**NASA TECHNICAL
MEMORANDUM**

OPTICAL CHARACTERISTICS OF AN ENERGETIC VACUUM CARBON ARC

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ABSTRACT

Absolute intensities of the ultraviolet spectral lines, from 800 to 2000 Å, emitted from an energetic vacuum arc were determined as a function of operating parameters. The arc under investigation is a 31-cm magnetically confined d.c. discharge with a current density greater than 300 A/cm^2, operating in a region where the background gas pressure is less than 10^{-3} torr. Absolute intensities were measured using a 0.5 meter Seya Namioka monochromator with a calibrated Sodium Salicylate coated photomultiplier tube as the detector. Calibration of the photomultiplier tube was obtained by measuring the currents produced in a double ion chamber by the photoionization of Xe when irradiated by the 977 Å carbon III line. It was found that under proper conditions photon fluxes of 10^{14} photons/cm^2 sec could be obtained at the exit slit of the monochromator.

INTRODUCTION

The magnetically confined vacuum arc discharge is one promising source of intense, steady state radiation in the vacuum ultraviolet region of the spectrum. Such a steady state source is desirable in the study of radiation interactions where high intensities are required due to small values of the reaction cross section.

Much of the research pertaining to magnetically confined d.c. discharges had its beginnings at the Oak Ridge National Laboratory (1) and at the Massachusetts Institute of Technology (2). The objective of the

research at Oak Ridge was to develop an efficient mechanism for dissociating high energy molecular ions within a magnetic field under vacuum conditions. This approach was used in the DCX thermonuclear experiment (3). This effort led to the discovery of a class of magnetically confined gaseous discharges which operate in a region where the background gas pressure is less than 10^{-3} torr. Such discharges are characterized by current densities of 100 A/cm^2 or greater, electron densities on the order of 10^{14}/cm^3 with the ion temperature higher than that of the electrons $(T_i > T_e)$, thus the name "energetic arc".

The present investigation was undertaken to further elucidate the optical characteristics of the energetic arc and to determine the feasibility of using such an arc as a high intensity photon source in the vacuum ultraviolet region.

Photon intensity measurements were made with different values of the arc parameters: arc current, magnetic field intensity, magnetic field shape, arc length, and gas flow. Different feed gases were introduced through the hollow tungsten cathode. From the spectral data attempts were made to determine the plasma properties of the arc column, such as electron and ion temperatures.

APPARATUS

Arrangement of the experimental apparatus (fig. 1) consists of the vacuum arc with associated magnetic field coils, 0.5 meter Seya monochromator and photometric detection system consisting of the double ion chamber and photomultiplier tube. Chamber vacuum pressure is maintained by use of a liquid nitrogen-trapped ten inch diffusion pump with a 50 CFM mechanical backing pump.

The arc discharge chamber is water cooled with an inside diameter of 15.24 cm arranged with two opposing ports for monochromator placement and alignment. The discharge is maintained at a background pressure of approximately 2×10^{-4} torr between a hollow tungsten cathode of 0.762 cm inside diameter, through which the feed gas is introduced, and a solid graphite anode. The graphite anode may be varied in length. It

is shrink fitted with a molybdenum cylinder which in turn is threaded into a water cooled copper support. Initiation of the arc is achieved at high gas flow using a commercial R. F. arc welding starter, with the confining magnetic field adjusted to produce an intensity of 4.4 kilogauss at the center section of the arc. After initiation the gas flow is considerably reduced. However, as the background gas pressure drops, the arc discharge passes through an unstable region where sufficient energy is fed back into the arc starter to cause major damage if bypass filters are not added. It should also be noted that if the argon gas flow is reduced below approximately 2 std cc/min at arc currents greater than 300 A, cathode melt down usually occurs due to insufficient cooling of the cathode by the feed gas. In Fig. 2 is shown a cathode that was operated under these conditions. The localized melting was caused by the impact of the carbon ions on the inside surface of the hollow cathode.

The monochromator is positioned so that the entrance slit is 34 cm from the center of the arc discharge. At this position there does not seem to be any contamination of the 1180 groove/mm grating due to vaporized carbon diffusing from the arc column. Deterioration of the grating has been observed due to the decomposition, by the ultraviolet radiation, of a thin film of diffusion pump oil which backstreamed from the monochromator diffusion pump. However, this has been considerably reduced by the addition of further LN_2 trapping in conjunction with the diffusion pump.

The double ion chamber follows the design originated by J. A. R. Swanson (4). Within the 800 to 2000 Å spectral range under consideration, xenon was chosen as the calibration gas to be photoionized so that it would be possible to compare, at more than one wavelength, the absorption coefficient measured in this experiment with the published values. The xenon flow system contained an instream activated charcoal filter in a dry ice acetone cold trap. Xenon pressures in the double ion chamber were measured by use of McLead gage with a dry ice acetone cold trap. Absolute intensity spectral data were recorded with a sodium salicylate-coated photomultiplier calibrated at the 977 Å C III and the 850 Å A IV wavelengths. Constant photon efficiency was assumed from 800 to 2000 Å.

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EXPERIMENTAL OBSERVATIONS AND PROCEDURES

Calibration of the sodium salicylate coated photomultiplier tube was accomplished by measuring the currents produced by the photoionization of xenon at several ion chamber pressures for each of the two wavelengths 850.6 Å A IV and 977.0 Å C III. Having determined the corresponding currents i_1 and i_2, the radiation intensity was computed by use of the following equations given in Ref. 4.

For plate 1

$$I_o \gamma = \frac{i_1/e}{e^{-\mu L_1}\left(1 - e^{-\mu d}\right)} \qquad (1)$$

For plate 2

$$I_o \gamma = \frac{i_z/e}{e^{-\mu L_1}\left(1 - e^{-\mu d}\right)} \qquad (2)$$

where

d	length of collection plates
γ	photoionization yield (1.0 percent for Xe)
L_1, L_2	distance from exit slit to first and second collection plate respectively

From the ratio of equations (1) and (2) the absorption coefficient is given by

$$\mu = \frac{\ln\left(i_1/i_z\right)}{L_2 - L_3} \qquad (3)$$

This when incorporated into Lamberti's law gives

$$I = I_o e^{-kx} \qquad (4)$$

where k is the absorption coefficient and x is the path length both at S.T.P.

The absorption coefficients thus determined agreed to within
10-percent of the values published by J. A. R. Samson (5). During all
calibration measurements the collector voltage on the ion plates was
varied to insure that the ion chamber was being operated on the pla-
teau of the ion current vs voltage curve.

Having thus calibrated the photomultiplier tube the arc spectrum
was recorded using 50μ entrance and exit slits. With the mono-
chromator positioned 34.29 cm from the arc column, the section of
the arc viewed was 21 cn from the anode face. The spectrum shown
in Fig. 3 and tabulated in Table 1 was obtained with argon as the sup-
port gas under the conditions shown in Table 2. The absolute intensi-
ties quoted are those available at the exit slit (photons/sec-cm^2 of
slit).

To determine the spectral characteristics as a function of arc
length a longer graphite anode was used so that it was possible to view
the arc column 12 cm from the anode face, while maintaining the same
view and position relative to the hollow cathode. The spectrum thus ob-
tained is shown in Fig. 4. The operating conditions are the same as
for spectrum of Fig. 3. Comparing Figs. 3 and 4 it is seen that with
the shortened arc length spectral lines of the lower ionization states
of carbon appear, i.e., 1274 Å C I, 1036 Å C II etc.

One could consider the arc column to consist of regions along the
length of the arc separated by diffuse boundries where different ioni-
zation populations exist, with the carbon atoms becoming progressively
more ionized as they approach the cathode from a primarily neutral
carbon gas cloud at the anode face. However, when operating with the
shorter arc gap, small amounts of carbon contamination were observed
at the monochromator entrance slit. Hence, no further observations
were made in this configuration. An arc spectrum was also taken using
a supporting gas mixture of 15-percent H_2, 15-percent N_2 and 70-percent
Ar to determine if a more abundantly-lined spectrum could be produced.
The operating characteristics were those of the solely argon-fed arc.
The only additional lines observed were those of the higher ionized states
of nitrogen.

Investigation of the effect of magnetic field strength and configuration on the argon and carbon line intensities showed little effect-either by a change in field intensities with the coils arranged as a solenoid or by changing the field shape to a mirror configuration by decreasing the current to the center coils. Intensity of the 977 Å C III line as a function of arc current is shown in Fig. 5. There is little increase in intensity until the 200 amp arc current point is reached after which the intensity increases very quickly. However, to prevent damage to the hollow cathode during arc operation the arc current was maintained at a level not greater than 240 amps.

Of the operating parameters discussed, changing the gas flow through the hollow cathode has the most pronounced effect on the radiation intensity as demonstrated in Fig. 6. At gas flows of 60 std cc/min and greater the arc column appears to be diffuse and is accompanied by low amplitude oscillations with primary frequencies of 130 to kHz. (As the flow is increased beyond 60 std cc/min the line intensities change slowly.)

As the gas flow is reduced from 60 to 24 std cc/min the arc column appears to become increasingly well defined and more hollow. At the same time, the oscillation amplitudes increase and the primary frequency shifts to 300 kHz with a band spread of 25 kHz. It is also in this flow region that the arc can become unstable so that R. F. power may be fed back into the electric circuitry. What is of interest in this flow region is the observation of a minimum point in the C III and C II line intensities, whereas the C I and C IV intensities vary monotonically. Parallel to these changes in the carbon line intensity, Fig. 7 shows that Ar III and Ar IV lines increase in intensity with the 834.4 Å line going through a broad maximum at approximately 43 std cc/min.

Further reduction in gas flow results in the arc column continuing to appear hollow and sharply defined accompanied by a decrease in arc oscillation amplitude and a shift in the arc plasma primary frequency to 10 kHz. At gas flow rates below 16 std cc/min (fig. 6) there is abrupt increase in the carbon II, III, and IV line intensities with a decrease in the C I and argon line intensities. At flow rates less than 6 std cc/min

there is a high probability of cathode melt down.

From the spectral data an attempt was made to determine the ion temperature from the degree of Doppler broadening of the lines. In general the temperature of the C III species is between 15 and 30 eV which is in gross agreement with measuremnts by C. B. Kretschmer (6) for a similar arc. However, several of the lines do deviate some-what from a gaussian profile. It was also felt that there was insufficient distinction between the Doppler broadening and the instrument broaden-ing at these wavelengths to make an accurate determination of the ion temperature.

Electron temperature was determined using the carbon line rela-tive intensity method outlined in Ref. 7. The electron temperature was found to be approximately 3.5 eV, under the operating conditions of Table 2. The ratio of the ion temperature to electron temperature is again in general agreement with that reported by Kretschmer and others for the tungsten carbon energetic arc.

THEORETICAL CONSIDERATIONS AND CONCLUSIONS

As a result of the ongoing research relating to energetic arcs, there have been many excellent reports relating the characteristics of the arc plasma. Of primary importance are those reports by J. R. McNally, Jr. (8) and (9), and C. B. Kretschmer (6). In wherein reference 9 the theory of excitation-heating is proposed to explain the unusual dynamic equilibrium wherein the ion temperature is much higher than the electron temperature. This is especially true of the long arcs (~5 m) studied by McNally. A critical parameter in the theory of excitation-heating is the density of the C III ion population which we observe to have a minimum value as the gas flow through the hollow cathode is varied.

As noted in the previous section the arc plasma produces oscilla-tions similar to those reported by C. B. Kretschmer. The primary frequency varies with gas flow. In the arc model proposed by Kretchmer these oscillations, as well as the higher ion temperatures, are attributed to a separate population of high-energy electrons, constituting a few percent

of the total electron density and having a temperature of a few tens of
eV.

At the present time it is not understood how the shift in primary
frequencies or the change in the C III line intensities as a function of
gas flow are related to the present models of the energetic arc. How-
ever one may conjecture that the arc ion heating proceeds by a form
of excitation - heating, as proposed by McNally, within certain re-
gions of the arc column where the ion, electron and neutral densities
are such that resonance conditions could exist. Arc plasma oscil-
lations reported by Kretschmer and observed in this investigation
may indeed be connected with a high energy electron imposed by the
hollow cathode sheath, which may oscillate as a function of the neu-
tral density.

As a steady state, vacuum ultraviolet source type of arc studied
herein can operate for several hours while providing line radiation
with intensities approaching 10^{14} photons/cm^2-sec.

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   on the Peaceful uses of Atomic Energy (United Nations, Geneva,
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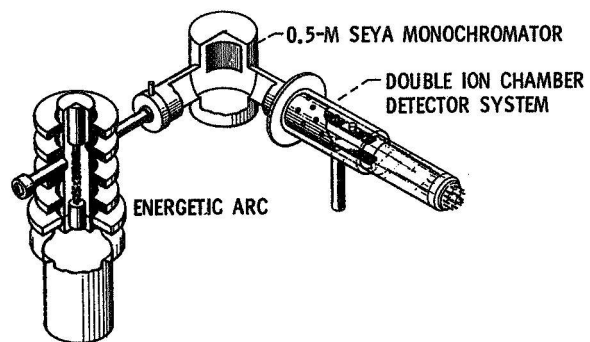9. J. R. McNally, Jr., Plasma Phys. 10, 903 (1968).

TABLE 1. - TABULATION OF AVAILABLE ABSOLUTE

LINE INTENSITIES

Line Å			Intensity, Photons/ sec-cm^2 of slit		Line Å			Intensity, photons/ sec-cm^2 of slit	
688.392	A	IV	3.91	(10^{11})	977.026	C	III	1.33	(10^{12})
714.879	C	III	4.75	(10^{11})	1175.620	C	III	1.47	(10^{12})
723.353	A	II	4.80	(10^{11})	1193.300	C	I	4.5	(10^{10})
800.573	A	IV	2.133	(10^{12})	1334.520	C	II	4.08	(10^{11})
826.371	A	I	9.83	(10^{11})	1548.195	C	IV	2.83	(10^{13})
834.397	A	I	1.57	(10^{12})	1550.768	C	IV	1.3	(10^{13})
840.029	A	IV	5.15	(10^{11})	1602.984	C	I	2.63	(10^{11})
843.772	A	IV	1.19	(10^{12})	1669.671	A	III	8.67	(10^{11})
850.602	A	IV	2.13	(10^{12})	1673.425	A	III	4.58	(10^{11})
878.728	A	III	2.58	(10^{11})	1675.484	A	III	2.50	(10^{11})
901.168	A	IV	1.83	(10^{11})	1699.95	N	III	2.33	(10^{11})

TABLE 2. - ARC OPERATING PARAMETERS

Arc current	220 amps
Arc voltage	100 volts
Argon gas flow	33.5 std cc/min
Magnetic field	4.4 kilogauss
Background pressure	$3 (10^{-4})$ torr
Current density	482.4 amps/cm^2

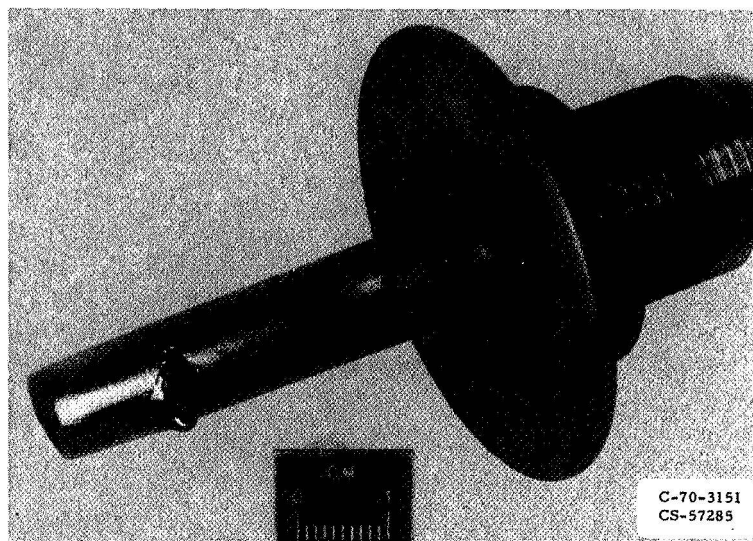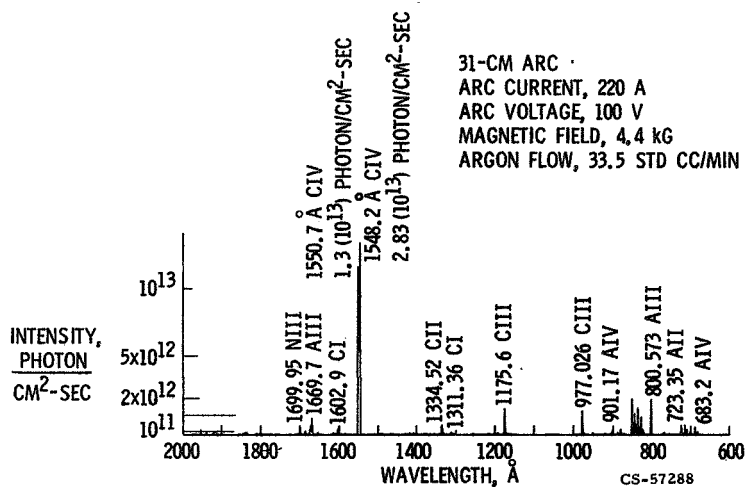Figure 1. – Experimental arrangement.

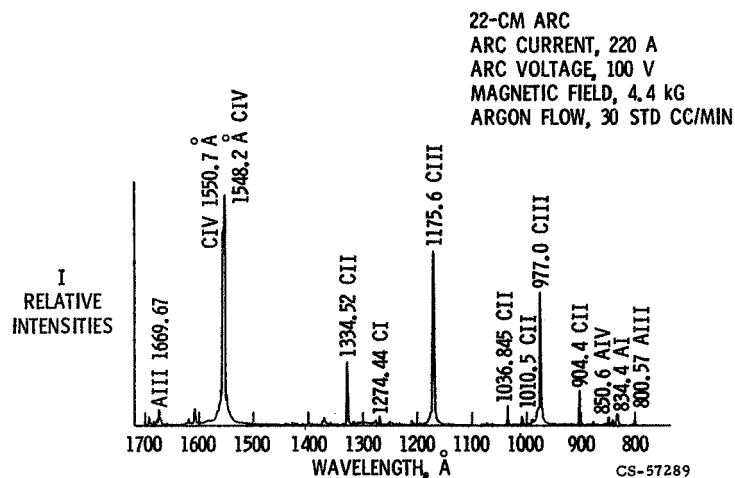Figure 2. – Tungsten cathode.
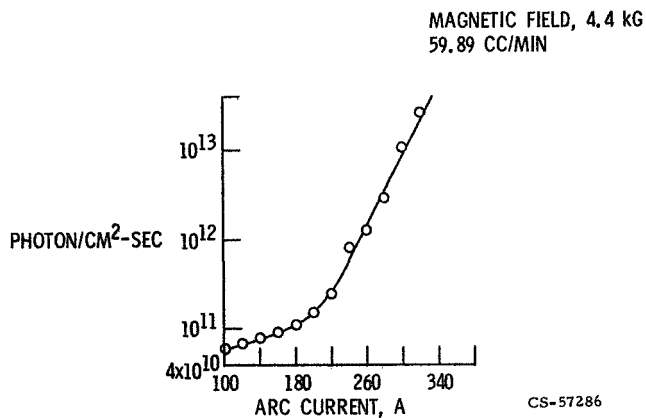
Figure 3. - Intensity versus wavelength.

Figure 4. - Relative intensity versus wavelength.
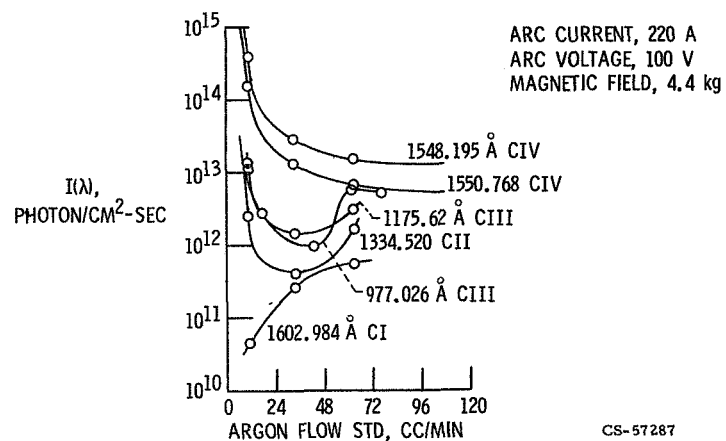

Figure 5. - I (977.026 A) versus arc current.

ARC CURRENT, 220 A
ARC VOLTAGE, 100 V
MAGNETIC FIELD, 4.4 kg

I(λ),
PHOTON/CM^2-SEC

1548.195 Å CIV
1550.768 CIV
1175.62 Å CIII
1334.520 CII
977.026 Å CIII
1602.984 Å CI

ARGON FLOW STD, CC/MIN

CS-57287

Figure 6. - Radiation intensity versus argon flow standard cc/min.

I(λ) PHOTONS/CM^2. SEC
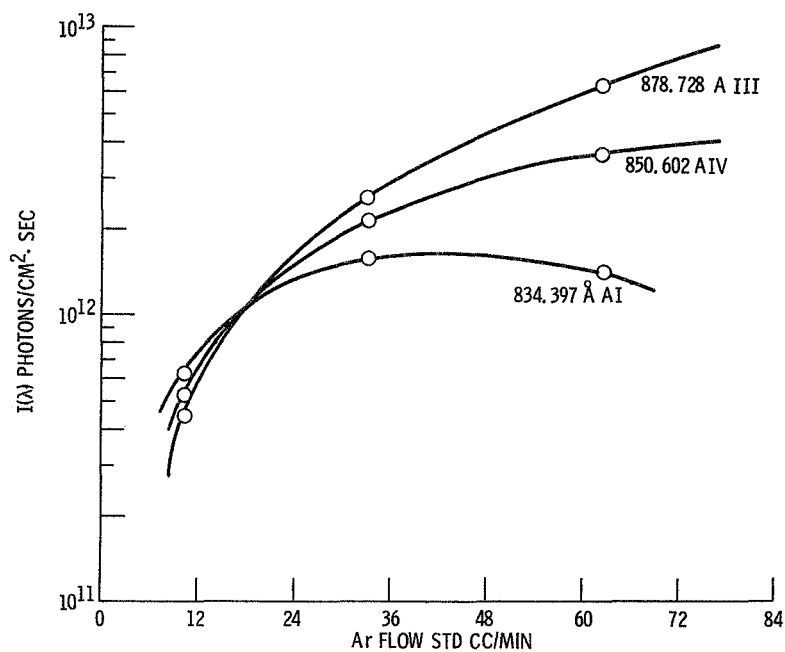
878.728 A III
850.602 AIV
834.397 Å AI

Ar FLOW STD CC/MIN

Figure 7. - I(λ) photons/cm^2. sec versus Ar std cc/min.