Conf-910801--27

WSRC-MS--90-343

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A HIGH-EFFICIENCY THERMOELECTRIC CONVERTER FOR SPACE APPLICATIONS (U)

by

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A paper for presentation and for publication in the proceedings at the
26th Intersociety Energy Conversion Engineering Conference
Boston, Massachusetts
4 - 9 August 1991

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ABSTRACT

This paper presents a concept for using high-temperature superconducting materials in thermoelectric generators (SCTE) to produce electricity at conversion efficiencies approaching 50% of the Carnot efficiency. The SCTE generator is applicable to systems operating in temperature ranges of high-temperature superconducting materials and thus would be a low-grade energy converter. Operating in cryogenic temperature ranges provides the advantage of inherently increasing the limits of the Carnot efficiency. Potential applications are for systems operating in space where the ambient temperatures are in the cryogenic temperature range. The advantage of using high-temperature superconducting material in a thermoelectric converter is that it would significantly reduce or eliminate the Joule heating losses in a thermoelectric element. This paper investigates the system aspects and the material requirements of the SCTE converter concept, and presents a conceptual design and an application for a space power system.

INTRODUCTION

The announcement of the discovery of new high-temperature superconducting (HTSC) materials in 1986 and 1987 has lead to the speculation of practical, everyday applications for HTSC's. Superconducting material, such as $YBa_2Cu_3O_7$, has been shown to become superconducting at 95 K and other materials have exhibited superconducting-like properties at temperatures approaching room temperature. [1] This paper introduces a concept for using HTSC materials in a high-efficiency, thermoelectric, low-grade energy converter. The superconducting thermoelectric converter (SCTE) concept is speculative since it has not been experimentally demonstrated, but the concept can be experimentally investigated using materials that are currently available. It is desirable that the material, or combination of materials, for the converter has a high Seebeck coefficient, a low thermal conductivity, and a low electrical resistivity. [2]

The SCTE is applicable to systems operating in temperature ranges applicable to the high-temperature superconducting materials and thus would be a low-grade energy converter. Potential applications are for systems operating in space where the ambient temperature is very low. The maximum temperatures on Neptune and Pluto are estimated to be less than 80 K and the earth's moon has low temperatures in the range of 100 K. On Mars the the night temperature varies from 210 K at sunset to 160 K at sunrise.[3] The advantage of using high-temperature superconducting materials in a thermoelectric converter is that it would significantly reduce or eliminate the Joule heating losses due to resistive heating (I^2R) in a thermoelectric element and result in a higher efficiency converter. Operating in the cryogenic temperature range provides the advantage of inherently increasing the limits of the Carnot efficiency by having a very low sink temperature. The SCTE converter also has the advantage of eliminating material compatibility problems in a TE converter associated with material thermal expansion and reducing system reliability concerns associated with operating at high temperatures. As HTSC materials are discovered that operate at temperatures approaching room temperature and higher, the potential for using HTSC's in high-efficiency SCTE converters increases.

This paper discusses the Carnot considerations for introducing the concept, the significance of eliminating the Joule heating in a thermoelectric generator's conversion efficiency, the material considerations for a SCTE converter, and the design considerations and integration of a SCTE into a system for space applications.

CARNOT EFFICIENCY

The Carnot efficiency, the highest theoretical thermodynamic conversion efficiency for converting thermal energy into work, is given by the familiar expression

$$\eta_{Carnot} = \frac{T_H - T_C}{T_H} ,$$

where T_H is the absolute temperature of the energy source and T_C is the absolute temperature of the energy sink of a thermodynamic system.

Figure 1 is a plot of the Carnot efficiency as a function of the temperature of the energy source and energy sink temperatures of 10 K, 20 K, 50 K, 100 K, and 800 K. This plot demonstrates that the limiting Carnot efficiency is very high when the energy sink is at cryogenic temperatures, even when the energy source is at temperatures as low as 200 K to 300 K. In contrast, when the energy sink is at temperatures in the range of 800 K the limiting Carnot efficiency is very low unless the heat source is at a very high temperature.

To take advantage of the high Carnot efficiencies associated with cryogenic temperatures, an energy conversion process needs to be identified that converts low-grade energy to work. Because of the low heat-rejection temperature intrinsic to this type of system, the efficiency of the cycle has to be large to avoid a prohibitively large radiator. There are several inherent advantages of a low-grade energy conversion system operating at low temperatures and a high efficiency: (1) the system does not require a heat source with a high energy density, (2) the system does not require as large a heat source as a system with a low conversion efficiency to produce the same amount of electrical energy, and (3) material and reliability concerns associated with a system operating at high temperatures are no longer a concern. In reference to a space-based power system, the advantages created by a low-grade system's high efficiency and smaller power source are less stringent operating conditions, less stringent material requirements, a lower system mass, an improved reliability, and a longer lifetime.

THERMOELECTRIC EFFICIENCY

Thermoelectric converters that are being developed for the SP-100 program are using alloys of the semiconductor SiGe/GaP and are being designed to operate at efficiencies of 5 to 8%. The hot shoe of the thermoelectric generators in the SP-100 system is being designed to operate at a temperature of approximately 1273 K and the cold shoe is being designed for a temperature of 873 K. [4] At these temperatures the thermoelectric conversion efficiency of the SP-100 TE converters is limited by a Carnot efficiency of approximately 31% (considering the TE converters as the system). The design hot shoe temperature of the SP-100 TE converters is dependent upon the maximum in the TE material's figure-of-merit as a function of temperature and the high-temperature limitations of the materials used in the system.

Static thermoelectric energy conversion can be envisioned at cryogenic temperatures if materials can be discovered that have a substantial Seebeck coefficient at these temperatures. If a substantial Seebeck effect is still present in materials that are superconducting, the obvious advantage is the elimination of Joule heating in the TE element and hence, the potential for achieving a high-conversion efficiency.

The conversion efficiency of a conventional high-temperature thermoelectric converter (HTTE), is [5]

$$\eta_{HTTE} = \frac{\eta_{Carnot}\, m}{\left[(1+m) - \frac{\eta_{Carnot}}{2} + \frac{(K_n + K_p)(R_n + R_p)(1+m)^2}{\alpha_{pn}^2 T_H}\right]} , \quad (1)$$

where m is $\frac{R_L}{R_p+R_n}$, K_i is $\frac{k_i A_i}{L}$, R_i is $\frac{\rho_i A_i}{L}$, and α_{pn} is α_p-α_n.

In Equation (1) the R's are resistances, the α's are Seebeck coefficients, k's are thermal conductivities, the A's are cross-sectional areas, L is the length (both the N and P legs are assumed to be of equal length), and the ρ's are resistivities of the N and P legs of the TE converter; the subscripts "p" and "n" indicate the thermoelectric N and P junctions. In deriving Equation (1) the resistances of the other components in the circuit are considered negligible compared to the resistances of the load and the P and N leg of the thermoelectric generator.

The figure-of-merit describes the performance of a material as a thermoelectric converter:

$$Z = \frac{\alpha_{pn}^2}{\left(\sqrt{\rho_n k_n} + \sqrt{\rho_p k_p}\right)^2} . \quad (2)$$

The figure-of-merit consists of material properties of both the P and N legs. A large value of the figure-of-merit of a material indicates that the material has the potential to be a good thermoelectric converter. A typical value of the figure-of-merit is 10^{-3}/K.

The efficiency for a TE converter, but with the assumption that there is no Joule heating in the TE converter's P and N junctions, using HTSC material is found to be

$$\eta_{SCTE} = \frac{\eta_{Carnot}}{1 + \frac{R_L(K_p + K_n)}{T_H \alpha_{pn}^2}} . \quad (3)$$

The conventional definition of the figure-of-merit does not apply to a SCTE since as the resistivity of the N and P legs go to zero and the figure-of-merit approaches infinity. Equation (3) provides a definition for an important thermoelectric dimensionless number that includes design parameters and material properties:

$$Me = \frac{T_H \alpha_{pn}^2}{R_L(K_p + K_n)} . \quad (4)$$

The dimensionless number Me is a ratio of the maximum energy generated by the converter, assuming that there are no resistive losses in the converter, divided by the heat that is conducted to the hot shoe of the converter.

When inserting Me into expression for the conversion efficiency of a SCTE, Equation (3), the result is

$$\eta_{SCTE} = \eta_{Carnot}\frac{1}{1 + 1/Me} = \eta_{Carnot}\frac{Me}{1 + Me} . \quad (5)$$

The expression for the conversion efficiency of a conventional thermoelectric converter, Equation (1), is also a function of Me:

$$\eta_{HTTE} = \eta_{Carnot}\frac{1}{\frac{1}{m}+1-\frac{\eta_{Carnot}}{2m}+\frac{1}{Me}\left[\frac{1}{m^2}+\frac{2}{m}+1\right]} \quad (6)$$

In Equation (6), as $(R_p + R_n)$ approaches zero, "m" approaches infinity, and η_{HTTE} approaches η_{SCTE}.

The thermoelectric figure-of-merit is analogous is the Prandtl number in thermal-hydraulics; it is a combination of properties and itself is a property of the material. The dimensionless number Me is more closely analogous to the Stanton number, a ratio of powers. In the remainder of the paper we will refer to Me as the Metzger/El-Genk number.

MATERIAL PROPERTIES

Inspection of the Metzger/El-Genk number and the figure-of-merit indicates that for an effective thermoelectric converter the Seebeck coefficient must be large and the thermal conductivity and resistivity must be small.

A plot presented in Reference 5 shows that insulators have the highest Seebeck coefficient and the lowest thermal conductivity. Metals have the lowest Seebeck coefficient and the highest thermal conductivity. Semiconductors fall in between for both properties and have the largest figure-of-merit. The resistivity is the greatest for an insulator and the smallest for a metal, but the product of the square of the Seebeck coefficient and one over the resistivity is the greatest for semiconductors. However, the figure-of-merit for the TE materials does not apply to a SCTE. Considering that an insulator material has the largest Seebeck coefficient and the smallest thermal conductivity indicates that for a SCTE that an insulator material may be the most appropriate.

For both metals and semiconductors the thermal conductivities increase with decreasing temperatures, but while the metal's thermal conductivity increases dramatically with a decrease in temperature the semiconductor's thermal conductivity does not exhibit a large variation with a decrease in temperature. [5] For insulators Bolz and Tuve [3] present a table of thermal properties of glass products (insulators). The trend is that the thermal conductivity of glass products decreases as the temperature decreases.

The Seebeck coefficients for semiconductors increase in magnitude and the Seebeck coefficient for a superconductor goes to zero as the temperature approaches 0 K. This dictates that a superconducting material alone cannot be used as a thermoelectric generator.

Upon the suggestion of F. J. Edeskuty at Los Alamos National Laboratory, as an alternative to using one material in a SCTE, it may be possible to put conductors of HTSC material in a matrix of TE material. The HTSC material would carry the electrical current at zero resistivity with no Joule heating while the TE matrix would provide the Seebeck effect. Since the SCTE generator is required to operate at temperatures below the critical temperature of the HTSC material in the generator, both the HTSC and the TE matrix materials would provide heat conduction paths between the energy source and the energy sink. The amount of heat conducted by either of the materials would be a function of their thermal conductivity and cross-sectional area relative to each other. The appropriate matrix TE material may be either an insulator or a semiconductor material.

EXPERIMENTAL VERIFICATION

To verify the concept experimentally, materials need to be identified. A material that is a potential candidate for verifying the concept is $(La_{1-x}M_x)_2CuO_4$, where M is either Ba, Sr, or Ca. Pure La_2CuO_4 behaves like a semiconductor and when a few percent of the La is replaced by either Ba, Sr, or Ca, the material becomes superconducting at temperatures below approximately 40 K.[6] Reference 6 indicates that the Seebeck coefficient of pure La_2CuO_4 behaves as a semiconductor material; that is, it is very high near near absolute zero, in the range of 800 μV/K, and approaches a constant value of approximately 500 μV/K at temperatures above 150 K. When the pure material is 7.5% doped with Ba or Sr, $(La_{1-x}M_x)_2CuO_4$ with x = 0.075, the resulting material is a very good superconductor with a nearly temperature-independent Seebeck coefficient with an approximate value of 20 μV/K above 40 K. Below 40 K, the material's Seebeck coefficient and the resistivity both go to zero. The resistivity of the material above 40 K is in the range of 0.5 to 2 mΩ-cm. As a point of reference, the value of the Seebeck coefficient for a typical high temperature TE material, 80% Si 20% Ge doped with GaP, is approximately 250 μV/K and its resistivity is approximately 2 to 3 mΩ-cm.[2]

Using $(La_{1-x}M_x)_2CuO_4$, x = 0.075, as the superconductor, the La_2CuO_4 material as the TE matrix, and operating an experiment below 40 K will allow the SCTE concept to be experimentally investigated. The experiment can be accomplished by using liquid helium at 4.2 K as the energy sink and liquid hydrogen at 20 K as the heat source. There are other materials, such as $YBa_2Cu_3O_7$, that may allow the use of liquid nitrogen at 77 K as the heat source; $YBa_2Cu_3O_7$ is superconducting at temperatures up to 95K. To construct a TE element requires legs of dissimilar materials. The second material may be a yttrium compound, $(La_{1-x}M_x)_2CuO_4$, doped with a different percent of Ba, Ca, or Sr, or $(La_{1-x}M_x)_2CuO_4$ doped with a Group IVA element such as Ti, Zr, or Hf. The actual materials necessary to construct a test TE element have not been identified.

APPLICATION AND DESIGN

SCTE Design Requirements

The Metzger/El-Genk number is always less then or equal to one, Me ≤ 1.0, since the electric power produced can never be greater then the power of the heat conducted to the hot shoe of the converter. As Me approaches 1.0 the thermoelectric converter is more efficient. For the SCTE, if Me equals 1 the maximum conversion efficiency of the converter is half the Carnot efficiency:

$$\eta_{SCTE\text{-}max} = \frac{\eta_{Carnot}}{2} \quad . \tag{7}$$

Figure 2 plots the conversion efficiency of a thermoelectric converter as a function of $\frac{R_L}{R_p + R_n}$ and the Metzger/El-Genk number. The graph indicates that as the Metzger/El-Genk number approaches a value of 1.0, the maximum theoretical efficiency of the thermoelectric generator approaches the maximum value of 50% of the Carnot efficiency. For a constant value of Me, the value of the Carnot efficiency has very little affect on the efficiency of the converter.

For a DC voltage source the maximum power transferred to a load resistor occurs when the load resistance is equal to the internal resistance of the source, m =1. The internal resistance of the source includes every resistive loss in the circuit except the load resistance. Assuming that "m" is equal to one, the maximum conversion efficiency of a conventional thermoelectric converter, Me =1, is bounded by 18.2% of the Carnot efficiency. From Figure 2, for a value of "m" equal to 20 the efficiency is very close to the maximum theoretical efficiency of the converter. By increasing the value of "m" to 20 the power delivered to the load will be reduced and is a trade-off that must be considered in the design of integrating a number of thermoelectric elements into a power generator.

The expression for the conversion efficiency of an SCTE, Equation (3), provides information on its load-following capability. For a value of Me less then one, the SCTE is inherently load following. As load resistance is added in parallel the equivalent load resistance decreases. As the load resistance decreases the value of Me increases toward a value of 1.0, and the efficiency of the SCTE increases, producing more power. Additional load resistance can be added in parallel until Me equals 1.0 and the SCTE is no longer load following. To decrease the value of Me, so that the converter is once again load following, requires an increase in the hot shoe temperature, T_H, which is accompanied by a decrease in the SCTE's conversion efficiency. An increase in the hot shoe temperature is accomplished by increasing the power output of the power source.

The same trend holds true for the conversion efficiency of thermoelectric elements given by Equation (6). As the load resistance decreases, "m" decreases, and Me increases, with a resulting increase in the conversion efficiency. Once Me reaches a value of 1.0 the thermoelectric converter is not load following. An increase in the energy input to the converter, an increase in T_H, will cause Me to be less then 1.0 and the converter will be load following

In evaluating the load-following capability of an SCTE, if Me is increased to values larger than 1.0 Equation (5) will yield values for the conversion efficiency approaching 100% of the Carnot efficiency; however, values of Me greater then 1.0 are not physically possible. When evaluating the conversion efficiency of a thermoelectric generator using Equation (6), values of Me greater than 1.0, with the associated change in the value of "m", will yield a reduction in the conversion efficiency. The important point is that for values of the Metzger/El-Genk number greater then 1.0 there is no physical meaning.

Figure 3 plots the geometric ratio of $\frac{L}{A_n}$ verses the ratio of $\frac{(k_p + k_n)}{\alpha^2_{pn}}$ for T_H's of 300 K and 1250 K, an R_L of 0.05 ohm, and assuming that the geometry of the P and N legs are the same. The value of Me used to construct the plot is 1.0. For values of Me less than 1.0 (decreasing percent of Carnot efficiency) the straight line plot would be parallel to and below the plot shown. Increasing the hot shoe temperature or decreasing the load resistance has the same effect on the plot as decreasing Me. The left extreme of the abscissa was chosen for a $(k_p + k_n)$ of 0.001 W/(cm-K) and an α_{pn} of 100 mV/K. The right extreme of the abscissa was chosen for $(k_p + k_n)$ of 0.1 W/(cm-K) and an α_{pn} of 10 μV/K. The design regime of a thermoelectric element operating with a specified hot shoe temperature is below and on the line. The ratio of the TE converters for the SP-100 is 2.71cm/cm^2 (L = 0.38 cm, $A_n = A_p = 0.14$ cm^2) and is indicated on the plot. [7] Constructing plots like Figure 3 provide guidance for determining the geometry, $\frac{L}{A_n}$, of a thermoelectric converter as a function of the thermoelectric material properties, the Metzger/El-Genk number, and the converter design specifications.

Radiator Design Consideration

A design consideration for a space-based, low-grade energy conversion system is the trade-off between the system's efficiency and the surface area of the system's radiator. Figure 4 is a plot of the surface area of a radiator as a function of the system's conversion efficiency and radiator surface temperatures of 300 K and 800 K. Each system produces 100 kW of electric power; in both cases the sink temperature is assumed to be 100 K and the emissivity of the radiator surface is assumed to be 0.85. To have similar radiator surface areas of less than 100 m^2, the system with the 300 K radiator would be required to convert energy at an efficiency of approximately 70% verses 5% for the system with a radiator surface temperature of 800 K. However, for the 67% Carnot efficiency of the 300 K system the maximum theoretical conversion efficiency can only approach 33.5%; that is Me is equal to one. From Figure 4, the radiator's surface area for the low-grade system would be approximately five times that of the hot system (~510 m^2 versus ~95 m^2). Even at a high conversion efficiency, the low-grade grade energy conversion system will require a larger radiator.

The size of the heat source of the hot-conversion system operating at 5% conversion efficiency is 2000 kW$_t$ to produce 100 kW electric power, while the size of the low-grade conversion efficiency operating with a 33.5% conversion efficiency is 300 kW_t to produce 100 kW_e. The trade-off is that an increase in the conversion efficiency of a system using SCTE converters will result in an increase in the radiator surface area, but will result in a corresponding decrease in the required size of the energy source and the temperature at which the heat source has to operate.

Conceptual System Design

The radiator incorporated into the conceptual low-grade system for a space application has to have a low specific mass (kg/MW) to offset its larger size when compared to a high-temperature conversion system. A candidate concept is a heat pipe radiator. To use a heat pipe radiator at a temperature of 300 K would require that the heat pipe working fluid is a cryogenic fluid or a refrigerant. For a lunar base, the heat reject portion of the system would be located on the dark side of the moon to take advantage of the low-temperature energy sink.

As stated above, with a 33.5% conversion efficiency to produce 100 kW electric power, the power source would need to be 300 kW, which is relatively small. This size of a power source could be solar collectors, a small low-power nuclear reactor, or even a radioisotope thermal source. If solar collectors cells are used as the heat source, the energy source and the heat rejection would need to be on opposite sides of the moon. If a nuclear reactor or a radioisotope thermal source is used as the energy source, it would have to be separated or shielded from the converters to prevent radiant energy from being deposited in the cryogenic portion of the system. Depending on the temperature of the coolant exiting from the power source, the power source may need to interface with the power conversion loop by a primary coolant loop and a heat exchanger. But if the coolant exiting the power source is in the temperature range required by the HTSC material, the primary coolant could interface directly with the SCTE converters.

CONCLUSIONS

Presented in this paper is a concept for using HTSC material in a TE converter to eliminate the Joule heating and increase the overall efficiency of the TE converter. Because of the projected operating temperature ranges of HTSC materials, the SCTE converter would be required to operate between cryogenic temperatures and room temperature. This concept is motivated by a desire to determine if it is possible to take advantage of (1) a low temperature heat sink, space, that inherently lends itself to high Carnot efficiencies and (2) the recent prospects for materials that exhibit superconductive properties at temperatures that approach room temperature and above.

From the analysis of the conversion efficiency of an SCTE a dimensionless number, the Metzger/El-Genk number, is defined that provides a guideline for the design of thermoelectric converters. The Metzger/El-Genk number is a ratio of the maximum electric power that can be converted divided by the amount of power in the form of heat that is conducted to the hot shoe of the thermoelectric converter. The Metzger/El-Genk number has values between one and zero, and as its value approaches one the ratio of the load resistance divided by the internal resistance of the converter gets large and the thermoelectric generator's conversion efficiency approaches its theoretical maximum conversion efficiency of 50% of the Carnot efficiency.

From the material considerations we concluded that realizing a single HTSC material to act as the electric conductor, the heat transfer medium, and the Seebeck effect may not be possible. However, an alternative is a matrix composition where HTSC material passes the electric current with no Joule losses and a matrix material, either a semiconductor or insulator, that provides the Seebeck effect.

The trade-off for low-grade energy systems is a reduction in the size of the energy source and an increase in the efficiency versus an increase in the heat rejection area. The obvious advantage of a cold, high-efficiency energy converter is that the energy source does not need to operate at the high temperatures that put stringent demands on materials and operation. On the other hand, due to the low temperature at which the system must reject energy, the mass of a radiator required to reject small amounts of energy could be a limiting system design consideration if high conversion efficiencies can not be realized. The key to the SCTE converter is the advances in discovering materials that exhibit superconductive properties at temperatures at or above room temperature.

With the motivation of a low-temperature heat sink in mind, we may also consider using dynamic cycles, such as the Rankin cycle, in space that operate under the vapor dome of refrigerants or cryogenic fluids. We can classify dynamic conversion cycles that use cryogenic fluids or refrigerants and the SCTE converter as cold or low-grade, high-efficiency, energy converters.

The SCTE converter concept is speculative and may be applied to only very special situations; that is, there must be a very low-temperature heat sink available. The concept as presented in this paper has not had the benefit of experimental verification and is dependent upon the further development of high-temperature superconducting materials for practical implementation.

ACKNOWLEDGEMENT

The information contained in this article was developed during the course of work done under Contract No. DE-AC09-89SR18035 with the U.S. Department of Energy.

PATENT APPLICATION

A patent application for this concept has been filed by the Department of Energy.

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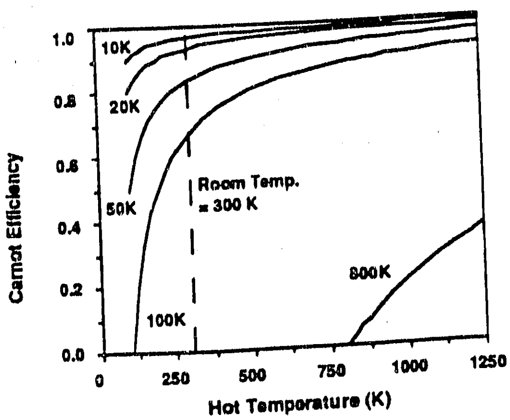

Figure 1. The Carnot efficiency plotted as a function of the temperature of the energy source and the energy sink.

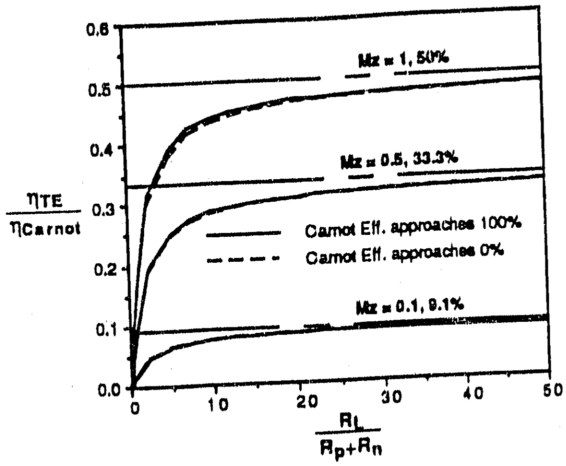

Figure 2: The ratio of the thermoelectric conversion efficiency as a function of the ratio of the load resistance over the sum of the resistances of the N and P leg of the converter, and the Metzger/El-Genk number.

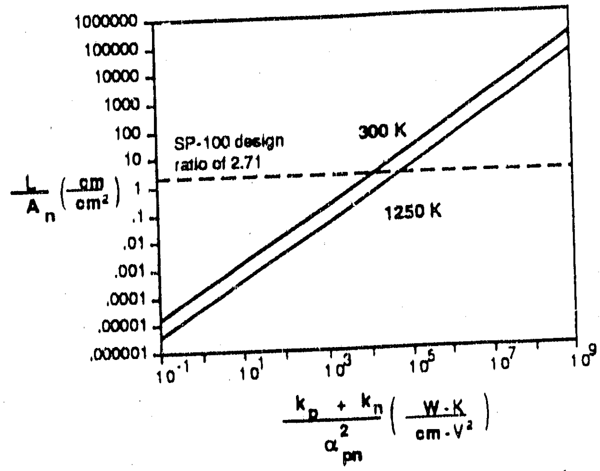

Figure 3: The ratio of the TE element length to the cross-sectional area; the load resistance is 0.05 ohm and Mc is 1.0, corresponding to the maximum thermoelectric efficiency of 50% of the Carnot efficiency.

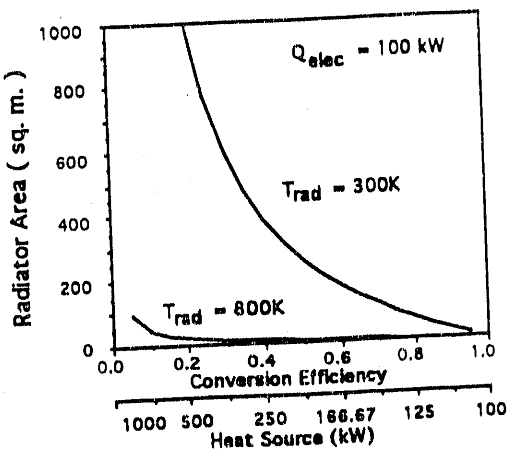

Figure 4: Surface area requirement of a radiator as a function of the system's conversion efficiency and the radiator surface temperature; in each case $\varepsilon = 0.85$ and $T_{sink} = 100$ K.

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