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THERMAL ENERGY TRANSFER IN A GASEOUS POWER SOURCE (U)

J. B. Gerardo, 5122; R. A. Hill, 5122;
and J. R. Banister, 5120

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INTRODUCTION

A study of the feasibility of a Kr^{85} power source for satellites revealed that the low thermal conductivity of krypton leads to a high central temperature in the absence of a gravitational field.[1] This large temperature difference is not experienced in a gravitational field as a convective flow develops when the internal temperature rises, but it could elevate the system pressure in the satellite's power supply. This report examines the ameliorating effect of secondary factors; namely, the contribution to the thermal conductivity by the free electrons and the role of radiative heat transfer from excited atoms. The possibilities of increasing the thermal conductivity through the addition of a light gas such as helium and the feasibility of adding metallic conductors in the interior are also examined. The role of electrons in the thermal energy transport is demonstrated to be completely negligible; the effect of radiative transport is minor. The addition of helium to the fuel cell is also found to be an unpromising approach. On the other hand it is pointed out that adding a metallic conductor could easily reduce the high internal temperatures while occuping a negligible portion of the vessel volume. It also emphasized the pressure increase incurred by the high central temperature is less than might be expected amounting to about a factor of two.

FREE ELECTRON CONTRIBUTION TO THERMAL CONDUCTIVITY

The study of the effect of the free electrons on the thermal conductivity of the medium requires estimating their density. An order of magnitude calculation can be made simply by setting the electron production rate equal to the loss rate. For a Kr^{85} mass density of 1.08 gr/cm^3 the number density is $7.66 \times 10^{21} cm^{-3}$. Using a half life of 10.3 years, the β ray production rate at this density is $S_\beta = 1.18 \times 10^{13} cm^{-3} sec^{-1}$. Assuming that the energy spent to produce each ion pair is 30 eV and the initial kinetic energy of the β is 3×10^5 eV, the production rate, S_e, for free electrons is $1.18 \times 10^{16} cm^{-3} sec^{-1}$. In steady state the net production rate is equal to the net loss rate through recombination, i.e.

$$S_e = \alpha N_e^2$$

or (1)

$$N_e = \sqrt{S_e / \alpha} \quad .$$

The recombination coefficient, α, is different for the various recombination processes that are possible. If we assume that the dominant recombination process is collisional radiative recombination[2]

$$Kr^+ + e + Kr \xrightarrow{\alpha_{cr}} 2\ Kr$$

then for Te $\approx 2000^{o}K$ and $N_{Kr} \approx 10^{22} cm^{-3}$ the recombination coefficient is on the order of $10^{-10} cm^{3} sec^{-1}$. This gives $N_e \approx 10^{13} cm^{-3}$. If, however, most of the ions in the plasma are molecular, which is probably the case, the recombination process of interest is

$$Kr_2^+ + e \xrightarrow{\alpha_d} 2\ Kr$$

and $\alpha_d \approx 6x10^{-7}$. In this case $N_e \approx 1.4x10^{11} cm^{-3}$. Collisional-dissociative recombination could also be of importance, i.e.

$$Kr_2^+ + e + Kr \xrightarrow{\alpha_{cd}} 3\ Kr \quad .$$

Very little is known about this reaction but we can probably put an upper limit on α_{cd} of about $\alpha_{cd} \leq 10^{-4} cm^{3} sec^{-1}$. Hence, we arrive at the conclusion that $10^{10} cm^{-3} < N_e < 10^{13} cm^{-3}$.

If the neutral gas atoms were not present the thermal conductivity of the free electron and ion gas would be approximately

$$K_e \approx 10^{-13}\ T^{5/2}\ cal\ sec^{-1} cm^{-1} deg^{-1} \qquad (2)$$

for the value of electron density determined above.[3] At a temperature of 2000 ^{o}K this reduces to approximately $3x10^{-5}$ cal/sec cm deg. In the presence of the neutral atoms this value is decreased considerably. It is difficult to precisely account for the effect of the neutral atoms on

the thermal conductivity of the free electron and ion gas but one estimate that is sometimes used is given by Chen et al.[4] This equation predicts that for the conditions of interest here $K_e \approx 10^{-11}$ cal $sec^{-1}cm^{-1}deg^{-1}$. This value is very much smaller than the thermal conductivity of the neutral gas which for equal temperature, i.e. T = 2000 ^{o}K, is approximately 2.4×10^{-4} cal/sec cm deg.

Hence, in conclusion, we find that for the conditions of the plasma medium of interest here, the thermal conductivity of the plasma medium is essentially that of the neutral gas constituent.

RADIATION FROM THE VOLUME

In the report by Kortier et al., they assumed that all of the energy produced by the decay of Kr^{85} was converted to kinetic energy of the gas. One might, however, expect some energy transport from the volume to the container wall by radiation. Of course, the high concentration of neutral atoms will absorb all resonant radiation and probably all atomic line radiation is trapped in the gas. The radiation that does reach the walls would have a backbody character for the strongly absorbed wavelengths. Due to the effect of pressure broadening, the lines will be quite wide and the blackbody radiation at the lines could cover a considerable percentage of the spectrum for radiation energy characteristic of the electronic transitions of Kr. Since, the gas is most

probably not in complete thermodynamic equilibrium and the temperature is definitely not spatially uniform, it is difficult to estimate the magnitude of the radiation which reaches the walls. One can definitely state, however, that if all atomic lines are optically thick the amount of radiation reaching the walls is at most a few percent of the total radiation available due to recombination. The remaining energy is spent in increasing the kinetic energy of the gas.

Of possible more importance than atomic line radiation, the medium will also radiate via molecular ion radiation. This, of course, assumes that molecular ions are formed and that they decay radiatively rather than by collisions with a second body. Since the molecular ion density is quite low, i.e., $\leq N_e \approx 10^{12} cm^{-3}$, this radiation is optically thin and passes freely to the walls. At most, however, one would not expect more than about 2 eV per recombination event to be radiated via this phenomena and possibly much less than this. Since it requires about 30 eV to produce an ion pair it is obvious that no more than about 7% of the β ray energy is transferred to the walls in this manner.

The above indicates that at most 10% of the energy from the decay of Kr^{85} is transferred to the walls by radiation. Hence, better than 90% is transferred by thermal conduction.

A significant increase in the amount of radiation reaching the walls might be achieved by the addition of

small quantities of an appropriate impurity gas or gases. The impurity gas would be chosen such that excitation energy of the Kr^{85} can be efficiently transferred to excitation energy of the impurity gas. If the pressure of the impurity gas is held to a sufficiently low value this radiation can easily reach the walls of the container if it does not coincide with a characteristic frequency of the krypton. For efficient transfer the impurity gas must be chosen such that resonant transfer of excitation energy is possible. It would be most effective if the metastable states of Kr^{85} could be efficiently depopulated by resonant transfer of energy to the impurity gas. In order to make an appropriate selection of the impurity gas, an extensive survey would be necessary and which will not be undertaken here. Since the appropriate cross section for resonant transfer of excitation energy from one gas to another is not well known, it is nearly impossible to even estimate the importance of this mechanism on this problem. We can only suggest that small amounts of impurity gas should be added to the vessel and then by experimentation decide whether or not any improvement in operation was achieved. Preliminary estimates indicate that if an effective impurity gas can be found, as much as several eV per recombination event can be transferred to the wall of the container by this mechanism. The addition of impurity gas would tend to increase the pressure in the same way as does the helium addition discussed in the next section.

IMPROVEMENT THROUGH THE ADDITION OF HELIUM

The addition of helium to the fuel cell has two obvious consequences which have compensating tendencies. The first is favorable; i.e., the thermal conductivity is increased because of the lower molecular weight of helium with an attendant reduction of the system pressure. On the other hand, the addition of helium also tends to increase the system pressure as we have more gas atoms per unit volume for the same system volume.

The reduction of the system pressure which is achieved through increasing the thermal conductivity is demonstrated in Fig. 1. We notice that the improvement which is achieved by increasing the thermal conductivity is quite limited; if the thermal conductivity (K) becomes infinite (i.e., K_{kr}/K becomes zero), the system pressure is reduced to about 58% of the pressure which is obtained when the medium's thermal conductivity is equal to that of krypton (K_{kr}). This curve, which is approximate, was calculated using the implications of the temperature profiles of the Battelle group with a graphic intergration implied by their system pressure derivation. We have also ignored the minor variation of the compressibility factor and used the relation

$$p \alpha \, 1 / \int_{o}^{r_o} \frac{rdr}{T} \qquad (3)$$

where p is the system pressure, r is the radius (r_o is the system radius), and T is the temperature. We selected a wall temperature of 1200 °F (649 °C) and have assumed the system dimensions of their report. Temperature profiles for various thermal conductivities were than approximately scaled from their curves. The error of our curve, including the variation of compressibility, may be as much as 15%. Specifically, we would expect the pressure to be somewhat less (perhaps 10%) because of the change in the compressibility factor for the lower range of K_{kr}/K.

The second effect, pressure elevation through addition of more atoms per unit volume to the gas, can be specified more precisely. The relation again ignoring the compressible factors is

$$\frac{p_t}{p_{Kr}} = \frac{p_{He} + p_{Kr}}{p_{Kr}} = \frac{1}{(1-F)} \qquad (4)$$

where p_t is total pressure, p_{He} is the partial pressure of helium, p_{Kr} is the partial pressure of krypton, and F is the mole fraction of helium. We assume, of course, that the number of moles of krypton is fixed as is the system volume.

The dependence of the thermal conductivity on the mole fraction of He for He-Kr mixture is displayed on Fig. 2. These results were taken from the experimental data summary presented by Saxena and Gandhi.[5] The net result of adding helium to the fuel cell may then be obtained by the use of

Figs. 1 and 2 and Eq. 4. The two figures provide the proportial reduction of pressure achieved through the increase of the thermal conductivity while the equation specifies the proportional pressure increase incurred by adding helium. It is found that the addition of small amounts of helium ($F < .1$) does not change the total pressure appreciably while larger amounts actually increase the total pressure.

ESTIMATION OF THE EFFECTIVENESS OF METALLIC CONDUCTORS

Our results thus far have been discouraging; we have established that most of the energy is transferred through conventional thermal conduction and that the system pressure is not reduced by adding a lighter gas (He) to improve the conductivity. A more optimistic result is now presented. We find that metallic conductors could easily reduce the system pressure. This metallic conductor could be fine mesh of metal which is placed in the cell interior.

The effective thermal conductivity (K) of such an arrangement is

$$K = K_{kr} \left(1 + V_f \left(\frac{K_m}{K_{kr}} - 1\right)\right) \qquad (5)$$

where K_{kr} is the thermal conductivity of krypton, K_m is the thermal conductivity of the metal and V_f is fraction of the available volume which is occupied by metal. In deriving this expression we have assumed that the metallic strands

are situated radially (parallel to the heat flow) and that the density of strands is proportional to the area through which the heat flows. The gas pressure which is increased because of the volume occupied by the metal is specified

$$p = \frac{p_o}{(1-V_f)} \tag{6}$$

at a given temperature if the fuel cell volume is not changed.

A typical value of the conductivity of a metal is 0.1 cal/cm sec K^o while the thermal conductivity of krypton at the operating temperature is about 10^{-4} cal/cm sec K^o. Substituting these values in Eq. 5 we find our working equation is

$$\frac{K_{kr}}{K} \simeq \frac{10^{-3}}{V_f} \quad . \tag{7}$$

We see that a small value of V_f (about 10^{-2}) will reduce the value of the ratio of thermal conductivities. Then turning to Fig. 1 and Eq. 6, we find the system pressure can be reduced effectively with the incorporation of metallic conduction. In fact, we expect that structural requirements and radiation damage considerations will call for larger volume of metal than is required for effective thermal transfer.

CONCLUDING REMARKS

Our examination of secondary energy transfer processes have established that they are of minor importance. We have also found that the addition of lighter gas to improve the thermal conductivity does not achieve a significant system pressure reduction. On the other hand, it seems clear that the use of metallic conductors can reduce the system pressure easily. We have also noticed and now emphasize that rise of the central gas temperature in the cell in the absence of gravitational field is not as catastrophic as might be thought. For example, for a vessel temperature of 1200 ^{o}R, the pressure is increased by about 70% by this effect.

ACKNOWLEDGMENT

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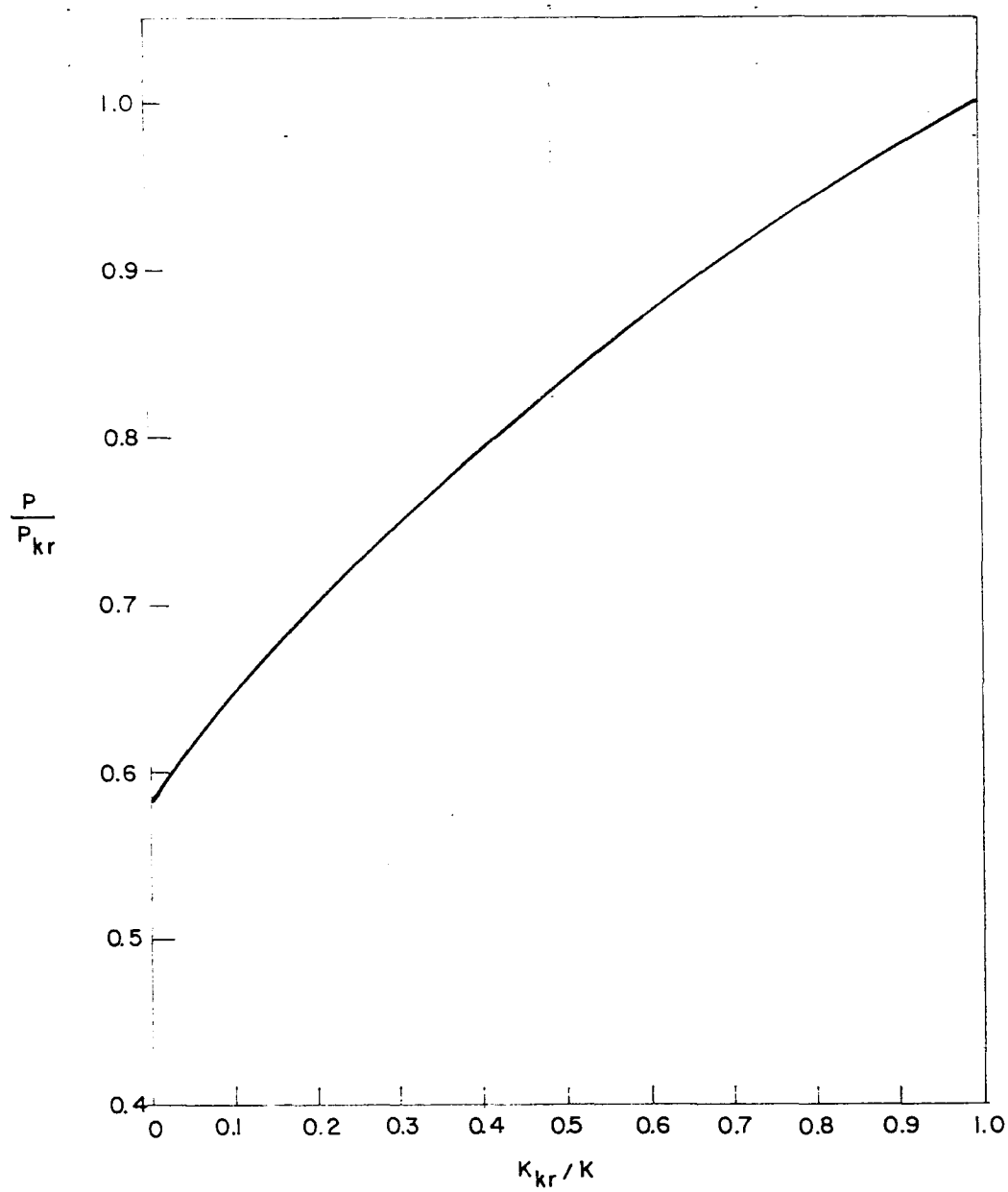

Fig. 1 Variation of the system pressure ratio (P/P_{kr}) with the thermal conductivity ratio (K_{kr}/K_{mix}) where P is the general system pressure and P_{kr} is the pressure for pure krypton. The symbol K_{kr} designates the thermal conductivity of pure krypton while K designates the general or effective thermal conductivity. A vessel wall temperature of 1200°F (649°C) was assumed and the curve was calculated by numerical methods discussed in the text.

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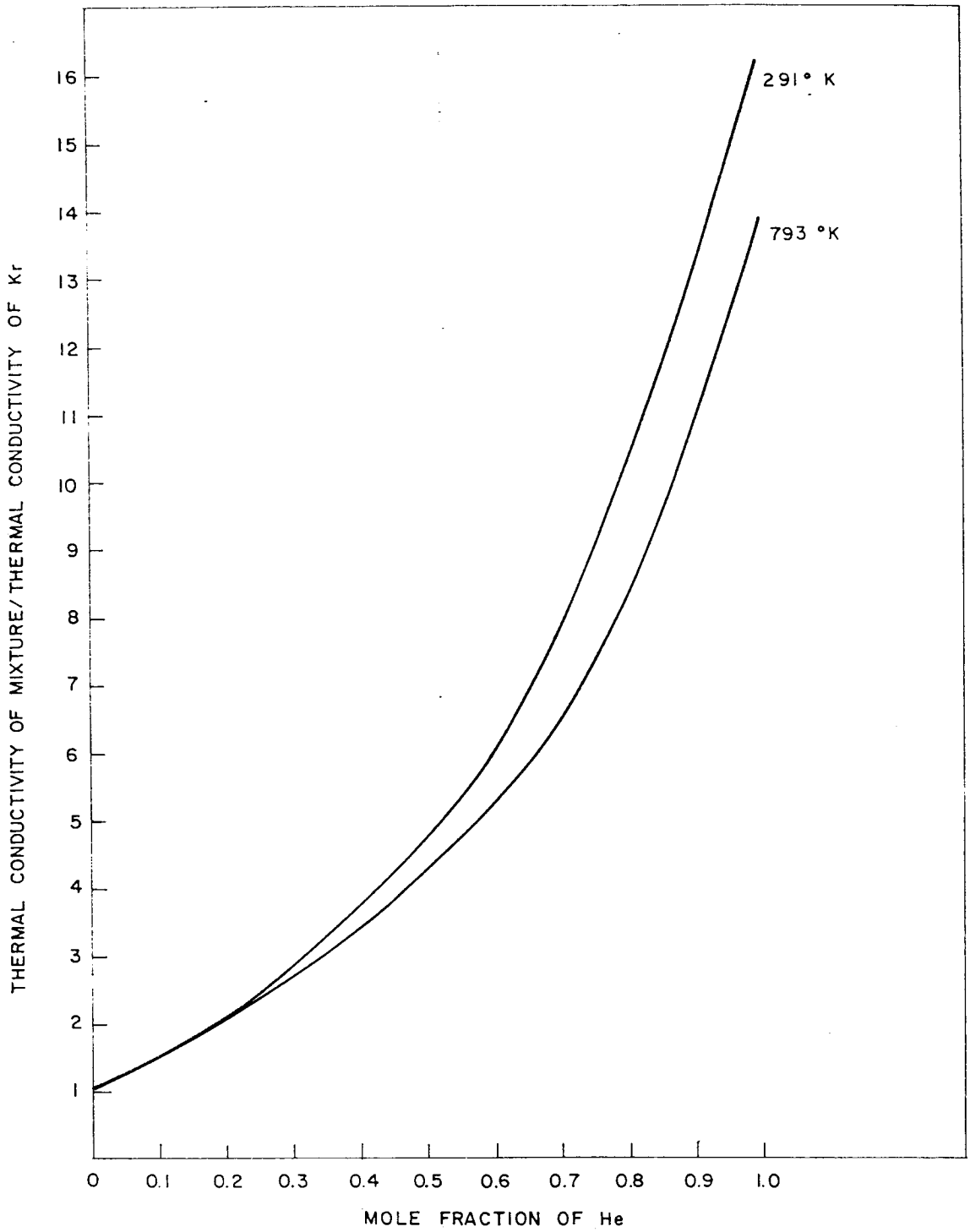

Fig. 2 Experimentally determined behavior of a mixture of krypton and helium as function of the mole fraction of helium. These values were published in a summary by Saxena and Gandhi.