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ELECTRON BEAM PREIONIZATION IN AN MHD GENERATOR

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Introduction

In order to operate a closed loop MHD generator with high power density at temperatures compatible with near-future nuclear reactors, the electrical conductivity of the plasma must be greatly increased within the generator while maintaining a gas temperature $\sim 1500^{\circ}K$. Such a condition can be achieved if a non-equilibrium state of the electrons can be created within the generator; (a non-equilibrium state is defined as that plasma state where the electron density is greater than that predicted by the Saha equation based upon the neutral particle temperature).

Various methods for achieving non-equilibrium ionization are currently under investigation. In addition to employing the self-induced electric field[1,2,3,4] various pre-ionization techniques may be used.[5,6] Although pre-ionization techniques require that some of the electrical energy must be reprocessed, proper pre-ionization will provide an independent control over the generator performance and may consume a very small fraction of the power generated. With proper design, pre-ionization can be used to increase the generator power density while maintaining reasonably modest magnetic field strengths.

Among the possible pre-ionization techniques are the use of photoionization, R-F beams, injection of electron-ion pairs, radioactivity, glow discharges, electron beams, etc.

The possibility of using an electron beam for pre-ionization in an MHD generator was first suggested by Karlovitz several years ago.[5] At that time a number of interesting experiments were attempted. These did not yield significant results since the MHD generator working fluid chosen was a polyatomic gas created by flame combustion.

Experimental results reported herein were obtained with argon seeded with cesium (monatomic working fluids). The purpose of this investigation was to experimentally demonstrate the feasibility of using an electron beam for preionization in an MHD generator operating above atmospheric pressure and at gas temperatures near $1500^{\circ}K$. The efficient operation of such a beam has been demonstrated.

Overall MHD Facility

An artists conception of the test facility is shown in Figure 1. Argon is brought to a preheater from a storage supply of sufficient capacity to allow one hour tests. The gas is heated in this preheater to $850^{\circ}K$, and then in a molybdenum mesh core heater to $1500^{\circ}K$ at a mass flow of ~90 grams/sec. After the heater, cesium is injected into the gas stream via a motor driven syringe. Approximately 25 cm downstream of the cesium injection the electron beam enters the channel. The pre-ionized plasma then proceeds toward the MHD generator channel, passing the first microwave horn at 19 cm, and entering the channel at 77 cm. A second microwave horn is located downstream of the channel at 157 cm. Finally, the cesium seeded argon is scrubbed to remove the cesium and cool the argon, and the latter is exhausted through the laboratory roof to the atmosphere.

Since non-equilibrium ionization depends to a large extent on the almost complete lack of polyatomic species, considerable care was taken to insure the purity of the gas used. As supplied by the vendor the argon had no more than 11 p.p.m. of O_2, N_2, CO_2, etc. The oxygen content of the flowing argon at the exit of our system was monitored by means of a Beckman Oxygen analyzer. The oxygen content of the cold gas always remained between 0.6 and 2.0 p.p.m. Typically, as the system begins to heat up the O_2 content rises to ~4000 p.p.m. but rapidly falls back to ~1 p.p.m. for the remainder of the run. In large measure, the purity which has been possible has been due to our use of a metal resistance heater for bringing the argon up to the desired high temperature.

Molybdenum Mesh Core Heater

The high temperature heater used in the present experiments has an electrical resistance element which is a molybdenum mesh core through which the argon is forced to flow. A 6 inch by 300 inch roll of molybdenum screen (20 mesh with 7 mil wire) was used to construct a laminated mat 50 inches long and 6 inches wide (see Figure 2); this mat was then rolled tightly along the 6 inch length to form the heater core. Each end of the core was inserted between pre-cut sections of molybdenum bar which were then welded together in an inert atmosphere. The mesh core, next to each molybdenum wire. The mesh core was then pulled through a dense alumina tube with an I.D. of 1-1/2 inches. This assembly was in turn placed within a nickel tube which was lined with a porous alumina tube. The electrical leads consist of molybdenum rods which extend through typical pressure fittings and fit into holes (drilled and tapped) within the molybdenum bars. The external end of each molybdenum rod is cooled by means of a water-cooled copper plate. The power input to the mesh heater is controlled by means of a saturable core reactor and a step-down transformer. In this heater the area available for heat transfer, A, is about 250 square feet per cubic foot of heater volume; this value is comparable to that given for "compact" exchangers. The turbulence created by the mesh core also increases the heat transfer coefficient, h, by at least a factor of 3. Values of hA in this heater were increased by around a factor of 24 as compared to the same size hollow tube heated externally. Calculations of the heat conduction losses from a hollow cylinder show this mechanism to be the main source of energy loss; although the heater element is operated at temperatures well in excess of 1000°K, radiation losses in a mesh core heater are negligible. To date, this heater has been operated during 30 experiments, each lasting around an hour. Typical exit argon temperature time curves are shown in Figure 3.

Electron Beam

The major problem in adapting an electron beam to an MHD generator is in the fact that even "high pressure" electron guns operate at pressures less than 10^{-1} mm of mercury; pressures much too low to be useful in the MHD generator. This required four-order-of-magnitude pressure differential must be maintained either by the use of a differential pumping system, or by the use of a thin foil "window." This differential pumping system has the disadvantage of being quite expensive and requiring additional power; (diffusion pumping speeds ~ 500 CFM would be needed even if choked flow orifices ~.05 cm in diameter were used). The problem associated with the window technique results from the energy loss of the electron beam as it passes through the window. (At electron beam energies less than 100 Kev, the electron collision cross-section is large enough to excessively heat even a reasonably thin foil.) The major mechanism of energy loss is due to inelastic collisions with the atomic electrons of the metal.[7]

Despite this (by the use of special cooling techniques) passage of a 50 Kev -.1 m.a. beam through a 0.25 mil aluminum window has been possible and beam operation has been as designed.* The beam had to have the right amount of energy to first penetrate the foil, and then to take part in electron-ion pair production within the flowing gas; the beam incident to the gas had to have an average range of 2 cm for the experimental duct. The range-energy expression given by Katz and Penfold[8] was used to specify the necessary beam voltage.

In addition to specifying the beam voltage, the desired beam current had to be determined. This was accomplished by requiring the beam to create a specified electrical conductivity. The details of this procedure will be discussed later.

A water cooled Faraday cup was used to calibrate the electron beam. The cup chamber was pumped down below 0.1 microns to eliminate errors due to secondary electron formation. An ammeter, placed between the cup and ground, was used to measure the current. The average energy of the emergent beam was calculated from the rise in temperature of the cooling water, once the current was known. Values of the average energy of the emergent beam agreed within 5% with the value obtained from Figure 4 (calculated from the Katz-Penfold relation).

Adequate foil cooling was achieved by a combination of water cooling of the exit aperture slit, and cool argon buffering between the window and the gas flow. The amount of injection of cool argon amounted to less than 0.1% by weight of the total argon flow through the generator. Several runs have now been conducted during which the foil was adequately protected although the static pressure was ~1-1/2 atmospheres and the total gas temperature was ~ 1500°K.

The electron beam system attached prior to the generator duct is shown in Figure 5. Here the electron beam is created within a large Bell Jar and focused into a 3 cm. diameter beam at the aluminum window region. Part of the circular beam passed through a water-cooled aperture slit and then through the aluminum window which is held in place by a foil retainer. Holes have been drilled in the foil retainer to accept slotted tubes for argon cooling. The cover opening is much larger than the exit aperture so as not to intercept any of the electron beam which is scattered by the foil. The cathode chamber in actural operation is shown in Figure 6.

MHD Generator Channel

Early test sections fabricated from porous and from medium porous alumina, permitted electrical shorting between the electrodes, and were severely damaged from thermal shock and erosion.

Test sections fabricated from GE A976 dense aluminum oxide were found to withstand the test conditions extremely well. The test section (shown in Figure 7) has 8" sections of GE A976 channel joined together by means of an external 20 mil molybdenum sleeve. The channel is then potted with alumina cement (Resco AA22 Cement) in a 316 stainless steel case. The inside dimensions of the rectangular duct are 1 cm x 3 cm. Cracks which developed due to thermal gradients caused no problem since the cracks are backed up with a laminated cement layer. Also, the cesium and mercury vapors do not visibly attack the dense

*Our beam current, actually 50 m.a., is intercepted in a narrow slit. This is not an essential loss as a cathode with 0.1 m.a. output and a sheet focus could be built.

alumina at temperatures up to 1500°K. It should be noted that the silicon dioxide content of the GE A976 dense aluminum oxide is well below 0.1%.

Electrodes which are easily fabricated, and which stand up satisfactorily under full scale MGD experiments, have been made by press-fitting a 316 stainless steel rod into a 1/16" thick disc of thoriated tungsten and then spot welding the joint. The electrode discs are 1/2" in diameter.

Other electrodes (made by spot welding a 316 stainless steel rod to 10 mil molybdenum and tungsten sheets) were 1 cm x 3 cm in dimension. Thermocouples placed on the back side showed that these electrodes (heated directly from the hot gas) followed the main gas temperature within 20°K.

Experimental Results

Two experiments during which the electron beam was in operation were carried out under the following conditions.

Gas

$T = 1325 - 1505\ ^{o}K$
$p = 1.5$ atmos.
$\dot{m} = 68.1$ gm/sec
$u \cong 468$ m/sec
$M \cong 0.7$
$X_{c_s} = 2.9 \times 10^{-3}$ mole fraction

Beam

$V = 40,000$ volts
$I = 50$ m.a.
$V_f = 17,000$ volts
$I_f = 0.1$ m.a.

The electrical conductivity of the pre-ionized plasma was measured by means of a two-station 60 KMC microwave interferometer. For this device the cutoff electron density is $\sim 4.5 \times 10^{13}$ electrons/cm^3, well above the electron densities measured in the experiments to be reported.

Shown in Figure 8 are electron densities measured by the microwave station 19 cm downstream of electron beam injection. The calculated values of electron temperature which would correspond to these electron densities are also shown. During the second run data were recorded as the system heated up so that three points were obtained each at different gas temperatures. The point marked "equilibrium check" represents a microwave measurement of n_e with no electron beam in operation.

Shown in Figure 9 are electrical conductivities calculated from these results. Clearly, non-equilibrium electrical conductivities 10-20 times the equilibrium values were achieved.

Further measurements are in progress to record non-equilibrium conductivities at different axial locations and at different beam currents in order to permit a more detailed analysis of the recombination process.

Discussion of Results

In the present paper we have only discussed in detail the performance of the electron beam and its ability to create non-thermal ionization. No information on actual generator performance has been reported. Accordingly, this leaves open the question of whether or not the generator can be made to work in the non-equilibrium plasma available. Despite this it is appropriate to make some estimate of whether or not the beam power would represent too large a drain on the power generated. To make such an approximate estimate we first evaluate our beam performance against a very simple theoretical model. Satisfied that our experimental observations are essentially the same as those given by a simple calculation, we next compare the experimental beam power to what might in principle be generated.

First, it is assumed that the electron beam creates electron-ion pairs uniformly throughout the plasma, and that electrons entering the plasma from the window are mono-energetic. It is then assumed that, on average, V_o(ev) energy is needed to create an electron ion pair. Thus, each entering electron creates E/V_o electrons. Finally, it is assumed that the volume within which the beam exists in the plasma is swept out uA times per second. Then knowing the total current flow in the beam as it enters (I) and its initial energy (E) we can calculate the electron density created from

$$I = (V_o uA\, n_e/E) \times 1.6 \times 10^{-19} \text{ amps}$$

Having established n_e we then make the assumption that the electron-ion pairs created by the beam come into a Saha equilibrium at some $T_e > T_g$. Only then can we calculate a corresponding σ.

It is important to note that since a considerable degree of non-equilibrium is created one must know T_e in order to make a proper calculation of σ. In addition, recombination of the non-equilibrium created by the beam is an important part of our problem. For three body recombination where the third body is an electron we know the recombination rate coefficient is strongly dependent on T_e ($\alpha\, T_e^{-9/2}$), so that it again is essential to know the value of T_e.

In both experiments I, E, and u were measured and A is known. If we then assume that $V_o = 20$ ev, which should be a conservative value for the cesium seed, we are led to an electron density of $n_e = 3.7 \times 10^{12}$/cc. This electron density is consistent with an electron temperature, $T_e = 1750\,^oK$. For the gas conditions of the first test ($T_g = 1505^oK$) this leads to an electrical conductivity of σ = 6 mhos/meter. Since the measured conductivity for the 19 cm station in this test was ~ 5 mhos/m a remarkably slow recombination rate must be assumed. If our estimate of V_0 was too high then using a lower value in our calculation would raise σ calculated somewhat, but a slow recombination is still predicted. Finally, it is possible that our approximate beam analysis is too inaccurate, and σ at the beam is really much higher than we calculate. In this case the recombination may be as rapid as would be predicted by simple arguments.

At the present time, additional measurements are underway to determine if recombination really does proceed slowly, or if our beam is more effective than we anticipated it would be.

Next, an estimate of the power input to the beam can be made. As noted earlier, we use a 50 m.a. beam and for convenience only take 0.1 m.a. out of it. If we assume that a 0.1 m.a. cathode were available, and we used a sheet magnetic focus to pass it through the foil covered slit, then ideally all the power to the cathode enters the plasma (neglecting that lost in the foil). In practice this is not quite correct as is shown in Figure 10. An efficiency figure here of 70% should be valid, however. Since in our eventual application, which will be a space power plant, a vacuum is available, one can anticipate using a differential pumping arrangement. If we make this assumption the foil loss can be neglected. The beam power is then

$$P_b = EI = \frac{17000 \times 0.1 \times 10^{-3}}{0.7} = 2.4 \text{ watts}$$

Next, an attempt must be made to estimate the generator power. If we assume that the electron beam can be situated physically at the channel entrance and neglect recombination we have

$$P_g = - \sigma (K-1) K u^2 B^2 AL$$

where K is the generator coefficient and will be taken to be 0.8. Again, the above expression will be assumed valid over the entire generator length. Then for the conditions of our experiment, and an assumed 50,000 gauss we have

$$P_g = 6 \times 0.16 \times (470)^2 (5.0)^2 \times 3 \times 20 \times 10^{-6}$$
$$\cong 300 \text{ watts}$$

Accordingly, use of the electron beam to create the necessary conductivity may result in the loss of only a few percent in generator efficiency. It is important to remember, however, that the above is only a very approximate estimate of what may be possible. It is sufficiently promising so that we are encouraged to pursue the subject further.

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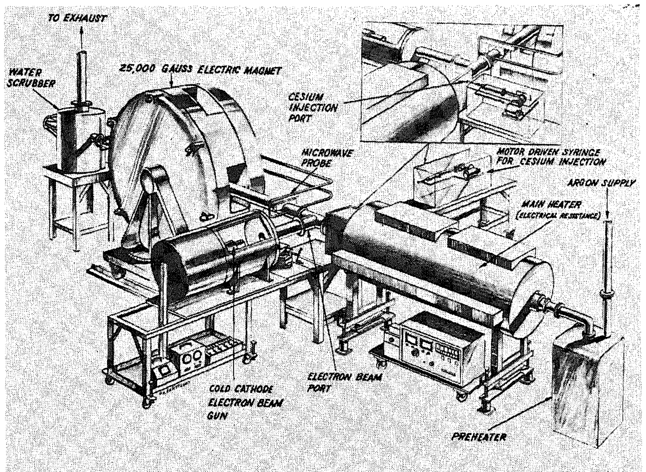

Figure 1. SEEDED GAS MHD FACILITY

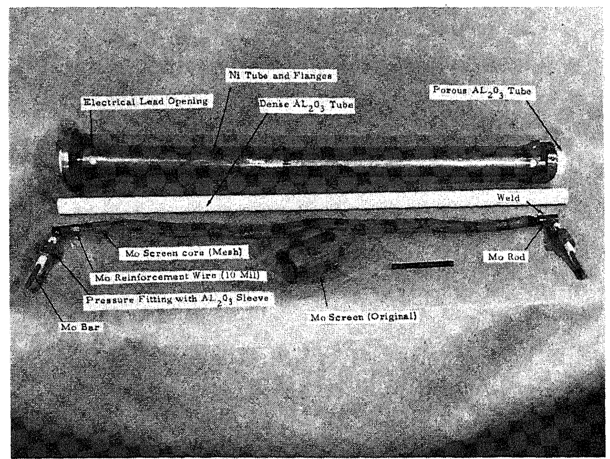

Figure 2. Heater Components

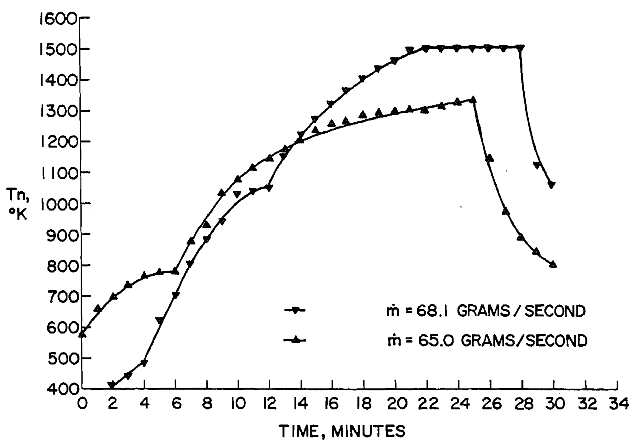

Figure 3. Temperature - Time Curves for Runs (Typical)

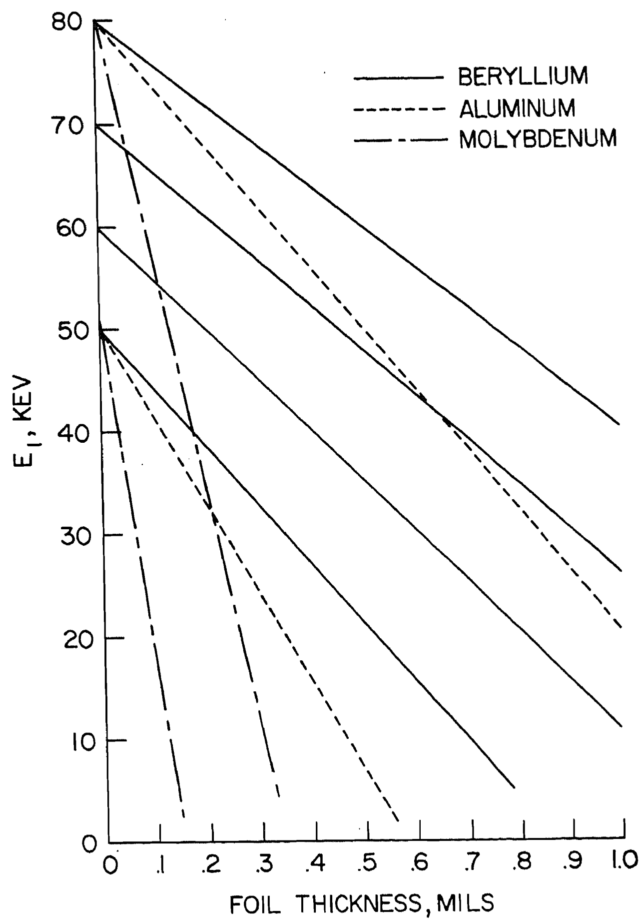

Figure 4. Most Probable Beam Energy Emerging from Foil vs. Foil Thickness (First Approximation)

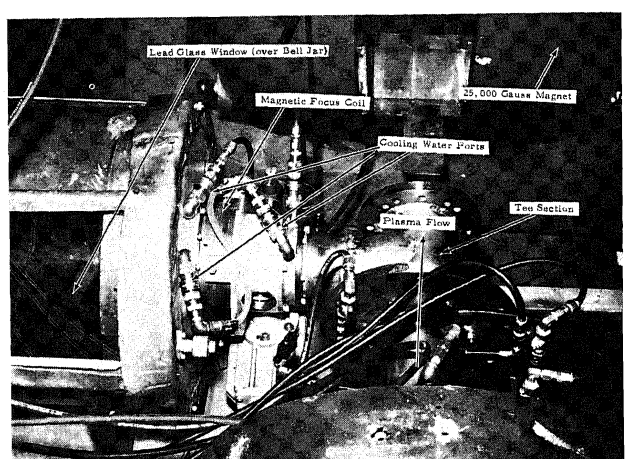

Figure 5. Electron Beam System Attached to MHD Facility

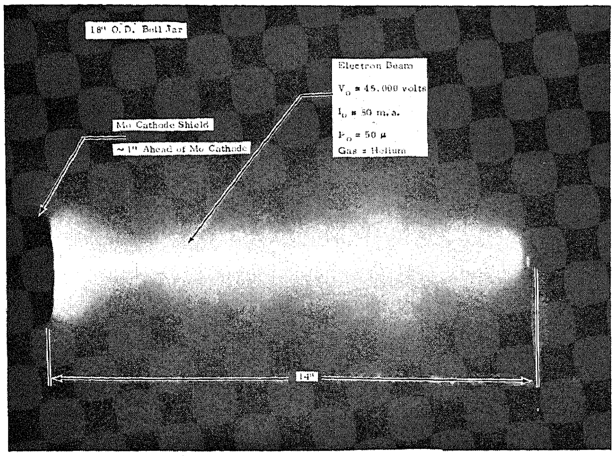

Figure 6. Electron Beam in Cathode Chamber

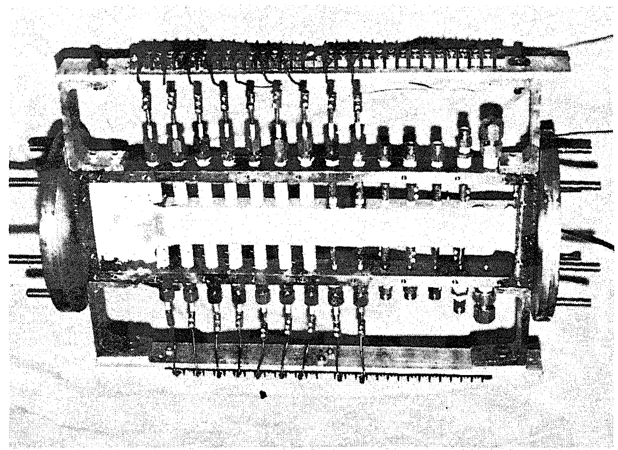

Figure 7. MHD Test Section

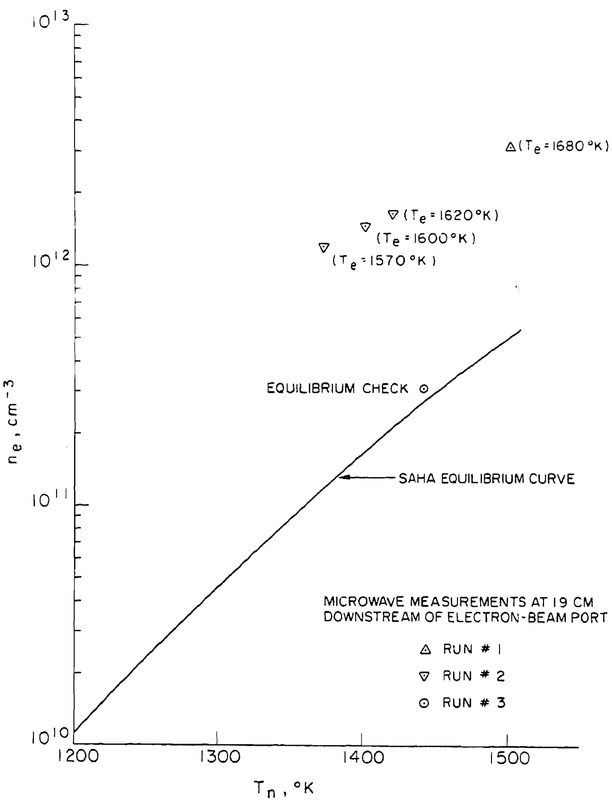

Figure 8. ELECTRON DENISTY VS. TEMPERATURE

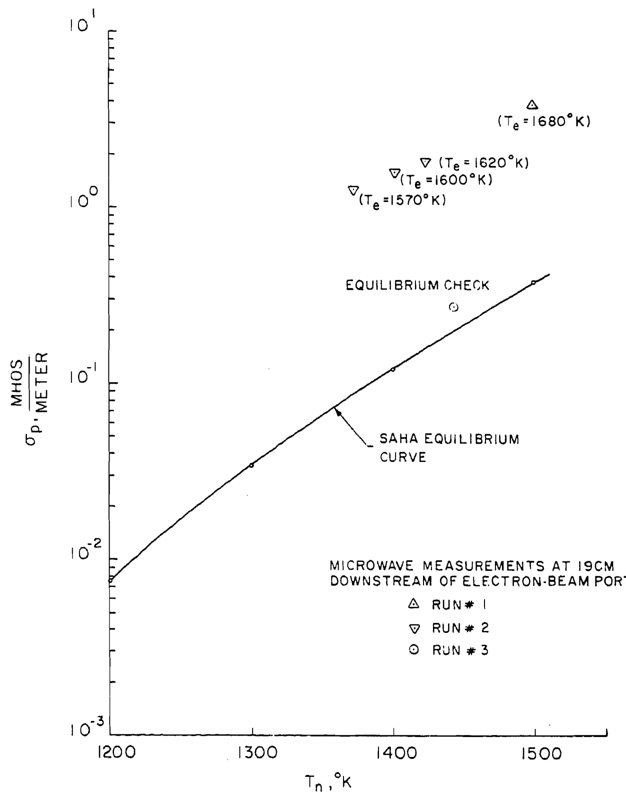

Figure 9. CONDUCTIVITY TEMPERATURE

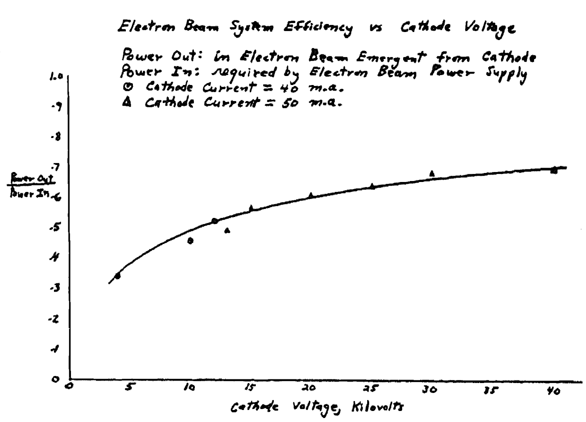

Figure 10