Oct. 21, 1958 H. L. IMELMANN 2,857,446
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METHOD AND APPARATUS FOR CONVERTING HEAT DIRECTLY TO ELECTRICITY

FIG. 2

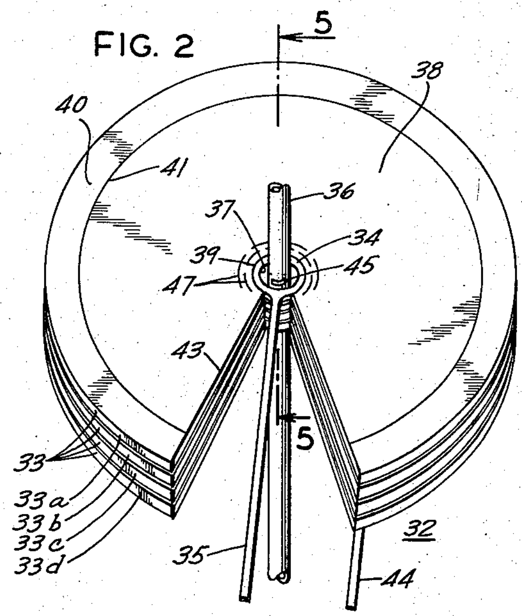


FIG. 1

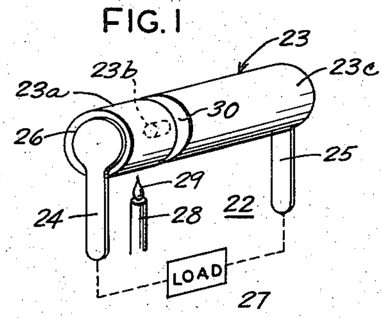


FIG. 6

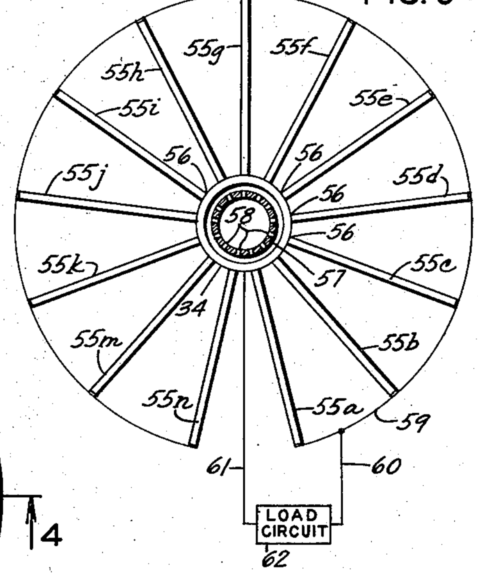
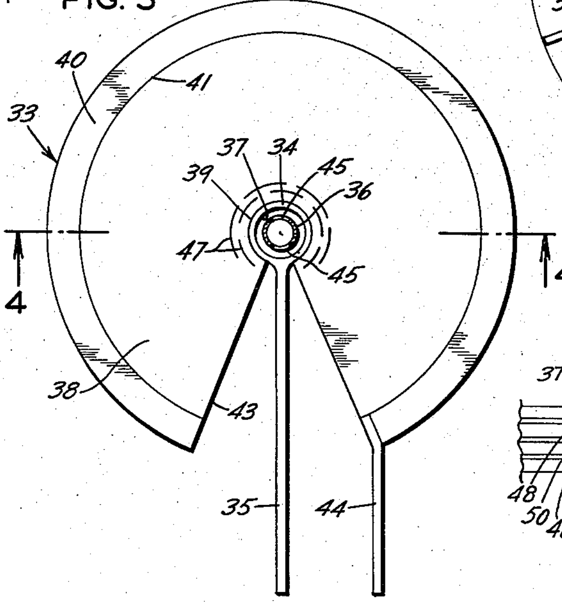


FIG. 3



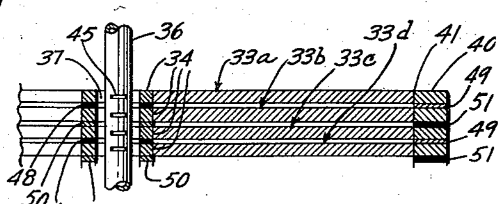
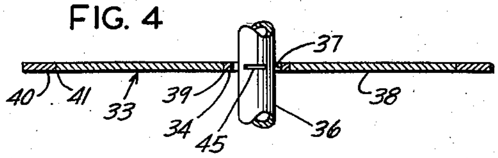


FIG. 5

FIG. 4



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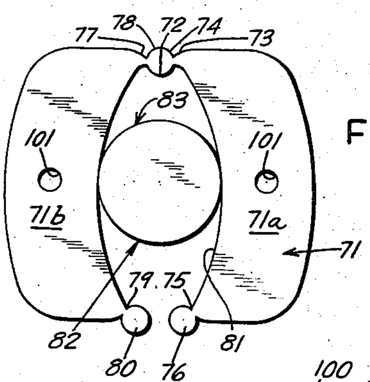

FIG. 8

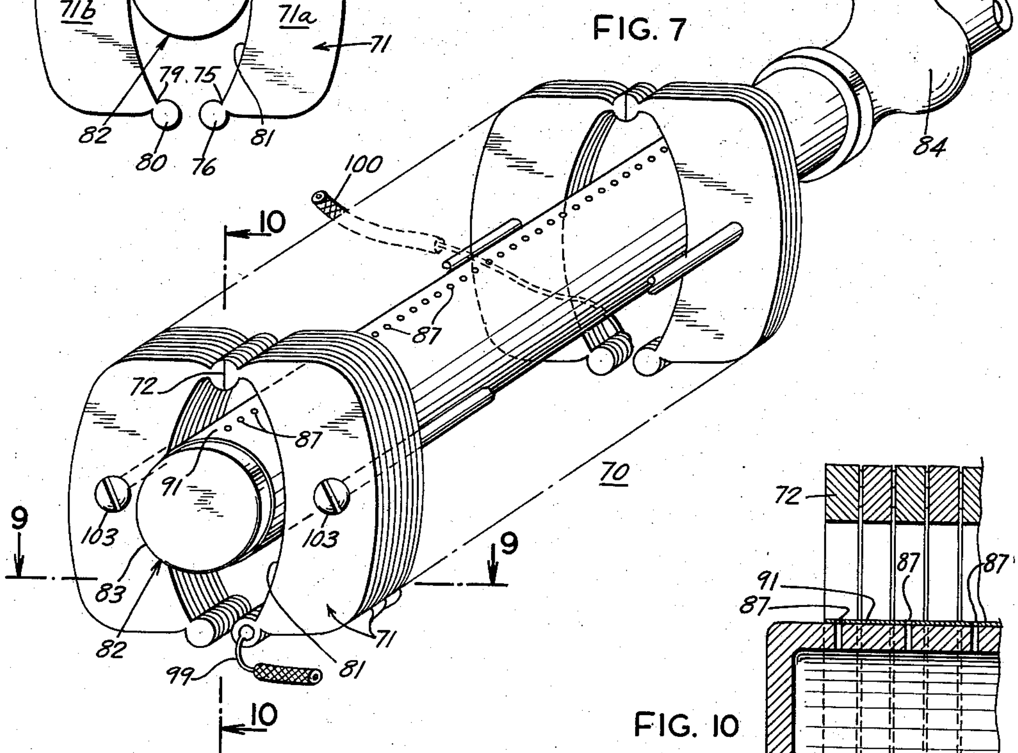

FIG. 7

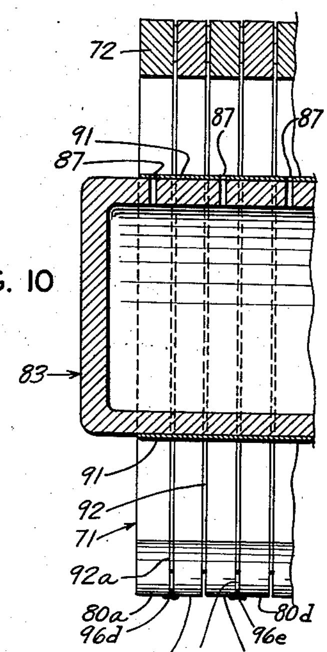

FIG. 10

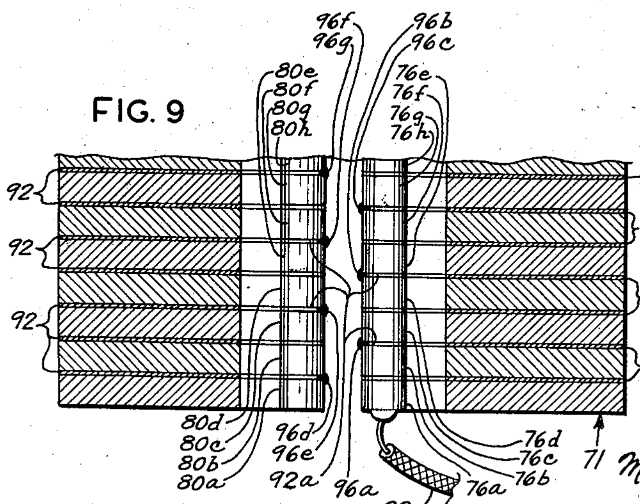

FIG. 9

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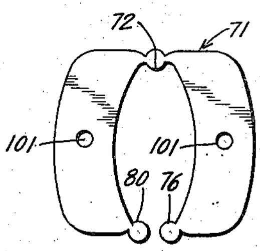

FIG. 11

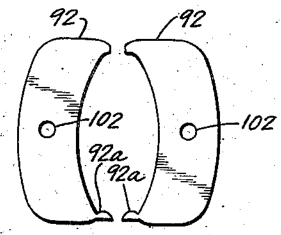

FIG. 12

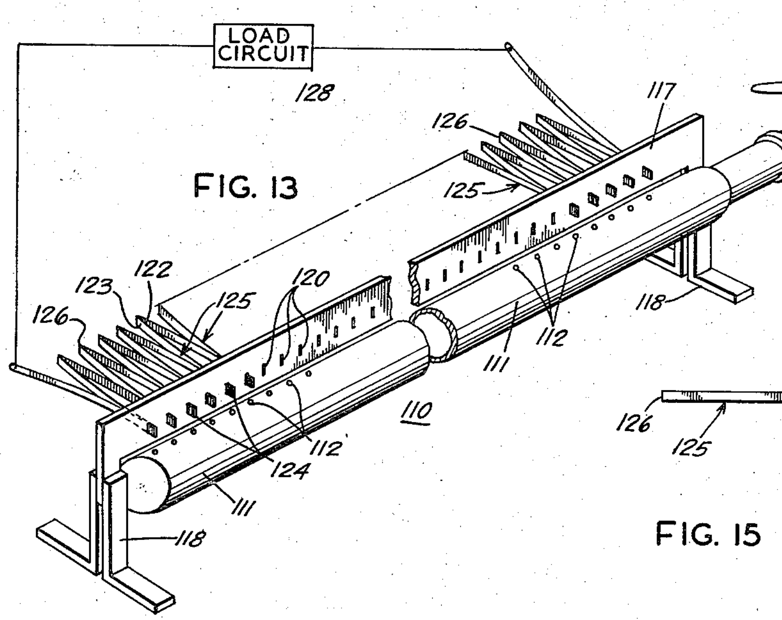

FIG. 13

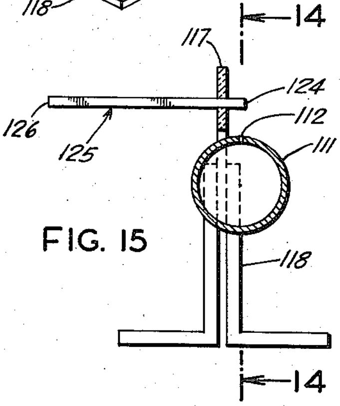

FIG. 15

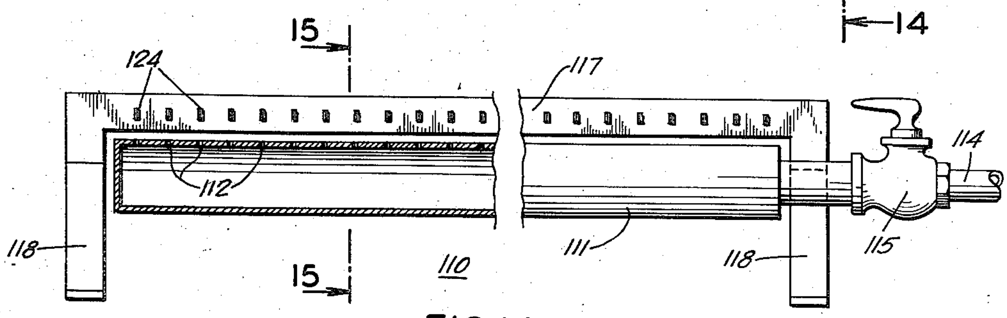

FIG. 14

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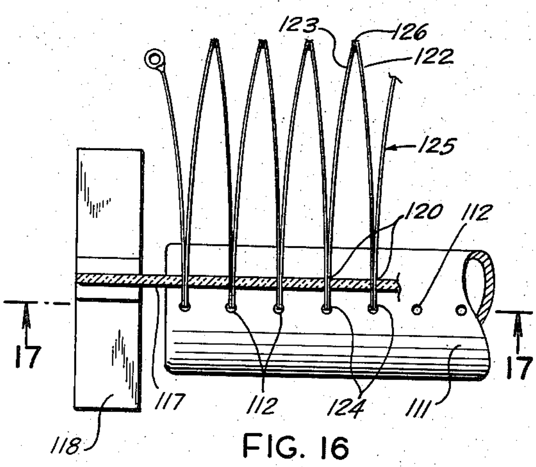


FIG. 16

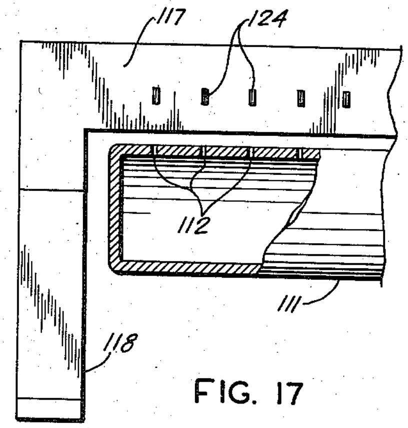


FIG. 17

FIG. 20

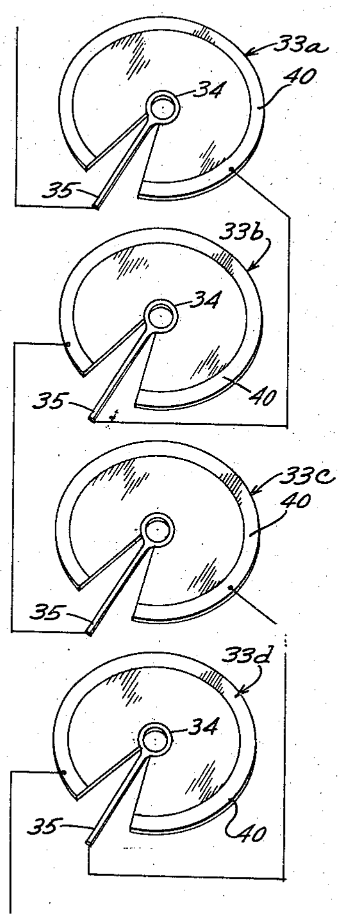
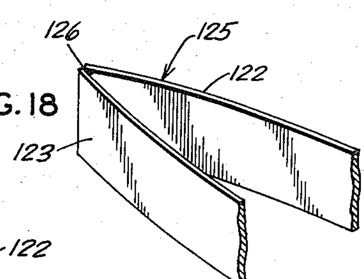


FIG. 18



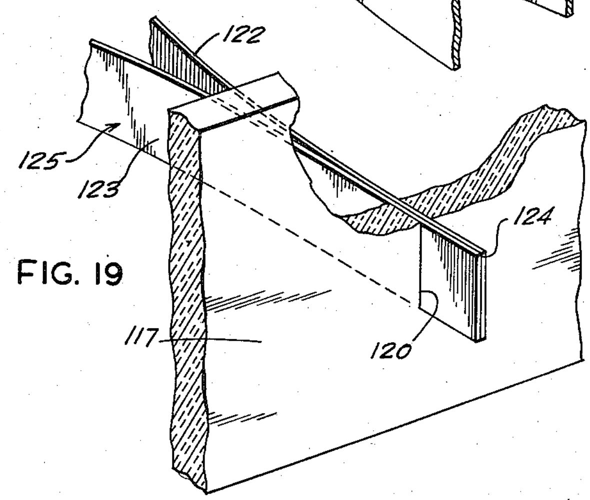


FIG. 19

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United States Patent Office

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2,857,446

METHOD AND APPARATUS FOR CONVERTING HEAT DIRECTLY TO ELECTRICITY

Henry L. Imelmann, Arlington Heights, Ill., assignor to Thermo Power, Inc., Franklin Park, Ill., a corporation of Illinois

Application September 1, 1953, Serial No. 377,766

3 Claims. (Cl. 136—4)

The present invention relates to a method and apparatus for converting heat directly to electricity by a new process which might be considered substantially the reverse of the conventional electric heating process, and, specifically, to a fuel cell defining a practical device for converting heat directly to electrical energy without the necessity of any movable or rotatable parts or the like.

Electric heating has been extensively used for many years in hundreds of applications in homes, industry and the like. Perhaps one of the best known applications is electric cooking, where upon supplying an electrical potential to the terminals of a resistance element electrical energy is converted directly to heat energy. The commonly used electrical potential is an alternating current potential, but, obviously, a direct current potential would work equally well for electric heating. I have discovered that this process of electric heating is reversible, and by applying heat to a resistance element direct conversion to electricity can be accomplished. The electrical energy obtained in this way is a direct current electrical energy. There have been, for many years, attempts to convert heat directly to electricity which have been broadly termed thermoelectric generators, and the present invention could also be termed a thermoelectric generator, although I prefer to term it a fuel cell or resistance generator. In general, such prior thermoelectric generators have depended upon the thermoelectric effect which was discovered in the first quarter of the nineteenth century by Seebeck. Seebeck discovered that if the two junctions in a closed circuit defined by two dissimilar materials were maintained at different temperatures, a steady electric current would flow in the closed circuit. The electromotive force causing the currents to flow in the Seebeck arrangement was found to be proportional to the temperature difference between the two junctions, and a function also of the materials making up the circuit commonly referred to as a thermocouple. In the years since Seebeck's discovery there have been numerous attempts to generate electricity directly from heat using the thermocouple principle. However, none of these numerous attempts have been successful, and prior to the present invention no practical thermoelectric generator using the thermocouple principle has been commercially successful because of the very small currents produced and the low efficiencies obtained. The thermocouple principle has been extensively used commercially only in the field of temperature measurement.

It is my belief that some phases of the thermocouple principle have not been fully understood, and that, actually, there are some misconceptions which have precluded successful thermoelectric generators from having been produced. Consequently, although there is some similarity between the present invention and prior arrangements, I prefer to consider the present invention as not embodying the thermocouple principle, but as embodying the reverse of the principle involved in resistance heating. In order to provide a complete un-

derstanding of the present invention, however, it will be necessary to keep in mind the thermocouple principle. In the ensuing discussion the relationship between the present invention and thermocouple generators which have been described heretofore will become apparent.

At the outset I have found that current can be generated in a resistance element by applying heat to one segment of the resistance element, and the magnitude of the current will be determined by the ohmic resistance of the resistance element. The voltage across the resistance element will be determined by the material from which the resistance element is made as well as the material of which the terminal connected to the hot end of the resistance element is made, and will also depend upon the temperature differential between the ends of the resistance element. For ideal conditions with certain configurations of the resistance element the hottest portion of the resistance element should be the one end connected to the above-mentioned terminal, and the other terminal of the resistance element should be the point thereon beyond which no heat is conducted from the hottest portion thereof. It is true that whenever terminals are applied to such resistance element a dissimilar material enters the picture, and there is a tendency then to consider that a thermocouple exists involving the thermocouple principle. In the ensuing description numerous references to the prior art thermocouple type generators are made in order to aid in understanding the present invention, even though it is believed that applicant's invention is concerned with a principle analogous to the reverse of the principle involved in the process of electric heating.

The literature is replete with articles on proposed thermoelectric generators with varying efficiencies, some writers contending that efficiencies in excess of 80% are possible, and others contending that efficiencies above 2% or 3% are not obtainable with materials presently known. The thermocouple itself upon which such prior art devices are alleged to be based is notoriously inefficient, even when operating at the highest allowable temperature difference. The conclusion generally arrived at by investigators in this field is that the problem of producing thermoelectric generators with efficiencies higher than a few percent can be solved only by finding new materials of high thermoelectric power and low specific electric resistance, or, in other words, high electric conductivity and low specific heat conductivity. Everyone working in this field heretofore has concluded that such materials presently are not available, and no practical thermoelectric generator employing the thermocouple principle has consequently been available on the market. The reasons generally given for the inefficient operation of prior thermoelectric generators of this type have been tied up with the fact that materials of low heat conductivity are usually also materials of low electrical conductivity, and, moreover, because of this, great difficulties have been encountered in maintaining a substantial difference in temperature between the so-called hot and cold junctions of such thermoelectric generators. I have discovered an arrangement using materials of the same type as in prior thermocouple generators, which, based upon a principle analogous to the reverse of electric heating, provides an efficient generator of electricity which, for want of a better term, might be called a resistance generator.

It would be desirable, therefore, to provide a generator employing presently known materials for producing a high electric current output having an efficiency comparable with that of presently known means of generating electricity and far in excess of anything heretofore considered in the thermoelectric generator field. I have discovered that such a fuel cell or resistance generator is practical in efficiencies greatly in excess of 2% or 3%, and, in fact, in efficiencies in excess of 50% which will produce outputs comparable from the standpoint of voltage and current with literally thousands of applications where other means of generating electricity are employed.

In the field of thermoelectricity, Lord Kelvin, in the nineteenth century, discovered what has come to be known as the Thomson effect. He showed that if there was a temperature gradient along a metallic conductor, it was accompanied by a small voltage gradient whose magnitude and direction depended upon the particular metal. It is believed that in the resistance generator in the present invention an electric current is effectively generated in a single resistance material due to the temperature gradient along this single material by heating one segment thereof. It is true that electric terminals connected to this single resistance material effectively provide a junction, but these terminals may be considered as part of the external circuit. The fact that a junction is present erroneously leads one to conclude that the thermocouple principle is involved, when, actually, it is not. A thermocouple always requires two junctions, a hot and a cold junction. With the present invention a cold junction is not required, and the material of which the other terminal is made makes no difference, since it merely serves as a conducting path. A resistance element formed of a length of constantan with copper terminals at each end can have its current output greatly changed merely by changing the length or cross-sectional area of the constantan. Effectively, therefore, the constantan may be considered as the generator of the current, with the copper terminals comprising part of the external circuit.

Prior to the present invention no one was able to convert heat directly to current with a single element and obtain currents of any magnitude. In fact, there is nothing in the prior art indicating that currents in excess of several amperes, and certainly not in excess of five amperes, were ever obtained by direct conversion of heat energy to electrical energy in a single cell. One of the common statements appearing in most of the literature relative to so-called thermocouple generators is to the effect that "as generators of electric currents thermocouples have little use owing to their small e. m. f., and their comparatively high internal resistance." The reason for such low current generation apparently resides in the alleged problem of keeping the cold junction cold, which problem is mentioned as being insurmountable in all the literature except at the expense of efficiency. Thus, the hot and cold junctions were separated substantial distances. Obviously, the ohmic resistance of the thermocouple increases substantially as the distance between the hot and cold junctions is increased, since the ohmic resistance of a conductor increases in accordance with the following well-known expression:

$$R=\rho\frac{l}{a}$$

where R is the resistance in ohms, l is the length in centimeters, a is the cross-sectional area in square centimeters, and ρ is the resistivity in ohm centimeters. With such well-known thermocouple materials as iron ($\rho=10$), copper ($\rho=1.7$), constantan ($\rho=49$), and Chromel ($\rho=100$), it will be apparent that a substantial increase in internal ohmic resistance of the thermocouple element will occur as the distance between junctions is increased. To obtain any current output, therefore, it was necessary to increase the cross-sectional area, which required a greatly increased mass at the hot junction to be heated. I have discovered that there is a fallacy in the heretofore accepted premise that to maintain a temperature differential between the two ends of a material such as the hot and cold junctions of a thermocouple they must be spaced a substantial distance apart. I have found that constantan in short lengths of less than an inch and of small diameter can have one end heated to 1500° F., and the other end will remain at room temperature. Thus, by using short lengths of material, the current flowing in a resistance element is greatly increased. I have been able with a single resistance element, solely by maintaining a temperature gradient along said element, to produce currents of the order of one hundred amperes with a relatively high voltage based on a substantial temperature gradient as well as on the particular materials employed.

It can be shown that if a short length of resistance material is provided with a substantial restriction in cross-sectional area for but a very small fraction of the length thereof, a substantial temperature differential can be maintained between the ends of the material without affecting the over-all electrical resistance, which will remain substantially unchanged. In other words, the thermal conductivity through this material will be greatly decreased. A great reduction in cross-sectional area, even though infinitely short, will greatly decrease thermal conductivity, but if very short will have little effect on electrical conductivity, since the over-all resistance of an electrical conductor is equal to the sum of the resistances of successive lengths thereof. Thus, if there is included a section of very small cross section but infinitely short, it will have little effect on the over-all resistance. Although in prior art thermoelectric generator disclosures the use of restrictions to reduce thermal conductivity was suggested, these restrictions were of such length as to greatly impair electrical conductivity and, hence, reduce current output to an impractically low value for power purposes. It would be desirable to employ this feature to provide a greatly increased current output from a single thermocouple element.

It will be appreciated that there are numerous applications requiring a source of energy which are presently supplied from internal combustion engines or similar means which are notoriously inefficient and have numerous disadvantages with respect to noise, moving parts and the like. It would be desirable to provide an arrangement for generating electricity useful for numerous power applications in which a source of heat such as might be obtained from natural or manufactured gas, or burning fuel of any nature can be converted directly to electricity which can be used in the conventional manner.

Accordingly, it is an object of the present invention to provide an improved process of converting heat directly to electricity with great efficiency.

It is another object of the present invention to provide improved apparatus for converting heat directly to electrical energy without the requirement of any movable parts, and wherein such conversion will be accomplished at an efficiency comparable with or in excess of the efficiencies of conventional prime movers such as internal combustion engines and the like.

It is another object of the present invention to provide a greatly improved and practical resistance generator with means for maintaining a substantial differential of temperature between the two ends of the resistance element of the apparatus without expending any power other than that required to heat a small portion thereof.

It is a further object of the present invention to provide a fuel cell which involves applying heat to a resistor element including means for restricting the thermal conductivity of the resistor element without substantially impairing the electrical conductivity.

It is still another object of the present invention to provide in a fuel cell employing a resistor, to a portion of which heat is applied, utilizing a configuration of the resistor wherein the electrical resistance is independent of length thereof while the heat conductivity between two portions of said resistor can be reduced to any desired minimum by increasing the length thereof.

Another object of the present invention resides in an improved arrangement of parallel connected fuel cells in a thermoelectric generator to provide a high current output with a very high efficiency.

It is another object of the present invention to provide a resistance generator in which with a single resistance element currents in excess of five amperes can readily be obtained with no problem of maintaining a temperature differential between two different portions of said element.

Further objects and advantages of the present invention will become apparent as the following description proceeds, and the features of novelty which characterize the invention will be pointed out with particularity in the claims annexed to and forming a part of this specification.

For a better understanding of the present invention reference may be had to the accompanying drawings in which:

Fig. 1 is a perspective view of a simple embodiment of the present invention;

Fig. 2 is a perspective view illustrating another embodiment of the present invention;

Fig. 3 is a top plan view, partly in section, of Fig. 2, assuming that the apparatus of Fig. 2 comprises only a single generator element rather than several connected in series;

Fig. 4 is a sectional view taken on line **4—4** of Fig. 3;

Fig. 5 is an enlarged sectional view of a portion of Fig. 2 taken substantially on line **5—5** of Fig. 2;

Fig. 6 is a somewhat schematic view of an arrangement to aid in understanding the embodiment of Fig. 2;

Fig. 7 is a perspective view illustrating another embodiment of the present invention;

Fig. 8 is an end view of a portion of the apparatus shown in Fig. 7;

Fig. 9 is a greatly enlarged sectional view taken on line **9—9** of Fig. 7;

Fig. 10 is another greatly enlarged sectional view taken on line **10—10** of Fig. 7;

Fig. 11 is a plan view of one lamination of the device of Fig. 7;

Fig. 12 is a plan view of insulating members utilized in the arrangement shown in Fig. 7;

Fig. 13 is a perspective view of another modification of the present invention;

Fig. 14 is a side elevational view, partly in section, of Fig. 13 with the portion in section taken substantially on line **14—14** of Fig. 15;

Fig. 15 is a sectional view taken on line **15—15** of Fig. 14, assuming that Fig. 14 shows the complete structure;

Fig. 16 is a top plan view, partly in section, of a portion of Fig. 13;

Fig. 17 is a sectional view taken on line **17—17** of Fig. 16, assuming that Fig. 16 shows the complete structure;

Fig. 18 is a greatly enlarged perspective view of a portion of Fig. 13;

Fig. 19 is a greatly enlarged perspective view of another portion of Fig. 13; and

Fig. 20 is a somewhat schematic exploded perspective view of a modification of Fig. 2.

The present invention is primarily concerned with an arrangement in which a resistance element is connected in an electric circuit and means are provided to heat a portion of said resistance element to maintain a temperature differential between different portions thereof whereby a potential difference will exist causing a current to flow in said electric circuit. Means are provided for maintaining only a minimum portion of the resistance element at a high temperature sufficient to set up the voltage. It will be understood that as far as the present invention is concerned the resistance material may comprise constantan, iron, Chromel, or numerous other materials, preferably resistance materials which are outside the so-called precious metal class.

It is recognized that only a very few types of thermoelectric generators have reached the production stage. The best known commercially produced apparatus is Gülcher's gas heated thermoelectric generator with an over-all efficiency of one-half of 1%. The early efforts at making thermoelectric generators have been summarized in book form by Peters, in 1908, in "Thermoelemente und Thermosäulen." Essentially, the fuel cell or resistance generator of the present invention consists of a single resistance element or a number of elements which are identical except perhaps for the material of which they are made. The thermal efficiency is not influenced by the number of elements involved, and it is possible to combine such resistance elements in series and parallel to obtain the desired currents and voltages. Preferably, it is desirable to determine the necessary output current and design single elements producing this current, and then combine them in series to obtain the desired output voltage. It is also preferable that the physical properties of the materials employed do not change during operation. The resistance generator requires terminals at the ends of the resistance material generally formed of copper. Thus, there are provided two dissimilar materials, i. e., the resistor material and one of the copper leads or terminals, thereby effectively defining the hot junction of thermocouple terminology. The hot junction requires welding or copper brazing or the like, and it should be free of any additional electrical resistance, since from the following discussion it will be apparent that maintaining the electrical resistance of the fuel cell at a minimum is essential. It will be apparent at once that the hot junction cannot be operated above a certain temperature limited by the melting points of the materials making up the fuel cell. Heretofore it has been established that because of the irreversible heat conduction occurring in any material, a considerable amount of heat is conducted away from the hot junction, and it was felt that this energy had to be removed by suitable cooling. I have discovered, however, that in all materials there is a point along the length thereof beyond which heat applied to one end will not travel. This can readily be demonstrated by inserting the end of an elongated piece of material such as iron or constantan into a flame or other heat source to raise the temperature thereof substantially. It will be found that under these conditions the other end of this material will remain at a relatively low constant temperature with no external cooling required. I have, moreover, discovered an arrangement for obtaining a minimum electrical resistance while permitting at the same time any desired distance between the hot and cold portions of the resistance element, and, consequently, insuring any desired temperature differential limited only by the materials involved.

Referring now to Fig. 1 of the drawings, there is illustrated one embodiment of the present invention which might be termed a very simple fuel cell or resistance generator, designated generally by the reference numeral **22**. As illustrated, this fuel cell comprises, a resistance element generally designated by the reference numeral **23**, and comprising three sections: a first short section **23*a*** of one cross-sectional area, a very short section **23*b*** of a very small cross-sectional area, and a third and longer section **23*c*** of the same cross-sectional area as **23*a***. The resistance material **23** might comprise constantan, Chromel, iron, or any of the materials commonly associated with thermoelectricity. Connected to the ends of the resistance element **23** are a pair of terminals **24** and **25**, respectively. These terminals are preferably copper, which is a conventional terminal material. It will be apparent that there is, therefore, provided between the end of the resistance material **23** comprising the section **23*a*** and the terminal **24** a junction which may be termed a hot junction, and is designated in Fig. 1 of the drawings by the reference numeral **26**. Preferably, the terminal **24** is welded, copper brazed or otherwise suitably secured to the resistance element **23** to define the hot junction **26**, while the terminal **25** may be connected by any suitable means such as silver solder or the like with the element 23. A load circuit, generally designated as 27, is illustrated as being connected across the terminals 24 and 25. A suitable source of heat for heating a portion of the resistance conductor 23 is schematically illustrated as a burner 28, having the flame 29 engaging the resistance element 23 at a point adjacent the hot junction 26.

The fuel cell 22 is so termed because it converts a combustible fuel and the heat energy contained therein to electricity and, hence, based upon the analogy of the dry cell, the term "fuel cell" is applied to the apparatus shown in Fig. 1 of the drawings.

It will be apparent that the portion 23*b* of the resistance conductor 23 defines a restriction or notch 30 in the element 23. In accordance with the present invention, this restriction or notch 30 is of very short length, preferably of the order of several thousandths of an inch, and not in excess of ten-thousandths of an inch. If the resistance 23 is constantan and the portion of the resistance element 23 at the junction 26 is heated to a temperature of 1500° F. while the other end of the resistance element 23 remains at room temperature, a potential will appear across the terminals 24 and 25 of the order of .05 of a volt (assuming terminal 24 is formed of copper), and a current will flow in the load circuit 27. By making the resistance of the resistance element 23 very low, very high currents of between ten and one hundred amperes can readily be obtained with the simple fuel cell 22 of Fig. 1, which is many times higher than was obtainable heretofore. If the resistance element 23 were made of No. 14 constantan wire, which has a diameter of .064 inch and a resistance of .006 ohm per inch, a current of ten amperes will flow if the conductor length is one inch, assuming the load impedance is negligible, and further assuming that the section 23*b* adds a negligible resistance, as will be shown hereinafter. If the resistance element 23 were reduced to one-half inch in length, theoretically the current would be doubled. Obviously, with a resistance element of larger diameter the current theoretically can be greatly increased.

It will be appreciated that the notch or restriction 30 clearly decreases thermal conductivity between the two terminals of the fuel cell 22 and has very little effect on the electrical resistance. For example, if the section 23*b* were reduced to a diameter of .032 inch, which would be the equivalent of a No. 20 wire, its resistance, if made of constantan, would be .024 ohm per inch. If the length of the portion 23*b* were five-thousandths of an inch, the resistance of that section would be .00012 ohm. Obviously, if this low resistance is added to the resistance of the remainder of resistance element 23, which for a one-inch length would have a resistance of .006 ohm, the increase in resistance would be negligible. However, since the cross-sectional area has been reduced by a quarter, the conductivity of heat from the terminal 24 of the fuel cell 22 to the terminal 25 is reduced fourfold. Thus, it will be apparent that with a simple fuel cell 22, a very high direct current can be obtained by directly converting heat to electricity without the requirement of any moving parts or the like. The fuel cell of Fig. 2 is very analogous to other well-known cells such as the dry cell, the storage battery and the like. Like the dry cell, for example, the voltage output is a function of the materials employed in the cell. As was stated above, the presence of a terminal of a different material is essential to set up the voltage, and the current is generated in the resistance element 23, the magnitude of which resistance will determine the magnitude of the current which will flow.

Although there has been illustrated the provision of a restriction 30, it will be apparent that the inherent resistance of the material from which the resistance element 23 is made to heat flow or thermal conduction may be sufficient so that the restriction 30 may be dispensed with.

As was pointed out above, many writers have recognized insofar as thermocouple generators are concerned, that if a material were available which was a poor heat conductor but a good conductor of electricity, and which was also capable of use to produce a voltage by virtue of the thermoelectric effect, that an efficient thermoelectric generator could be produced. Every writer, however, has also recognized that no such material was available. I have discovered that such material has been available all along but has not been appreciated, and, in fact, that any of the well-known resistance materials conventionally usable in thermocouples will satisfy the requirements when used in a resistance generator in the manner described hereinafter. This is based primarily upon the fact that a conductor such as a circular disk, for example, can be shown to have an ohmic resistance from the center of the disk to the outer periphery which is independent of the diameter but dependent solely on the resistivity of the material and the thickness of the disk. This is also substantially true for a rectangular sheet of material insofar as the resistance from a point at the center of the material to a point at the outer periphery is concerned. If the resistance from the center to the periphery of a circular disk is independent of the diameter, then it will immediately be apparent that a desired low resistance can be obtained by proper choice of material and thickness thereof, and at the same time by providing the hot and cold terminals, respectively, at the center and the extremity of the disk, the effective low heat conductivity between these terminals can readily be obtained by producing sufficient space between the center of the disk and periphery, or, in other words, by increasing the disk diameter. Obviously, restrictions may also be employed to reduce thermal conductivity without substantially impairing electrical conductivity. Effectively, therefore, it will be appreciated that there has been provided a configuration of material which is capable of having a very low resistance and yet wherein, without affecting the resistance, the heat conductivity from the center to the periphery can be controlled merely by increasing or decreasing the distance between the center and the periphery. In Figs. 2 to 5 there has been illustrated what might, for certain applications where very high currents are necessary, be considered the preferred embodiment of the present invention. As illustrated in Fig. 2, a fuel cell 32 is described comprising a series of substantially complete disks 33, each including a resistance element arranged in a vertical stack. To distinguish the individual disks, each of which is illustrated as being substantially identical in shape, they are designated in Figs. 2 and 5 by the same reference numeral but with a different subscript. Thus, in Fig. 2 there are illustrated a plurality of disks 33*a*, 33*b*, 33*c*, 33*d*, etc., disposed in spaced parallel relationship. The construction of an individual disk is best shown in Figs. 3 and 4. Each disk comprises one terminal in the form of an annular center section 34 of a good conductor such as copper. In the event the fuel cell comprises a single disk, the section 34 will have an integral extension 35 defining a terminal connecting portion. In a stack comprising a plurality of disks 33 as shown in Fig. 2, at least one disk 33 will have a terminal connecting portion 35. The annular terminal member 34 is preferably of small diameter sufficient only to permit a suitable conduit 36 or source of fuel or other combustible material to extend through the central opening 37 thereof.

In accordance with the present invention, each disk 33 is effectively a fuel cell having a main resistance portion 38 of constantan, Chromel, or any other suitable resistance material. This resistance portion 38 of each disk 33 is joined to the annular copper terminal 34 as by copper brazing or the like, effectively to define what might be termed the hot junction 39.

To provide the other terminal of the fuel cell defined by each plate 33, there is provided a conductor 40 around the periphery of the portion 38 and suitably joined thereto to define a circular junction **41**. The terminal portions **34** and **40** and the main resistance portion **38** of each disk **33** are preferably defined in a single plane, as shown in Fig. 4, and may be manufactured as suitable stampings. The portions **34** and **38** are preferably brazed to define the hot junction **39**, while the portions **38** and **40** are silver soldered or otherwise suitably electrically connected to define the junction **41**.

As illustrated in the drawings, disks **33** are each provided with a segmental notch **43** to accommodate the terminal connecting portion **35** if it is to be brought out in the plane of the disk. It will be apparent, however, that where a stack of disks are employed such as in Fig. 2 where the resistance portion **38** of alternate disks is of different material, as described hereinafter, the terminals **35** are not necessary and preferably complete circular disks will be employed. In fact even the end disk having terminal **35** can be a circular disk if the terminal **35** need not be in the plane of the disk. Where a single disk is employed, as shown in Fig. 4 of the drawings, a suitable terminal connecting portion **44** will be connected to the terminal or peripheral conductor **40**, and a suitable load circuit can be connected across the conductors **35** and **44**. Where a stack of disks **33** are employed as in Fig. 2, the conductor **44** is connected to the disk at the opposite end of the stack from the disk having the terminal **35**.

For the purpose of heating a portion of the resistance element **38** of each disk **33** adjacent the annular terminal **34**, the conduit **36** referred to above is provided which may have suitable orifices or elongated slots **45** to supply a flame and heat to the annular portions **34** and, hence, the inner peripheries of the resistance elements **38**. The conduit **36** may be connected to a source of fuel through suitable control means, as described in connection with other embodiments of the present invention.

Considering the single disk **33** of Figs. 3 and 4, it can be shown that the resistance between the terminals **34** and **40** can be made very, very low by choosing the proper thickness of the disk **33**. At the same the heat conductivity from the inner periphery to the outer periphery of the resistance element **38** can be maintained at any value by merely increasing the spacing therebetween or, in other words, increasing the diameter of the disk **33**. Obviously, if the disk is made of a very large diameter, no temperature change will occur at the cold junction **41** by virtue of any temperature increase at the hot junction **39**. I have found, as a practical matter, that with relatively small diameters of the disk **33** of the order of three or four inches, the hot junction **39** may be maintained at 1500° F., for example, and the cold junction **41** will remain at room temperature.

Suitable restrictions in the form of narrow slits **47** may be provided in the plates **33** in the portion **38** closely adjacent to the hot junction **39**. These slits **47** may be obtained merely by piercing the plate without removing any material therefrom. They will greatly reduce thermal conductivity and, hence, permit using disks **33** of very small diameter.

The fact that a circular disk will have a resistance from the center to the periphery thereof which is independent of the diameter of the disk can readily be proved mathematically. It will be noted that for a constant disk thickness as the length of the current path is increased, which is accomplished by increasing the diameter of the disk, the effective cross-sectional area of the current path is also increased. Both of these parameters appear in the resistance equation set forth above and with a disk of constant thickness they both appear as a first power, one directly and the other inversely. Thus, they neutralize each other so that resistance is independent of diameter. With the arrangement in Figs. 3 and 4, therefore, a very high current can be obtained with a single element such as is shown in Fig. 3, and by connecting a large number of elements in series the desired voltage may be obtained.

The disks **33** may be connected in series in several different ways. If alternate disks have the resistance elements thereof formed of different materials so that the current flows in opposite directions in alternate disks, then a simple arrangement for obtaining series connection of the disks, as shown in Figs. 2 and 5, can be utilized. If the disks are all formed of the same material, then the arrangement of Fig. 20 for connecting them in series must be utilized. In Figs. 2 and 5 it is assumed that disks **33*a***, **33*c***, etc., have the portions **38** thereof formed of constantan, while the disks **33*b***, **33*d***, etc., have the portions **38** thereof formed of Chromel. These particular materials have such characteristics as to cause current flow in opposite directions when the hot junctions **39** are subjected to heating. Obviously, any other two materials having this opposite characteristic may be employed instead of Chromel and constantan, which are cited by way of example only. On the assumption that alternate disks **33** of Figs. 2 and 5 are formed of different resistance materials, it may be observed that the corresponding terminals of two adjacent disks or plates **33** will be insulated from each other, while the other corresponding terminals are electrically interconnected thereby to connect adjacent plates in series to produce increased voltage output depending upon the number of plates or disks **33** connected in series. As illustrated, alternate adjacent terminals **34** are electrically interconnected and the other alternate adjacent terminals **34** are insulated from each other. Likewise, the peripheral terminals **40** are alternately interconnected and insulated from each other. This is best shown in Fig. 5, where it may be observed that between plates **33*a*** and **33*b*** the terminals **34** are insulated from each other by an insulating spacer **48**. Between these same plates, however, the terminals **40** are electrically interconnected, as by the conducting spacer **49**. On the other hand, a conducting spacer **50** is interposed between the terminals **34** of the plates **33*b*** and **33*c***. Between these same plates **33*b*** and **33*c*** there is provided an insulating spacer **51** to insulate the terminals **40** thereof. In this manner successive disks or plates **33** are connected in series, and a terminal connecting portion such as **44** will be connected to the bottom disk in the stack of disks of Fig. 2. It will readily be appreciated that complete disks can be employed with even greater advantages than the notched disks illustrated.

Where the disks **33** are all formed of one material so that current flow in all disks is in one direction, either from the terminal **34** to the terminal **40**, or vice versa, the arrangement of Fig. 20 for connecting the disks in series may be employed. As there illustrated, the terminal **40** of disk **33*a*** is connected to the terminal **35** of disk **33*b***, the terminal **40** of disk **33*b*** is connected to the terminal **35** of the disk **33*c***, while the terminal **35** of disk **33*c*** is connected to the terminal **40** of the disk **33*d***, etc. The terminal **35** of disk **33*a*** then becomes one terminal of the series connected fuel cells, and the terminal **40** of the last of the stack of fuel cells becomes the other terminal. It should be understood that Fig. 20 is a schematic representation, and the illustrated connections between disks would be short low resistance connections in an actual installation.

It may be appreciated that, effectively, a disk such as **33** comprises a very large number of individual resistance elements connected in parallel, and this can best be appreciated by an examination of Fig. 6 of the drawings where a plurality of resistance elements **55*a***, **55*b***, **55*c***, **55*d***, **55*e***, **55*f***, **55*g***, **55*h***, **55*i***, **55*j***, **55*k***, **55*m***, and **55*n*** are connected in parallel and are all arranged with their common ends connected to an annular terminal **34** to define a plurality of hot junctions **56** disposed around the periphery of a tubular member **57** having a plurality of orifices **58** so that a flame may be directed to heat the terminal 34, and, hence, the adjacent ends of the resistance elements 55. The ends of the resistance elements 55 remote from the terminal 34 are indicated as being connected to an annular conductor or terminal 59 which is suitably connected to a conductor 60. A conductor 61 is illustrated as connected to the terminal 34, and a load circuit 62 is connected to conductors 60 and 61. As the number of resistance elements in the arrangement shown in Fig. 6 is increased, one will eventually arrive at a complete circular disk with the maximum current rating.

The operation of the arrangement shown in Figs. 2 to 5 will readily be understood in view of the detailed description included above. It will, moreover, be apparent that there has been provided an arrangement in which maximum current is obtainable with a very simple configuration. The advantages of the present invention are obtainable even though only a portion of a circular disk is employed, and it will be appreciated that the resistance element of Fig. 1 is effectively a portion of the disk resistance element of Fig. 3. One can obtain some of the substantial benefits of the present invention by employing only a small segment of the disk 33. It will, furthermore, be appreciated from the above discussion that the desirable characteristics of the arrangement of Fig. 2 are to some extent carried over into arrangements such as that shown in Fig. 1 where instead of a disk or segment of a disk only conductive wires are employed. This is by virtue of the fact that in any material or conductor there is a point along the length thereof beyond which heat will not be conducted when one end thereof is heated.

In certain applications of the present invention where maximum current is not a factor, numerous other designs of the fuel cell are available. In Figs. 7 to 12 of the drawings there is disclosed an arrangement which permits excellent heat control and which does not require a terminal connection at the hot end of the resistance element.

Referring now to Figs. 7 to 12 of the drawings, there is illustrated in Fig. 7 a generator designated by the reference numeral 70. This generator 70 is illustrated as comprising a substantial number of identical units, each comprising two resistance elements joined together to define a hot junction. These elements are specifically illustrated as laminations 71 of somewhat symmetrical configuration, each lamination comprising a section or cell 71*a* of one material, and a section or cell 71*b* of a different material, united as by copper brazing or the like at a junction 72. By using two different resistance materials for each lamination with current flow in opposite directions in each section relative to the hot junction, it is readily possible to connect a plurality of laminations 71, each of which really comprises two cells, in series in the manner of Figs. 2 and 5 of the drawings contrasted with the arrangement of Fig. 20. As illustrated, these laminations are of somewhat U-shaped configuration with the junction 72 occurring at the bight of the U. The elements 71 can be defined as laminations, since in a manufacturing operation they would be manufactured as laminations by a suitable punching operation or the like. Preferably, the laminations have a configuration best shown in Figs. 7 and 8 of the drawings, in which the section 71*a* terminates in a narrow neck portion 73 at one end thereof, which narrow neck portion is connected to a semicircular disk 74. Similarly, the other end terminates in a restricted area portion 75 terminating in a small disk portion 76. The section 71*b* has a similar neck portion 77 of restricted cross section integrally connected with a semicircular disk 78. The semicircular disk portions 74 and 78 when welded or brazed together form a circular disk having the junction 72 at the united edges thereof. The other end of the section 71*b* is connected by a narrow neck portion 79 with the disk 80, the neck portions 75 and 79 being identical, and the disk portions 76 and 80 also being identical. It will be appreciated that if heat is applied to the junction 72, a potential will appear across the terminals 76 and 80, and if connected to an electrical circuit a current will flow. The potential at the disks 76 and 80 will be dependent upon the temperature differential between the junction 72 and the terminals 76 and 80, and will also be a function of the particular materials of which the sections 71*a* and 71*b* are formed. The direction of current flow will, of course, be dependent upon what the materials of section 71*a* and 71*b* comprise, but, in any event, it will be a direct current. The laminations 71 are formed to define a central opening 81 to accommodate a suitable heat source generally designated by the reference numeral 82. It will be understood that the source of heat could be quite varied. For example, electrical heating might be employed for heating the junction 72. Obviously, in a practical application, electrical heating will not be employed, since if a source of electrical energy is available, there would be no point in converting it to heat and then back to electrical energy. In a practical application the source of heat 82 might generally comprise some sort of fuel or combustible material. In the simplest application, it might comprise natural or artificial gas, or it might be a gasoline or kerosene jet. If gasoline is employed as the fuel, a suitable gas generator, not shown, will be incorporated in the generator. In a large power plant, it might comprise other burning fuel such as coal or the like. As specifically illustrated in the drawings, the source of heat 82 has been shown as a tubular conduit designated by the reference numeral 83 in Fig. 10 of the drawings, which is connected through a suitable valve 84 with a source of gas or other suitable fuel supplied thereto by conduit 85. As illustrated, the tube 83 is provided with a plurality of orifices 87, one positioned immediately adjacent the hot junction 72 of each of the laminations 71 employed in the apparatus 70. If the apparatus 70 embodies one hundred laminations, then preferably the tube 83 will have one hundred orifices, each positioned immediately adjacent the corresponding junction 72. If the laminations are relatively thin, as described hereinafter, the plurality of orifices might comprise an elongated slot. As illustrated in the drawings, the conduit 83 is of circular cross section. It should be understood that any other cross section, and perhaps a cross section conforming to the opening designated by the reference numeral 81 between the sections 71*a* and 71*b* of the laminations 70 may be employed. Suitable insulation 91 is provided between the conduit 83 and the laminations 71.

It will be understood that each lamination 71, which is effectively two cells, comprises a source of electrical energy having a predetermined voltage determined by the temperature differential between the hot junction 72 and the ends 76 and 80, and the materials of which the sections 71*a* and 71*b* are formed. The current flow will depend, of course, on Ohm's law, which means that the lower the resistance of this electrical circuit the higher the current that will flow. The voltage obtainable at the terminals of each resistance is independent of the distance between the hot junction and the terminals. Obviously, the shorter the length of the materials involved the lower the resistance. For the purpose of increasing the output voltage, a plurality of laminations such as 71 may be connected in series, thus permitting the building up of any desired voltage. The laminations 71 are admirably suited for this type of arrangement, and, as illustrated, a plurality of laminations 71 are stacked with interposed insulating laminations 92 of the configuration shown in Fig. 12 of the drawings. As illustrated, a pair of insulating laminations 92 are shaped somewhat like one of the laminations 71 already described, except that semicircular or partial extensions 92*a* are provided at the ends of the insulating laminations adjacent the circular disks such as 76 or 80 of the laminations 71. The insulating laminations 92, preferably formed of mica or other suitable insulation, are positioned between the laminations 71.

For the purpose of connecting the successive laminations 71 in series, alternate adjacent disks 76 are electrically interconnected, as are also alternate adjacent disks 80. In a particular arrangement embodying the present invention, the laminations 71 had external dimensions of the order of one inch by one inch, and a thickness of fifteen-thousandths of an inch, while the insulating laminations 92 were formed of mica and had a thickness of one-thousandth of an inch. In this embodiment the sections 71*a* and 71*b* comprised, respectively, Chromel and constantan. To complete the electrical circuit between the lamintions 71, the disks 76, and designated specifically as 76*a*, 76*b*, 76*c*, 76*d*, 76*e*, 76*f* and 76*g*, in Fig. 9 of the drawings, are alternately connected and insulated from each other. As illustrated, disks 76*a* and 76*b* are insulated from each other. Disks 76*b* and 76*c*, however, are electrically interconnected by a suitable means such as silver solder, designated as 96*a* in Fig. 9 of the drawings. A similar electrical connection 96*b* is interposed between disks 76*d* and 76*e*. Likewise, a similar electrical connection 96*c* is interposed between disks 76*f* and 76*g*. The disks 80 have been designated in Fig. 9 by the same subscripts as the disks 76 immediately opposite thereto. Although the disks 76*a* and 76*b* are electrically insulated from each other, the disks 80*a* and 80*b* are electrically interconnected by a suitable means 96*d*. Similarly, disks 80*c* and 80*d* are electrically interconnected by the means 96*e*, although the opposite disks 76*c* and 76*d* are insulated from each other. Likewise, also, disks 80*e* and 80*f* are electrically interconnected by means 96*f* even though the opposite disks 76*e* and 76*f* are insulated from each other. Similarly, disks 80*g* and 80*h* are electrically interconnected by means 96*g*, and the opposite disks 76*g* and 76*h* are insulated from each other. Preferably, the electrical interconnection which might be called the cold junction may be a silver solder connection which can readily be accomplished in the space defined between the disks 76 and between the disks 80 not filled with the insulation 92. This is by virtue of the fact that the extensions 92*a* do not completely fill the space defined between the disks 76 and between the disks 80. This can readily be observed from Figs. 9 and 10 of the drawings. With this arrangement it will be apparent that one terminal of the fuel cell may be defined by the conductor 99 connected to the disk 76*a*, and the other terminal 100 is connected to the particular disk 80 at the opposite end of the stack of laminations 70. The electrical circuit will then proceed from the terminal 99 through the section 71*a* of the first lamination, through the hot junction 72 of the first lamination, through the section 71*b* of the first lamination, through the electrical interconnection such as silver solder 96*d* to the second lamination, and around the second lamination back to the disk 76*b*, through the silver solder connection 96*a* to the third lamination, and successively back and forth through the laminations 71 until the terminal 100 is reached. The potential across the terminals 99 and 100 will be the sum of the potentials across the individual laminations. If a potential of fifty millivolts appears across the disks 76 and 80 of each lamination when a predetermined temperature differential exists between the hot junction 72 and these terminals, then, obviously, a hundred laminations in the fuel cell 70 will produce an output voltage across the terminals 99 and 100 of five volts.

For the purpose of securing the laminations 71 and the insulating laminations 92 in a unitary stack, the laminations 71 are preferably provided with openings 101, and the laminations 92 are provided with openings 102, which openings 101 and 102 are aligned to receive suitable fastening means 103, which, obviously, must be insulated from the laminations 71.

One of the important features of the present invention resides in the restricted cross section of the laminations 71, particularly the restricted cross sections 73 and 77, although also including the restricted cross sections 75 and 79. It will be appreciated that such restricted cross section will greatly reduce the thermal conductivity of the laminations 71, and, hence, will tend to prevent heat from being conducted away from the hot junction 72. It will, moreover, be appreciated that the restricted cross-sectional area at the portions 73, 77, 75 and 79 is such as not effectively to introduced any electrical resistance as far as the currents produced by the laminations 71 or the thermoelectric generator 70 are concerned, this for the same reason as discussed in detail in connection with Fig. 1 of the drawings. The restrictions in the cross-sectional area may take various forms quite different from those illustrated.

Another important feature of the arrangement shown in Figs. 7 to 12 of the drawings resides in the chimney effect produced between the laminations 71 at the junctions 72. This is accomplished by virtue of the fact that the insulating laminations 92 are discontinuous at the portion thereof corresponding to the semicircular disk portions 74 and 78 so that a space is defined between adjacent disks including the junctions 72, and this space acts as a chimney for combustible materials providing a heat source for the junctions 72. Maximum efficiency of the heat source is thus obtainable, and, moreover, the junctions 72 can be heated in a manner so as to heat a minimum portion of the junction. Preferably, the junction may be heated to a temperature of the order of 1500° F., while the disks 76 and 80 are maintained substantially at room temperature.

From the above description it will be apparent that there has been provided a generator which can produce a direct current output voltage solely by direct conversion of heat to electricity. Moreover, by connecting sufficient laminations 71 in series, any desired voltage may be obtained. Furthermore, a plurality of generators such as 70 may be connected in parallel to give any desired current output, although, as was noted above, a single lamination is preferably designed to give the desired current output. It will, moreover, be appreciated that a very small compact unit is involved, since, for example, a five-volt fifteen ampere unit can be confined in an area of the order of one inch by one inch by three inches.

In view of the detailed description included above, the operation of the generator disclosed in Figs. 7 to 12 of the drawings will readily be appreciated.

In Figs. 13 to 19 of the drawings there is illustrated a modification of the present invention quite similar to the fuel cell of Figs. 7 to 12 of the drawings. As illustrated in Fig. 13, there is provided a generator 110 which comprises a tubular conduit 111 having a plurality of orifices 112 therein quite similar to the conduit 83 of the preceding embodiment. This conduit 111 serves as a source of heat and is connected to a source of natural gas or other fuel supplied thereto by a conduit 114 to a suitable control valve 115. Mounted adjacent the conduit 111 is a suitable insulating support 117, which might be a sheet of asbestos board or similar material held in spaced parallel relationship with respect to the conduit 111 by any suitable means. As illustrated, the insulating support 117 is mounted on suitable standards 118, one disposed at each end of the support 117. The support 117 is provided with a plurality of spaced openings 120, one disposed slightly above each of the orifices 112, so that each orifice 112 has associated therewith a corresponding opening 120 in the insulating support 117. Protruding through the openings 120 in the insulating support 117 are the adjacent joined ends of two dissimilar resistance materials specifically designated as elongated elements **122** and **123**. These elements **122** and **123** extending through the openings **120** are suitably joined as by copper brazing or the like to define a junction **124** disposed immediately above a corresponding orifice **112**. The junction **124** may be defined as a hot junction, and the dissimilar resistance materials **122** and **123** might be Chromel and constantan, as in Figs. 7 to 12 of the drawings, or any other combination of materials capable of producing a thermal electromotive force. The dissimilar materials **122** and **123** joined to form a hot junction **124** effectively define a fuel cell hereinafter generally referred to as element **125**. In Fig. 13 a large number of these elements **125** are illustrated as being connected in series by having one arm of one element **125** connected to the adjacent arm of an adjacent element **125** thereby defining a cold junction **126**, best shown in Fig. 18 of the drawings. The electrical interconnections between adjacent elements **125** preferably comprise silver solder or similar material. The number of elements **125** connected in series is determined by the desired output voltage, and, as illustrated in Fig. 13, a suitable load circuit **128** is connected across the end terminals of the two end elements **125**. If desired, suitable restrictions of the cross-sectional area of the element **125**, which will adversely affect the heat conductivity but not substantially affect the electrical conductivity as described above, may be provided. With this arrangement the desired current output from each element **125** and from the fuel cell **110** may readily be obtained.

From the above description it will be apparent that there has been provided an improved process of generating electricity directly from heat by means of a fuel cell which may have numerous applications and which can be produced commercially to have an efficiency comparable with or in excess of presently used means for generating electrical energy, and, moreover, which can be confined in a very small space. It is believed that the present fuel cell or resistance generator can and will displace prime movers such as are presently employed on lawn mowers, power boats and the like.

Although the correct explanations for the operation and underlying theory of the fuel cells described above are believed to have been set forth, it should be understood that these explanations and theory are enunciated to facilitate an understanding of the operation of applicant's new process and apparatus, and are not to be construed as limitations of the invention disclosed therein.

While there have been illustrated and described several embodiments of the present invention, it will readily be understood that various changes and modifications will occur to those skilled in the art. It is intended in the appended claims to cover all changes and modifications of the present invention which fall within the true spirit and scope thereof.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. In a fuel cell, a sheet metal stamping formed in somewhat of a U-shaped configuration with one arm and one half of the bight of the U formed of one material, and the other arm and the other half of said bight of said U formed of a different material, means for integrally uniting said materials at substantially the center of said bight to define a junction, said materials being such that upon the application of heat to said junction a potential will appear across the arms of said U, and means defining a restricted cross section in said element.

2. In apparatus for converting heat directly to electricity, a stack of laminations, each lamination formed in somewhat of a U-shaped configuration with one arm and one half of the bight of the U formed of one material, and the other arm and the other half of the bight of said U formed of a different material, means for integrally uniting said materials at substantially the center of said bight to define a junction, said materials being such that upon the application of heat to said junction a potential will appear across the arms of each U, insulating means for insulating adjacent laminations from each other, means for securing said laminations with interposed insulating means into a rigid assembly, means for connecting said laminations in a series electrical circuit, and means for simultaneously heating said junctions of each of said laminations in said stack.

3. In apparatus for converting heat directly to electric energy, a stack of laminations, each lamination formed in somewhat of a U-shaped configuration with one arm and one half of the bight of the U formed of one material, and the other arm and the other half of the bight of said U formed of a different material, means for integrally uniting said materials at substantially the center of said bight to define a junction, said materials being such that upon the application of heat to said junction a potential will appear across the arms of each U, insulating means for insulating adjacent laminations from each other, means for securing said laminations with interposed insulating means into a rigid assembly, means for connecting said laminations in a series electrical circuit, an elongated tube disposed between the arms of said U, a plurality of orifices in said tube directed toward said junctions, and means for supplying a combustible material to said tube whereby said junctions are simultaneously heated.

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