect ratios are selected such that under operating conditions the segments of the plurality of segments operate at optimal efficiency.

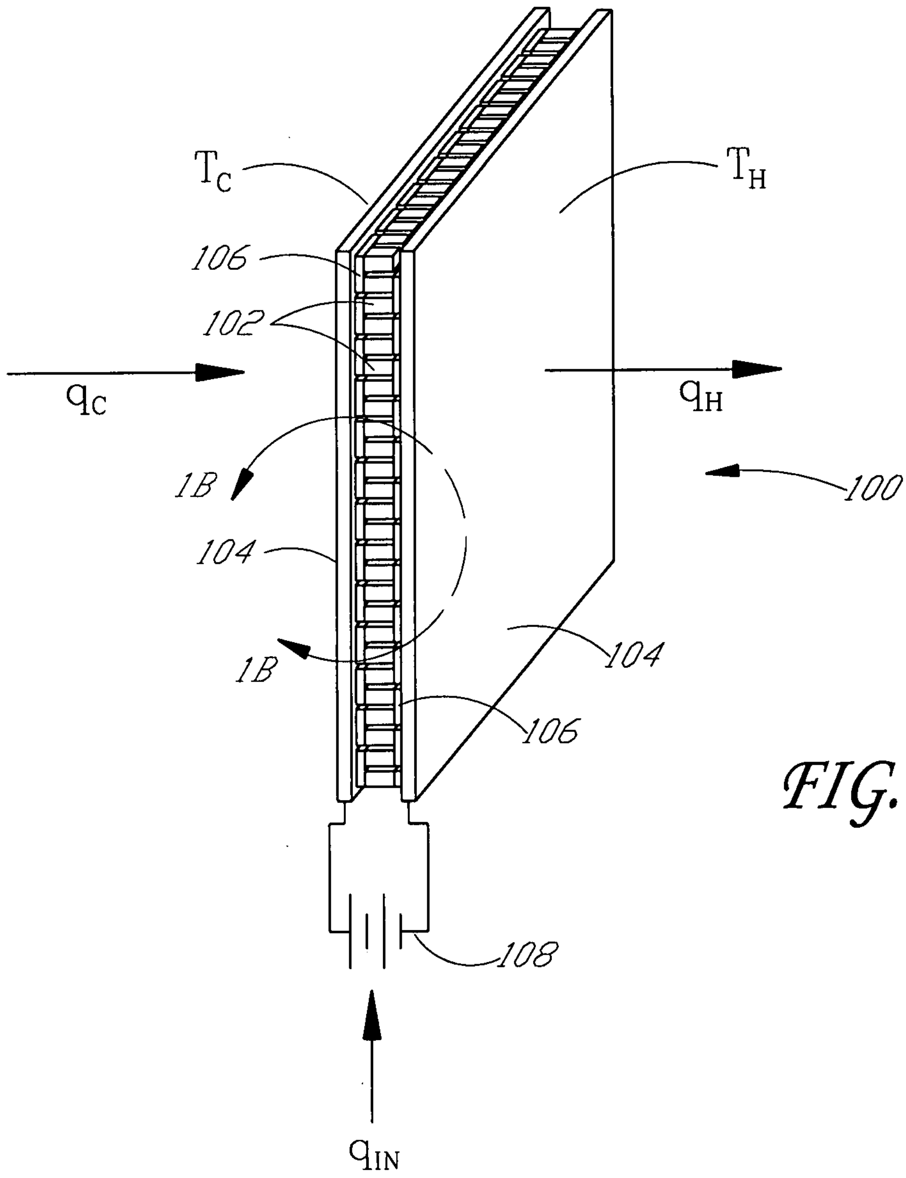

T_C
T_H
106
102
q_C
q_H
1B
100
104
1B
104
106
108
q_IN

FIG. 1A

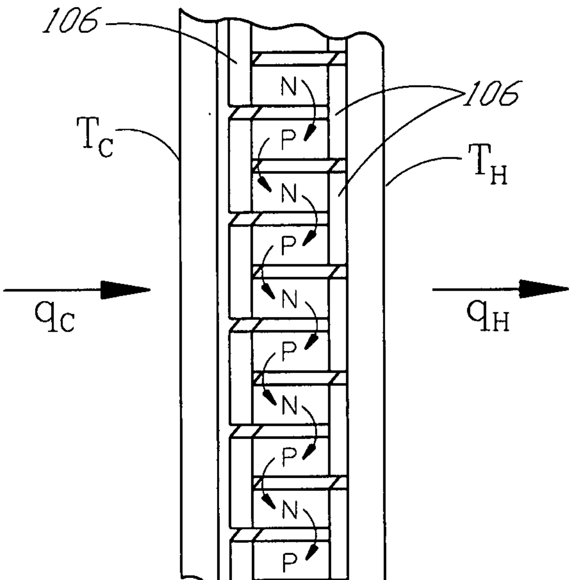

106
106
T_C
T_H
q_C
q_H
N
P
N
P
N
P
N
P
N
P

FIG. 1B

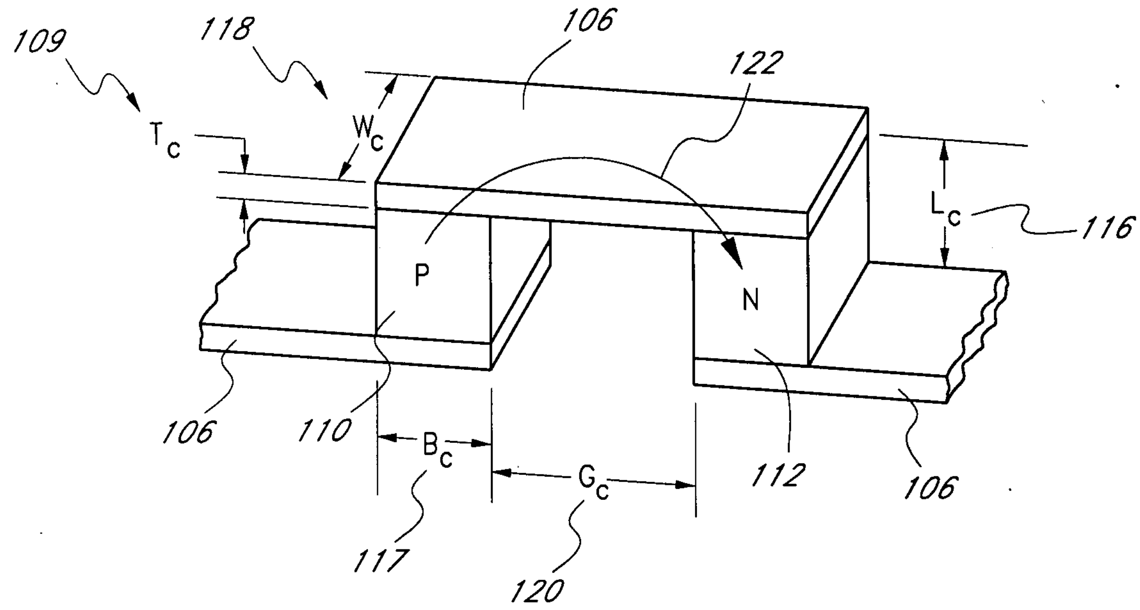


FIG. 1C

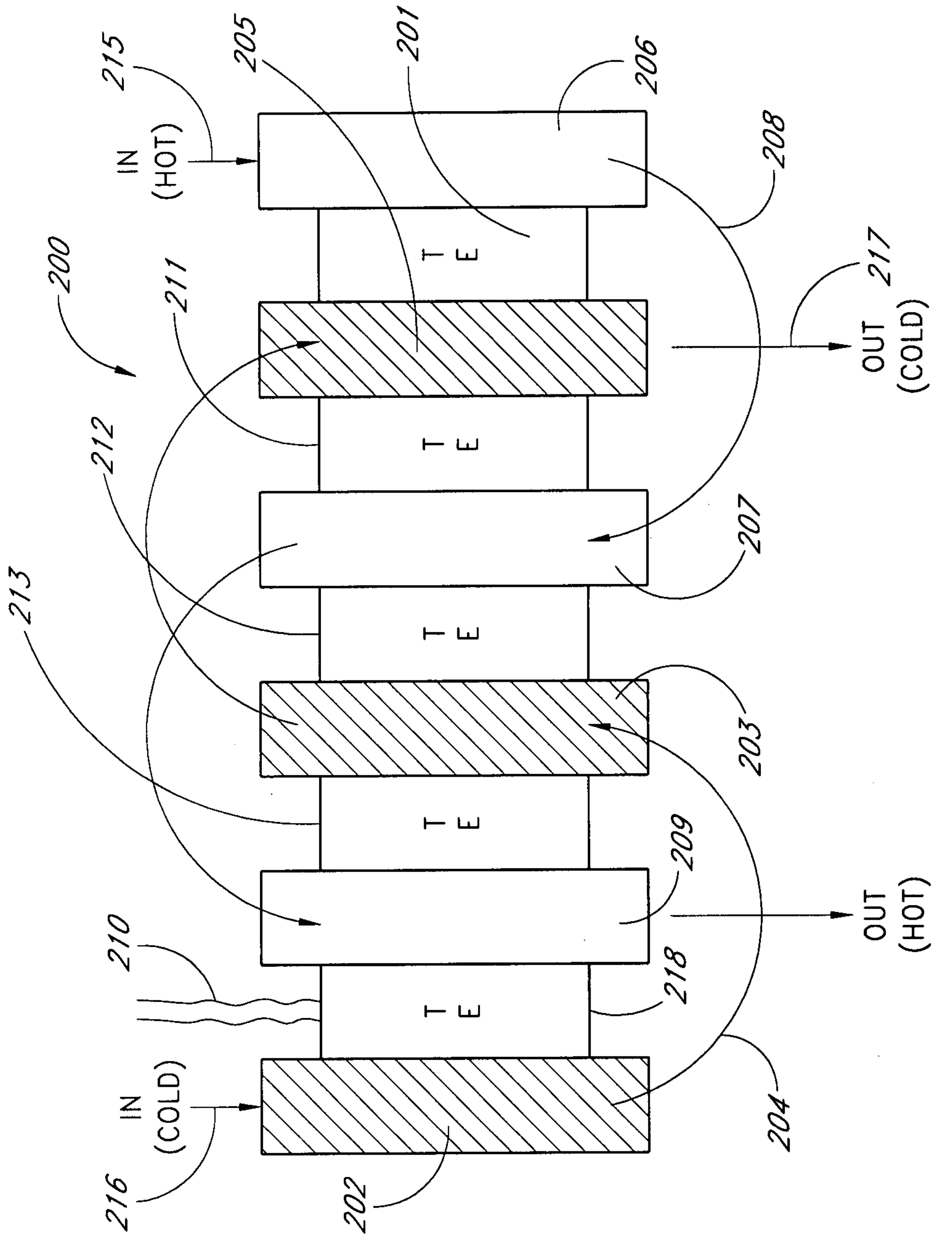

200
201
202
203
204
205
206
207
208
209
210
211
212
213
215
216
217
218
IN (HOT)
IN (COLD)
OUT (COLD)
OUT (HOT)
T E
T E
T E
T E
T E

FIG. 2

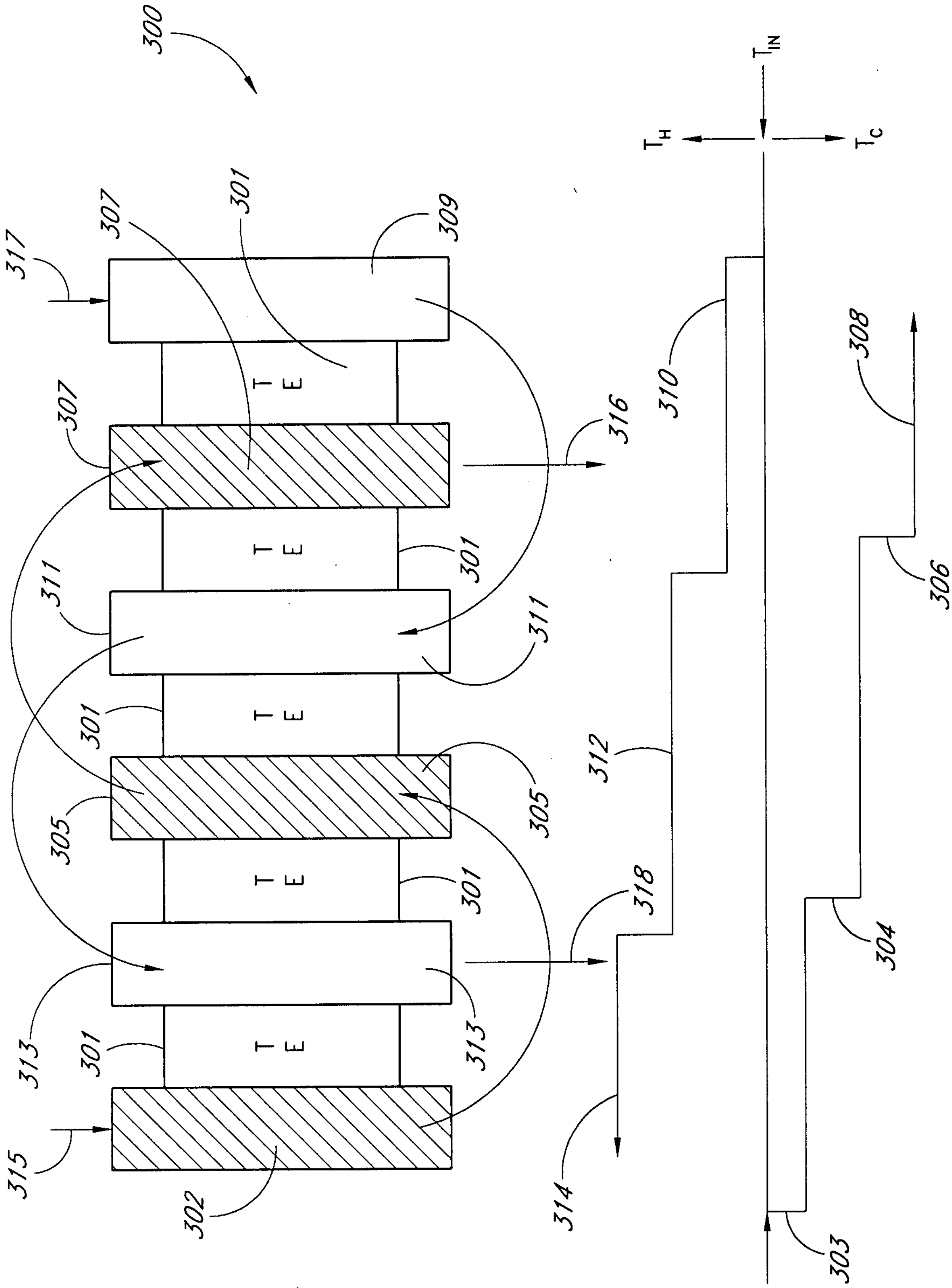

300
317
307
301
309
316
310
308
TE
301
311
306
312
305
318
313
304
315
302
314
303
T_H
T_{IN}
T_C

FIG. 3

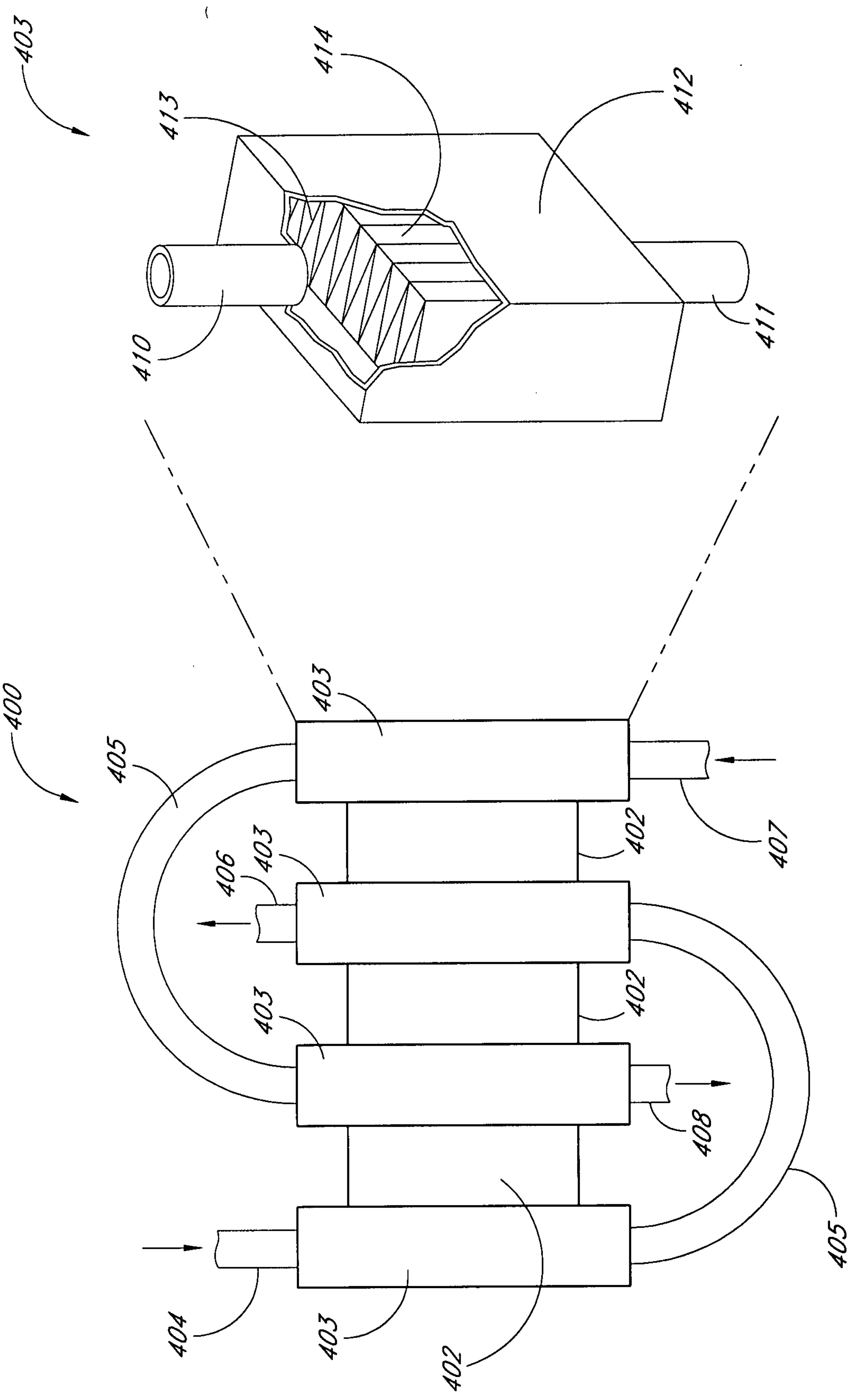


FIG. 4B

FIG. 4A

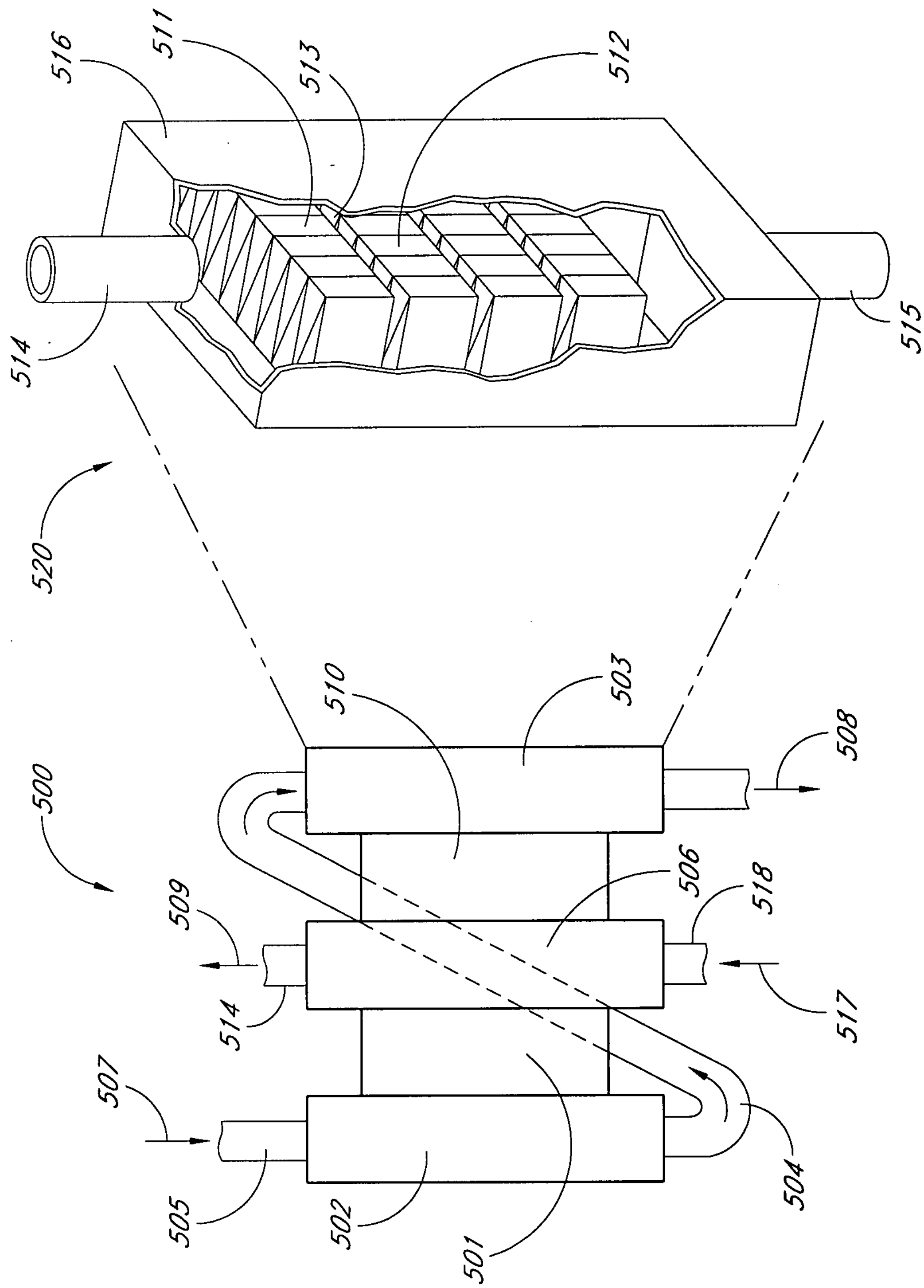

516
511
513
512
514
515
520
500
510
503
508
509
506
518
514
517
507
504
505
502
501

FIG. 5B

FIG. 5A

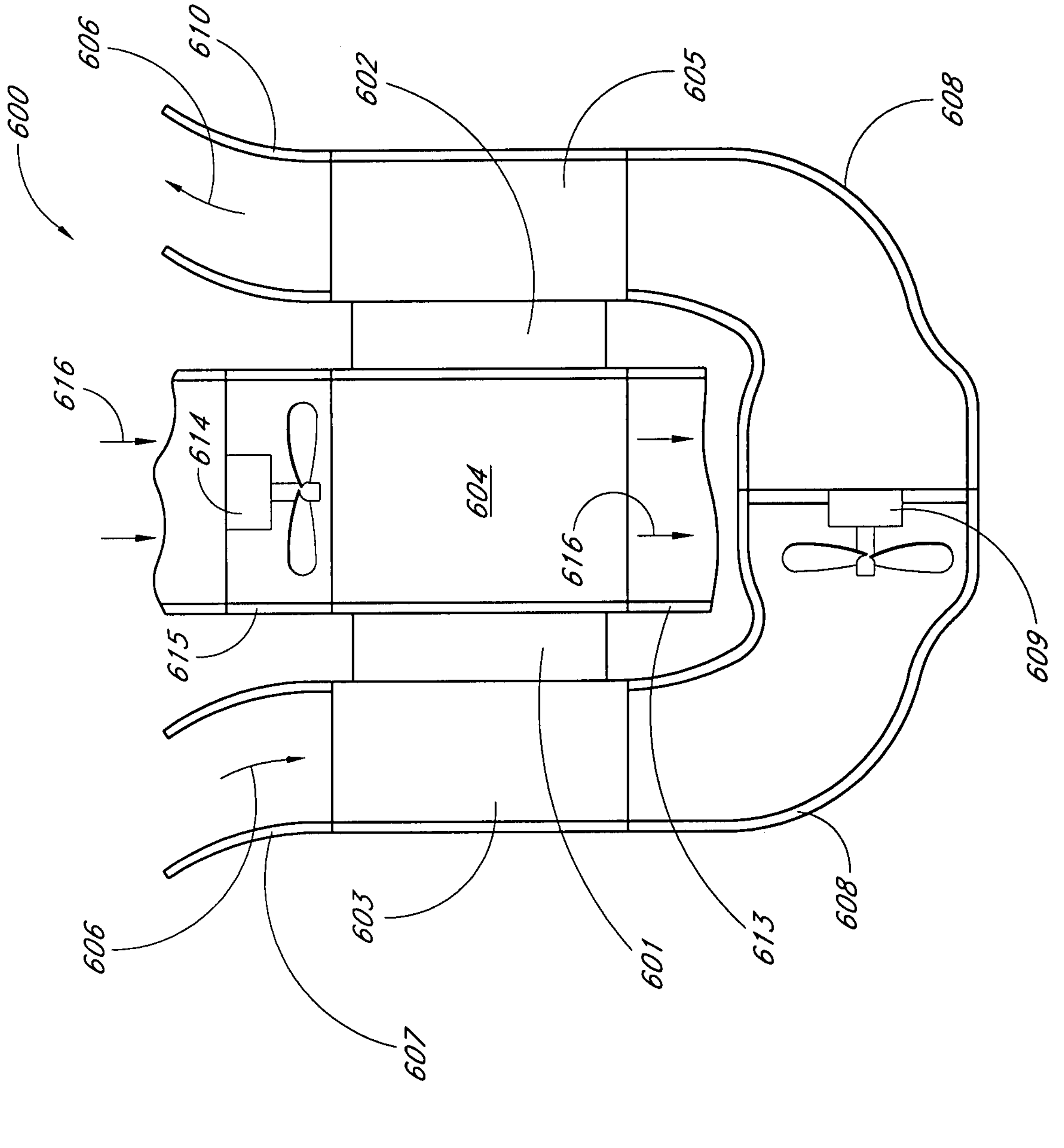

600
606
610
602
605
608
616
614
604
616
615
609
606
603
601
613
608
607

FIG. 6

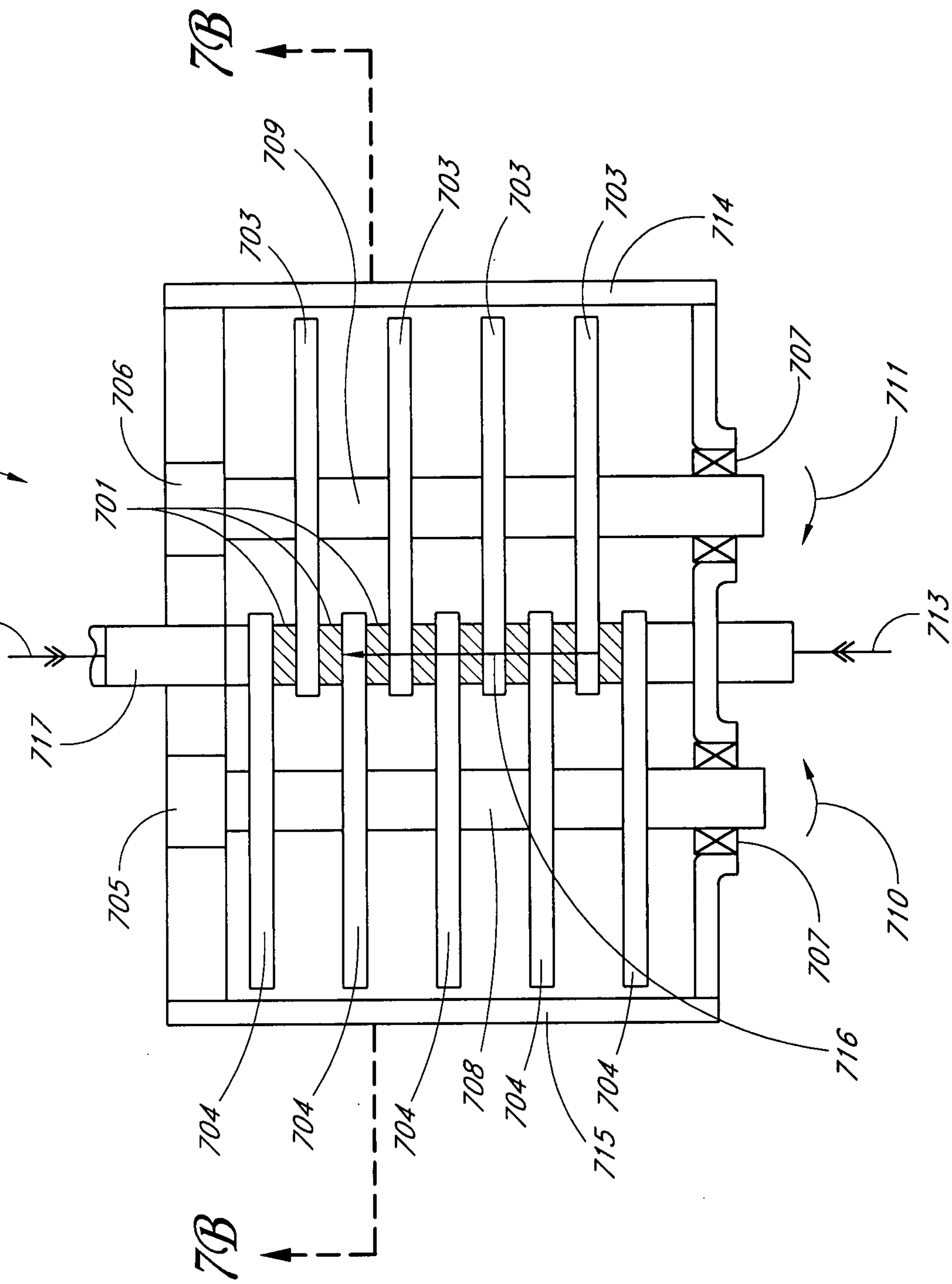

7B
700
706
701
712
717
705
709
703
703
703
703
714
707
711
713
710
707
716
704
704
704
708
704
715
704
7B

FIG. 7A

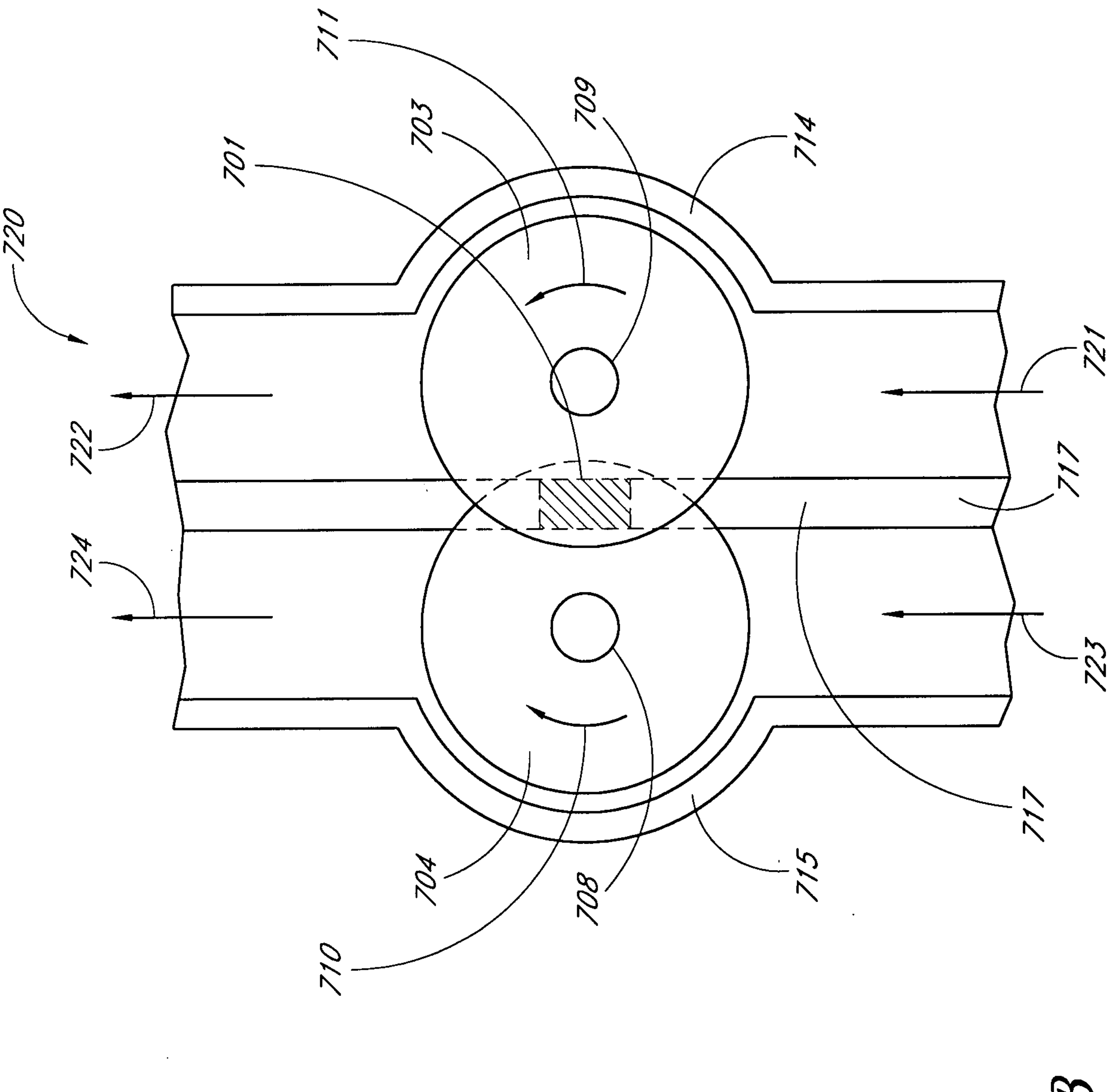


FIG. 7B

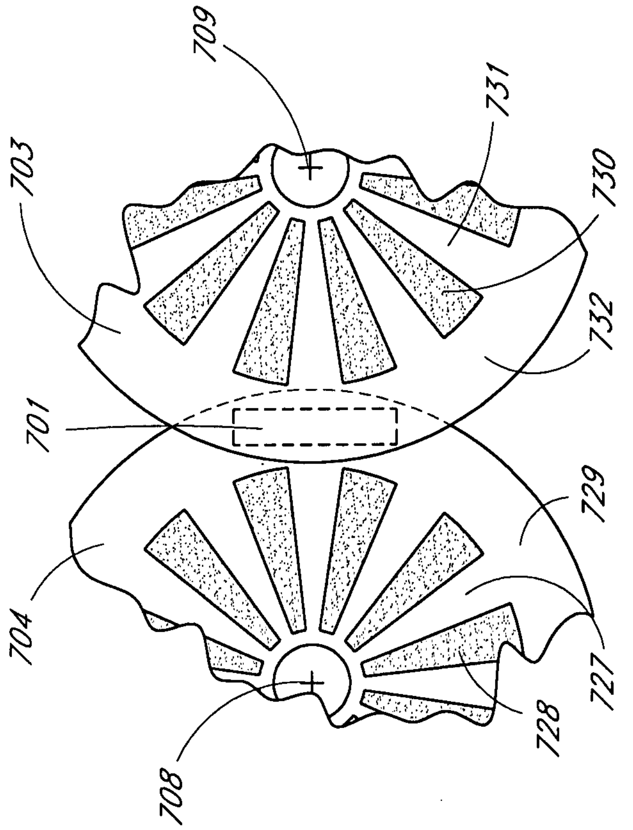

709
731
703
730
732
701
729
704
727
728
708

FIG. 7D

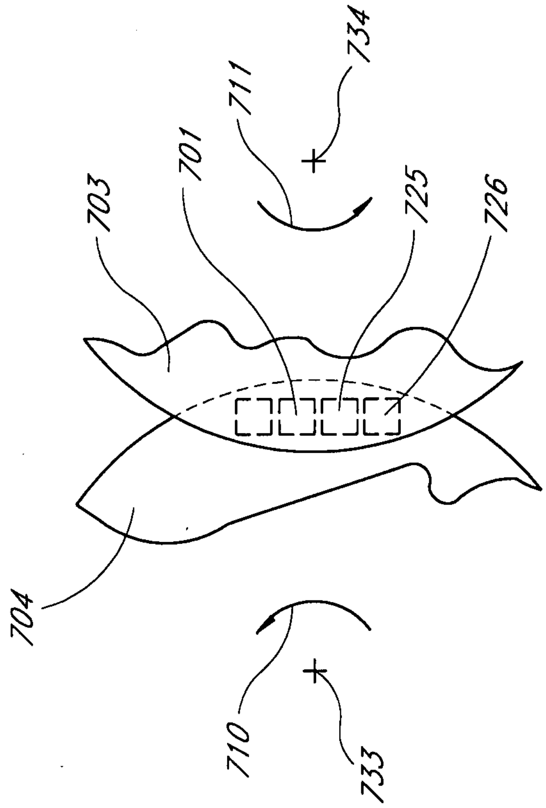

734
711
701
703
725
726
704
710
733

FIG. 7C

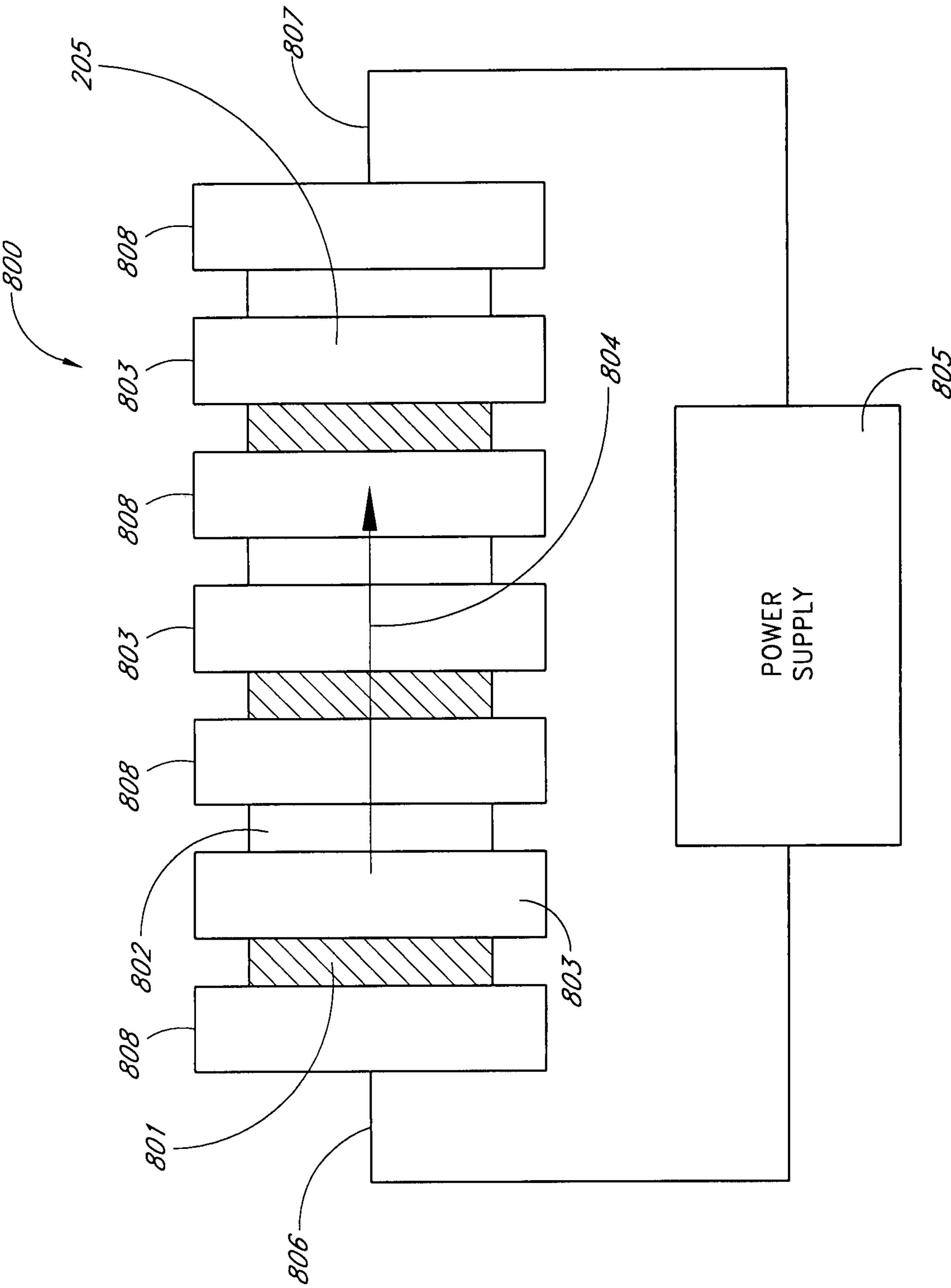

800
205
807
808
803
808
803
808
803
808
804
805
POWER SUPPLY
802
801
806

FIG. 8

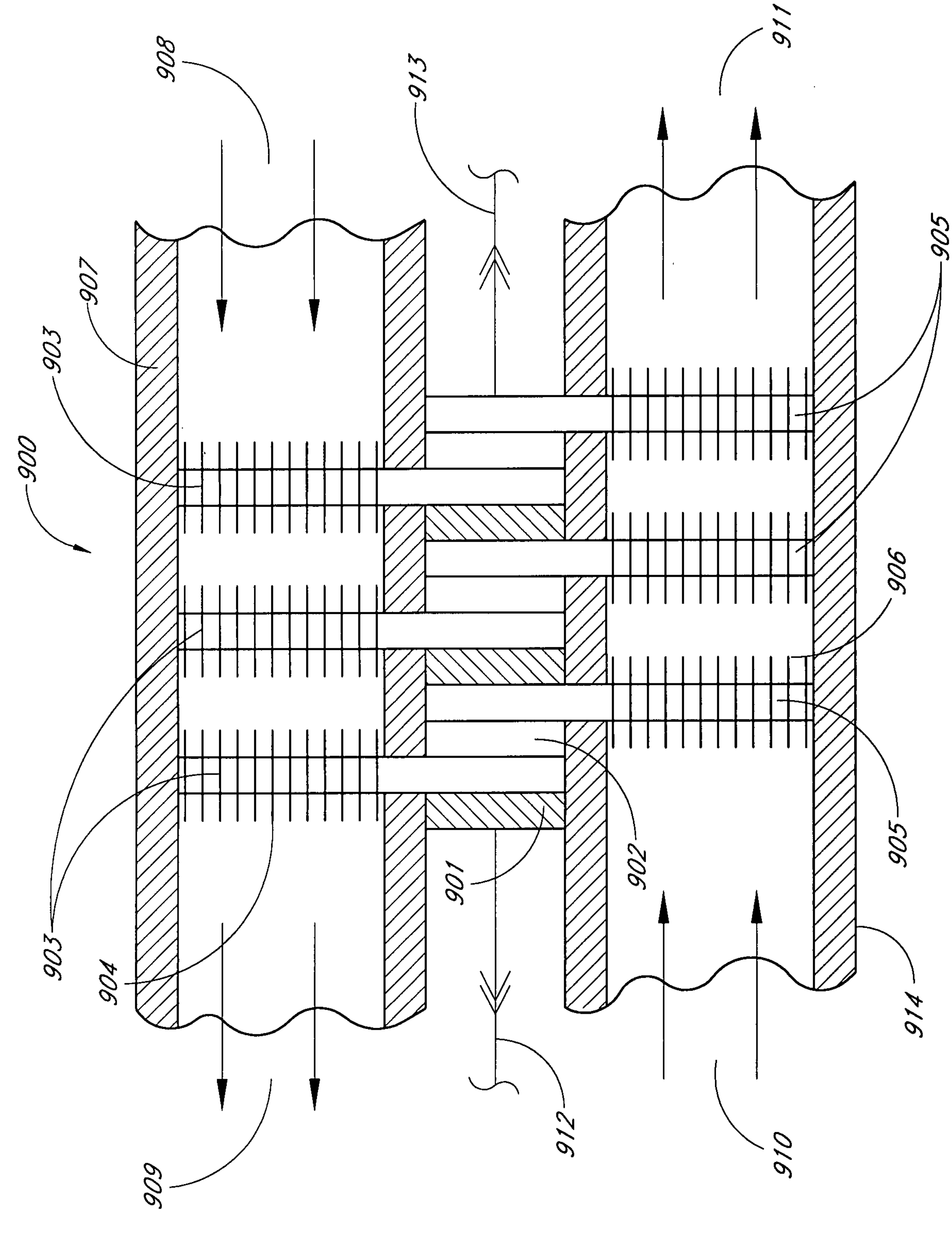

900
901
902
903
903
903
904
905
905
906
907
908
909
910
911
912
913
914

FIG. 9

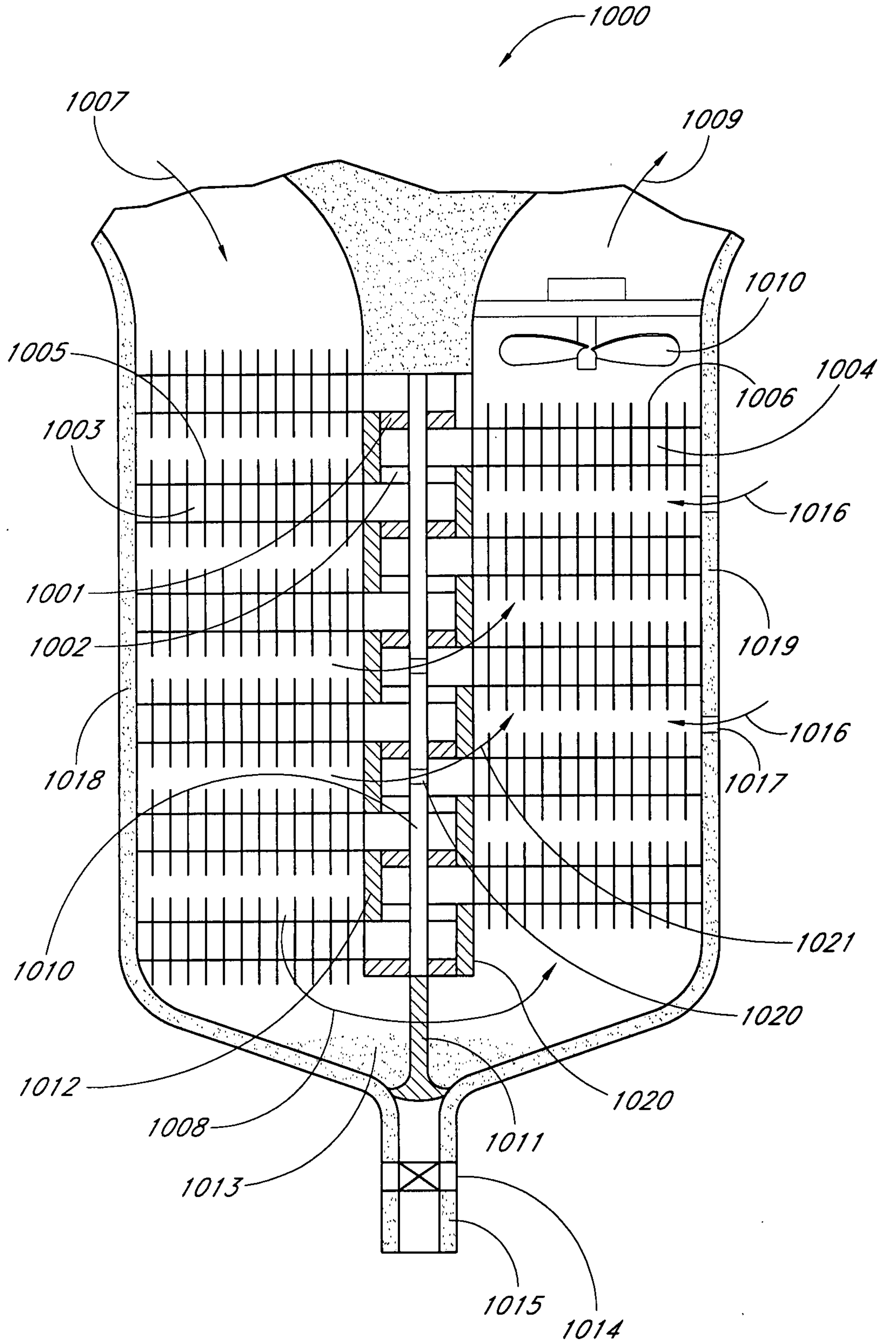

1000
1007
1009
1010
1005
1006
1004
1003
1016
1001
1002
1019
1016
1018
1017
1021
1010
1020
1012
1020
1008
1011
1013
1015
1014

FIG. 10

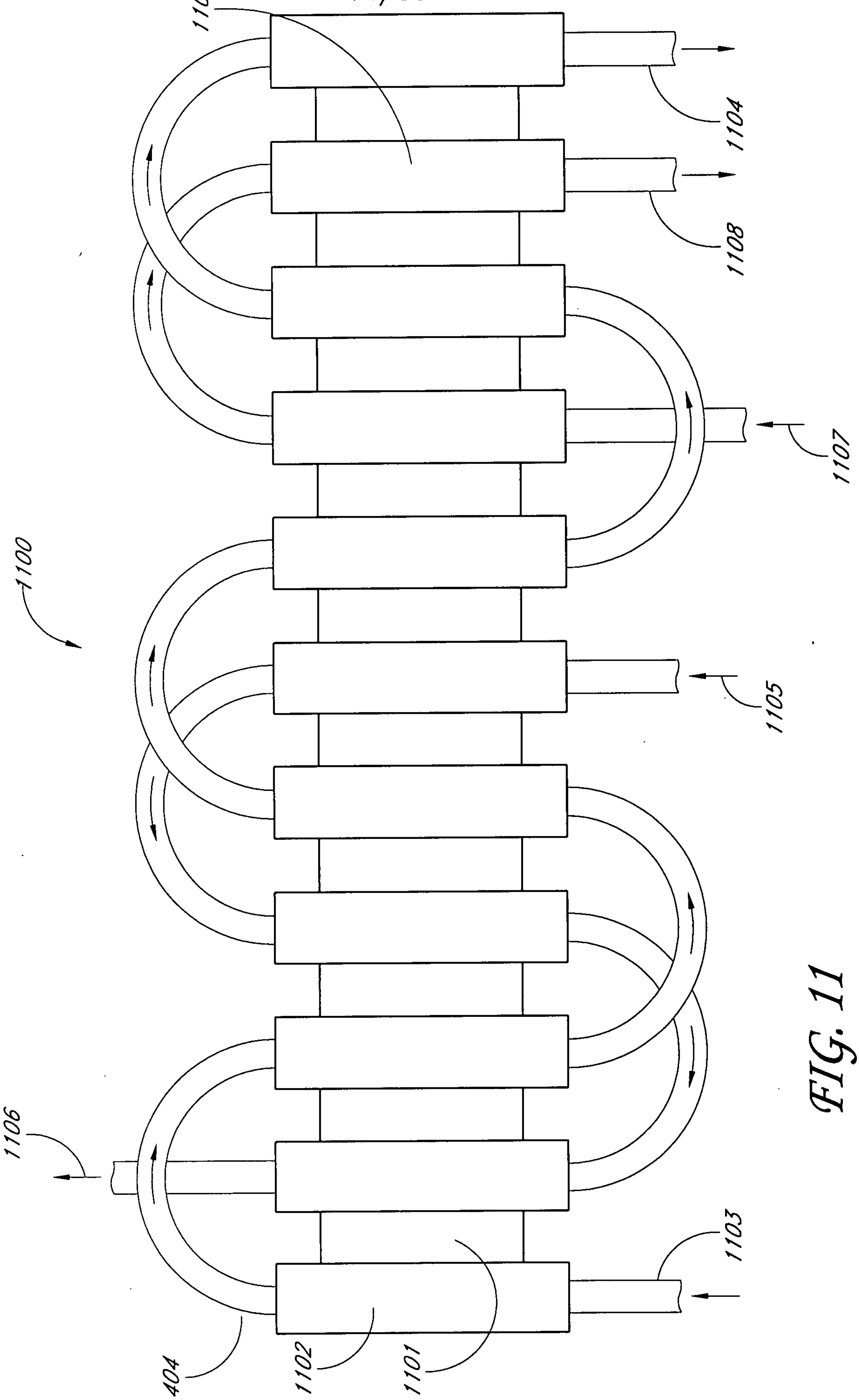


FIG. 11

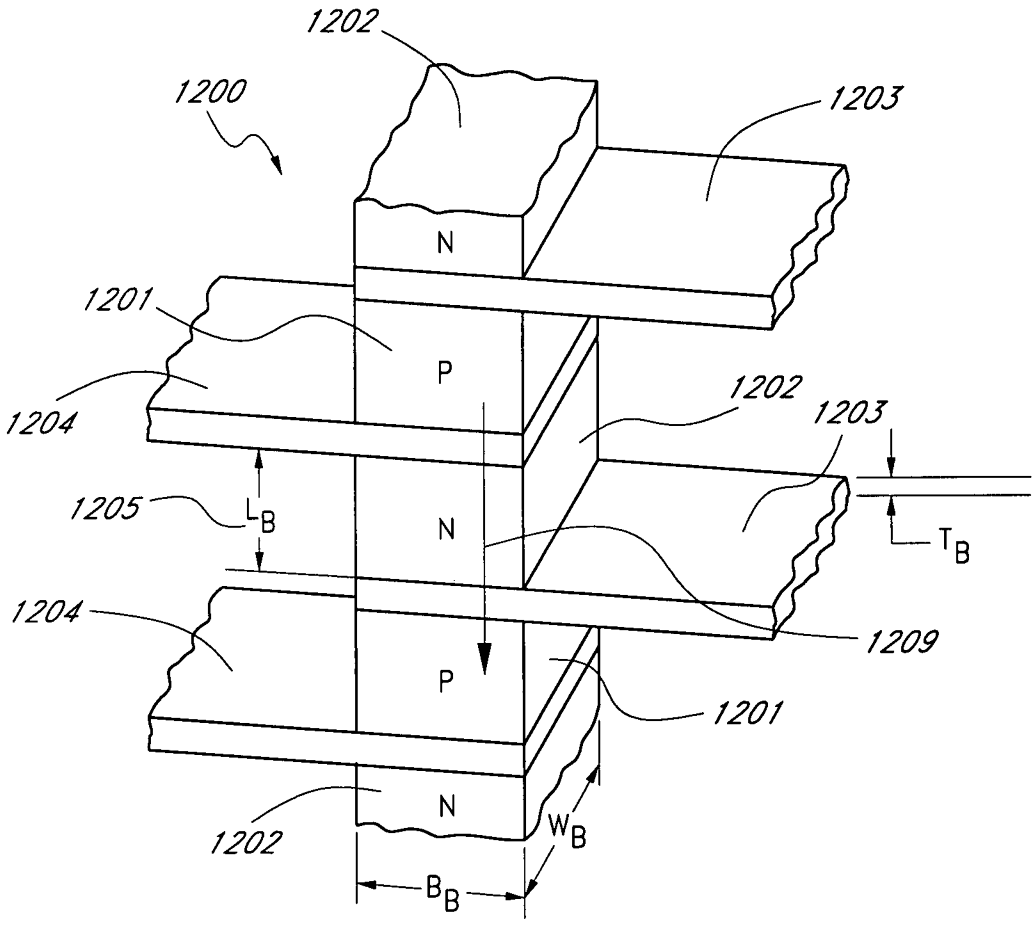

1202
1200
1203
N
1201
P
1204
1202
1203
1205
L_B
N
T_B
1204
1209
P
1201
N
1202
W_B
B_B

FIG. 12

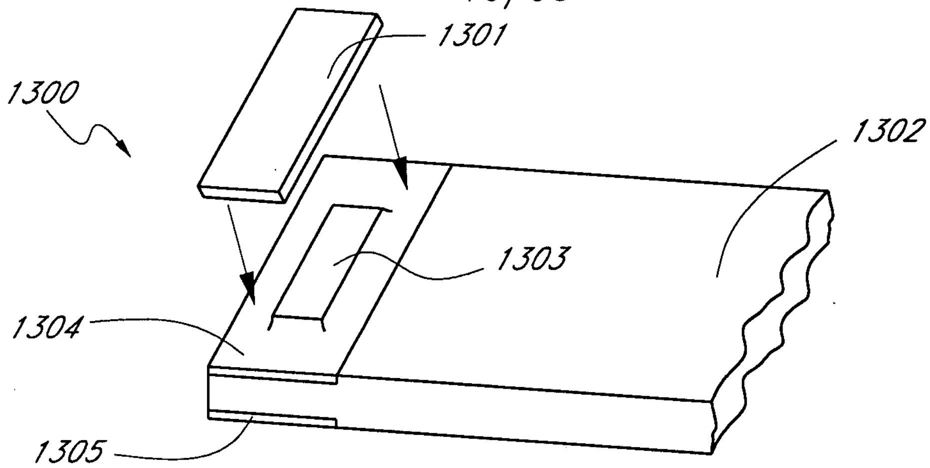


FIG. 13A

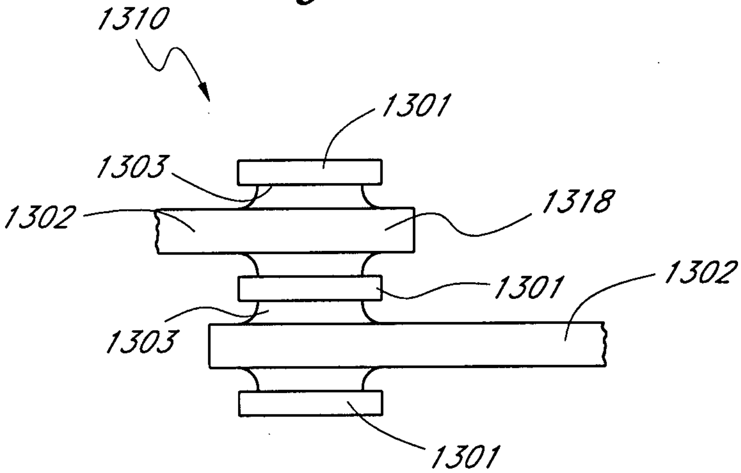


FIG. 13B

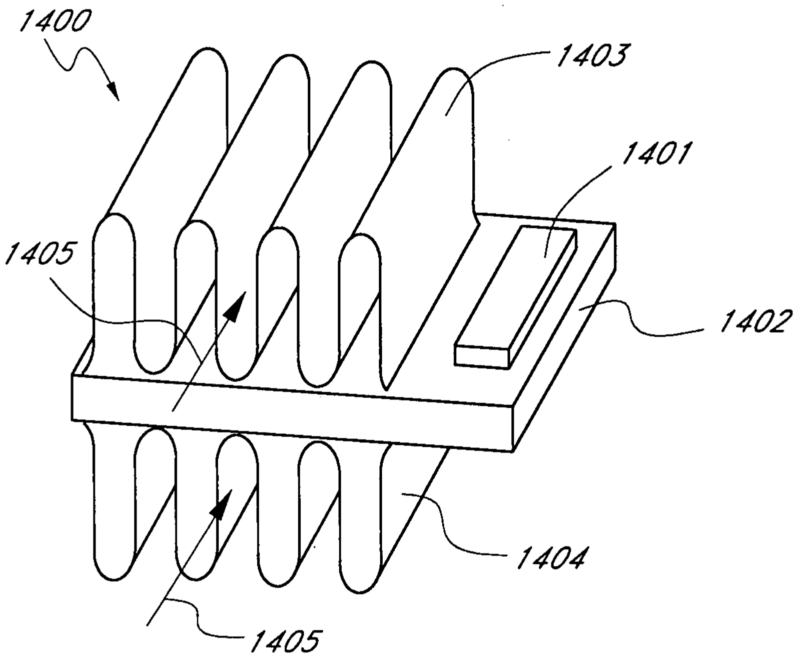


FIG. 14

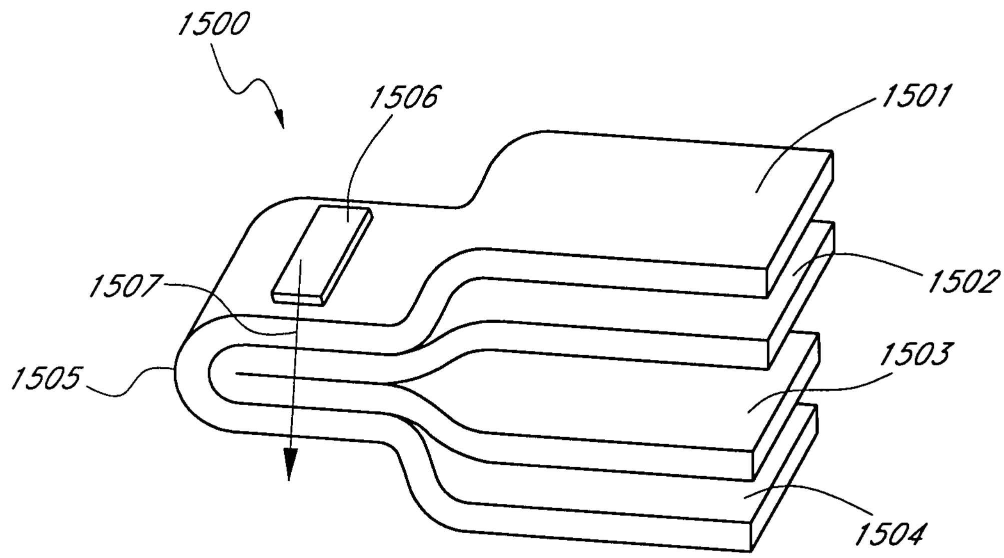

1500
1506
1501
1502
1507
1503
1505
1504

FIG. 15

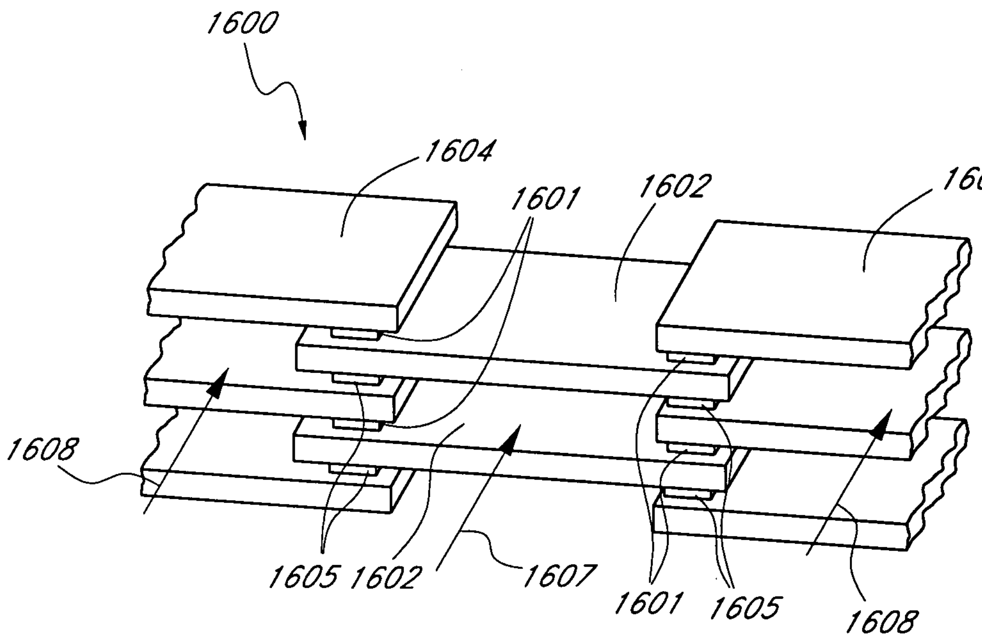

1600
1604
1601
1602
1603
1608
1605
1602
1607
1601
1605
1608

FIG. 16

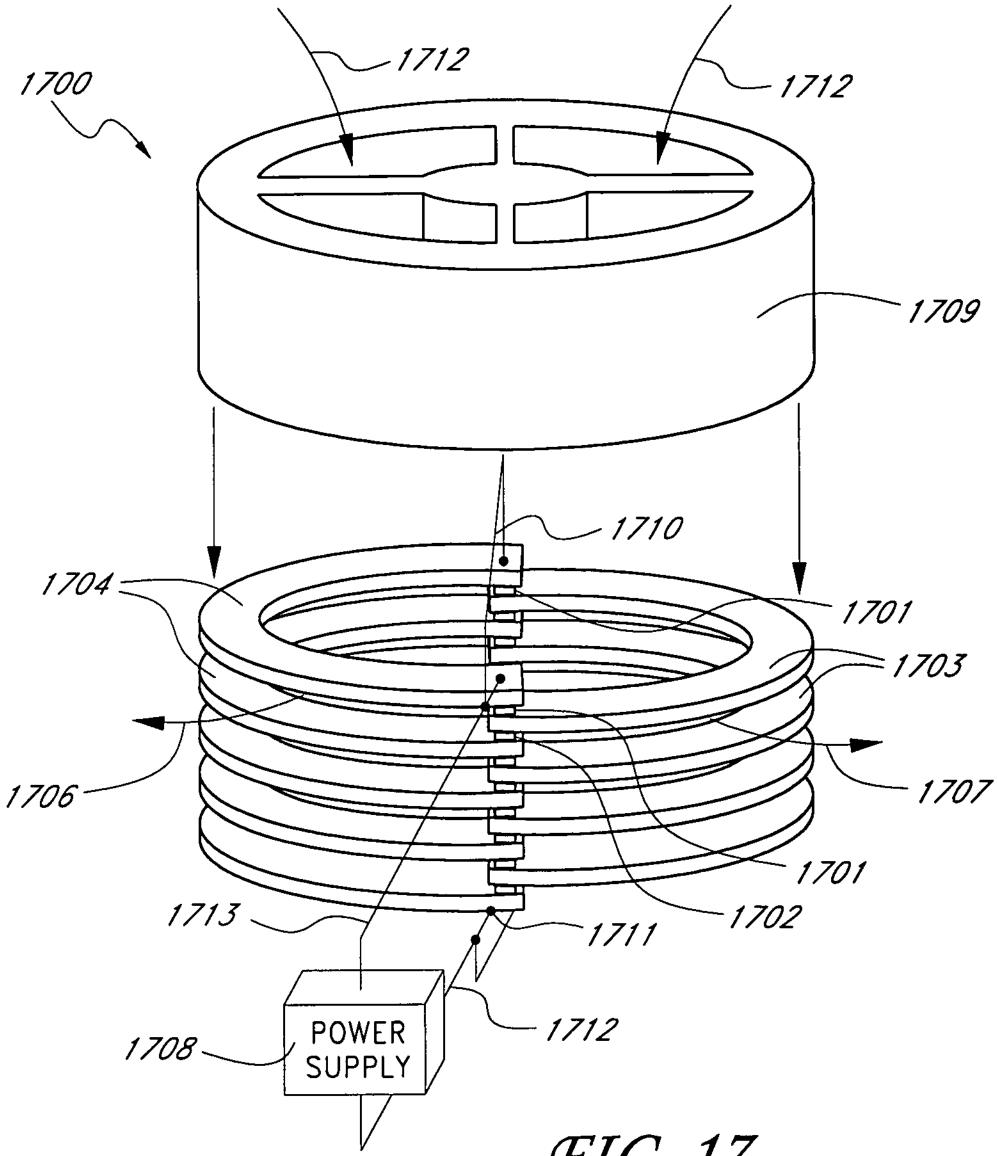

1700
1712
1712
1709
1710
1704
1701
1703
1706
1707
1701
1702
1713
1711
1712
1708
POWER SUPPLY

FIG. 17

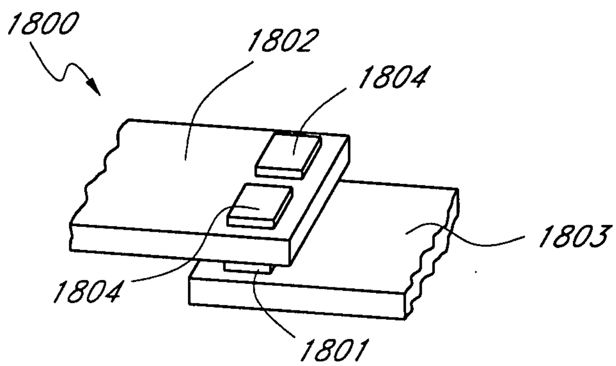

1800
1802
1804
1803
1804
1801

FIG. 18

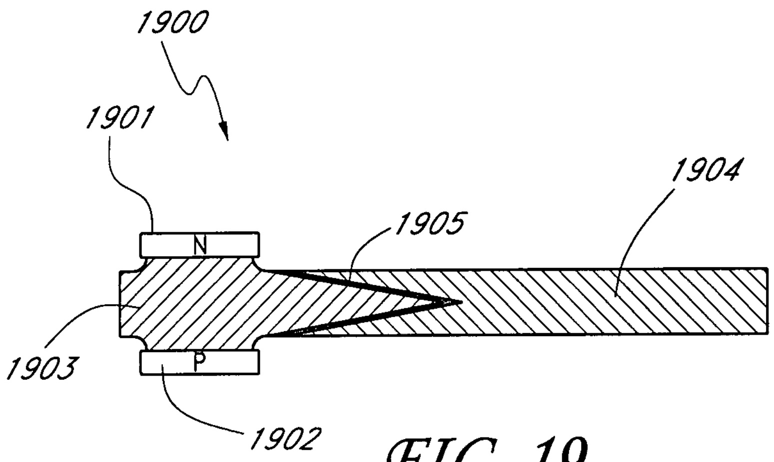


FIG. 19

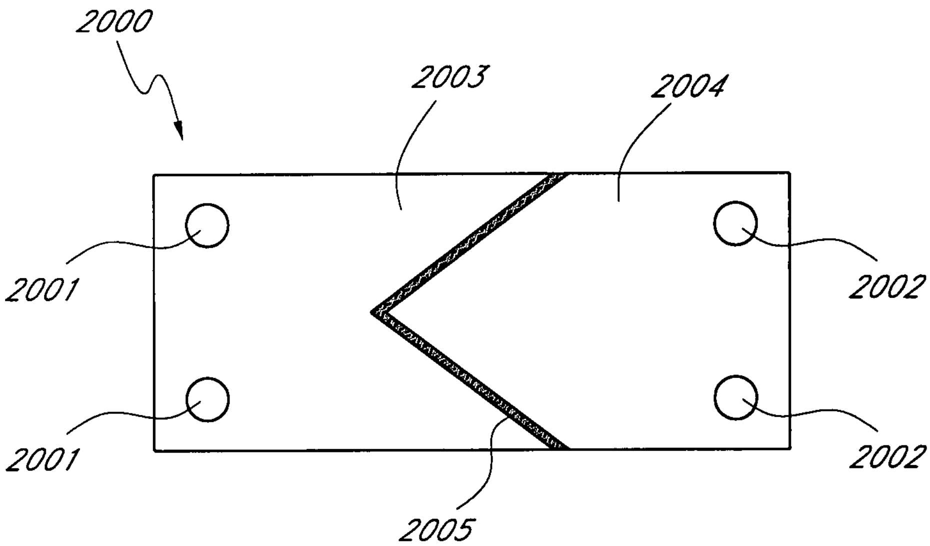


FIG. 20

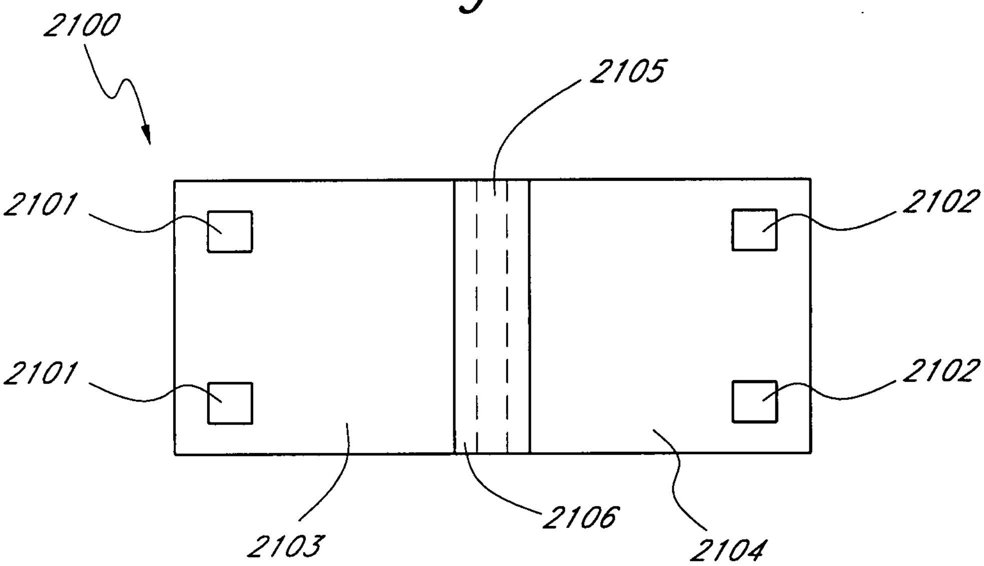


FIG. 21

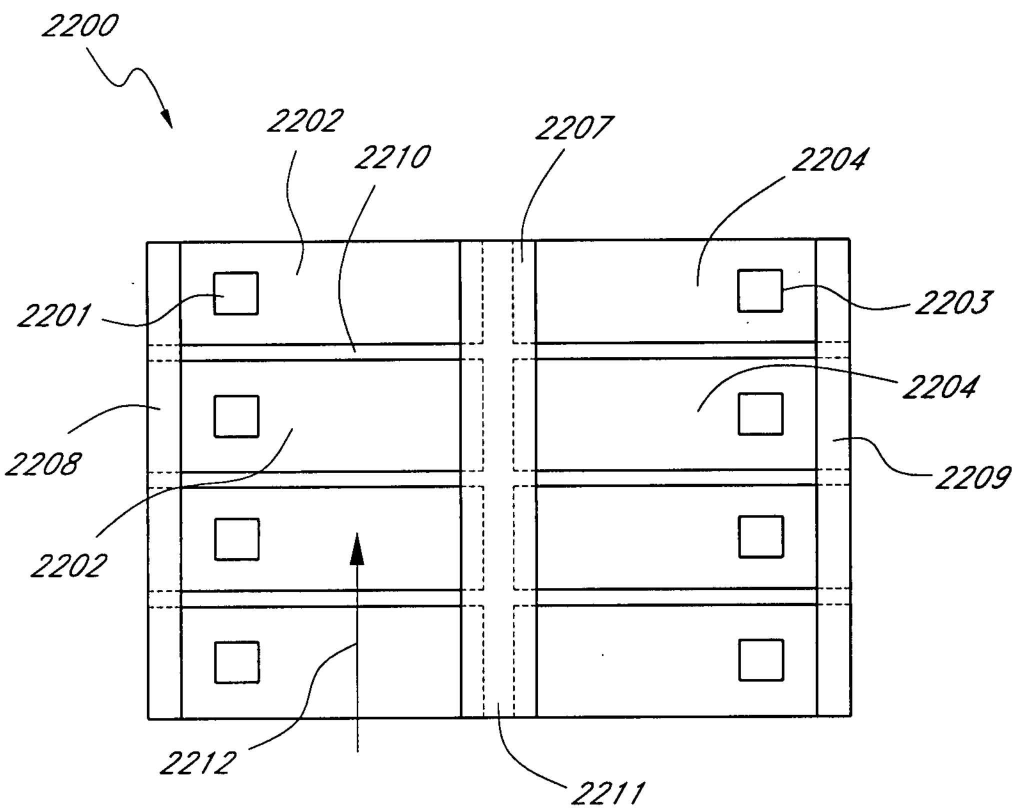

2200
2202
2210
2207
2204
2201
2203
2204
2208
2209
2202
2212
2211

FIG. 22

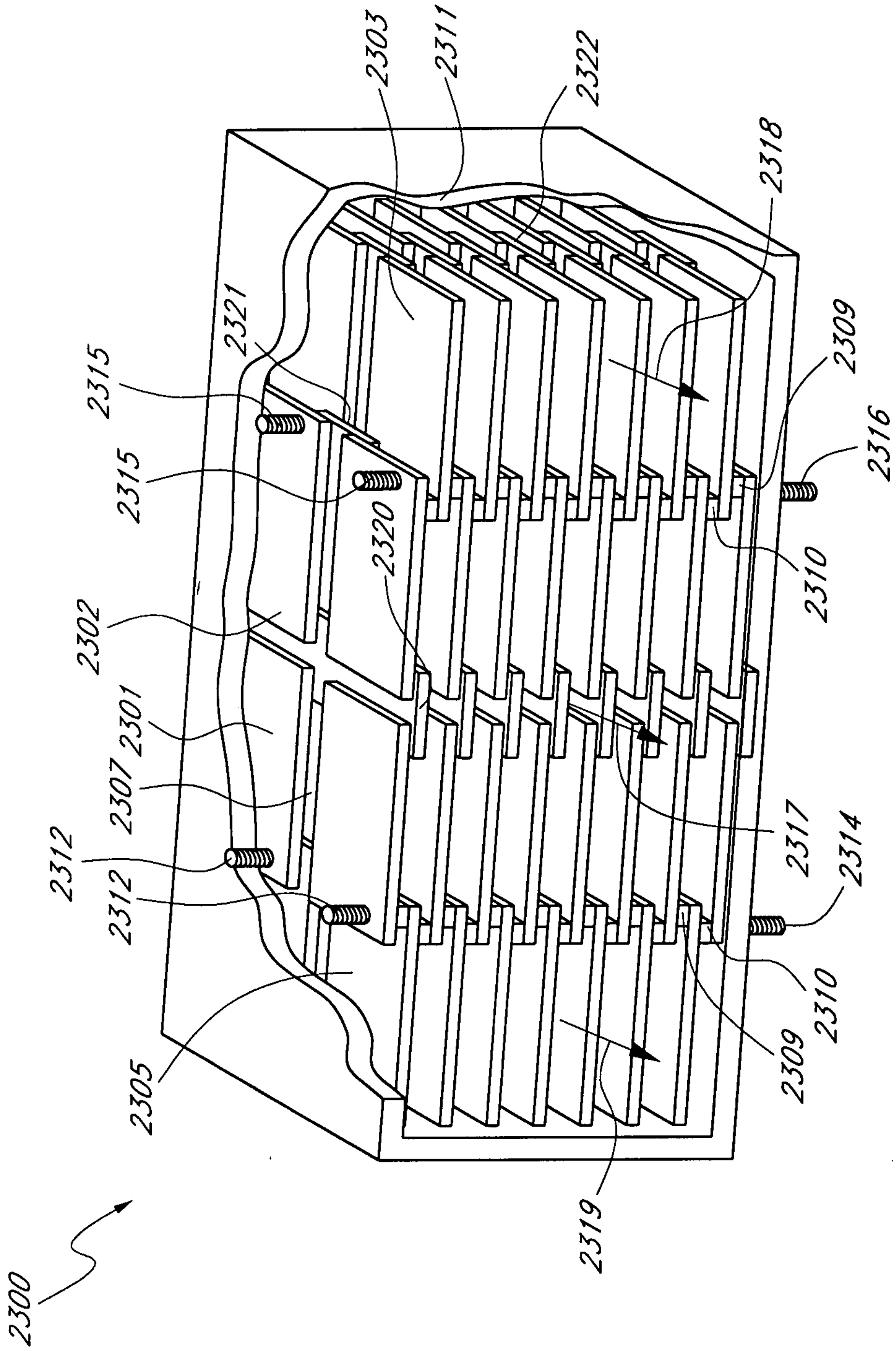

2303
2311
2322
2318
2321
2315
2309
2315
2316
2320
2302
2310
2301
2307
2312
2312
2317
2314
2305
2309
2310
2319
2300

FIG. 23

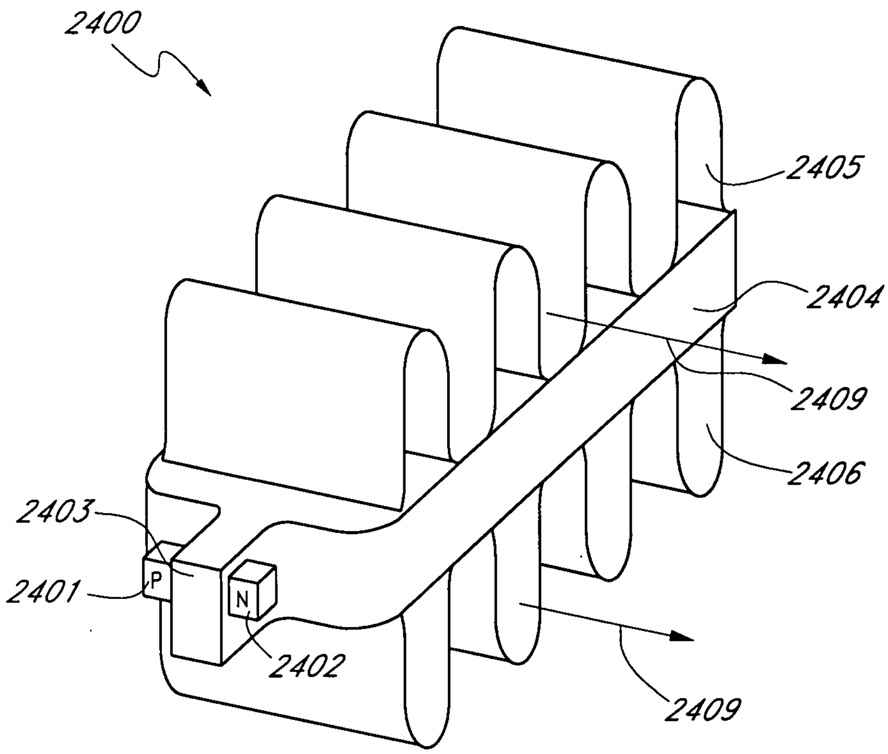


FIG. 24A

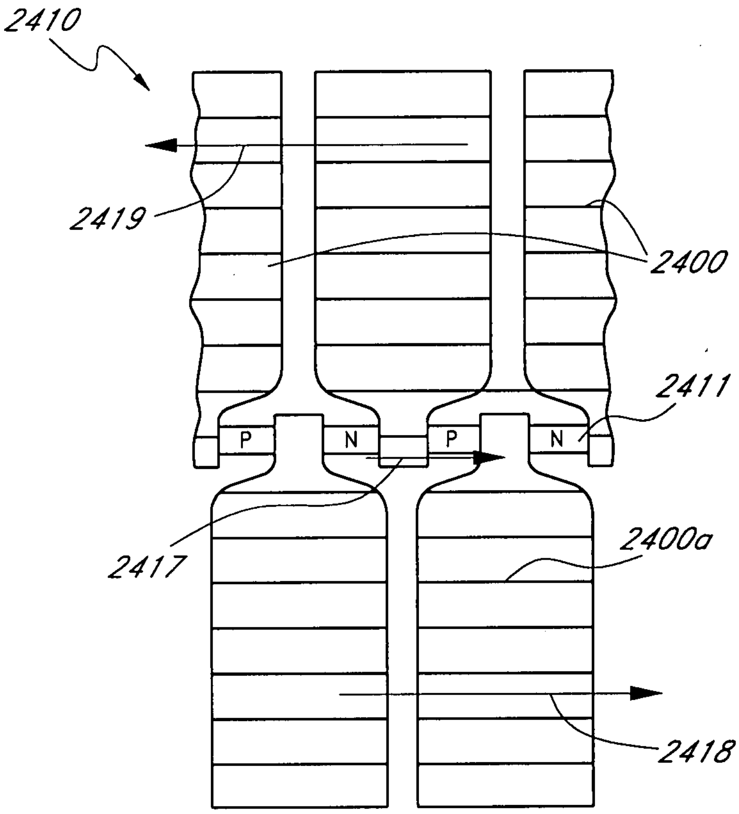


FIG. 24B

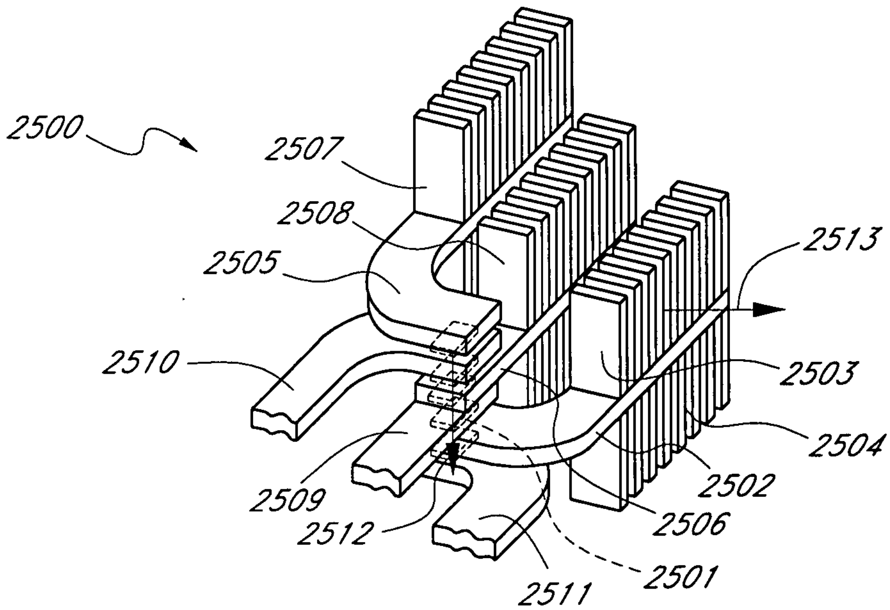


FIG. 25A

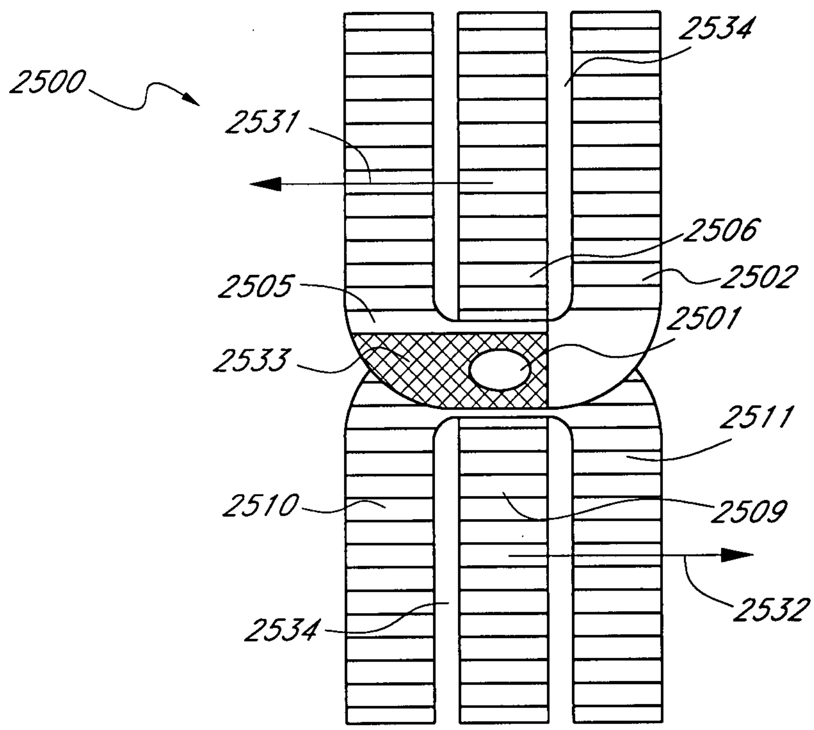


FIG. 25B

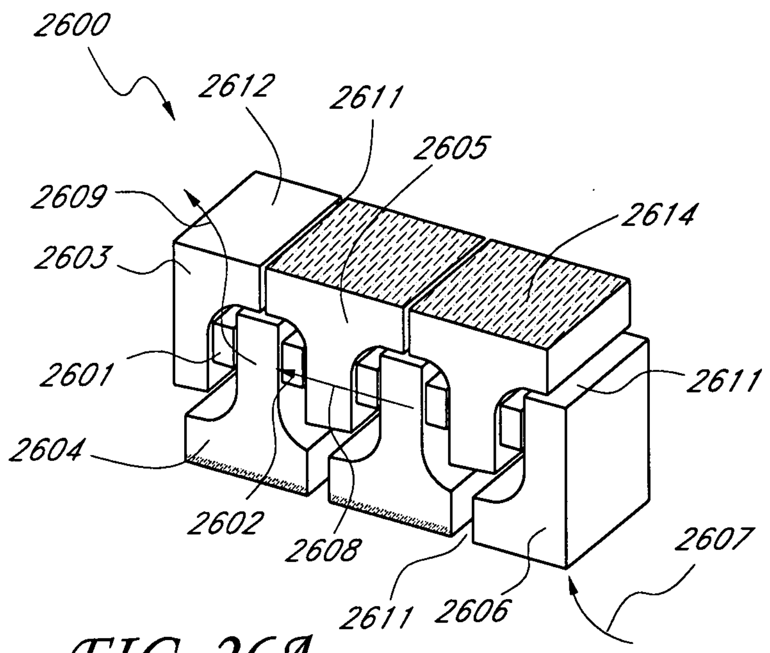


FIG. 26A

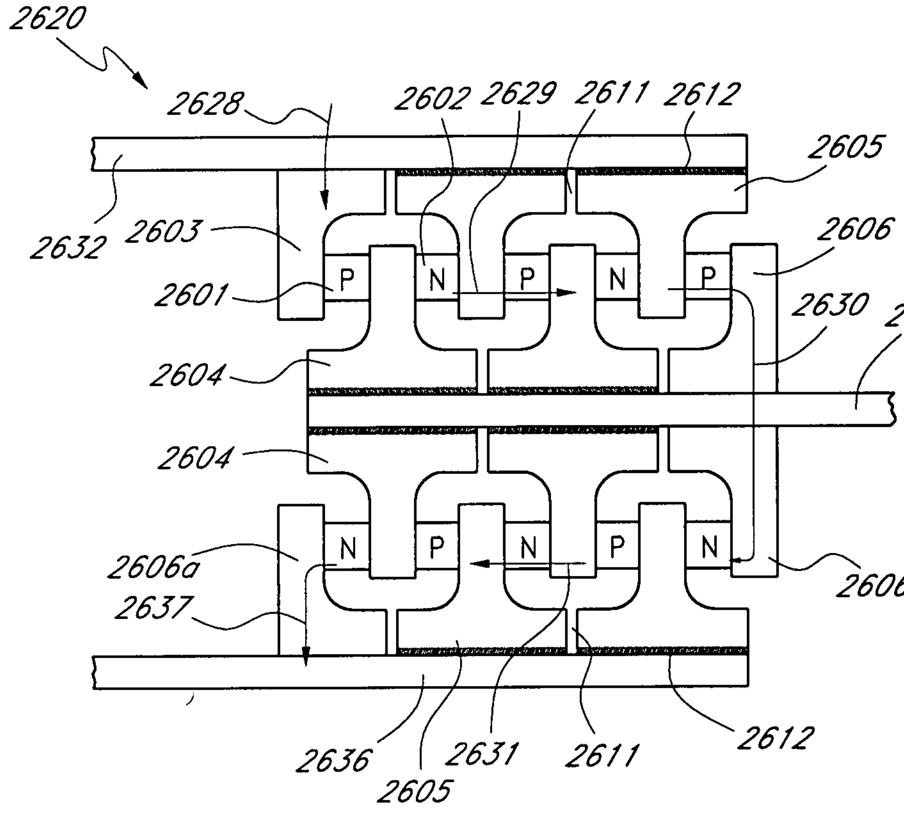


FIG. 26B

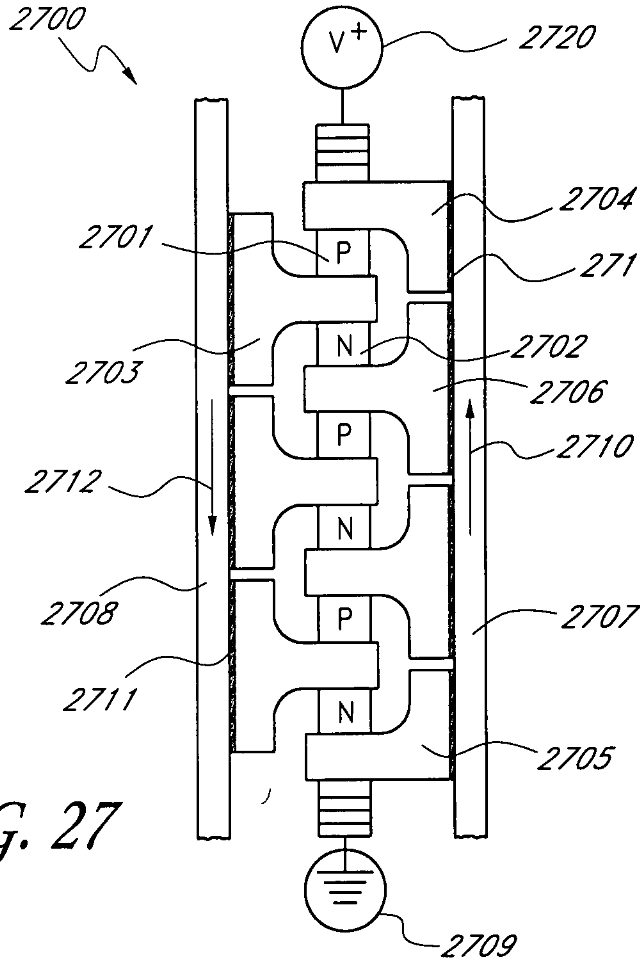

2700
V+
2720
2704
2701
P
2711
N
2702
2703
2706
P
2710
2712
N
2708
P
2707
2711
N
2705
2709

FIG. 27

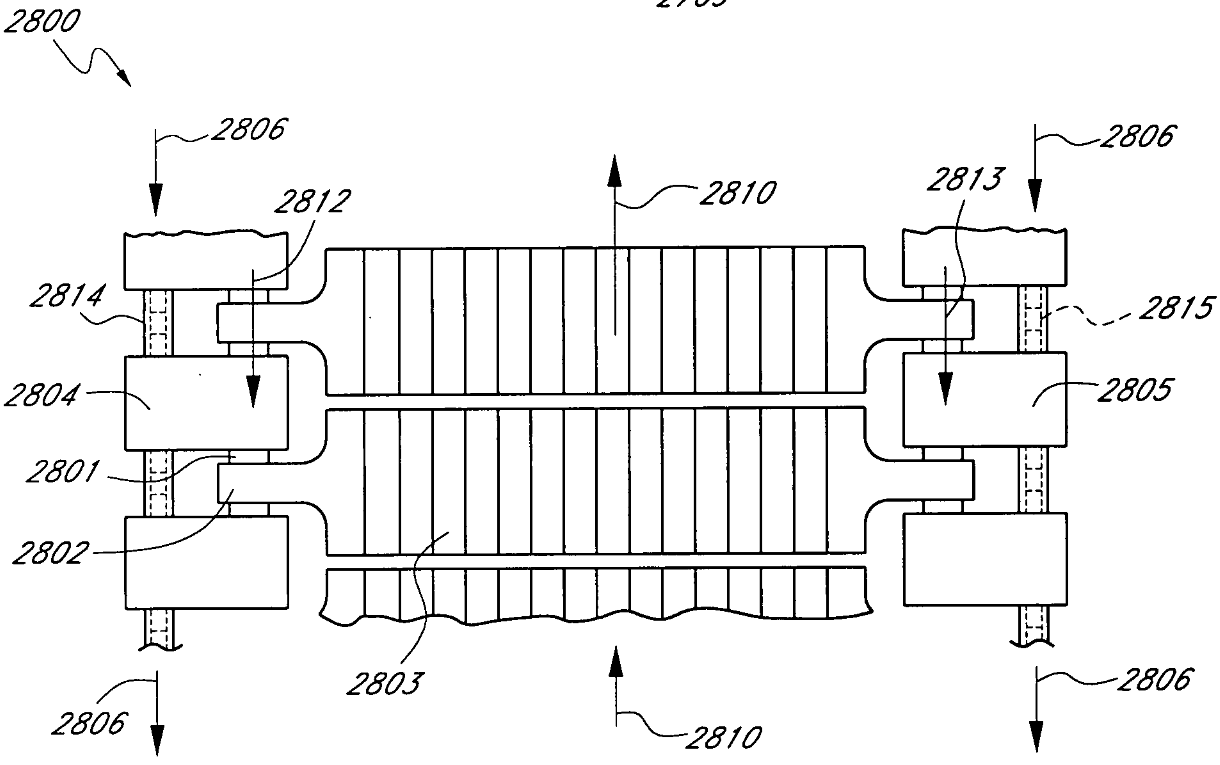

2800
2806
2812
2810
2813
2806
2814
2815
2804
2805
2801
2802
2803
2806
2810
2806

FIG. 28

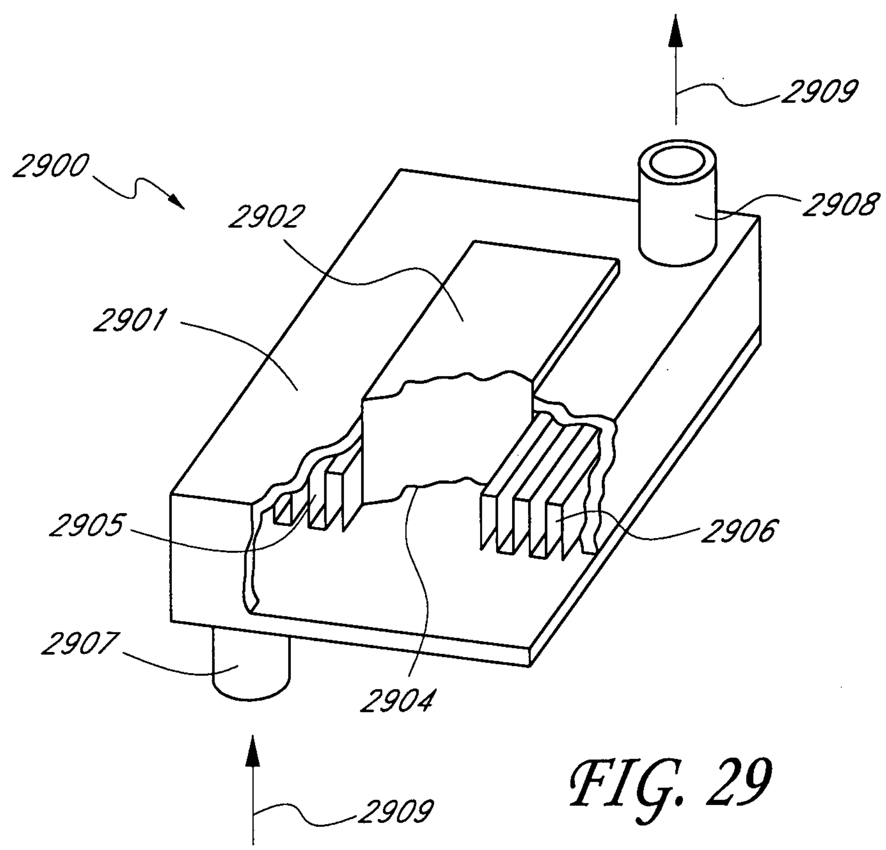

2909
2900
2902
2908
2901
2905
2906
2907
2904
2909

FIG. 29

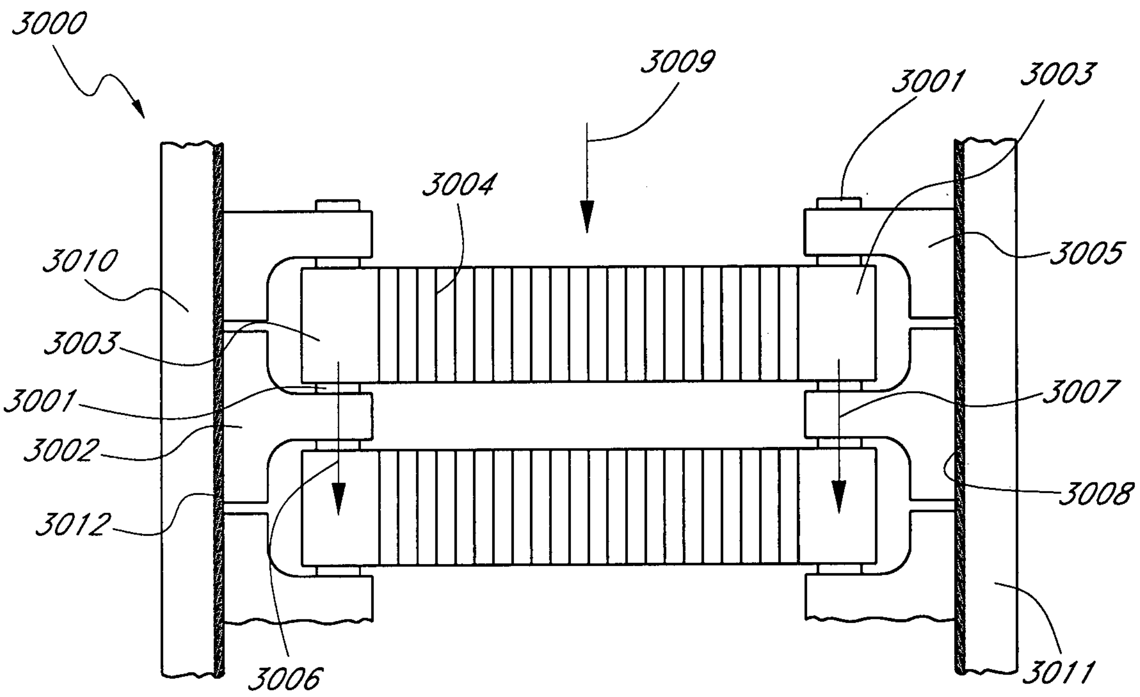

3000
3009
3001
3003
3004
3005
3010
3003
3001
3007
3002
3008
3012
3006
3011

FIG. 30

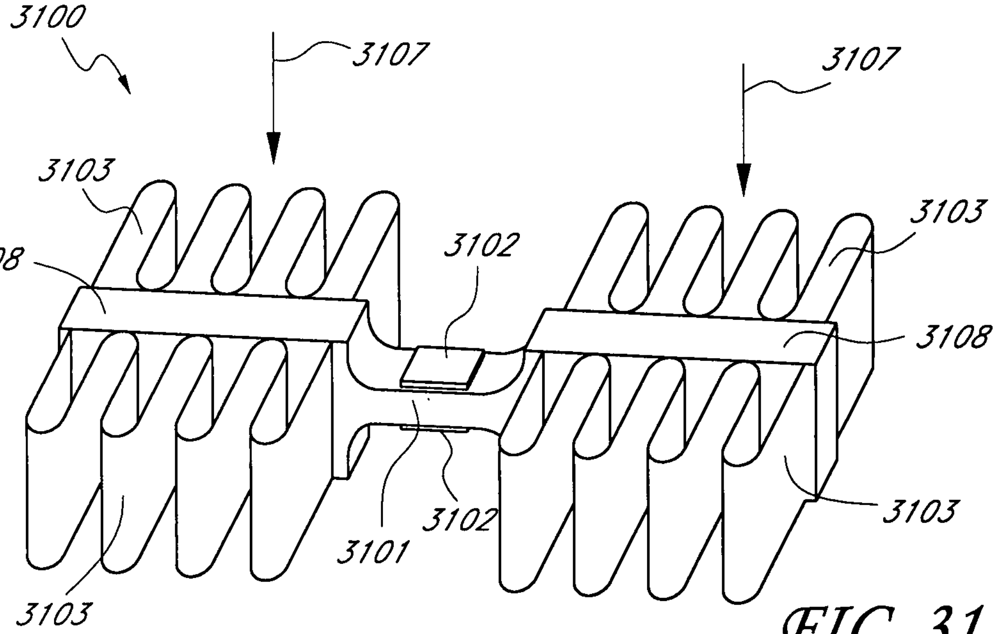


FIG. 31A

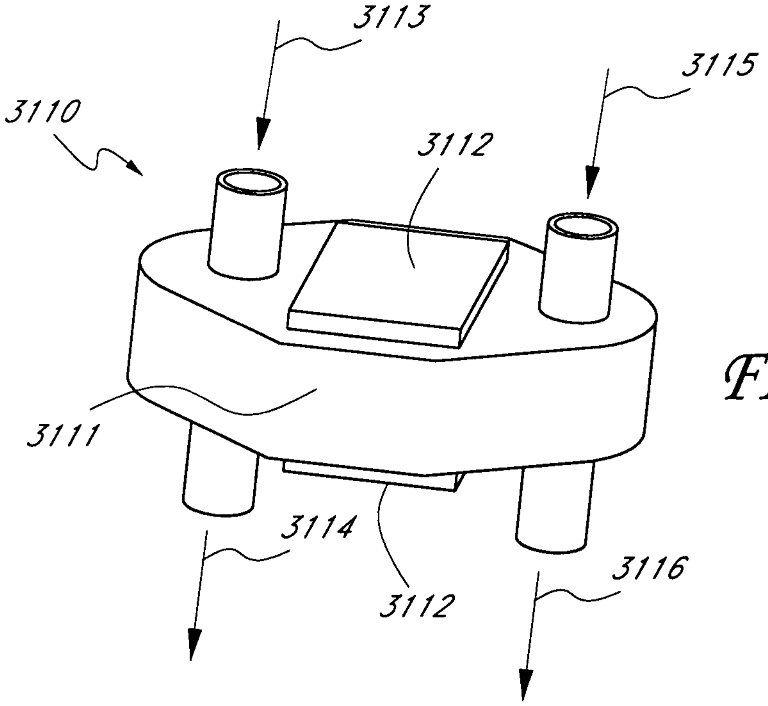


FIG. 31B

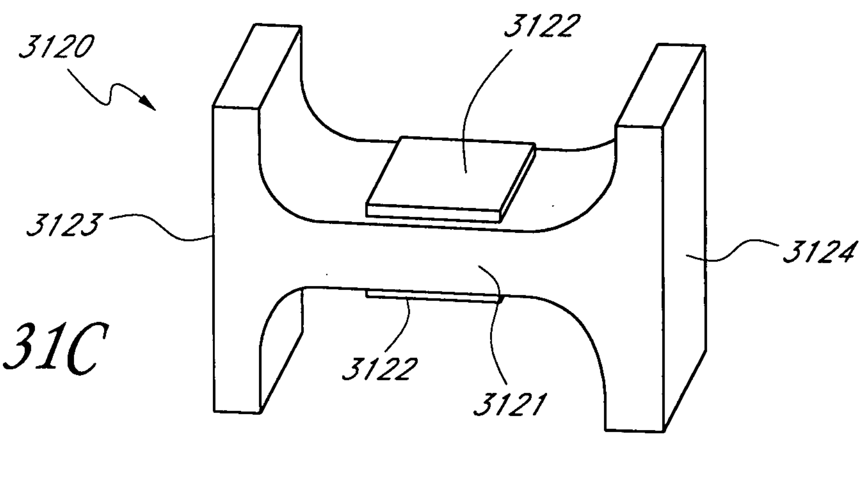


FIG. 31C

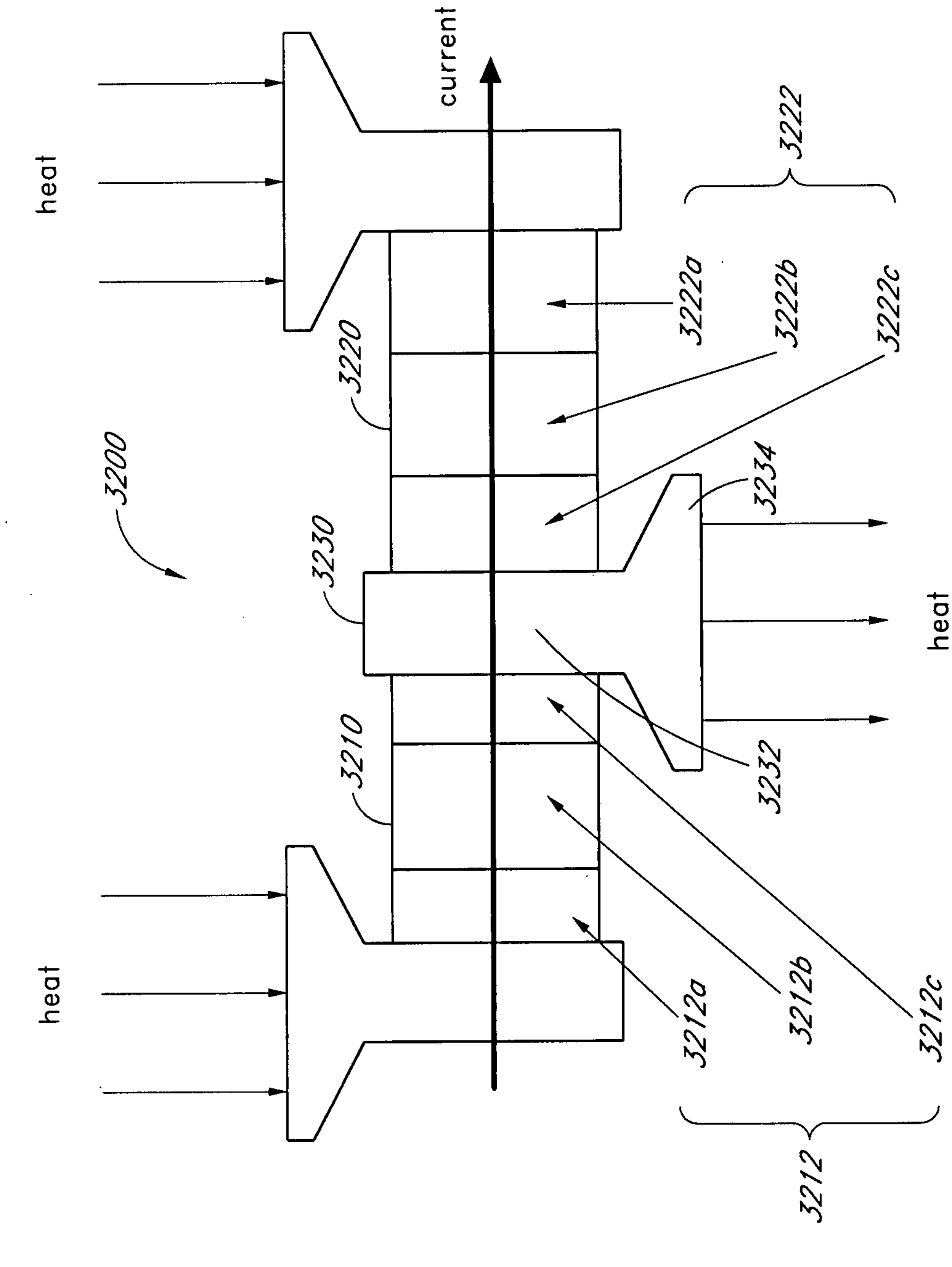

heat
current
3222
3222a
3222b
3222c
3220
3200
3234
3230
heat
3210
3232
3212a
3212b
3212c
3212
heat

FIG. 32

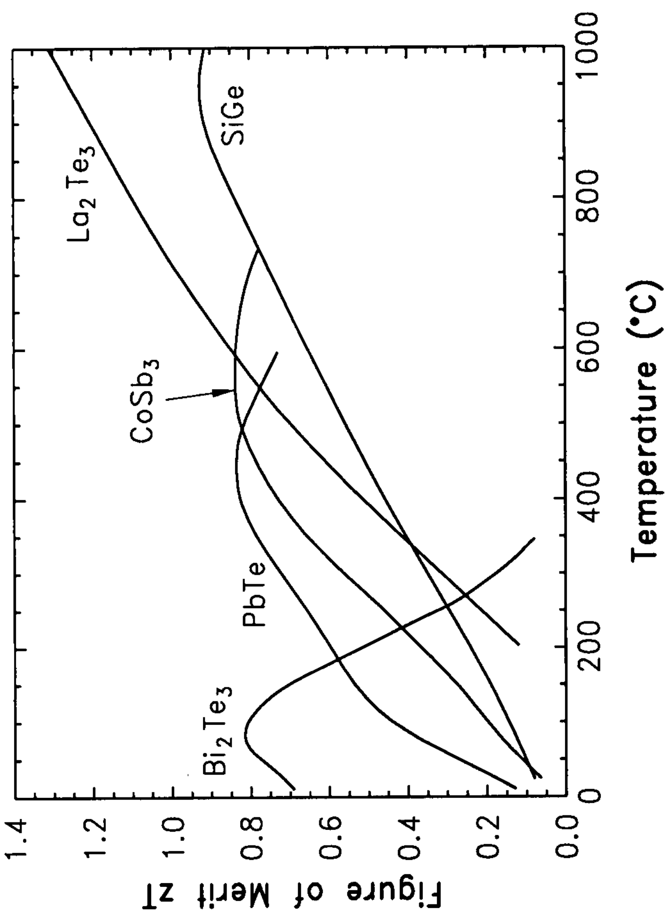


FIG. 33B

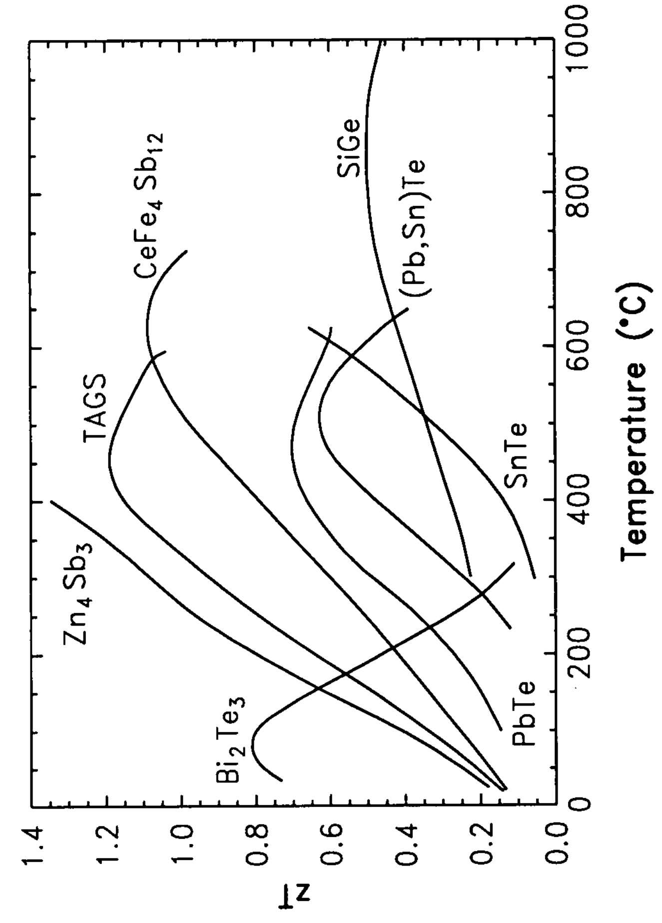


FIG. 33A

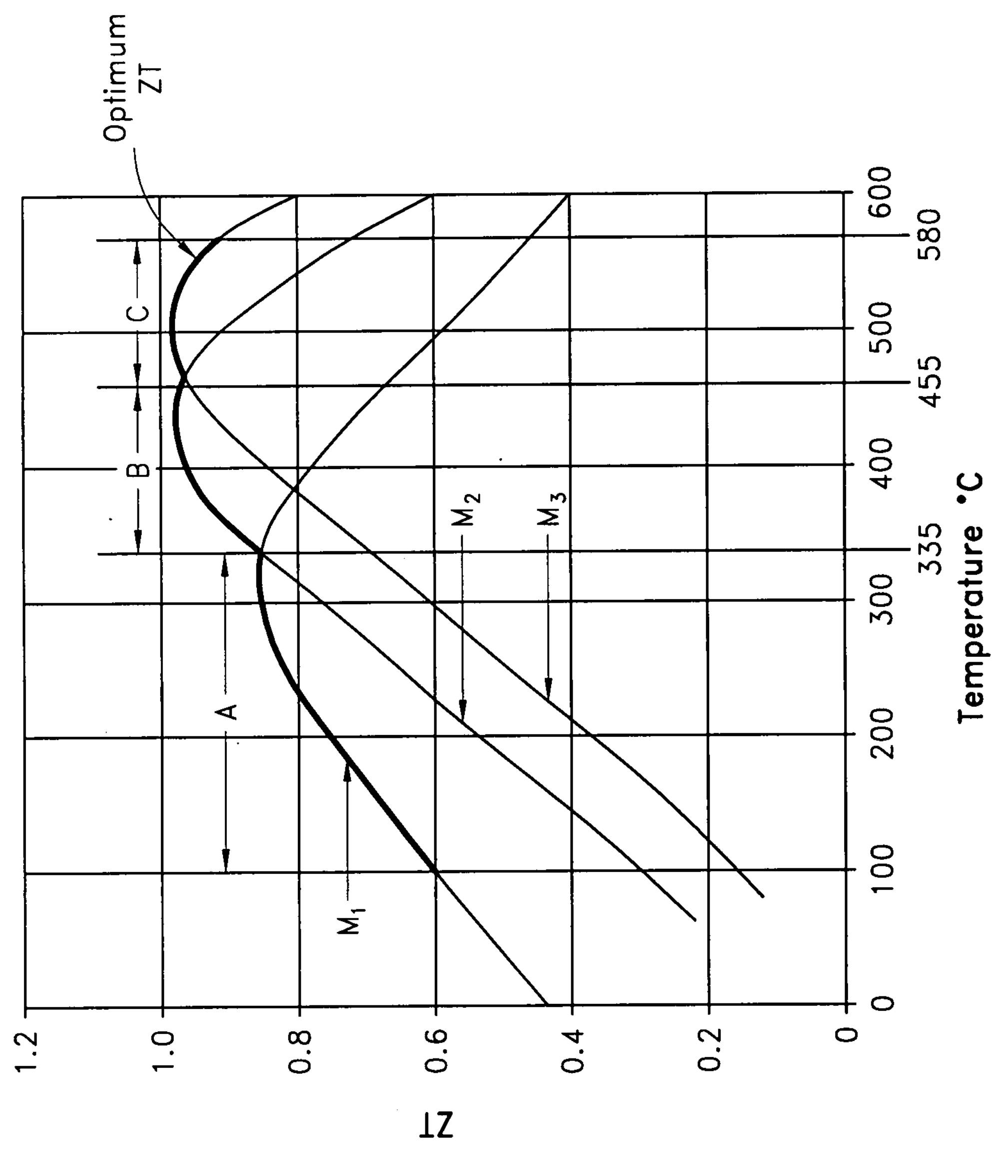

Optimum ZT
A
B
C
M_1
M_2
M_3
ZT
1.2
1.0
0.8
0.6
0.4
0.2
0
Temperature °C
0
100
200
300
335
400
455
500
580
600

FIG. 34

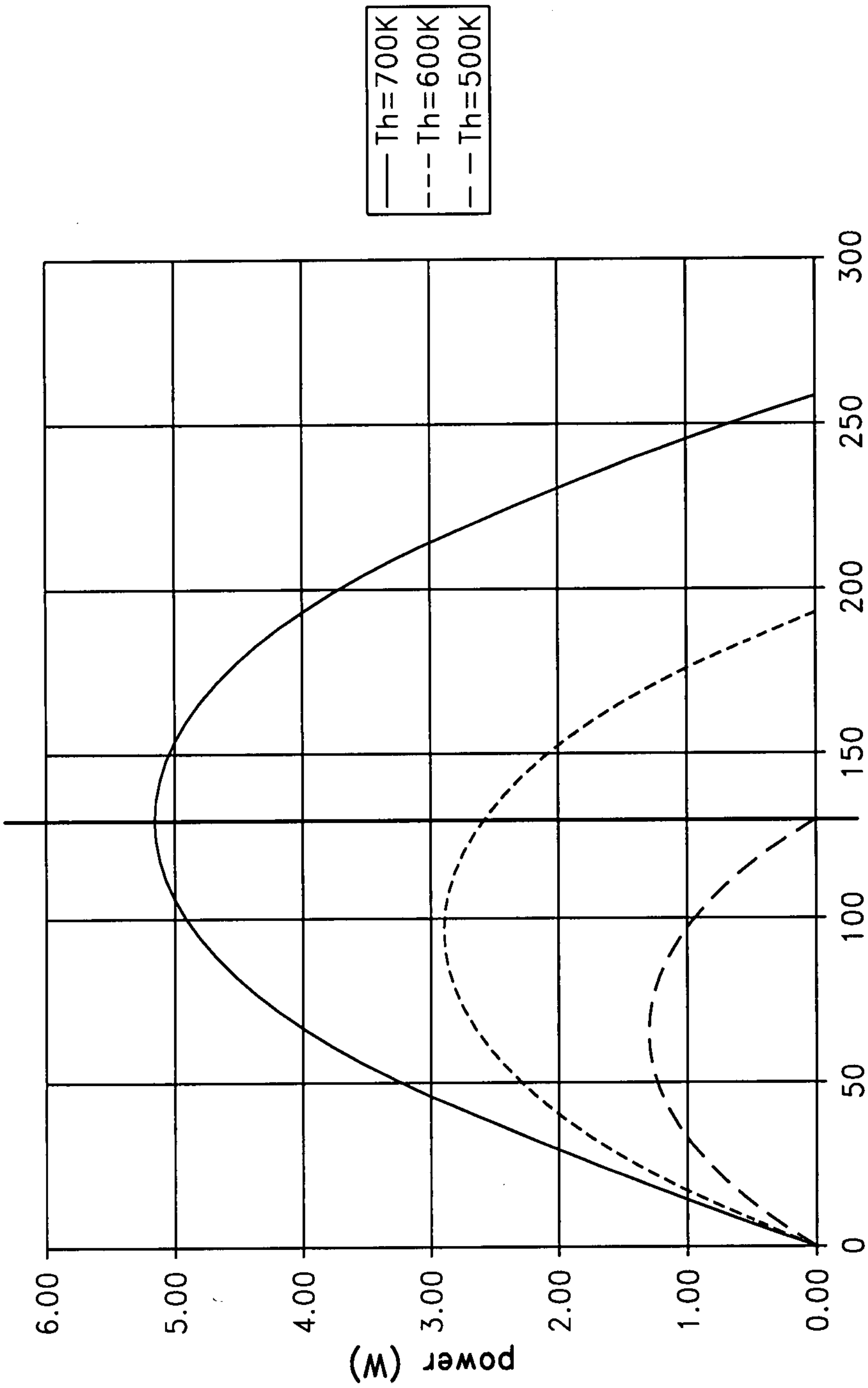

Th=700K
Th=600K
Th=500K
power (W)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
current (A)
0
50
100
150
200
250
300

FIG. 35

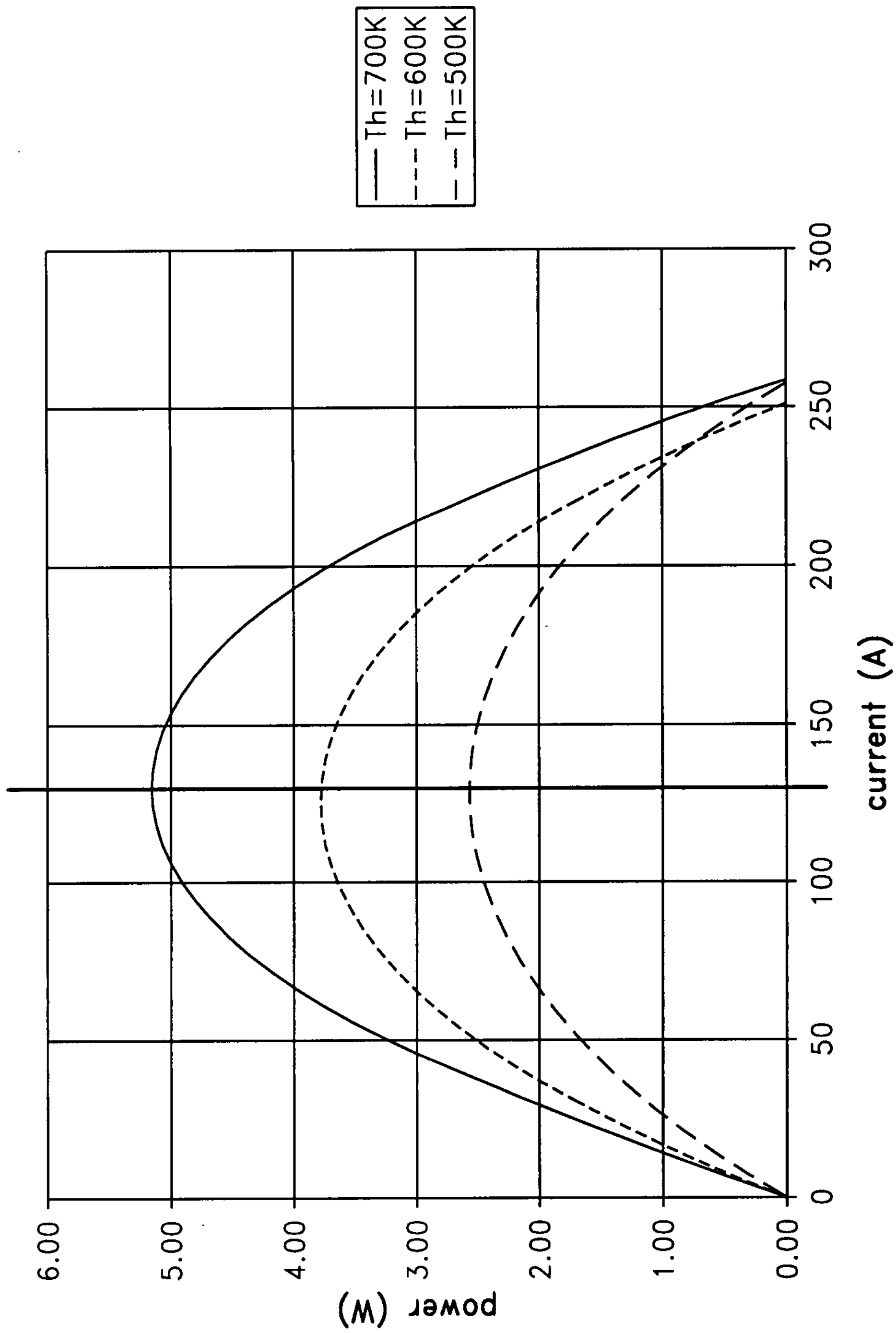

Th=700K
Th=600K
Th=500K
power (W)
0.00
1.00
2.00
3.00
4.00
5.00
6.00
current (A)
0
50
100
150
200
250
300

FIG. 36

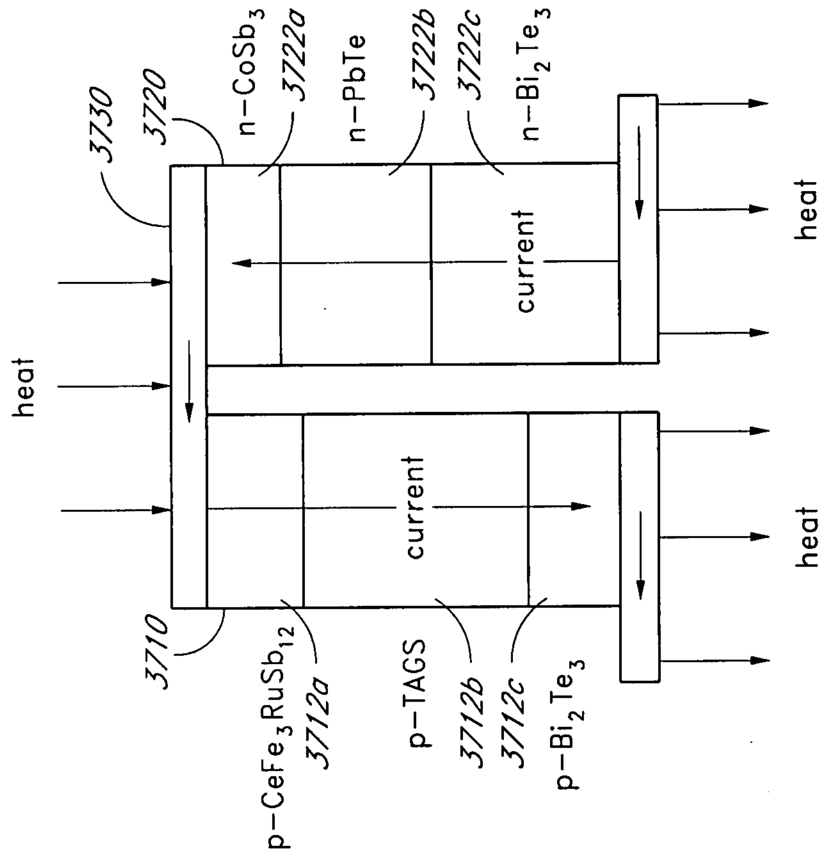

3730
3720
n-CoSb3
3722a
n-PbTe
3722b
3722c
n-Bi2Te3
heat
current
heat
current
heat
3710
p-CeFe3RuSb12
3712a
p-TAGS
3712b
3712c
p-Bi2Te3

FIG. 37

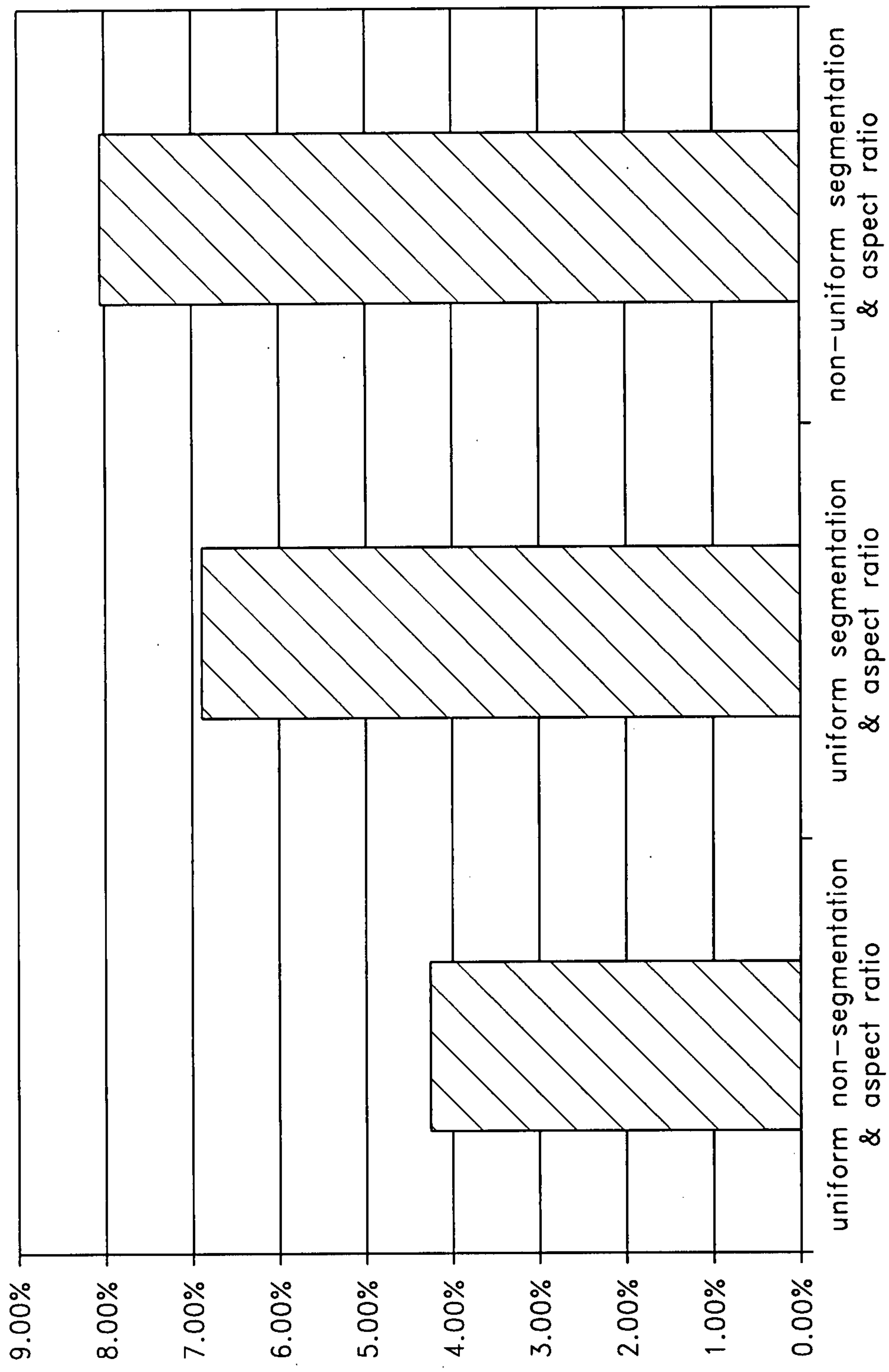

9.00%
8.00%
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
uniform non-segmentation & aspect ratio
uniform segmentation & aspect ratio
non-uniform segmentation & aspect ratio

FIG. 38

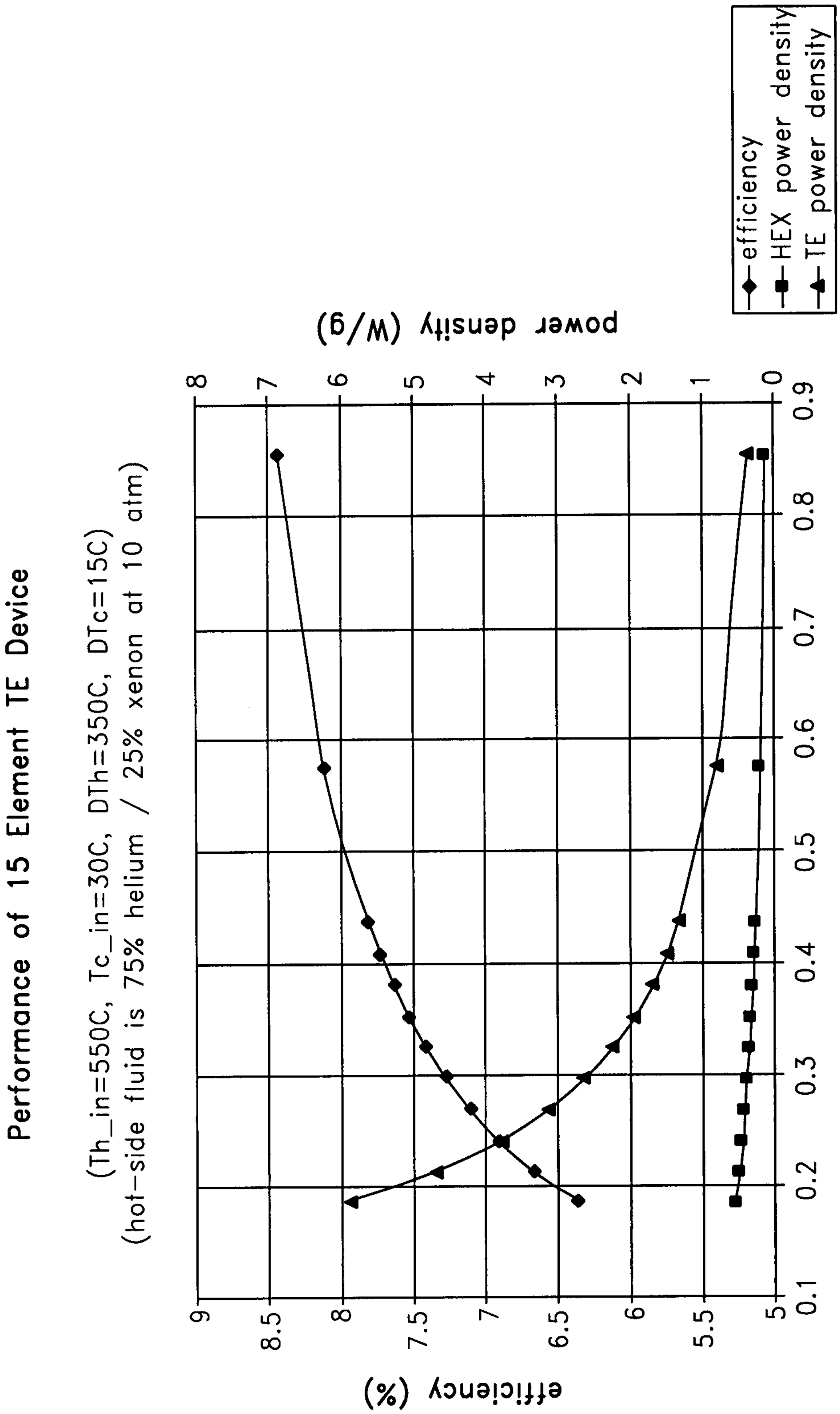

Performance of 15 Element TE Device
(Th_in=550C, Tc_in=30C, DTh=350C, DTc=15C)
(hot-side fluid is 75% helium / 25% xenon at 10 atm)
efficiency (%)
9
8.5
8
7.5
7
6.5
6
5.5
5
power density (W/g)
8
7
6
5
4
3
2
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
maximum TE thickness (cm)
efficiency
HEX power density
TE power density

FIG. 39

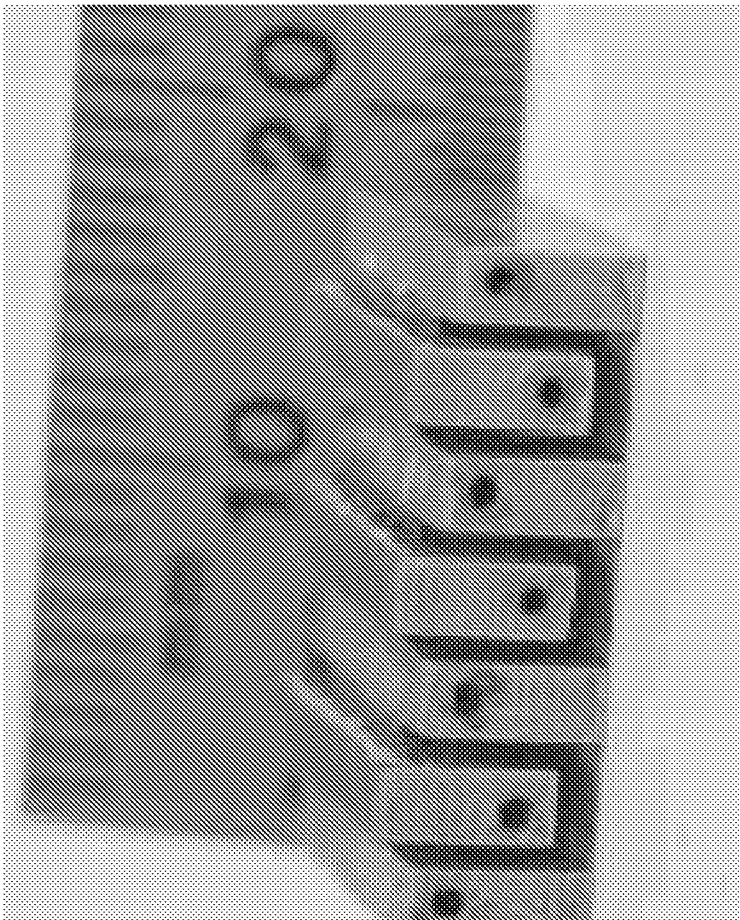
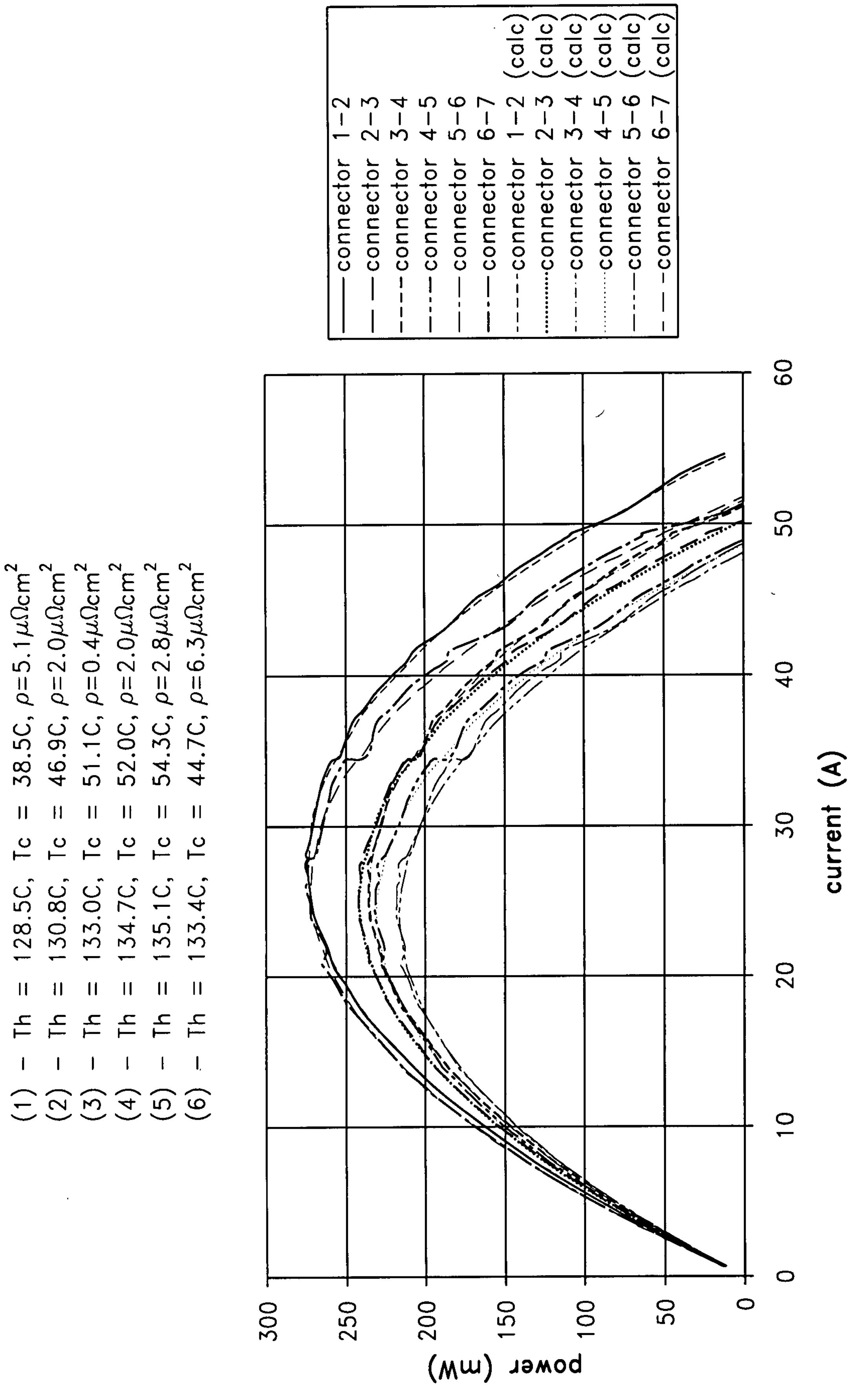


FIG. 40



(1) – Th = 128.5C, Tc = 38.5C, ρ=5.1μΩcm²
(2) – Th = 130.8C, Tc = 46.9C, ρ=2.0μΩcm²
(3) – Th = 133.0C, Tc = 51.1C, ρ=0.4μΩcm²
(4) – Th = 134.7C, Tc = 52.0C, ρ=2.0μΩcm²
(5) – Th = 135.1C, Tc = 54.3C, ρ=2.8μΩcm²
(6) – Th = 133.4C, Tc = 44.7C, ρ=6.3μΩcm²
connector 1–2
connector 2–3
connector 3–4
connector 4–5
connector 5–6
connector 6–7
connector 1–2 (calc)
connector 2–3 (calc)
connector 3–4 (calc)
connector 4–5 (calc)
connector 5–6 (calc)
connector 6–7 (calc)
power (mW)
300
250
200
150
100
50
0
current (A)
0
10
20
30
40
50
60

FIG. 41

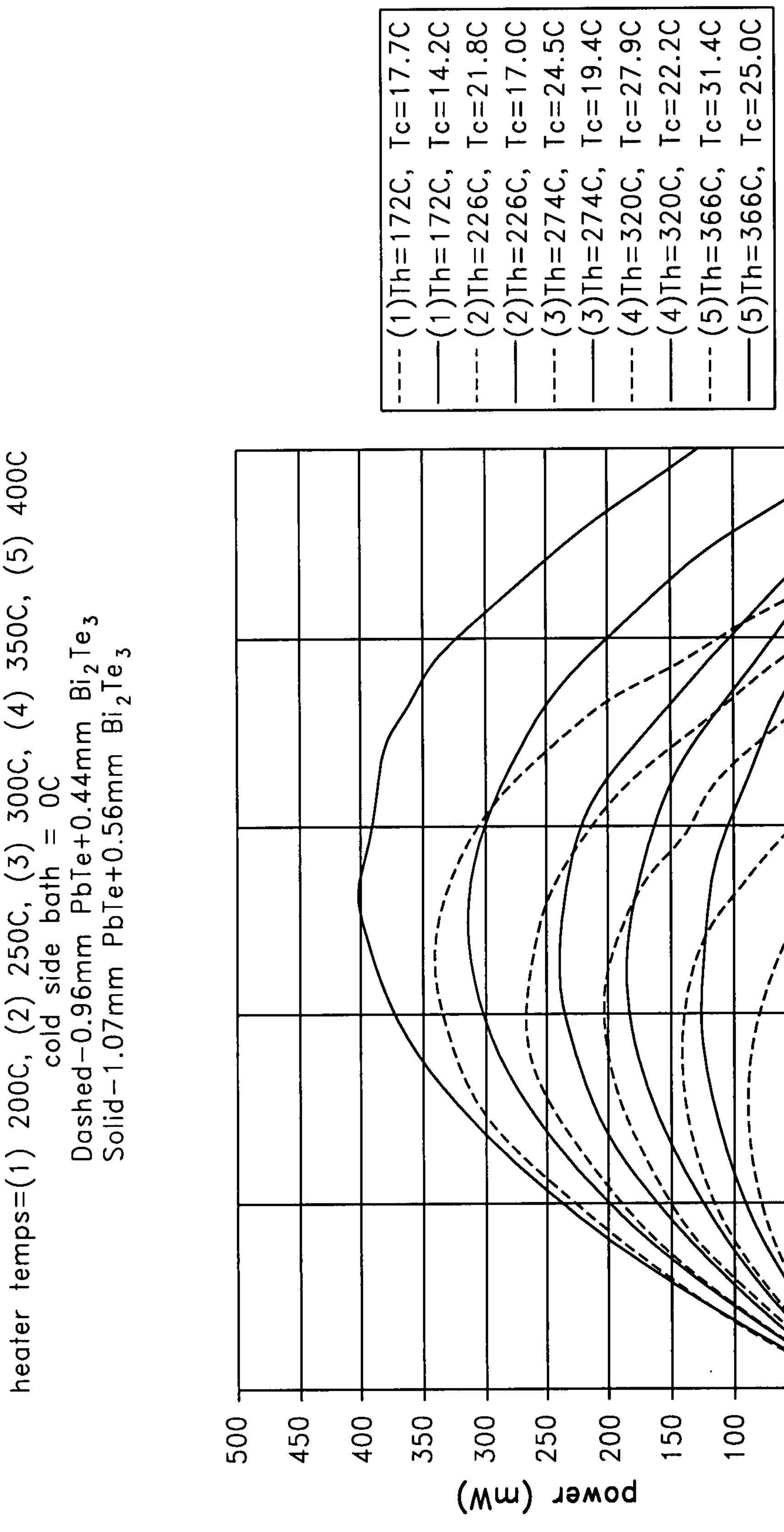

heater temps=(1) 200C, (2) 250C, (3) 300C, (4) 350C, (5) 400C
cold side bath = 0C
Dashed-0.96mm PbTe+0.44mm Bi2Te3
Solid-1.07mm PbTe+0.56mm Bi2Te3
(1)Th=172C, Tc=17.7C
(1)Th=172C, Tc=14.2C
(2)Th=226C, Tc=21.8C
(2)Th=226C, Tc=17.0C
(3)Th=274C, Tc=24.5C
(3)Th=274C, Tc=19.4C
(4)Th=320C, Tc=27.9C
(4)Th=320C, Tc=22.2C
(5)Th=366C, Tc=31.4C
(5)Th=366C, Tc=25.0C
power (mW)
500
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
current (A)

FIG. 42