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CONVERSION OF THERMAL ENERGY INTO ELECTRICITY WITH THE AID OF THERMOELECTRIC EMISSION

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THE development of cathode electronics has recently followed several new trends, which go far beyond the confines of its previous scope of activity. One such new trend, vigorously developing since 1958, is the use of thermoelectronic emission for highly efficient conversion of heat into electricity. Reports have already been made of small laboratory conversion units, in which the efficiency η reaches 15%, and the specific power ω (per unit cathode surface) reaches 30 w/cm^2. Even these figures are impressive, and judging from convincing arguments, they will probably be considerably improved. In addition, these units, being high-temperature devices, can be connected in series with equipment of different type, operating at lower temperatures, thus noticeably increasing the overall efficiency of the entire installation. Mention must be made here first of the suggestion made by A. F. Ioffe, that such "vacuum thermoelements" be combined with ordinary semiconductors.[1] Combined operation with steam-turbine units, etc, is also conceivable, as is the use of the heat released directly in nuclear fission in such devices.

The existing laboratory models of thermoelectronic converters can be grouped into two categories; 1) vacuum, and 2) gas or vapor filled; because of their peculiarities (see below), the latter have been most persistently developed. In view of the small total number of investigations in this field, we have thought it advantageous to adhere in the following description to the historical order, illustrating the operating features of each converter with data obtained by investigation of related devices.

1. INITIAL STAGE OF DEVELOPMENT (1949 — 1957)

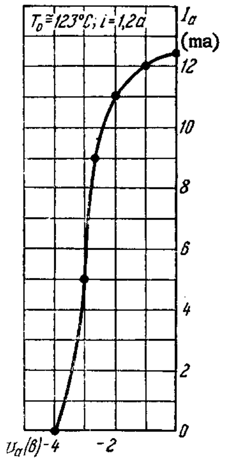

FIG. 1

Although the question of power efficiency of thermoelectronic emission was raised long ago, the essential development began in 1949,[2] when the first effective principle was proposed and experiments on such a conversion were performed. These experiments followed the main trend of almost all modern researches in this field. The particular investigation referred to concerned thermoelectronic emission from pure tungsten in cesium vapor. It was found possible to obtain a volt-ampere emission characteristic which was close to saturation and shifted noticeably to the left, as shown in Fig. 1 for a cathode temperature T = 2500°K and for a cesium vapor tension corresponding to t = 123°C ($p \approx 4 \times 10^{-3}$ mm Hg). The reason for this is the presence of a noticeable contact potential difference $v_k = (\varphi_k - \varphi_a)$ with the anode positive. Actually, in this case the cathode work function, $\varphi_k \approx 4.5$ ev (the tungsten temperature is so high that the absorbed cesium film cannot be retained on it), is considerably greater than the anode work function, $\varphi_a \approx 1.6$ ev (relatively cold metal, such as nickel covered with a thin film of cesium). In addition, the short-circuit electron current I_0 (in the absence of anode voltage) is in this case quite close to saturation, because of the practically complete neutralization of the electron space charge by the cesium ions produced by thermal ionization on the surface of the cathode.[3] The production of a "left-hand" characteristic, of the type shown in Fig. 1, is quite remarkable, since it proves that the tube is a generator of a current I, of approximately constant magnitude, and a certain effective emf $\approx v_k$, capable of delivering to an external resistance R a useful power $W_u = I^2R \leq Iv_k$. All this is clear from Fig. 2, where $\tan\theta = R$ and the shaded area is equal to W_u. At the optimum, $IR = v_k$, the efficiency of such a system is found to be

$$\eta = \frac{Iv_k}{W_l}, \tag{1}$$

where $W_l = W_i + I\varphi_k$ is the total power delivered to the cathode, $\omega = Iv_k$ the optimum cathode specific useful power, and W_0 is the power lost to radiation. Furthermore, for a conversion emf ϵ, in the case of an idealized characteristic consisting of a horizontal portion of extent v_k followed by a Maxwellian "tail," we obtain;

for $I_k \gg I_a$

$$\varepsilon = \left[v_k + \frac{kT_k}{e} \ln \frac{I_k}{I_a} \right].$$

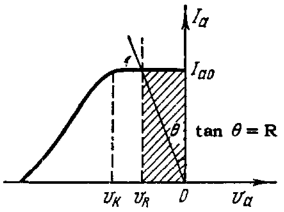

FIG. 2

The experiments set up to verify all these conclusions[2] confirmed all the foregoing. Figure 3 shows the load characteristics I(R), v(R), and $W_u(R)$ obtained for the converter shown in Fig. 1. Actually, as R is varied, the delivered useful power W_u goes through a maximum when R equals the internal resistance R_i; at this maximum we obtain $\eta \approx 1\%$, $\omega \approx 0.9$ w/cm^2, and $v_{Rm} \approx 2.4$ v. In addition we have here $I_0 \approx 0.4$ amp/cm^2, $R_i \approx 6$ ohm/cm^2 and $\epsilon \approx 3$ v.

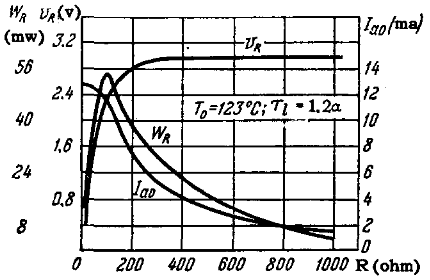

FIG. 3.

The values obtained for all these parameters are in good agreement with those expected, in particular, from Eq. (1). In addition, it follows from this formula that the quantities η and ω can be noticeably increased by raising the cathode temperature. For example, with T = 2800°K we could obtain $\eta \approx 10\%$ and $\omega \approx 10$ w/cm^2. It was emphasized in reference 2 that in this case a certain fraction of the thermal energy delivered to the cathode is converted directly into electricity through the use of the contact difference of potential.

The same investigation[2] has simultaneously clarified, under the foregoing conditions (Fig. 1), two other facts, of great importance to the characteristics of devices of this type: 1) the electron current can be controlled by applying an external magnetic field parallel to the cathode, as can be seen from Fig. 4; 2) when the space charge at the cathode is completely neutralized the ratio of the electron current I_e to the ion current I_p is

$$\gamma = \frac{I_e}{I_p} \approx \frac{1}{2}\sqrt{\frac{M}{m}} \approx 250.$$

This agrees also with the results of reference 4, where by using a probe technique it has been shown that under similar conditions an analog of an ion-electron plasma is produced near the cathode. We note that the latter problem was considered theoretically in detail in reference 5; its importance lies in the correct choice of the cesium vapor pressure necessary for the operation of the converter. It is interesting to note that the cesium ions on the cathode may find themselves later on in a "trap," owing to poor neutralization on the cathode and owing to the positive contact potential of the anode. The quantity γ must therefore be quite large, and only in the limit, when IR = v_k, do we obtain $\gamma \approx \sqrt{M/m}$. Finally, fluctuations of the anode current may be observed here.[3]

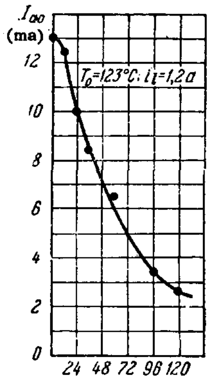

FIG. 4.

Somewhat later, in reference 6, still another important conclusion was drawn regarding the features of such a conversion, that to increase η and ω further by *increasing the electron emission* I_e from the cathode, it is also necessary to increase simultaneously the ion current $I_p = I_e/\gamma$, which neutralizes the space charge, that is to say, it is necessary to increase the vapor pressure p of the cesium vapor. This can be seen from the relation $I_p = \alpha e p (2\pi M k T_0)^{-1/2}$, where $\alpha = [1 + 2(v_i - \varphi) \exp(e/kT)]^{-1}$ is the probability of the surface ionization. For we can assume $\alpha \approx 1$ for cesium on tungsten ($v_i < \varphi$). Under these conditions, that is, at large values of I_e and p, we unavoidably arrive at a possible occurrence of "combined" low-voltage arc discharge in the cesium vapor, with a potential drop v_p.

The efficiency is thus

$$\eta = \frac{I(v_k + v_0 - v_p)}{I(\varphi_k + v_0) + W_0}, \qquad (2)$$

where $v_0 \approx 2k(T_k - T_a)/e$: the quantity W_0 should now include also the losses by heat conduction through the cesium vapor; consequently, the values of η and ω will unavoidably be somewhat smaller here. This discharge will be combined because the positive ions will be due both to thermal ionization on the cathode and partially to impact ionization within the volume. This may reduce the cathode potential drop and in the limiting case of thermal ionization, $\gamma \approx \sqrt{M/m}$, may cause it to vanish completely. In this case, under the reasonable condition $\lambda_e \ll d$, the interelectrode gas will simply play the role of an additional ballast resistance with a potential drop v_p.

Earlier investigations (1949 — 1950) of ordinary low-voltage arc discharges in cesium vapor[7] yielded much valuable information on processes that are also very important in the converter problem. These researches have disclosed, in particular, 1) the complete possibility of obtaining in this case a rather small $v_p \lesssim 1$ v, especially at small interelectrode distances d, and 2) a limited possibility of phase control of the current, similar to that of a cesium thyratron, as shown in Fig. 5 for $t = 250°$ C, i.e., $p \approx 0.5$ mm; the latter is connected with possible flow of thermal current in the control grid, which is also coated with a cesium film and heated by the discharge. Another reason why it is important in principle to be able to control the current in the tube to suit the experimental conditions, either with a magnetic field (Fig. 4) or with a grid (Fig. 5), is that it becomes possible to modulate the current in the converter and to transform the converter voltage to any desired value. Without the last circumstance, the converter output voltage is quite low ($\approx v_k$). The internal resistance decreases therefore with increasing converter power, making the resistance of the optimum external load low and operation difficult. It is thus advantageous to connect converters in series.

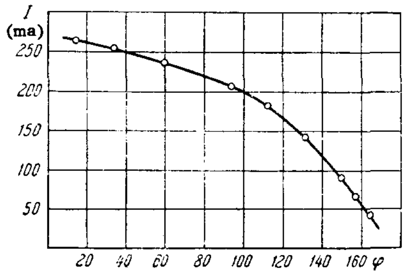

FIG. 5

This cycle of investigations yields also many valuable data on the properties of the converter anode. In fact, during converter operation the anode should be coated by a cesium film preferably one atom thick, so that φ assumes a minimum value, φ_m, somewhat less than the value of φ_∞ corresponding to the case of a thick cesium film. Our latest investigations, performed directly by the contact-potential method in the cold state, yielded for the cesium-tungsten system $\varphi_m \approx 1.3$ ev, $\varphi_\infty \approx 1.6$ ev. But the converter heats up in operation, since the power developed in it is $W_a = [I(\varphi_a + v_a) + \beta W_0] \approx I\varphi_a$, where $\beta < 1$ and v_a is the anode potential drop. Figure 6 illustrates heating of this type produced in a copper (1) or covar (2) anode, made in the form of a sleeve over a low-voltage cesium arc discharge at a typical $t = 260°$ C ($p \approx 0.6$ mm Hg).[7] It must be pointed out that there is nothing wrong with this temperature rise, for the hot anode can be used as the heating element for the next stage (thermoelectric or steam) of the converting device. Even in the now readily attainable $I_e \approx 12$ amp/cm^2 we obtain in a plane-parallel system $W_a \approx 20$ w/cm^2, approximately as in modern steam-boiler installations. It is important, however, that the anode temperature T_a be not high enough to produce either a noticeable reverse current, the limiting value of which (when $IR = v_k$) is $I_a = AT_a^2 \exp(-e\varphi_a/kT_a)$, or a noticeable desorption of the cesium film from the anode. At cesium vapor pressure this desorption can no longer be investigated by the well known Langmuir classical electronic method, owing to space ionization. A method recommended for this case is that of the adsorption probe,[8] the application of which to a molybdenum substrate is illustrated in Fig. 7. It is seen from this diagram that near $t \approx 260°$ C the desorption of the cesium film begins at rather high values, $T \approx 1300°$K. In addition, from the analysis of a similar family of curves we can determine the work function φ and the adsorption energy q for an optimum film on the substrate; values $\varphi = 1.1$ ev and $q = 1.5$ ev were obtained for the Cs-Mo combination.

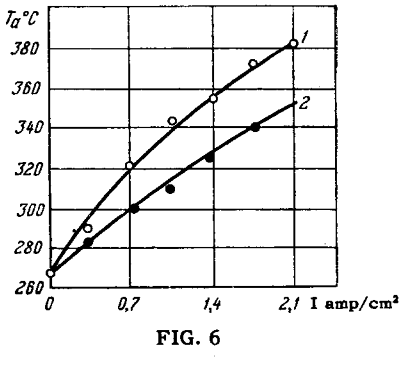

FIG. 6

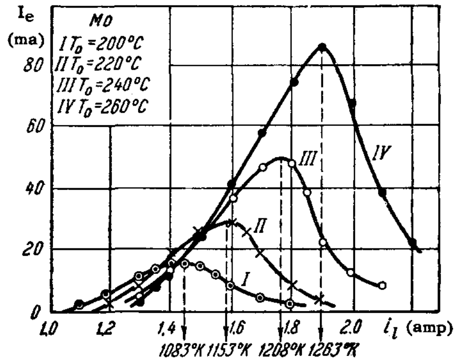

FIG. 7

Thus, along with producing effective thermoelectric conversion, this cycle of investigations[2,6,7,8] yielded much information of value to the understanding of its operating principle. Naturally, some of these data, of purely illustrative character and obtained incidentally in connection with another problem (the investigation of low-voltage cesium discharge[7]), must now be improved upon if they are to be applied directly to the converter. The possibilities and prospects of such a conversion are illustrated in Fig. 8, taken from reference 9, which shows the values obtained from Eq. (1) for the conversion efficiency at different values of work functions φ_k and cathode temperatures T. It is assumed here that $\varphi_a = 1.8$ ev (corresponding approximately to a thick film of cesium on the metal), and that the cathode has the same radiating ability as tungsten. We see here a possibility, of great practical significance, of obtaining very high efficiencies, provided

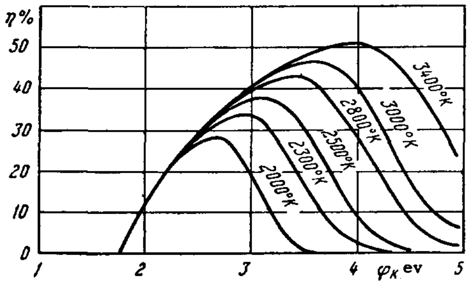

FIG. 8

that stable and long-lived cathode materials corresponding to the data of Fig. 8 are found.

A detailed theoretical paper[10] appeared in 1951, devoted to thermoelectronic energy conversion and to the calculation of the efficiency of a vacuum thermoelectronic converter for the cases $\varphi_k > \varphi_a$ and $\varphi_k < \varphi_a$. These calculations yielded many curves for the efficiencies under different experimental conditions. For $\varphi_k > \varphi_a$, naturally, an expression analogous to (1) was obtained, but unfortunately no emphasis was placed on the role played here by the contact potential difference, in the sense indicated above. Later in the same year a brief note was published,[11] also reporting a similar energy conversion due to the presence of a suitable contact potential difference; it is demonstrated, however, under much poorer experimental conditions. In this work, a low-voltage arc discharge was produced in an atmosphere of inert xenon at $p = 0.1$ mm Hg. The cathode was made of tantalum and the anode was metal coated with a film of barium. The results under these conditions were $\epsilon = 0.8$ v, $I = 0.5$ amp, and $\eta \approx 0.3\%$. So far, this is the only example of conversion without the use of cesium. In view of the total lack of thermal ionization on the cathode, we have here an ordinary low-voltage arc discharge. On the other hand, if cesium is used, we obtain for quite understandable reasons a combined discharge with a much lower value of v_p, meaning with a higher efficiency, as follows[6] from Eq. (2), and a film with low value of φ_a is automatically produced on the anode.

For several years following the publication of that paper, no one investigated thermoelectronic energy conversion experimentally. Only a few theoretical calculations were published,[12] dealing with electron current flow in vacuum. These papers emphasized, in particular, the advantages of reduction of interelectrode distances to a minimum so as to decrease the electronic space charge and to obtain the maximum possible short-circuit electron current (see below), since the power delivered was found to be $w = (IkT/e)\exp(-l)\ \mathrm{cm}^{-2}$.

II. CONTEMPORARY RESEARCH (1958 — 1959)

In 1958, great interest developed in the problem of thermoelectronic energy conversion, and a large number of scientific publications and publicity releases began to appear in print. Many laboratory models have been produced, particularly of devices in which the converter cathode was heated by nuclear fission. It is interesting to note that the indispensable element in almost all these converters is cesium vapor, which performs the two important functions indicated above;[2] 1) production of a suitable contact potential difference to increase the efficiency of conversion, and 2) neutralization of the electron space charge by thermal ions from the cathode.

Reference 9 deals with conversion by using high temperature tungsten cathode in cesium vapor. The idea, the procedure used, and the results obtained in this work essentially duplicate those of reference 2, but in a larger temperature range, from 2350 to 2910° K. The experimental efficiencies obtained here are represented by circles in Fig. 9; they are in good agreement with the theoretical curve, plotted from formula (1) for $v_k = 2.5$ v, yielding $\eta \approx 10\%$ at 2900° K. The table for ω, taken from the same reference, is of interest; here $\omega = Iv_k$ for $v_k = 2.5$ v, the efficiency η is calculated from (1), and q is the rate of flow or evaporation of the cathode tungsten, in millimeters of thickness per thousand hours of work (the melting point of tungsten is 3650° K). We note, incidentally, that in a cesium atmosphere the sputtering of tungsten from the cathode to the anode should not disturb the operation of the converter and that this loss in tungsten material is fully recoverable. Such a converter could be presumed energetically feasible at 3000 — 3200° K were a source of such high temperatures available. Finally, the same paper advances the idea, not verified experimentally, of obtaining substantial short-circuit electron currents by means of external fields, a plasmatron system, etc.

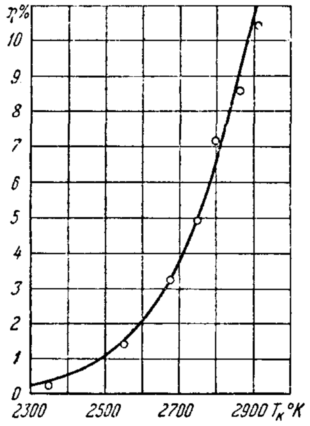

FIG. 9

T° K	I $\frac{\text{amp}}{\text{cm}^2}$	$\frac{\text{w}}{\text{cm}^2}$	η %	q $\frac{\text{mm}}{1000\ \text{hr}}$
2600	0.7	1.8	2.1	0.02
2800	3.5	8.7	6.6	0.2
3000	14.2	35.0	15.8	1.8
3200	47.8	120	27.9	12.4
3400	142	350	38.6	66.6

One might think that high-temperature pure metals other than tungsten could be used as cathode material for a converter, for example Re and Ta.[13] Tantalum was indeed used[14] in an experimental tube of greatly improved construction, in which the following could be produced: 1) controlled heating of an equipotential tantalum cathode by electron bombardment, 2) independent and accurate control of the temperatures of the copper anode and of the cesium vapor, etc. A plot of useful power obtained in this manner vs. the load is shown in Fig. 10 for different cathode temperatures and for $t = 253°$ C ($p \approx 0.5$ mm Hg). At the maximum, $T = 2900°$ K, values of $\omega = 10$ w/cm^2 and $\eta \approx 5\%$ were obtained, as well as a short-circuit current $I_0 \approx 20$ amp/cm^2. In this case a combined low-voltage discharge was produced in the interelectrode space, and this gave the authors grounds (in our opinion insufficient, see below) to call this converter "plasma thermocouple."

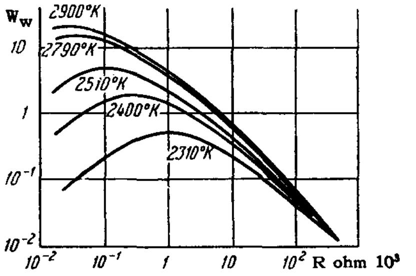

FIG. 10

This investigation was subsequently[15] continued, and the author could obtain with the same system $\eta \approx 15\%$, $\omega \approx 30$ w/cm^2, and $I_0 = 62$ amp/cm^2. It is easy to estimate from the last value the temperature of the tantalum cathode in this experiment, found to be approximately 3000° K. This is obviously a very high temperature, considering that tantalum melts at 3270° K, and it is indeed this temperature that is responsible for these converter parameters. Figure 11, taken from this reference, shows the dependence of the conversion emf on the cathode temperature at various cesium-vapor pressures; a) $p = 0$, b) $p = 10^{-5}$ c) $p = 10^{-2}$, d) $p = 0.4$ mm Hg. The same figure shows clearly how sharply the occurrence of an interelectrode discharge reduces the emf, as follows from (1) and (2).

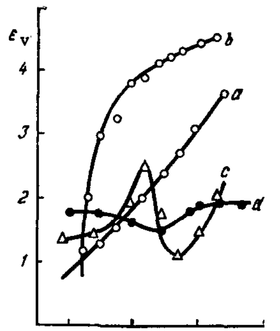

FIG. 11

The classical method of decreasing electron space charge in a vacuum by bringing the electrodes very close together was used in reference 16. The converter electrodes were two identical low-temperature metal-film hollow cathodes, separated by $d_{ak} \approx 10\,\mu$. In the case of a similar "vacuum thermocouple," where the contact difference of potentials should be zero, high efficiency is attainable only if a large electronic short-circuit current I_0 is produced simultaneously with low power consumption, as in similar low-temperature cathodes.[13] The foregoing pertains to some degree also to the case of a low-temperature cathode (i.e., with small φ_k) in an atmosphere of cesium vapor, where the contact potential difference will also be relatively small. The result obtained in this investigation for $T_k = 1270°$ C, $T_a = 540°$ C, and $d_{ak} = 10\,\mu$ is shown in Fig. 12 in the form of two delay curves, experimental to the left and theoretical to the right. The left curve can be obtained from the right by assuming that a voltage $v_k = 0.3$ volts of suitable sign is produced here by some means. The optimum values obtained from the data of this figure are $\omega \approx 0.8$ w/cm^2 and $\eta \approx 13\%$; there are grounds for assuming, however, that the last figure is somewhat overestimated. The authors believe that a pile of 30 cathodes would deliver a useful power of 0.5 to 1.0 kw at $\epsilon \approx 15$ to 20 volts and $\eta \approx 10$ to 15%. At the present time this is the only experimental investigation with a vacuum gap between the converter electrodes, although in a recent theoretical paper[17] there is an indication of a similar, experimental investigation as yet unpublished.

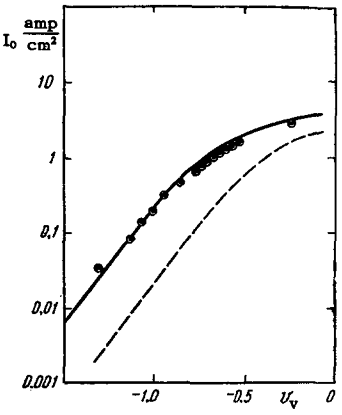

FIG. 12

It is appropriate to ask here the following question: is it possible to use an inactive low-temperature cathode, for example the same hollow cathode, but in cesium vapor, to obviate the need for such small interelectrode distances, which are difficult to maintain between large cathode surfaces? This question is important because low-temperature (1000 — 1500° C) heat sources will undoubtedly remain more readily available than high-temperature ones (2800 — 3000° C). To answer this question we used in the second stage of our investigation[18] the idea of producing positive cesium ions by local ionization of grains of the metal-film cathode. These grains were shaved off from microregions of the cathode surface, where $\varphi \geq v_i(Cs) = 3.9$ v. In view of the applicability of two known wave inequalities in this case, $\lambda_p \ll a$ and $\lambda_e \gg \lambda_p$ (where λ_p and λ_e are the ion and electron wavelengths, and a is the linear dimension of the shaved microregions), one can expect not only a noticeable ion current, but also a substantial interaction between the space charges of the ions and electrons, i.e., significant values of I_0, η, etc. The experiments confirmed all the foregoing. One of the load characteristics obtained is shown in Fig. 13. It pertains to a hollow cathode at 1300° C and t = 180° C ($p \approx 3 \times 10^{-2}$ mm). These curves are similar to those of Fig. 3, the optimum occuring at $\omega = 0.6$ w/cm^2, $\eta \approx 5\%$, $R_i \approx 0.6$ ohm/cm^2, $v_{Rm} \approx 0.7$ v, and $I_0 = 2$ amp/cm^2. The value obtained for the emf shows that $v_k \neq 0$. A serious shortcoming of such a cathode, compared with a purely metallic one, is its relatively limited operating life, owing to gradual evaporation of the active emitter, barium. The calculated lifetime in this case, for example, is approximately 200 hours. One must also note the low values of I_0, ω, and other parameters, obtained in the experimental part of reference 19, also with a hollow cathode in cesium vapor. We, too, obtained similar results with a pressed Ba-Ni cathode of rather high grade, from the point of view of its ordinary emission in vacuum. This can obviously be attributed to the production of a relatively small amount of cesium ions, owing to the high homogeneity of the active barium film on the cathode. From this point of view, a metal-film cathode of "average" quality is obviously needed for the energy converter. Finally, we must note that under suitable conditions an adsorbed film of cesium can be formed on the surface of such a cathode,[20] impairing the operation of this converter.

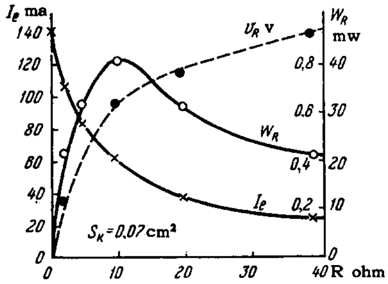

FIG. 13

The feasibility of low-temperature effective (for example, metal-film) cathodes was recently analyzed also in reference 21. The author indicates that a converter yielding $\eta \approx 25$ to 30% at 1100° C, used in conjunction with a steam turbine, could raise the overall efficiency to as high as 50 or 60%. He considered in this light a hypothetical system consisting of a cathode with $\varphi_k = 1.7$ ev (for example, a hollow cathode) and an anode with the rather low $\varphi_a = 1.0$ ev (BaO-Ni etc). Such a system can actually yield a noticeable ω and very large η. For example, at 1130° C with the obtainable $I = 9$ amp/cm^2, the author's calculations yield $\omega \approx 6$ w/cm^2 and $\eta \approx 32\%$. To neutralize the electron space charge, the author proposes to place in the interelectrode space a purely-metallic incandescent surface with a work function $\varphi'_k > v_i$, on which the necessary ions, say of cesium, will be produced. This surface should have a positive potential $v = (\varphi'_k - \varphi_k)$ with respect to the cathode, as can be seen from the potential diagram of the system (cathode, anode, and ionizer), shown in Fig. 14 for $IR = v_k$.

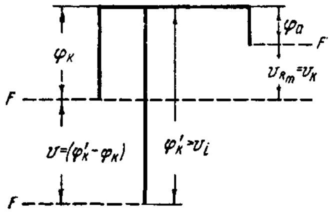

FIG. 14

No attention is paid, however, to the following difficulties: 1) the ionizer will also consume a certain amount of power, thus reducing the system efficiency, 2) at $I = 9$ amp/cm^2 the cesium ion current density at the cathode must be rather high, $\gtrsim 50$ ma/cm^2, and will therefore be difficult to control under these conditions, and, 3) at the high cesium vapor pressure necessary for operation under these conditions, the anode surface will probably be coated with a thick film of cesium, having $\varphi_a \approx 1.6$ ev. To produce a monatomic coating with a low φ_a, ≈ 1.0, the temperature will have to be so high (see Fig. 7) that these very delicate surfaces will probably be damaged. Incidentally, these factors are partially touched upon in the experimental paper by Wilson.[22]

Wilson[22] returns, so to speak, to a purely metallic cathode. He uses a molybdenum cathode ($\varphi_k = 4.2$ ev) and a Cs-O-Ag anode of the photoelectric type, with a proposed $\varphi_a \approx 1.0$ ev to produce a maximum contact potential difference. He also uses an additional ionizer (see above) in the form of a filament placed in the interelectrode space, at approximately 1 volt above the cathode potential. It must be pointed out first that the effect of this ionizer was quite inconclusive. Its use raised the conversion efficiency in one case and reduced it noticeably in another. The article contains no explanations of these facts. Turning to the operation of this converter in the diode mode, without an ionizer, which the authors themselves used to illustrate the operation of the system, the results at T = 1900° K and t = 290° C ($p \approx 2$ mm Hg), were $I_0 = 4$ amp/cm^2, $v_{Rm} = 0.8$ v, $\epsilon = 0.8$ v, $\omega \approx 3$ w/cm^2, and $\eta \approx 9.2\%$. To obtain this emission at this value of T it is necessary that the emitting surface have a work function $\varphi_k = 3.0$ ev (A = 120 amp/cm^{2}deg^2). However, since thermal ionization of the cesium on the cathode necessitates $\varphi > v_i(Cs) = 3.9$ ev, it is concluded that under these conditions the cathode surface is only partly covered by the adsorbed cesium film, i.e., that it has "spots" with $\varphi = 3.0$ and 3.9 to 4.2 ev. It can be shown at the same time that these experimental data can be explained even without resorting to this hypothesis, by assuming that the entire cathode is homogenously coated with a cesium film having $\varphi_k \approx 3.0$ ev. The point that at such high values of cesium vapor pressure, even at the low thermal-ionization probability $\alpha \approx 2 \times 10^{-3}$ obtained here, the number of cesium ions produced on the cathode may be sufficient to neutralize the electron space charge. It is difficult to say how convincing the foregoing arguments are. The very fact that an efficiency $\eta \approx 9.2\%$ was obtained with a purely metallic cathode at 1900° K is undoubtedly of great interest.

In the third stage of our investigation[23] we turned to a search for a single-component cathode material of intermediate properties, capable of noticeable emission at $T \gtrsim 2000°$ K at not too small a work function φ_k. The latter is necessary both to obtain noticeable thermoionization over the entire cathode surface, and to obtain significant values of v_k, i.e., ω and η. We chose for this purpose thorium bicarbide, ThC_2, on which only very skimpy data were available[13] The preliminary results of this investigation have disclosed that the thermoelectronic and thermoionic emissions in cesium vapor were quite satisfactory for our purpose. In particular, the figure $\varphi = 3.2$ to 3.4 ev was confirmed. The material was subsequently tested in a converter. One of the resultant load characteristics is shown in Fig. 15, for $T = 2100°$ K and $t = 250°$ C ($p \approx 0.5$ mm Hg). This characteristic has the usual appearance (see Figs. 3 and 13), and yields at the optimum $\omega \approx 16$ w/cm^2 and an efficiency between 10 and 15%, with $I_0 \approx 19$ amp/cm^2 and $\epsilon \approx 1.7$ v.

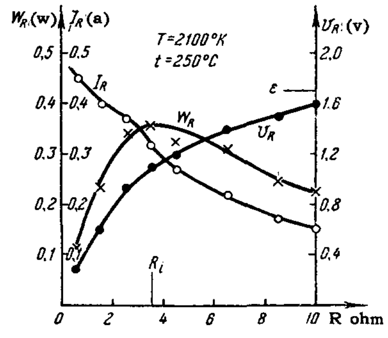

FIG. 15

In addition, this investigation yielded many other data, on which we shall not dwell here. We do submit, however, Fig. 16, which summarizes our data on tungsten (I) ThC_2 (II), and hollow cathode (III) from Figs. 3, 15, and 13 in the form of delay curves with indication of the values of v_{km}. This figure shows, in particular, the great advantages of the use of pure metallic cathodes for conversion purposes, although unfortunately they make high operating temperatures necessary. It is interesting to note a recently published brief communication,[24] also concerning the use of thorium carbide in cesium vapor for thermoelectronic energy conversion. It merely cites $\omega > 15$ w/cm^2 and $\eta > 15\%$ for this material, but does not state the conditions.

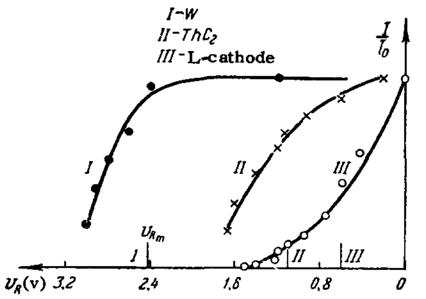

FIG. 16

We note, finally, new theoretical papers[25] devoted to the analysis of the operation of converting devices with allowance for the contact potential difference.

Of very great interest are experiments in which the converter cathode is heated directly by nuclear fission, i.e., in which the nuclear energy is converted directly into electricity. At present there are two brief communications on the subject. The first[26] describes a cathode in the form of a rod of uranium compound (6.3 mm in diameter and 19 mm long), operating at $T = 1900°$ K. The anode and the cesium vapor were at 300° C. This system operated continuously for 12 hours, delivering 25 watts. These data lead to the estimates $\omega \approx 6$ w/cm^2 and $\eta < 8\%$. In a second, more detailed communication[15] it is indicated that the cathode used was a ZrC : UC solid solution in cesium vapor, placed in a five megawatt reactor with a neutron flux of 10^{13} cm^{-2} sec^{-1}. Although values $I_0 \approx 35$ amp and $\epsilon \approx 3.5$ v were obtained, the maximum useful power at $T_k = 2000°$ C was only 30 w at $\eta \approx 5\%$.

After a certain forming operation, the converter could operate five hours without noticeable change in its parameters; a schematic diagram of the converter is shown in Fig. 17. Mention should also be made of another project,[21] as yet untested, of a similar sectionalized cesium-filled converter with a Th-W cathode on a UC core and a Cs-O-W anode, the schematic

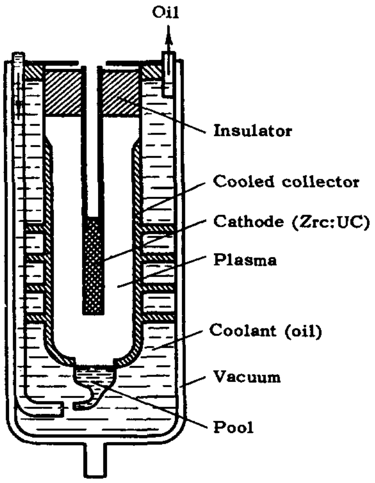

FIG. 17

diagram of which is shown in Fig. 18. It is indicated that such a setup should produce 27 kilowatts with an efficiency $\eta = 9.7\%$.

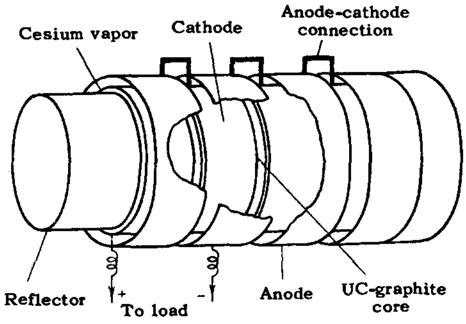

FIG. 18

In all these cases, it must be remembered that the possibility of radiation damage to the cathode material and the effect of the strong neutron flux in the reactor on the thermionic emission still remain undetermined.[27] It is suggested[21] that since the cathode is not made of single-crystal material, these effects should not be significant. The favorable effect of ionization of the interelectrode gas by the gamma rays from the reactor is also mentioned.

In conclusion we return briefly to the physical operating principles of such converters. It is interesting to note that along with the foregoing considerations, it was *recently shown*[28] *that the ordinary formula for the* Seebeck thermal emf yields in the case of an interelectrode plasma at $T_k = 3000°K$, $T_k - T_a = 2000°$ and $n_e = 10^{15}\,cm^{-3}$ a value of about 3 volts for ϵ, the same as experiment. The same paper lists many useful data on such a plasma. A rough estimate suggests an attainable efficiency on the order of 25%.

However, without denying the need for taking into account the many features of this plasma, as indicated in reference 28, one might think at the same time that the essential factor in the operation of most modern converters is precisely the use of the contact difference of potential. This follows from the results of many experiments, in particular, from Fig. 9, where good quantitative agreement has been obtained between experiment and Eq. (1). In addition, it must be borne *in mind that the polarity of the thermal emf of the electron plasma* should be the opposite of the one which is actually obtained and which makes possible the operation of the converter. The fact that this thermal emf plays a minor role in the experiment may be due to the fact that the energy released in the plasma by the flowing current leads to ordinary heating of its electron gas, that is, in fact to a violation of the correspondence between this temperature and the temperatures of the two contacts; this can be seen from reference 7. It is therefore more likely that we deal here with a certain unique type of heat machine with certain features of a galvanic cell, the current of which has a purely thermoelectronic, i.e., thermal, origin. *The presence of this* current is due to the heating of the cathode, i.e., a definite temperature difference $T_k - T_a$ must be produced in the converter; it cannot exceed the ordinary thermoelectronic saturation current. On the other hand, the processes in the interelectrode space determine the internal resistance of the converter, R_i, which can be changed, for example, by neutralizing the electron space with positive ions. The latter may be produced by a variety of methods; 1) thermoionization on the cathode or on a separate ionizer, 2) impact ionization in the interelectrode plasma or in a separate discharge, etc. By virtue of this, we have tentatively named this converter, in agreement with reference 10, a "thermoelectronic cell".[18] Naturally, we do not pretend this name to be the best or the most descriptive.

Summing up, the use of thermoelectronic emission *for direct conversion of heat energy into electricity* can be thought to offer serious promise of practical solution of many important problems of modern technology. However, much research and technical work is still necessary, and it is hoped that this will be successfully carried out in the nearest future.

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