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Leo Szilard

THERMO-ELECTRIC GENERATOR

BASED ON THERMIONIC EMISSION IN AN ALKALI

METAL VAPOR ATMOSPHERE,

In the following is described a thermo-electric generator. A number of features which are applicable to this generator have been previously described on pages dated January 16, January 19, January 21, January 22, January 23, February 8, and February 11, Mar 18 and the figures referred to on ~~these~~ pages. The present disclosure adds to the above mentioned disclosures and also amends and clarifies the previous disclosures inasmuch as they are relevant to a thermo-electric generator in which thermionic emission is maintained in an atmosphere which contains an alkali metal vapor, such as for instance cesium. It is desirable to be able to draw from the generator a current of the order of 30 amps per cm^2 cathode surface or anode surface, across a retarding voltage of 1 volt, so that one may obtain a power output of the order of magnitude of 30 watts per cm^2, with cathode temperatures which are of the order of magnitude of 2000 K and a ratio of cathode temperature and anode temperature of the order of magnitude of 2.

If one uses a metal tube as cathode~~, for instance a niobium or tantalum tube,~~ it is desirable to operate at a low cathode temperature in order to reduce the evaporation of the cathode to a minimum. One can obtain a saturation emission of the order of magnitude of 30 amps per cm^2 at a low temperature if one lowers the work function of the cathode by maintaining a suitable atmosphere of vapor inside the generator unit. Depending on the surface of the cathode and its temperature and depending on the cesium vapor

March 18, 1959 Witnessed Evelyn R. Rogers pressure, a smaller or greater number of cesium atoms will be adsorbed by the cathode surface and will increase the termionic emission. If in addition to cesium vapor, barium vapor is also maintained in the generator unit, there will be an additional increase in the thermionic emission of the cathode due to the adsorbed barium atoms.

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Assuming for the sake of argument that the generator contains ~~only~~ cesium vapor ~~which neutralizes the space c~~ ~~and that the cesium vapor pressure is less than 10 mm Hg,~~ which reduces the otherwise substantial negative space charge then we may write

(1) $$I\,(V_o + V_i) = W_1 - W_2$$

where I represents the current drawn, V_o represents the retarding voltage, and V_i the voltage "loss" inside the generator. W_1 represents the work function of the cathode and W_2 represents the work function of the anode. This equation holds whenever I represents a substantial fraction of the saturation emission of the hot cathode. I x V_o is the power output of the generator.

The same equation holds also for the vacuum diode in which the negative space charge is neutralized by maintaining a very small vapor pressure of cesium. In the limiting case of $W_1 = W_2$ and with a retarding voltage $V_o = 1$ volt, it would be thus not possible to obtain a current that represents a substantial fraction of the saturation emission of the hot cathode, in such a generator unit.

It is possible, however, to escape equation (1) by maintaining a very high vapor pressure of cesium in the generator. It is not desirable to have the cesium vapor pressure vary steeply with the temperature of the cold anode near the operating point of the generator. Such a steep variation with the temperature can be avoided if the quantity of cesium contained in the generator unit is small enough, so that essentially all the cesium goes into the vapor phase when the generator unit is heated up and before the operating

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temperatures are reached. The lowest temperature within the operating generator might for instance be 750°C, and the cesium vapor pressure at the operating temperature might be 760 mm Hg within the generator unit. This pressure is less than the saturation pressure of cesium at 750°C (it corresponds to saturation pressure of cesium at 690°C), which is 60° below the lowest temperature within the operating generator unit.

Depending on the construction of the generator unit, and particularly if the gap between the anode and the cathode is of the order of 1 mm or larger, the optimal cesium pressure might be lower than 760 mm Hg. The minimal cesium pressure necessary for satisfactory operation (from the point of view of escaping equation (1)) is determined by two considerations. There is a narrow region near the anode where there is a positive space charge. The width of this region must be larger than the mean free path of the electrons (within this region) in order to permit the electrons to establish by Coulomb interrection with each other an approximately Maxwellian distribution within this region, when currents of the order of magnitude of 10 amps per cm^2 are drawn.

Further there must be maintained in the plasma, in the gap between the anode and the cathode, a sufficiently high density of electrons, for the electrons in the plasma to transmit to the cesium atoms and ions about 0.1 watt/centigrade or more.

As the cesium vapor pressure increases, the resistivity of the plasma increases when the mean free path for collision of electrons with neutral cesium atoms begins to be comparable with the mean free path for the collision of electrons with cesium ions. This consideration is less important if the gap between cathode and anode is very small than when the gap is of the order of magnitude of 1 mm, but for gaps of the order of magnitude of

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1 mm this consideration may limit the cesium pressure which one may employ to values below 1 atmosphere.

When an electron collides with an atom or ion in the plasma, the energy transferred from the electrons in the plasma to the atoms and ions in the plasma is improved if in place of, or in addition to, cesium vapor one maintains the vapor of an alkali metal lighter than cesium. From the point of mass ratio, the lightest of alkali metals would be best. However, lithium may be ruled out because its saturation vapor pressure at the temperature of the cold anode is too low. Also the ionization potential of the lighter elements is higher, which means that fractional ionization for the lighter elements will be lower. Since the collision cross section of the ions for electrons is much higher than the cross section of the neutral atoms, the heat transfer to the light alkali vapor by the electrons will be greater if the fractional ionization is greater. Taking all these considerations into account, one might choose potassium among the lighter alkali metals as the most suitable for our purposes.

The potassium vapor pressure that one may thus maintain is limited only by the saturation pressure of potassium at the spot of the lowest temperature within the operating unit. If this lowest temperature is above 700°C, potassium pressures of about 400 mm Hg may be maintained.

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If the generator tube is vertical, the hot cathode being on the outside and the cold anode being on the inside and the hot cathode tube surrounding the cold anode tube, there will be a convection current of alkali metal vapor in the gap between the anode and cathode. At the outer edge of the gap the vapor will move upward and at the inner edge of the gap the vapor will move downward. This convection current can be reduced by maintaining suitable pressure of helium inside the generator unit. Due to thermal diffusion the relative abundance of helium will be higher near the inner edge of the gap and can effectively reduce the specific gravity of the vapor near the inner, colder edge of the gap (i.e., in the vicinity of the anode tube). If the cathode and anode temperatures are known and if the alkali metal vapor pressure in the operating unit is known, one may compute the amount of helium which must be contained in the generator unit in order to eliminate the thermal convection which one would have obtained in the absence of helium.

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(Thermo-electric generator based on thermionic emission in an alkali metal vapor atmosphere)

pressure, a smaller or greater number of cesium atoms will be adsorbed by the cathode surface and will increase the thermionic emission. If in addition to cesium vapor, barium vapor is also maintained in the generator unit, there will be ~~an~~ a ~~additional~~ further increase in the thermionic emission of the cathode due to the adsorbed barium atoms.

Assuming for the sake of argument that the generator contains cesium vapor which reduces the otherwise substantial negative space charge, then we may write

(1) $$I(V_0 + V_i) = W_1 - W_2$$

where I represents the current drawn, V_0 represents the retarding voltage, and V_i the voltage "loss" inside the generator. W_1 represents the work function of the cathode and W_2 represents the work function of the anode. This equation holds whenever I represents a substantial fraction of the saturation emission of the "hot cathode." I x V_0 is the power output of the generator.

~~A manner~~ Ways of maintaining a suitable cesium vapor pressure and barium vapor pressure in such a generator unit ~~has~~ was ~~been~~ disclosed ~~described~~ earlier on some of the pages referred to above. It may be, however, desirable to maintain the cesium vapor pressure and perhaps also the barium vapor pressure in a manner which changes less ~~change~~ steeply with ~~is not very sensitive to~~ the temperature of the coldest spot in the generator unit. Concerning the cesium vapor pressure, for instance, ~~this can be achieved~~ by choosing the quantity of cesium located within the generator unit low enough, so that essentially all the cesium goes into the vapor phase when the generator unit is heated up ~~and~~ before the full operating temperature ~~is~~ are reached. The principle involved may be illustrated by assuming, for the sake of argument, that the spot of lowest temperature within the operating generator unit ~~may be~~ is for instance ~~about~~ 750°C and that in the stationary state the cesium vapor pressure within the operating generator unit is 760 mm Hg. 760 mm Hg is the saturation pressure of cesium at 690°C, and, therefore, the ~~p~~ cesium vapor pressure in the operating generator ~~of 760 mm Hg~~ is substantially less~~t~~ than the saturation pressure of cesium at~~t~~ the temperature of the coldest spot of the operating generator unit. The same principle can be applied for the Barium vapor pressure maintained in the operating generator unit.

The choice of the cesium vapor pressure (vapour in the operating generator unit) is mainly governed by the following considerations. If the cesium vapour pressure is raised ~~above the~~ much considerably above ~~order of magnitude of~~ 1 mm Hg or if the gap between the~~s~~ anode and the cathode surface substantially exceeds the order of magnitude of 1 mm, then increasing the cesium pressure will begin ~~increase~~ appreciably the internal voltage loss of the generator unit. ~~This is~~ Beyond a certain point this is not desirable. On the other hand, increasing the cesium vapor pressure substantially above ~~the order of magnitude of~~ 1 mm Hg may ~~will~~ lower the work function of the cathode and thereby lower the temperature at~~w~~ which ~~a substantial~~ the desired current may be drawn from the ~~generator~~ cathode. This is desirable. Further, maintaining a high ~~pressure of~~ cesium vapor pressure reduces the rate of ~~operation~~ evaporation of the cathode ~~and this is desirable~~. Depending on the width of the gap between the anode and the cathode, cesium pressure up to ~~between 1 mm Hg and~~ 760 mm Hg might be usefully maintained. ~~The upper limit of this pressure~~ Pressures close to ~~range~~ the upper limit of this pressure range, however, ~~would~~ demand a rather narrow gap~~s~~ between the anode and the cathode in order to ~~minimize~~ keep the power loss in the gap of the generator unit low enough. Because practical considerations ~~set~~ may sets a lower limit for the width of this gap, the ~~most~~ suitable cesium pressure ~~is~~ may be substantially below 760 mm Hg.

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Whenever it is desirable to reduce the rate of operation of the cathode, it is advisable to maintain as high a cesium vapor pressure as considerations of the power output of the generator unit permit. The evaporation rate of the cathode is affected by the gaseous atmosphere within the generator unit in several ways. When the generator operates, the temperature~~s~~ in the gap between the cathode and the anode will be higher than the temperature of the cathode. As a result of this, if the tubular generator unit stands with its axis vertical, the vapor in the gap towards the center of the gap between the anode and the cathode would stream vertically ~~tawax~~ upward, and the vapor in the vicinity of the cathode and in the vicinity of the anode will stream vertically downward. We may designate this motion as the gravity induced convection. There is in the annular gap between the anode and the cathode also a radial hydro-dynamic flow which moves from the center of the gap towards the cathode on the one hand, and from the center of the gap towards the anode on the other hand. This flow is counterbalanced by the diffusion of the cesium vapor from the cathode towards the center of the gap and from the anode towards the center of the gap. Atoms evaporating from the cathode have to diffuse against this stream and this effect tends to keep the rate of evaporation of the cathode low.

The rate at which the cathode evaporates can be further lowered by maintaining in addition to the cesium vapor a certain partial pressure of an inert gas in the generator unit. Particularly suitable for this purpose are the noble gases. We shall discuss both the addition of a heavy noble gas, such as for instance xenon, and the addition of a light noble gas, such as for instance helium.

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If we maintain in the operating generator unit a pressure of a heavy noble gas, for instance xenon, at a level which is several times as high as the cesium vapor pressure, we may thereby substantially decrease the evaporation of the cathode without substantially increasing the electrical resistivity of the plasma in the gap between the hot cathode and the cold anode. The reason for this is that the cross section of xenon for the scattering of the atoms of the elements which compose the cathode and evaporate from it is about the same as the cross section of the cesium atoms and cesium ions for the atoms of these elements. In contrast to this, the cross section of xenon for the scattering of electrons which carry the current in the gap between the cathode and the anode is small compared to the Coulomb cross section of the cesium ions for these electrons. Therefore, the fractional ionization of the cesium vapor is substantial. The xenon pressure which considerably reduces the rate of evaporation of the cathode will not substantially increase the electrical resistivity of the plasma in the annular gap between the cathode and the anode. Concerning the effect on the rate of evaporation of the cathode, xenon is roughly equivalent to cesium because the atomic weights are about equal.

If we replace the heavy noble gas with a light noble gas, such as for instance helium, keeping the product of the density times cross section the same, then we increase the velocity of the hydro-dynamic flow in the annular gap between the cathode and the anode, which is directed from the center of the gap towards the cathode and towards the anode, and at the same time we decrease the gravity induced convection. From this point of view helium is preferable to xenon. Helium however, changes the characteristic of the generator unit for several reasons. The heat conductivity of helium is higher than that of xenon, and, therefore, helium lowers the temperature in the gap between the cathode and the anode. Further, the mass ration of electron to atom is larger in the case of helium than in the case of xenon. Optimal conditions might be obtained if a~~n~~ mixture of helium and xenon (or krypton) is used and if the ratio of a light noble gas and a heavy noble gas is chosen from~~t~~ the point of view of giving both the desired characteristc for the generator unit and~~a~~ sufficient reduction in the evaporation rate of the cathode. The optimal ratio~~n~~ depends on several factors, including the material of the cathode and the operating temperature of the cathode.

Role Gas. Atoms
Rate
~~Gas~~ Atoms

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In the following ~~there shall be~~ disclosed means to reduce the evaporation of the hot cathode in the operating region of the cathode, where the temperature is maximal. We shall assume for the purpose of the concreteness of our discussion here that the alkali metal is cesium. If a cesium vapor pressure is chosen which is substantially above 10 mm Hg, the rate of evaporation of the surface of the cathode at a fixed cathode temperature is appreciably reduced.

We shall assume now for the sake of the concreteness of our discussion that the surface of the cathode is tantalum. For a fixed cathode temperature the rate of evaporation of tantalum is lower when the cesium pressure is higher. For a fixed saturation current ~~of~~ from the cathode, the needed required ~~temperature of~~ the cathode temperature falls with increasing cesium pressure and thus ~~so that the rate of evaporation of the tantalum cathode goes down with increasing cesium pressure for two reasons, so that~~ for a fixed saturation emission of the tantalum cathode the rate of evaporation of ~~the cathode~~ the tantalum falls with increasing cesium vapor pressure for two reasons: First, because at a fixed cathode temperature the rate of evaporation of the tantalum ~~goes down with~~ falls with increasing cesium pressure, and second, because the cathode temperature falls with increasing cesium pressure.

We shall discuss here only the first of these two effects.

In the annular gap, between the anode and the cathode, the temperature of the gas will be higher in the center of the gap than ~~near the cathode~~ the temp. of the cathode (the temperature in the center will, of course, also be higher than the temperature ~~of~~ the anode). ~~As a result of this, there will be a hydro-dynamic flow in the vapor phase in the annular gap moving from the center of the gap towards the cathode on the one hand and towards the anode on the other hand. The molecules evaporating from the cathode must diffuse against this hydro-dynamic flow of gas. This effect slows the evaporation of the cathode.~~ The slowing effect increases if the velocity of the hydro-dynamic flow increases and the slowing effect increases

As a result of this, there will be a gravity induced convection in the annular gap in the vapor phase. If the cylindrical generator unit stands with its axis vertical, the gas will move upward in the center of the gap. If we move from the center of the gap towards the cathode ~~At~~ a certain distance from the cathode the velocity will be 0, ~~and from this~~ beyond this point on the gas will move downward. point Somewhere between this point and the cathode the downward velocity will be maximal, ~~and at~~ At the cathode surface the velocity will be again zero! ~~0~~. ~~The evaporation rate of the cathode depends on how fast atoms from the cathode will diffuse to a distance where the velocity of the downward motion is appreciable, and on the velocity of this downward motion. Increasing the cesium pressure will increase the gravity-induced convection but it will also decrease the diffusion of the atoms evaporating from the cathode.~~

Let us, for the sake of argument, start out with very low cesium pressure and ask ourselves what happens when the cesium pressure is increased. We may say the following: at very low cesium pressure ~~there will be~~ at a fixed cathode temperature the cathode will evaporate at a certain rate and all the atoms ~~moving~~ leaving the cathode will condense on the anode.

At a higher cesium pressure the rate of evaporation of the cathode is reduced. A certain fraction of the atoms evaporating from the cathode will be carried away by the convection current in the gas phase, and the ~~reamining~~ remaining fraction will be deposited on the anode. As long as the fraction which deposits on the anode is a substantial fraction of the atoms evaporating from the cathode, the rate of the evaporation of the cathode can be substantially reduced by increasing the cesium pressure. Beyond this point, however, raising the cesium pressure will not appreciably reduce the rate of evaporation of the cathode, because raising the cesium pressure will not only slow the diffusion of the atoms evaporating from the cathode into the gas layer moving along the gap, but it also will increase the velocity of the convection, and the two effects tend fully to counter-act each other when the fraction of atoms which is deposited on the anode is very small compared to the fraction of the atoms which are carried away by the convection.

The rate of the evaporation of the cathode may be slowed by maintaining in the operating generator unit in addition to ~~a certain pressure of an alkali metal vapor also a certain~~ cesium vapor a considerably larger pressure of an inert gas, preferable a noble gas. The noble gas may be a light noble gas, such as helium or neon, a heavy noble gas, such as xenon, or a medium heavy noble gas, such as argon or krypton.

We shall discuss first the light noble gases.

Assuming that the partial pressure of the noble gas is high compared to the partial pressure of the ~~alkali vapor, which might again be cesium~~ cesium vapor, it may be seen that if we use helium at a pressure where the fraction of the atoms which evaporate from the cathode and which deposit on the anode is small compared to the fraction of atoms which are carried away by the convection current, the rate of evaporation of the cathode will be about 3 times less than if cesium vapor at the same pressure were substituted for helium.

If in place of helium we use xenon, which has about the same atomic weight as cesium, then no such advantage results.

Nevertheless, it is ov advantage to use a low pressure of cesium and a high pressure of xenon rather than to replace the xenon with cesium vapor of equal pressure. The reason for this is as follows: the electrical resistivity of the plasma is independent of the cesium vapor density at low cesium pressures.

Nevertheless, maintaining a mixture of xenon and cesium, where the xenon pressure is large compared to the cesium pressure, has an advantage over~~n~~ maintaining cesium vapor alone in the generator unit. The reason is as follows: if we were to raise the cesium pressure to the point where no substantial further advantage could beobtained with respect to~~t~~ the evaporation rate of the cathode, by raising the cesium pressure even further, we may, depending on the circumstances under which the generator unit operates, unduly increase the electrical resistivity of the plasma. The cross section of the neutral cesium atoms for the electrons which carry the current in the plasma is of the order of 3×10^{-14}, whereas the Coulomb cross section of the cesium ions is about 3×10^{-11}. When the fractional ionization falls below 3%, the neutral cesium atoms make an appreciable contribution (of more than 10% of the resistivity). Further, the fractional ionization of the cesium vapor goes inwardly with the square root of the cesium vapor pressure. This sets a limit to the cesium vapor pressure which it is desirable to maintain. The cross section of the light noble gases ~~is~~ for the electrons which carry the current in the plasma may be 20 to 100 times less than the cross section of the neutral cesium atoms.