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THERMAL INVESTIGATION OF AN ELECTRICAL HIGH-CURRENT ARC
WITH POROUS, GAS-COOLED ANODE


Translation of "Thermische Untersuchung Eines Elektrischen Hochstromlichtbogens Mit Poroser, Gasgekühlter Anode;"

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546. DECEMBER, 1984
The following quantities have been measured on a high-intensity electric arc with tungsten cathode and transpiration cooled graphite, anode burning in argon: electric current and voltage, cooling-gas flow rate (argon), and surface temperature of the anode and of the anode holder and temperature profile in three cross-sections of the arc column. The last-mentioned values were obtained from spectroscopic photographs. From the measured quantities, the following values were calculated: the heat flux into the anode surface, the heat loss of the anode by radiation and conduction, and the heat which was regeneratively transported by the cooling gas back into the arc space. Heat balances for the anode were also obtained. The anode losses (which are approximately 80% of the total arc power for free burning arcs) were reduced by transpiration cooling to 20%. The physical processes of the energy transfer from the arc to the anode are discussed qualitatively.
Symbols

\( A_m^n \), Transition probability of the line;
\( E_m^k \), Excitation energy of the line;
\( F \), Anode surface;
\( F_h \), External surface of the anode holder;
\( g_m \), Statical weight of the excitation turn of the line;
\( h \), Planck's constant;
\( I \), Electrical current intensity;
\( I_L \), Intensity of a spectral line;
\( I_1 \), Enthalphy of the cooling gas at the cathode spot temperature \( T_1 \);
\( I_2 \), Enthalphy of the cooling gas at the entrance \( T_0 \);
\( k \), Boltzmann's constant;
\( L \), Layer thickness of the heater;
\( \dot{m} \), Mass flow of the cooling gas (argon);
\( n^- \), Particle density of the electrons;
\( n^+ \), Particle density of the ions;
\( n \), Particle density;
\( \dot{n}^- \), Particle flow of the electrons per unit of area;
\( \dot{n}^+ \), Particle density of the ions per unit of area;
\( \dot{n}_s^- \), Particle flow of the electrons formed by ionization per unit of area;
\( Q_a \), Heat flow from the arc to anode surface;
\( Q_g \), Perceptible heat of the arc plasma plus about 4% cathode losses;
\( Q_k \), Heat absorption of the cooling gas in the anode;
\( Q_i \), Heat loss through the anode holder;
\( Q_0 \), Electrical arc power;
\( Q_s \), Radiation losses of the anode;
\( r \), Radial distance from the arc axis;
\( R \), Arc radius;
\( s \), Thickness of the anode;
\( T \), Absolute temperature;
\( T_0 \), Temperature of inflow of cooling gas to the anode holder;
\( T_1 \), Surface temperature of the spot;
\( T_2 \), Average anode surface temperature outside of the focal spot;
\( U \), Electrical drop of voltage between the electrodes;
\( \nu \), Velocity of drift of the electrons;
\( \nu^+ \), Velocity of drift of the ions;
\( \bar{\nu} \), Average outlet velocity of the cooling gas from anode (referred to the anode surface);
\( x \), Ratio of the focal spot area to the anode area;
\( z_0^{(i)} \), Partial function of the excitation

**Greek symbols**

\( \epsilon \) Emissions capacity of the anode and the anode holder;
\( \eta \) Coordinate (See Fig 13);
\( \lambda \) Coefficient of thermal conductivity of the anode holders;
\( \nu \) Frequency of the line;
\( \sigma \) Stefan-Boltzmann constant
\( \xi \) Distance from the optical axis;
\( \zeta \) Loss coefficient of the anode.
THERMAL INVESTIGATION OF AN ELECTRICAL HIGH-CURRENT ARC WITH POROUS, GAS-COOLED ANODE

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Introduction

A new area of application has been found most recently for the electrical arc, inasmuch as it is used to heat gases to temperatures on the order of 10,000°C. At such high temperatures a part of the atoms are split into electrons and ions, and thus the gas becomes electrically conductive. These gases, called plasmas, are expanded in wind tunnels, in which an attempt is made to imitate the conditions which a spacecraft returning to the atmosphere or a missile will find. Moreover they are used for propulsion in rockets, or to produce electricity in generators without rotating parts. For these applications, we are interested in feeding the greatest possible fraction of the electrical energy converted in the arc to the heated gases. On the other hand in modern plants, which are mostly operated with water-cooled copper anodes, often more than half of the power supplied as heat is lost in the cooling water of the anode and the walls of the container in which the arc burns. The first loss can be reduced to a considerable extent by manufacturing the anode of a porous material and allowing a cooling gas to pass through the pores into the combustion chamber. This cooling process which has already

*Numbers in margins indicate pagination in foreign text.

The investigation was carried with financial support from the Aeronautical Research Laboratory at Wright Patterson Air Force Base, Ohio.
been used in technology for several years for other purposes and known as transfiguration cooling was to our knowledge applied for the first time for anode cooling by Sheer \cite{1}. The purpose of this investigation, on which a partial record is given in this article, is to determine the thermal conditions in a porous, gas-cooled anode and in the neighboring zone of the arc, to obtain the heat balance of the anode and to explain the mechanism of heat transfer on the anode. The investigation concerned primarily a high current arc burning in argon, so as not to allow the number of the parameters determining the process to become too large.

**Experimental Equipment and Measurement Program**

Figure 1 shows the experimental equipment in its main parts. The arc burns between the cathode (a), a bar of tungsten of 6 mm in diameter, ending at the top in a cone with 45° aperture angle and whose other end is inserted in a water-cooled copper holder (b), and anode which consists of porous graphite of the type NC 60 of National Carbon Company (Division of Union Carbide Corporation) USA. The anode (c) is in the shape of a disk, with a diameter of 12.5 mm and is 5 mm thick with a porosity of 50 percent and a pore diameter of about 30 microns. The disk is connected with a graphite holder (d) to the cooper anode head (e), which is used simultaneously to feed the cooling gas (argon) flow. The graphite holder is designed in such a way that heat losses by dissipation are kept as small as possible and can be measured with high precision. For this reason the aluminum disk (f) is also provided which keeps the arc radiation and convection flows away from the holder. A slow flow of argon is blown in through an annular area (g) surrounding the cathode holder. It was established with preliminary experiments that air is thus kept far from the arc. The spectrographic measurements to be discussed later were carried out with a similar experimental equipment, except that the anode disk was 12 mm thick, and the graphite holder was replaced by a water-cooled copper holder. The latter anode with its holder is shown in the upper portion of Fig 1. This holder is somewhat easier to operate than the one first discussed. A series resistance, which consisted of a water-cooled stainless steel tube of 1Ω total resistance was connected in the arc circuit to regulate the current. By means
of a sliding contact it was possible to regulate the effective resistance continuously on it. The source of voltage was a 34 kw dry rectifier. The arc was ignited each time with a high voltage impact. Figure 2 shows the arc in operation, ready for a spectrographic measurement. The natural radiation of the arc reaches the spectrograph slit through an iris diaphragm inserted in the window visible on the right hand side. On the left hand side of the arc a source of adjusting light may be seen.

Figure 1
Arc equipment
A. With graphite anode holder
B. With water-cooled anode holder
   a. tungsten cathode
   b. cathode holder
   c. anode
   d. anode holder
   e. anode head
   f. protective plate
   g. ring channel
   h,i. thermocouple elements
The Figures 3 to 5 show photographs of the arc for different cooling gas flows, electrode distances and current intensities. For comparison Figure 5 also shows an arc, which burns between a tungsten cathode and a water-cooled copper anode. The magnetic lines of force surrounding the arc and the electrical arc generate electromagnetic forces (Lorentz forces) which near the cathode because of the conical shape of the arc have components in the direction of the arc axis $\vec{z}$. Thus a gas flow is produced, which is to be directed on the anode at considerable velocity and which for its part affects to a considerable extent the shape of the arc. In Figures 3 to 5 this cathode beam meets the cooling gas flow emerging from the porous cathode. The flow conditions are shown once again schematically with a solid line on Fig 7. We will return later to its effect on the thermal conditions in the anode.

Calorimetric Measurements

The measurement program included the following quantities; surface temperature of the anode, amount of cooling gas, arc current and arc voltage and temperatures in the arc. The surface of the anode was measured with an optical pyrometer. It was found that the
Figure 3.  $S = 12.5\text{mm}, I = 100\text{A}, m/F = 0.9492\text{g/s cm}^2$

Figure 4.  $s = 3.75\text{mm}, I = 200\text{A}, m/F = 1.3560\text{g/s cm}^2$
Figure 5. $s = 15\text{mm, } I = 200\text{A, } m/F = 1.2363 \text{ g/s cm}^2$

Figure 6. $s = 6\text{mm, } I = 100\text{A, } \text{water-cooled anode}$
portion of the anode, through which the electrons enter (anode spot) has a practically constant local temperature. This anode spot generally does not cover the total anode surface. Outside the spot, the temperature decreases in the radial direction. Table 1 contains the measurement results for the different series of experiments. The results of several experimental series were given in reference [1]. \( T_1 \) is the temperature of the anode spot, \( T_2 \) is the average temperature of the anode surface outside the spot. The size of the anode spot was determined visually. The ratio of the spot area to the total anode area is designated by \( X \) in Table 1. The temperature of the external surface of the anode holder was measured in several points (See Fig 8), also with the pyrometer. The results of the measurements are given in Fig 8. The mass flow \( \dot{m} \) of the cooling gas was determined with a flow gauge. It is given in the first column of Table 1. The second column gives the mass flow per unit of area \( \dot{m}/F \) of the anode surface. The temperature of inflow of the cooling gas to the anode was measured with a thermocouple (h) (Fig 1). The temperature \( T_0 \) fluctuated for the experiments by about 1 degree around the value 38°C. The electrical current \( I \) was measured with an amperometer through a secondary connection. It was kept constant for one series of experi-
ments. The electrode voltage was measured with a tube voltmeter (Table 1). A certain irregularity is found in the variation of the voltage values. These were caused by spontaneous melting or evaporation of electrode material. Generally measurement series which were extended over a very large area of the cooling gas flow, showed a slight increase of the voltage $U$ with increasing amount of cooling gas.

**TABLE I**

Carbon-Anode Holder ($l = 5\text{mm}, s = 12.5\text{mm}, I = 100\text{A}$)

<table>
<thead>
<tr>
<th>$\dot{m}$ ($\text{g/s}$)</th>
<th>$\dot{m}_F$ ($\text{g/s cm}^2$)</th>
<th>$U$ (V)</th>
<th>$Q_a$ (kW)</th>
<th>$T_a$ ($^\circ\text{K}$)</th>
<th>$T_e$ ($^\circ\text{K}$)</th>
<th>$x$</th>
<th>$Q_v$ (kW)</th>
<th>$Q_i$ (kW)</th>
<th>$U$ (V)</th>
<th>$P$ (kW/cm$^2$)</th>
<th>$I/x_F$ ($\text{A/cm}^2$)</th>
<th>$\dot{m}_x$ (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4347</td>
<td>0.3444</td>
<td>23.5</td>
<td>2.35</td>
<td>2811</td>
<td>2200</td>
<td>0.0</td>
<td>0.55</td>
<td>0.33</td>
<td>0.250</td>
<td>17.7</td>
<td>0.25</td>
<td>1.10</td>
</tr>
<tr>
<td>0.5796</td>
<td>0.4584</td>
<td>26.5</td>
<td>2.65</td>
<td>2811</td>
<td>2200</td>
<td>0.8</td>
<td>0.71</td>
<td>0.31</td>
<td>0.250</td>
<td>21.3</td>
<td>0.21</td>
<td>1.30</td>
</tr>
<tr>
<td>0.7244</td>
<td>0.5737</td>
<td>25.0</td>
<td>2.50</td>
<td>2756</td>
<td>2200</td>
<td>0.7</td>
<td>0.85</td>
<td>0.27</td>
<td>0.250</td>
<td>27.4</td>
<td>0.21</td>
<td>1.60</td>
</tr>
<tr>
<td>0.8004</td>
<td>0.6802</td>
<td>31.0</td>
<td>3.10</td>
<td>2589</td>
<td>2089</td>
<td>0.7</td>
<td>0.98</td>
<td>0.21</td>
<td>0.250</td>
<td>31.1</td>
<td>0.15</td>
<td>1.68</td>
</tr>
<tr>
<td>1.0143</td>
<td>0.8015</td>
<td>22.5</td>
<td>2.25</td>
<td>2700</td>
<td>2164</td>
<td>0.5</td>
<td>1.10</td>
<td>0.31</td>
<td>0.250</td>
<td>45.6</td>
<td>0.20</td>
<td>2.56</td>
</tr>
<tr>
<td>1.1592</td>
<td>0.9168</td>
<td>22.0</td>
<td>2.20</td>
<td>2756</td>
<td>2256</td>
<td>0.5</td>
<td>1.31</td>
<td>0.33</td>
<td>0.250</td>
<td>45.6</td>
<td>0.22</td>
<td>2.92</td>
</tr>
<tr>
<td>1.2978</td>
<td>1.0280</td>
<td>22.5</td>
<td>2.25</td>
<td>2756</td>
<td>2256</td>
<td>0.5</td>
<td>1.38</td>
<td>0.19</td>
<td>0.250</td>
<td>44.8</td>
<td>0.20</td>
<td>4.95</td>
</tr>
</tbody>
</table>

Spectrographic Measurement of Temperature

To obtain the temperatures in the arc gas, the arrangement shown above in Fig. 1 with water-cooled anode holder was used. The evaluation of the spectrographic photographs assumes rotational symmetry. Of several photographs those were selected in which this condition was best satisfied. The temperatures in the arc given below were measured for a current intensity of 200A, an electrode distance of 15 mm and a cooling gas flow of $\dot{m}/F = 1 \text{g/s cm}^2$.

The spectrographic investigations were carried out with a two-meter two-grid spectrograph of the Bausch and Lomb Company. For reasons of image representation techniques it was necessary to dismantle one of the two grids and to mount the remingning one in the optical axis. The image of the vertically burning arc was formed by an achromatic system ($f:400\text{mm}$) on the spectrograph slit and a proportion 1:1:1. A reversing mirror connected in-between turned the image by $90^\circ$, so that it came to lie horizontally on the slit. Figure 9 shows the optical experimental equipment in a schematic manner.
The arc equipment was mounted on the bed of a heavy grinding machine (Fig 2), so that the arc could be adjusted in three dimensions with regard to the optical axis of the spectrograph. By vertical adjustment of the equipment, the image of the arc was shifted sideways in front of the spectrograph slit, and the arc cross-section to be studied was adjusted. We give below the results of evaluation for two cross-sections, shown in Fig 7. The first cross-section (I) is 2.5mm under the anode surface, the second (II) in the center between anodes and cathodes.

Kodak 1 N spectrographic plates were used for the photographs. The spectral sensitivity of the plates used was determined by means of the carbon arc standard described by Euler, whose spectrum was
Figure 9. Schematic representation of the Bausch and Lomb two-grid spectrograph with arc equipment

Key: 1) spherical mirror  5) slit
2) deflecting mirror  6) condenser
3) grid  7) arc level
4) camera  8) adjusting table

graduated with a 7-stage filter of the Jarrel-Ash Company. Figure 10 shows in the lower portion of the spectrum of the carbon arc standard. The measured relative intensities of the wave length region from 7400Å to 8200Å overlapped with the actual relative radiation intensities of the Euler arcs, so that a correction of the line intensities obtained from the blackenings of the plate was superfluous. The most favorable lighting times were obtained by lighting tests of 1/30 to 1/40 s. The light plates were developed for two minutes with Kodak D-19 developer at 20°C temperature and then further processed normally.

In addition to the carbon arc standard, figure 10 shows three superimposed argon spectra, which correspond to the three arc-cross-sections studied. The lines used for the evaluation are characterized by arrows. Figure 11 is a spectrographic photo in the direction longitudinally to the arc axis with wide slit. Blackening and width of the atomic and ionic lines
indicate temperature distribution along the arc axis. The appearance of ion lines shows high temperatures in the vicinity of the cathode. The characteristic lines are identified in the longitudinal spectrum in Fig 11. The Fe-arc spectrum is used only to identify the unknown lines in the gas-cooled light spectrum.

Figure 10. Transversal spectra in the arc cross-sections I,II,III and carbon arc standard
Key: 1) carbon arc standard

Figure 11. Longitudinal spectrum taken with 50μ slit width and iron arc reference spectrum
Key: 1) iron arc reference spectrum
Evaluation of Experiments

Evaluations of the Calorimetric Experiments

From the above-described measurements thermal balances may be established for the arc and for the anode. The electrical power converted per unit of time is:

$$Q_e = UI.$$  \hspace{1cm} (1)

The amount of heat $Q_k$, which is absorbed by the cooling gas in the passage through anode and carried back to the combustion area was determined from the measured anode surface temperatures and the corresponding amounts of gas flowing through. It was assumed that on the anode surface, the gas temperature is equal to the anode temperature, which is justified because of the small pore diameter. It was moreover assumed, that the specific mass flow $\dot{m}/S$ is constant over the entire anode surface. In reality in the focal spot, because of the higher temperature prevailing there (higher viscosity of the gas) it is somewhat smaller than in the cooler area not affected by the arc current. According to approximate calculations, the last effect causes only a negligible error of a few percent in the calculated amount of heat $Q_k$. The latter was obtained with the following equation:

$$Q_k = \dot{m} [c_i \cdot (v_i - i_0) + \rho_i (v_i - v_h)].$$  \hspace{1cm} (2)

The indices of the gas enthalpies $I$ indicate the corresponding gas temperatures of the focal spot, in the external zone of the anode and before the entrance of the gas into the anode.

The heat radiation of the porous anode surface:

$$\dot{Q}_e = \varepsilon \cdot \sigma \cdot F [\chi T_1^4 + (1 - \chi) T_2^4]$$ \hspace{1cm} (3)

where $\varepsilon$ indicated the emission ratio of the anode surface, with $\sigma$ as the Stephan-Boltzmann constant, and $F$ designating the anode surface. The emission ratio of graphite was determined by Sieber [6] and $\varepsilon$ equals 0.78. Euler [5] found similar values. The heat flow $Q_1$ transferred from the anode disk to the anode holder is emitted partly from the external surface $F_h$ of the anode, partly dissipated through annular cross-section of the anode holder in the actual direction (Fig 8) and transferred to the anode heads. A third component, which
is carried away to the cooling gas by the internal wall of the anode holder, is carried with the cooling gas into the combustion area and should be not included with $Q_1$. The heat flow $Q_1$ is thus

$$ Q_1 = \tau \int T \, dF_a + \lambda (dT/dx) F_a $$

(4)

$T$ indicates the surface temperature of the anode holder, $F_a$ is cross-section area and $\lambda$ the thermal conductivity of graphite. The second term in equation (4) is small in the present experiment as compared with the first term, therefore an approximate determination of the temperature gradient $dT/dx$ from Fig 8 is sufficient. From the temperature of the aluminum disk ($f$) measured with the thermocouple element ($i$) it is found, that reflection in the anode holder was negligibly small. It is possible to calculate with the heat balance

$$ Q_0 = Q - Q_1 - Q_2 $$

(5)

$Q_0$ is a quantity which represents the energy remaining after subtracting the anode losses. These include among other things the cathode losses which according to earlier experiments came to less than four percent.

With the above thermal flows it is possible to establish a loss coefficient of the anode.

$$ \eta = \frac{Q_a}{Q_0} \cdot \frac{Q_1}{Q_0} $$

(6)

The amount of energy $Q_a$ transferred from the arc to the anode consists of the amount of heat absorbed by the cooling gas in the anode and the anode losses according to the relationships

$$ Q_a = Q_h + Q_c + Q_t $$

(7)

The heat flows and the anode loss coefficients are given in Table I for different amounts of cooling gas.

The heat flows can be clearly followed in the picture of the heat flow in Fig 12. It may be seen how the greater portion of the heat given off from the arc to the anode is transferred by the cooling gas back to the combustion area. The heat loss of the gas-cooled anode is 20 percent of the arc power (Fig 12). On a free burning arc with water-cooled anode (Fig 6) according to other published measurements, for
otherwise similar operating conditions, nearly 80 percent of the electrical energy was given off to the cooling water of the anode.

In the previously described experiments the decrease of weight of the porous anode was less than 0.1 grams per hour.

Evaluation of the Spectrographic Photographs

To evaluate the spectrographic photos it is assumed that in the gas-cooled arc column, thermodynamic equilibrium prevails locally. In this case the reaction equilibria between atoms, ions and electrons, as well as thermodynamic material values (viscosity, thermal conductivity diffusion coefficient) are clear functions of pressure and temperature. The assumption of local thermodynamic equilibrium applies in the arc column of arcs burning under atmospheric pressure with approximation as is shown by many investigations carried on such arcs [7]. The intensity

![Figure 12. Picture of the heat flow of the anode.](image)

\( Q_g \) is the perceptible heat in the arc plasma plus about 4\% cathode losses \( Q_r \) residual heat. \( Q_v = Q_s + Q_I \) anode loss.
of a spectral line of the light emission from the optically thin layer of the arc is then related with the temperature \( T \) as follows:

\[
I_L = \frac{1}{4\pi} A^*_\alpha n^*_\alpha \frac{g\hbar}{m_e} \exp\left( \frac{E_\alpha - kT}{h \cdot r} \right).
\]

(8)

The symbols used are clarified in the list of symbols. This equation was applied for two spectral lines of the same particle. If the factor common for two lines is designated

\[
k = \frac{n^*_\alpha n^*_\beta}{4\pi \frac{g\hbar}{m_e}}
\]

(9)

we obtain by establishing the logarithm and conversion

\[
\log \frac{I_{L\alpha}}{I_{L\beta}} = \frac{1}{T} \log k.
\]

(10)

Using equation (8) to obtain the local temperature in the arc, care must be taken that in this case the radiation of the individual lines comes from an inhomogeneous temperature field. Each beam which passes through the spectrograph, consists of radiation from different areas of the arc. This may be discussed on the basis of Figure 13, in which the circle represents a cross-section through the arc. A light beam which passes through the arc at the distance \( \xi \) from the arc axis, carries all the radiation which is emitted along this section, to the spectrograph. If the intensity of the line which is emitted at the distance \( r \) from the arc axis is designated by \( I_L(r) \), the line intensity, which is observed from the spectrograph by means of the photographic plate becomes

\[
I_L(\xi) = \int I_L(r) \, d\eta
\]

with

\[
d\eta = \frac{r}{\sqrt{r^2 - \xi^2}} \, dr
\]

we obtain

\[
I_L(\xi) = 2 \int_0^r \frac{r_I L(r) \cdot r \, dr}{\sqrt{r^2 - \xi^2}}.
\]

(11)
The intensity of $I_L(\xi)$ can be determined from the spectrographic photograph of a line. Such a line is shown schematically on the left in Fig 13. The blackening of the line at the distance $\xi$ was measured with a densitometer. The individual blackening values were then converted into intensity ratios by means of the blackening curve obtained from the carbon arc standard, and they were finally plotted over the line width. The last stage is indicated schematically in the upper portion of Fig 13. The area under the curve is proportional to the quantity $I_L(\xi)$. By means of the Abel integral transformation (11) now $I_L(r)$ can be calculated. The calculation was carried out on an electronic computer (Univac Model 1103) in such a way that the integral of the equation (11) was converted into a summation with 24 finite steps.

The evaluation was carried out for the two neutral argon lines with wave length 8115.311 Å and 7503.867 Å. By forming the difference of equation (10) for the two lines it is possible to eliminate the constant $K$ and thus calculate the temperature $T(r)$ assuming that the other values occurring in the equation are known. The absolute
transition probability $A_n^m$ has, according to information provided kindly by private communication from Dr. H. Olsen of the Linde Company, Indianapolis/Ind. the values:

$$A_n^8115.311 = 1.5 \times 10^7 \text{s}^{-1}$$
$$A_n^87503.867 = 4.2 \times 10^7 \text{s}^{-1}$$

All other values were taken from the tables published by Moore. The temperature for profiles obtained in this way are shown in Fig 14 for the arc cross-sections I and II.

![Figure 14. Temperature profiles in the arc cross-sections I and II.](image)

**Key:**
1) Temperature
2) Cross-section
3) Arc radius

Discussion of the Experimental Results

The determination of the heat flow $Q_a$ from the arc to the unknown allows the calculation of a specific heat flow $Q_a/xF$ per unit of area of the anode focal spot. For conditions in Table I the heat flow load of the unknown fluctuates between 1.10 and 4.95 kW/cm², therefore reaches values which occur only in rare cases in technology. On water-cooled anodes, heat loads of the same order of magnitude were measured [9,107]. This makes it understandable, that a permanent operation of plasma generators with electrical arc raises difficulties with regard to the burning off of the water-cooled anodes, and the heat losses are extraordinarily high on the anodes. The gas cooling of the anode does not reduce indeed the heat load under all circumstances, as may be seen in comparing the values given in references [9,107].
and \( Z_1 \), but most of the energy transferred in the anode is carried back to the combustion chamber by the cooling gas. Through regenerative process the anode losses may be reduced to about 20 percent of the electrical arc power.

It is also interesting that the amount of cooling gas \( \dot{m}_x \), which flows through the spot of the anode, remains approximately constant independently of the cooling gas flow \( \dot{m} \). The arc seems therefore to create itself the most favorable temperature of the spots by regulating the size of the spot. This temperature is so high, that porous metal anodes are destroyed by melting on the spot.

A quantitative study of the physical processes which caused the heat flow on the anode must be postponed until other more detailed measurements are available (electrical field intensity, size of the anode drop). A quantitative consideration can however be carried out on the basis of the existing results and a thorough investigation of the arc with water-cooled copper anode \( Z_9,10 \) to this end let us first consider the conditions in the arc with water-cooled anode.

The electrical current is carried in the arc by the electrons emerging from the cathode and entering the anode. As a result of the presence of the electrical field with regard to the gas filling the space between the electrodes, we have an average velocity \( v^- \), the so-called drift velocity. This process may be compared with a diffusion process. The drift velocity has according to gas kinetic calculations \( Z_9 \) in an argon arc, an order of magnitude of 300 to 1000 m/s. As a result of the space charge connected with it, the electrons would require an enormously large drop of voltage between the electrodes, if the space charge was not compensated by positively charged ions. The ions are produced by thermal ionization of the gas as a result of the high temperature. The field intensities measured in the arc column are such that the gas must be practically neutral, that means that the number of electrons \( n^- \) per unit of space must be equal to the number of the ions \( n^+ \) per unit of space. The ions have because of the electric field also a drift velocity of \( v^+ \) with regard to the gas, which is directed towards the cathode. This velocity is however much smaller because of the low velocity of the ions as compared with the electron mobility. According to gas kinetic calculations \( Z_9 \) \( v^+ \) is of the order of magnitude 1 m/s.
It was already mentioned earlier that in the gas filling the arc area, a mass flow also exists as a result of the Lorentz forces. The corresponding mass velocity $v$ is directed mainly in the arc column from the cathode to the anode. This velocity $v$ is according to reference 37 and 97 of the order of magnitude 100 m/s. Thus we obtain for the velocities of the electrons and ions the following conditions with regard to the electrodes. The electrons move with a velocity of the order of magnitude $v_e^{-} + v$ to the anode. The drift velocity $v_e^{-}$ is large as compared with the mass velocity $v$. The average trajectory lines of the electrons are therefore only influenced little by the mass flow. Figure 7 shows these trajectories plotted in dash-lines. The velocity of the ions with regard to the electrodes is of the order of magnitude $v - v_i^+$. The drift velocity $v_i^+$ of the ions is very low as compared with the mass velocity $v$. The ions are therefore mainly carried with the mass flow from the cathode region towards the anode. Therefore in rough outlines the conditions may be illustrated by the superimposition of two flows: the mass flow of an ionized gas with a current line field, as shown in Fig 7 in solid lines, and the flow of an electron gas with a source in the cathode surface and a depression in the anode surface. The similarity with a diffusion process is further emphasized.

The conditions may be rendered somewhat clearer by a quantitative consideration. Here we will limit ourselves to the average conditions in the arc column, therefore be satisfied with a unidimensional study. The particle density $n_e^{-}$ of the electrons is according to what was stated above practically equal to the arc column to the particle density $n_i^+$ of the ions.

$$n_e^{-} = n_i^+$$

Let $n_e^{-}$ be the particle flow of electrons per unit of area and time. This flow contains not only the electrons emerging from the cathode, but also those formed by ionization in the vicinity of the cathode. Let the latter be called "secondary" electrons, and let their particle current density be $n_s^-$. Since the latter are formed from neutral atoms, we have

$$n_s^- = n_i^+$$

(13)
if \( n^+ \) in the case the particle current of the ions per unit of area. Moreover we have

\[
\begin{align*}
    \eta^- &= n^- (v^- + v) \\
    \eta^+ &= n^+ (v^- - v^-)
\end{align*}
\]

(14)

(15)

From the four above equations it follows that

\[
\frac{n^-}{n^+} = \frac{v^- + v}{v^- - v^-}
\]

(16)

or approximately

\[
\frac{n^-}{n^+} = \frac{v^-}{v^-} + 1
\]

(17)

since \( v^+ / v \) is small as compared with 1. From the earlier given data on the values of the individual velocities it follows, that the total electron current is about 4 to 11 times as large as the current of the "secondary" electrons.

In the vicinity of the cathode, conditions prevail which we can now explain in a simplified manner by the superimposition of two flow processes, a mass flow of an ionized gas with a nature of stagnation point flow (Fig 7) and the falling flow of an electron gas, which contains the electrons closing the circuit. The heat transfer to the mass flow may be calculated with good approximation, since the gas is only slightly ionized and consequently the lowest number does not deviate too much from the value 1 \( Z_1 \). The calculation shows that about 15 to 25 percent of the total heat flow \( Q_a \) is carried to the anode by convection through the mass flow to the water-cooled copper anode. The electron gas carries its total enthalpy (consisting of internal energy and kinetic energy) to the anode and gives off moreover an amount of energy to the anode, which is released in the entrance into a solid body, the electron entrance work (similar to the condensation energy). If the enthalpies are calculated from the temperature of the arc column in the vicinity of the anode and from velocity \( v^- + v \), we obtain for the heat flow given off by the electron gas to the anode surface as about 50 percent of a total heat flow \( Q_a \). The remaining 25 to 35 percent are caused by the following processes. The mass flow towards the anode implies a boundary layer which in the present conditions is about 1mm thick. Within this boundary layer the tempera-
ture drops from the value in the arc column (about 12000°K) to the value of the anode surface. Accordingly the degree of ionization corresponding to thermal equilibrium also drops. On the other hand, however, the electron flow must be maintained. This means either an increased drift velocity of electrons according to equation (14) or an electron density which is larger than the ion density or field ionization. Each of these possibilities requires however, an increased field intensity. Actually in the vicinity of the anode the so-called anode drop is observed, which requires a field intensity which is much larger than that in the arc column. This implies a production of heat (Joule heat), which is limited to the immediate vicinity and is therefore given off practically totally to the anode. It can thus be calculated from the mentioned value that the electrical current and the voltage drop in the anode drop region.

Now it should be possible to study how far the conditions are different in the gas-cooled porous anode. The mass flow is basically altered as shown by Fig 7. The ion flow is essentially like the mass flow. But now in the vicinity of the anode there must be a source of ions instead of an ion trap. The convective heat transfer through the mass flow is certainly greatly reduced just like the case of transpiration cooling of a wall (10). The flow of the electron gas is affected by the mass flow only indirectly, that is through the temperature field. Thus essentially the heat flow transferred through the electron gas to the anode is altered to the extent to which the temperature in the vicinity of the anode and the electron entrance work are different. The internal heat production in the form of Joule heat depends on the final run on the electrical drop of voltage in the region of the anode fall.

The temperature profile reproduced in Figure 14 shows a gradual increase in the gas temperature in the direction from the anode surface towards the cathode. The conditions are different in the water-cooled copper anode, where a greater increase in the temperature was measured in a layer only about 1mm thick. In the evaluation of the temperature it must be recalled that argon contains traces of carbon vapor when emerging from the anode. It is possible that the electron temperature is higher than the gas temperature at least in the cross-section I. The nonuniform variation of the temperature profile in
the cross-section II indicates that in this mixed zone considerable deviation from axial symmetry occur. The spreads occurring in the evaluation of the spectral lines in the cross-section III were so large that they made it impossible to determine the temperature profile, but the position of the line intensity maxima outside the arc axis allows the conclusion to be drawn that in this cross-section temperatures of at least 150000K prevail.

Literature
11. R.S. Brokaw, Personal communication.