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THE FLUID TRANSPIRATION ARC AS A RADIATION SOURCE FOR SOLAR SIMULATION

SEMI-ANNUAL PROGRESS REPORT P-3/312

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by

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ERL

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FOREWORD

This semi-annual report was prepared by staff members of the Plasma Engineering Laboratory of the Electronics Research Laboratories, Columbia University, New York, N. Y., under contract AF 49(638)-1395, for the Mechanics Division, Air Force Office of Scientific Research, Office of Aerospace Research, USAF. The work is being performed under Project-Task 9783-02 and is under the technical cognizance of Mr. Paul A. Thurston SREM, of the Mechanics Division, AFOSR.

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ABSTRACT

This report covers the period January 1, 1967 to June 30, 1967, during which time the project to develop a fluid transpiration arc radiation source for solar simulation was initiated. The background of the fluid transpiration arc, including a discussion of both the cylindrical offset and conical coaxial geometries, is presented. A description of certain features that offer possibilities of improved source performance is also included. In particular, the high ionization of the FTA anode column plus the effectiveness of high velocity cathode injection to enhance brightness and inhibit cathode ablation has led to a new concept for a plasma source. This involves a colinear opposing flow geometry to generate a large stagnant zone in the arc region of maximum excitation. A preliminary successful experiment on this configuration at 1 atm. pressure is described.

The report also describes design and procurement of the first source of this type designed to operate at high pressures, including pressure vessel and recirculation system, as well as a complete system for radiometric measurements.

AUTHORIZATION

The work described in this report was performed at the Electronics Research Laboratories of the School of Engineering and Applied Science of Columbia University. The report was prepared by C. Sheer and S. Korman.

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I. INTRODUCTION

This document is the first in a series of semi-annual progress reports describing the work done on applications of the fluid transpiration arc, (hereinafter abbreviated as "FTA"). The application under way at present is the development of an efficient radiation source designed specifically for improved performance in solar simulation.

Although the official starting date for this study was January 1, 1967, the project was not activated until May 9, 1967. Hence only the actual progress made during the period May 9, 1967 to June 30, 1967, will be described. Despite the accelerated rate of effort expended during this period, only preliminary results are available. The major portion of this report will therefore be concerned with background, design, and procurement. The preliminary experimental results to be reported are of considerable interest despite the paucity of data since they have led to the adoption of a new arc configuration with promising features as a radiation source.

II. BACKGROUND

The central feature of this study is the FTA plasma generator, which differs from other types of plasmajet devices in that the working fluid is injected into the arc by transpiration through a porous anode, entering the discharge across the anodic arc terminus. This type of plasma device has been thoroughly treated in previous reports [1,2] and only a brief description will be given here for purposes of orientation.

A. CYLINDRICAL FTA

This is the original form the FTA and its operation may be understood by reference to the simplified drawing of Fig. 1. The working fluid (argon) is supplied under suitable pressure through a cylindrical channel in the anode holder entering the rear face of a tapered cylindrical porous anode (graphite or sintered tungsten), and emerges from the front face directly into the positive column (i.e., the portion of the conduction column issuing from and flowing away from the anode).

The cathode is a thoriated tungsten rod, having a conical tip, disposed so that the tip is slightly below the level of the positive column, its axis inclined at an acute angle to the anode axis. In this configuration the negative column (portion of the conduction column beginning at the cathode tip and flowing away from the cathode) merges smoothly with the positive column, resulting in quiet,

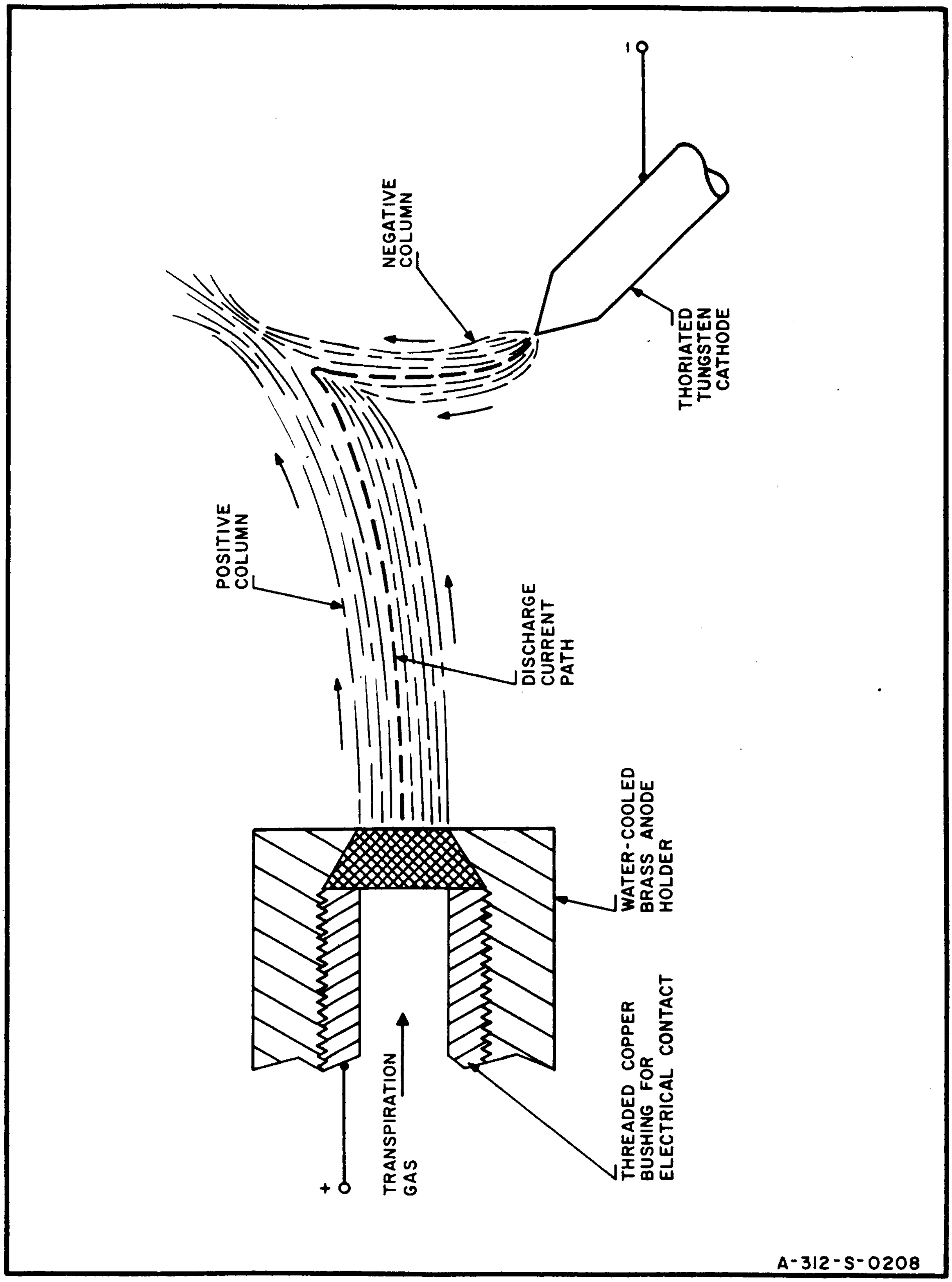

FIG. 1 SKETCH OF CYLINDRICAL FTA

stable operation. A photograph of the FTA operating in this geometry is shown in Fig. 2.

As may be seen from Figs. 1 and 2, the FTA is a completely "free-burning" arc plasma system, all parts of which are accessible. No thermal or other constraints are applied to the conduction zone, as in the case of the wall-stabilized or vortex-stabilized arcs. The system operates stably despite the convection of relatively large amounts of gas through the arc. Also, because of the absence of water-cooled surfaces close to the column plus the regenerative convective cooling of the porous anode by the transpirant, the system has an unusually high energy transfer efficiency. Upwards of 90 percent of the input power may be transferred to the working fluid.

Of more interest to the present application is the fact that the gas in the positive column is characterized by considerably higher than equilibrium ionization at the prevailing temperatures. This has been attributed to field ionization in the anode sheath where the average electron-neutral collision energy may be ~ 5 ev or more. On the assumption of a quasi-Maxwellian distribution of collision energy about a 5 ev average, we see that in the sheath a considerably higher fraction of collisions will have energies exceeding the ionization energy than in the normal arc column where the average collision energy is < 1 ev. Therefore if the surface pores in the anode are of appropriate size and distribution so that an appreciable amount of the injected gas penetrates the sheath, the ionization of cold neutral atoms by direct electron impact in the sheath region is favored. As a result the effluent gas is immediately endowed with high electrical conductivity upon emerging

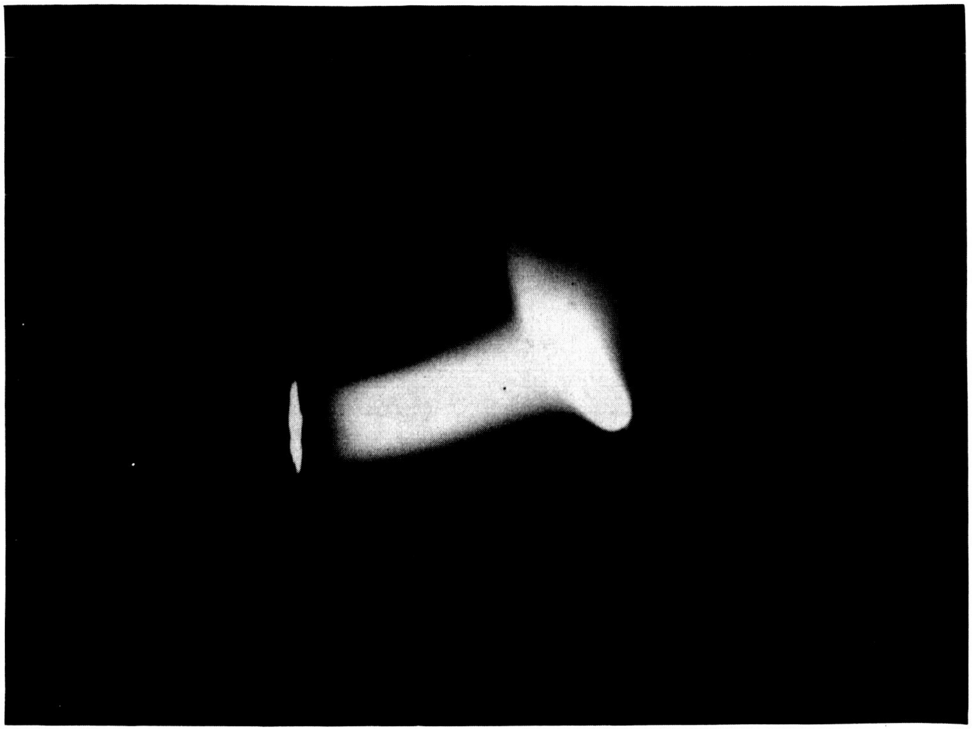

FIG. 2 PHOTOGRAPH OF CYLINDRICAL FTA IN OPERATION

from the anode, despite the low gas temperature.* Furthermore the non-equilibrium degree of ionization persists for a considerable distance into the column owing to the weak electron-neutral coupling. (Electron-neutral relaxation time 3.2×10^{-6} sec, as compared with 10^{-11} sec for electron-electron, or 2.5×10^{-9} sec for neutral-neutral, encounters).** The existence of an abnormally high degree of ionization in the FTA is manifested by a higher plasma electrical conductivity and more intense continuum radiation than can be correlated with the plasma temperature[3]. The increase in the relative intensity of continuum radiation (which varies as the square of the free electron density) is of especial importance, since this type of spectrum is most useful for solar simulation.

B. CONICAL FTA

In this modification, the electrodes are coaxially disposed, with the porous anode in the form of a truncated conical shell, located behind the tip of the conical cathode. This configuration is sketched in Fig. 3. The positive column assumes the form of a conical lamina converging toward the tip of the cathode and merging with the negative column very close to the cathode tip. The result of injecting the highly ionized conical plasma stream from the anode into the cathode stream very close to the tip (a region where the arc current density becomes high) is to generate an elongated tear-drop shaped plasma bubble of high luminosity. Photographs of this unit in operation are shown in Fig. 4. In the top photograph the arc was operated

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* Note the dark space next to the anode in Fig. 2.

** For argon gas at 1 atm.

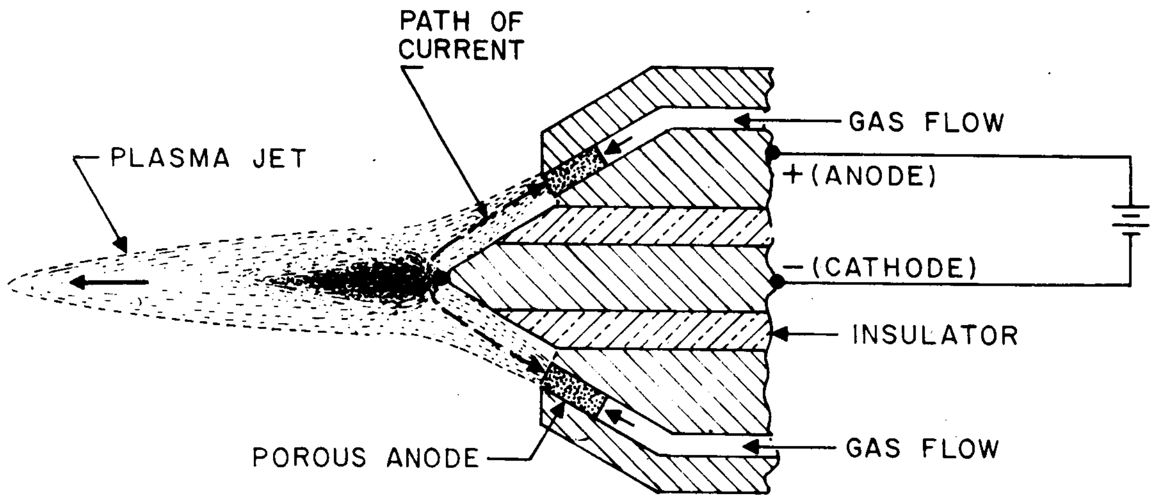

FIG. 3 SKETCH OF CONICAL VERSION OF FTA

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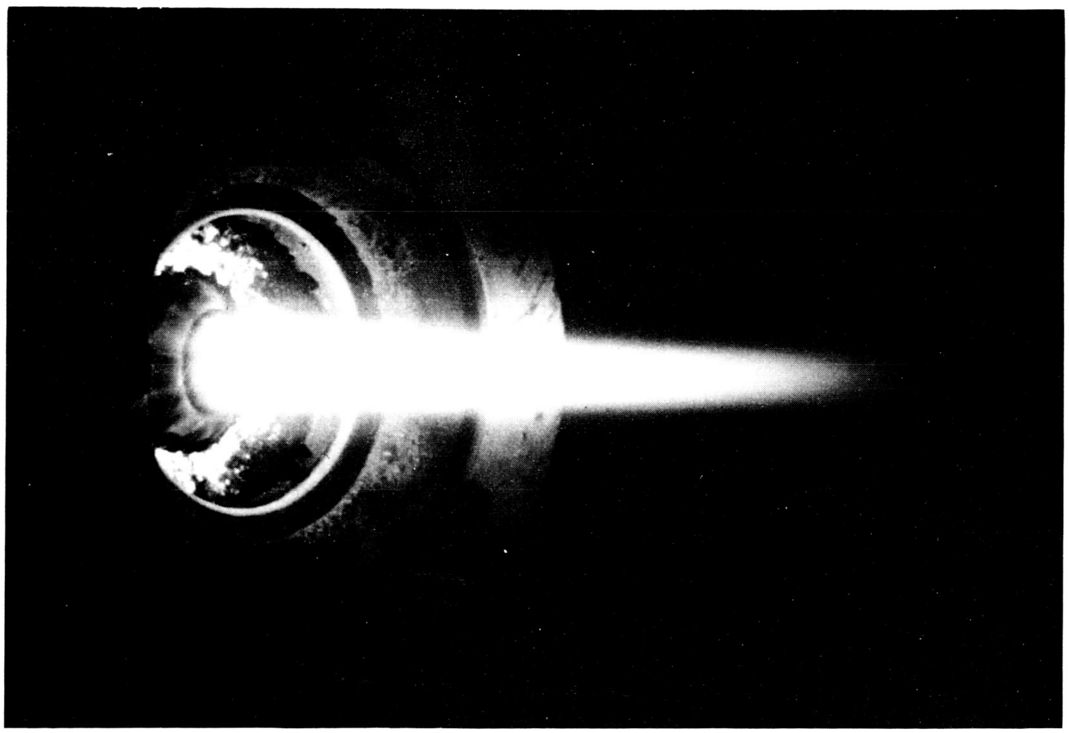

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FIG. 4 PHOTOGRAPHS OF CONICAL FTA IN OPERATION :
A - POWER LEVEL, 10 KW (NORMAL RATING) ;
B - POWER LEVEL, 25 KW (OVERLOADED TO SHOW ANNULAR POROUS ANODE SURFACE)

at its maximum power rating of 10 KW, input. The elongated, brilliant plasma bubble is clearly seen. In the bottom picture the unit was momentary overloaded (25 KW input) causing the annular anode surface to become visible and extending the length of the high luminosity plasma zone. In early work[4] on this modification of the FTA a peak source brightness of 5000 candles per sq. mm. was measured just off the cathode tip at 300 psi (argon) chamber pressure and 14 KW power input.

As a light source, the conical FTA appears to possess several attractive features. From Fig. 3, the large solid angle up to (8 steradians) available for light collection is readily apparent. Although systematic spectral radiance measurements are lacking, it is a reasonable presumption that the high degree of ionization and favorable spectral quality of the emitted radiation exists in this modification as was found for the cylindrical configuration. Further it may be anticipated that the convergent flow of a highly ionized anode column into the peak brilliancy zone of the cathode column would enhance the total radiance, particularly the continuum component.

One of the difficulties with this source was the elongation of the peak brilliancy zone by the codirectional flow of both cathode and anode columns. This has the tendency of elongating the effective emitting zone, increasing its area while decreasing its average radiance. Although the total flux radiated at a given power level is not much influenced by flow, the spreading of the zone over too large an area might present difficulties in the design of an effective light collection system. This consideration has led to some testing of a new configuration during the few weeks of actual experimentation available during the report period. This involves an opposed geometry with an attempt to focus the anode flow on the cathode bright zone, so as to retain the advantages of the conical geometry while eliminating the objectionable spreading feature. Thus will be discussed in Sec. III below.

C. FORCED CONVECTION INTO THE CATHODE COLUMN

For several years prior to the current report period, the influence of injecting a high velocity stream of gas into the negative column of an arc has been investigated. Some of the results of this investigation have a direct bearing on the present work in that they have led to the incorporation of cathode convection as an important feature in the new FTA configuration mentioned above. Accordingly a brief description of the phenomenon and a discussion of the most significant results will be presented here. The descriptive material is a condensation from a previous report[5] while the discussion of results has been abstracted from a Technical Report on this subject which is presently in process of preparation.

Although the behavior of electric arcs subject to parallel gas flow surrounding the cathode column has been described in the literature,[6] no attention has been given to the influence of the amount of flow and the manner of injection upon the characteristics of the column. Apparently previous use of coaxial parallel flow around the column has been aimed at achieving a fluid mechanical constriction[7] of the column in the manner of the water-cooled channel. Parallel flow is reported to stabilize the arc more effectively than the water-cooled metallic constrictor or vortex flow, and, of course, does not occlude the emitted radiation.

The work done at CUERL, on the other hand, was concerned with injecting gas into the column near the base of the column constriction at the negative terminus of the arc, rather than enveloping the entire column. Even without forced convection, the column will aspirate gas from the surrounding medium into the column near the cathode spot as a result of the natural decrease of column diameter in this region. This effect was explained by Maecker[8] as due to the increase in current density in the column contraction zone near the small cathode spot. The resulting non-homogeneous self magnetic field (which increases toward the cathode) causes a body force on the conductive plasma propelling the latter along the column axis away from the cathode tip and giving rise to the well-known natural cathode jet inside the column. The movement of gas away from the cathode tip decreases the local gas density in this region resulting in the aspiration of ambient gas into the column to maintain the jet. If the surrounding atmosphere is air, (as was the case in the early studies of the FTA argon positive column) the system becomes contaminated with atmospheric components. In fact, it was in the attempt to replace the naturally aspirated air with intentionally intentionally injected argon so as to reduce contamination that this study was first undertaken. However, it was soon demonstrated that, when the gas was injected very close to the cathode spot, profound and unanticipated changes occurred in the properties of the negative column.

The initial studies of forced cathode convection were carried out with the apparatus sketched in Fig. 5. The

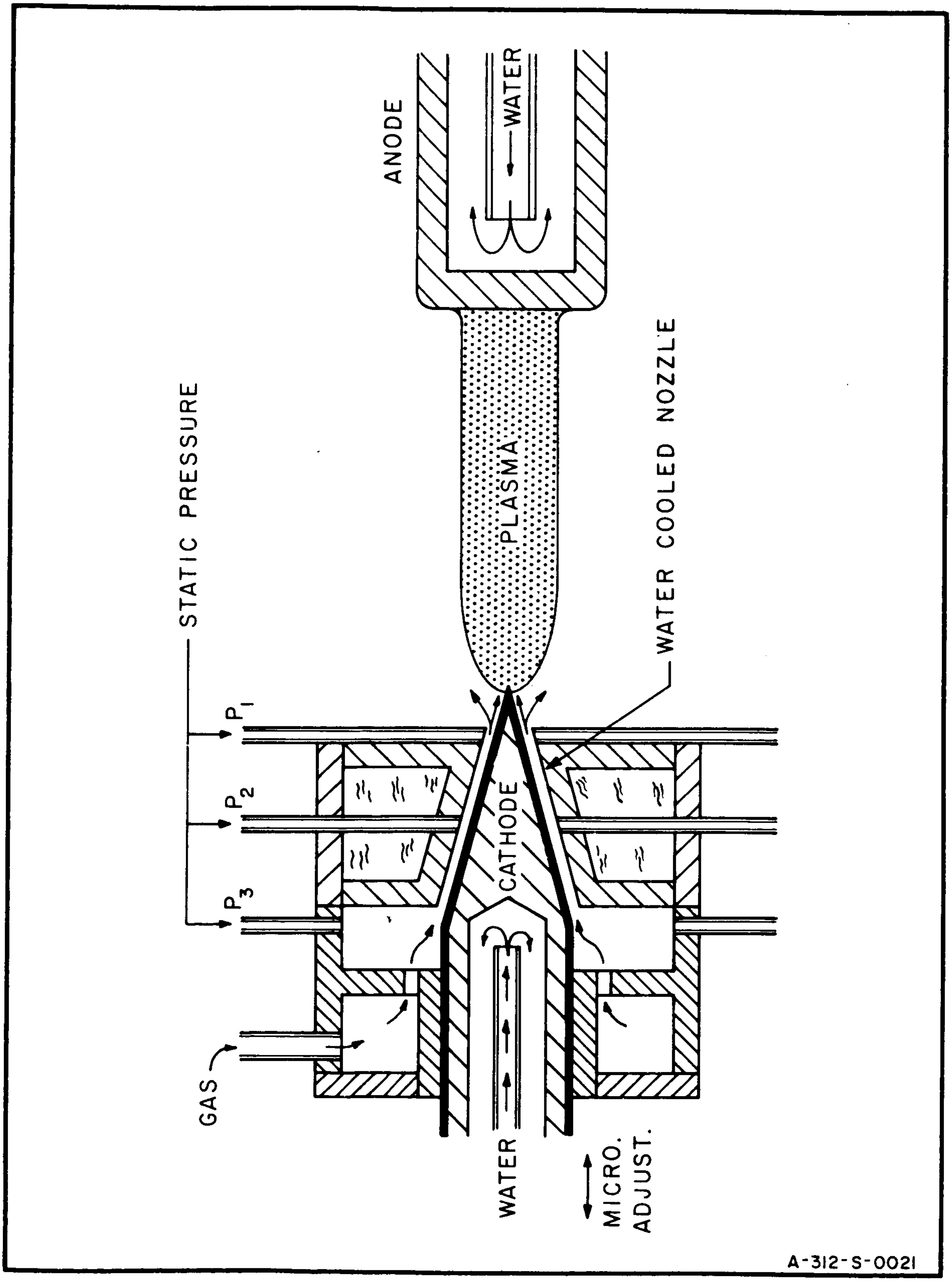

FIG. 5 APPARATUS USED TO STUDY EFFECT OF FORCED CONVECTION INTO COLUMN AT THE CATHODE CONSTRICTION

cathode consisted of a 1/4 in. diameter thoriated tungsten rod internally water-cooled and tapered to a conical tip with a 30° apex angle. An annular nozzle mating with the conical surface of the cathode formed the injection nozzle, the annular arifice of which was positioned several mm behind the cathode tip. Adjustment of the cathode axial position by means of a micrometer screw permitted the area of the annular orifice to be varied and therefore, together with the inlet pressure, allowed regulation of the gas flow. Flow velocity was monitored by measuring the static pressure developed in 3 small side arm tubes (P_1, P_2 and P_3) during operation.

The anode consisted of a 1 in. diameter copper tube, having 1/8 in. wall thickness and vigorously water-cooled. The arc gap was usually maintained at 3 cm during the study, and, obviously, there was no positive column in the sense that no gas flow away from the anode occurred. The observed effects of forced convection could then be attributed entirely to the gas introudced near the cathode. Fig. 6 is a photo of this unit in operation with a flow of 0.1 gms/sec of argon injected into the base of the column.

Among the effects of forced convection into the base of the column (i.e., in the manner illustrated by Figs. 5 and 6) are radical alteration in the terminal characteristic of the arc, changes in the radial distribution of current density and axial potential distribution, as well as changes in the peak temperature (and luminosity) of the column at a given current level. A detailed description of these effects is given in the Technical Report on this subject mentioned above, which is presently in preparation, and hence these details will not be included here. However two pertinent

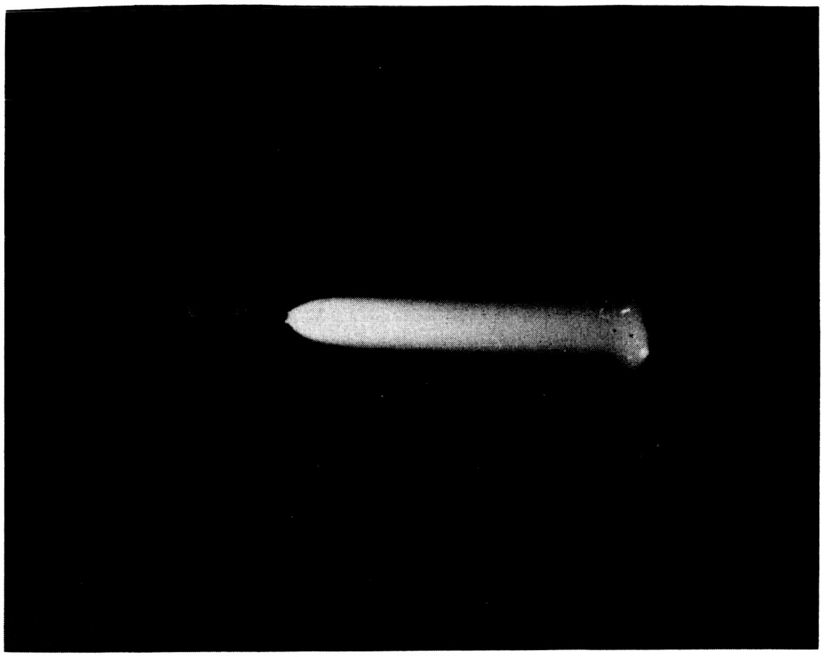

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FIG. 6 PHOTOGRAPH OF FORCED CATHODE CONVECTION ARC IN OPERATION.
ξ = 6 gm/sec-cm^2, $\dot{m}$ = 0.1 gm/sec, I = 200 amp., V = 35 volt,
ARCGAP = 3.5 cm, 1 atm. ARGON.
(NOTE HIGH BRIGHTNESS OF COLUMN ON THE LEFT, AND ABSENCE OF EXTENSIVE GLOWING OF CATHODE BEHIND THE SPOT)

observations will be included to illustrate the extent to which this kind of forced convection can influence the properties of the arc column.

Radial temperature distributions of the column (cf. Figs. 5 and 6) were measured at various axial positions, using crossed slits and making a chordal scan of the intensity of a given line (Ar I-6965Å) or at a given point in the continuum (5000Å). Abel inversion of the intensity scans yielded the (equilibrium) column temperatures in accordance with well-known practice. One of the parameters of the measurement was the mass flux density, ξ, defined as follows:

$$\xi = \frac{\dot{m}}{A} \text{ gms/sec-cm}^2$$

Where $\dot{m}$ = total mass flux (gms/sec)

A = aperture area of annular nozzle orifice (cm^2).

Since $\dot{m} = \rho v A$ (where ρ = gas density in gms/cm^3 and v = gas velocity in cms/sec) it follows that $\xi = \rho v$, and is a measure of the jet momentum just prior to injection into the base of the column. The observation to be described is correlated to the parameter ξ as indicated in Table I. (The data shown were taken at a point on the axis 3 mm off the cathode tip).

TABLE I

INFLUENCE OF FORCED CATHODE CONVECTION ON COLUMN TEMPERATURE

ξ ($gm\text{-}sec^{-1}cm^{-2}$)	$\dot{m}$ (gm/sec)	I (amps)	V (Volts)	P (KW)	T_o (°K)
2.5	0.2	150	38	5.7	13,400
5.0	0.2	150	42	6.3	18,200
20.0	0.2	150	52	7.8	12,600

In this experiment, the total mass flux ($\dot{m}$) as well as the arc current (I) were held constant. Variation in the parameter, ξ, i.e., the injection velocity, at constant flow rate, was accomplished by varying the nozzle orifice area A. Observe that the arc voltage (V) and hence the power input (P) rose some 37% as ξ was increased from 2.5 to 20 gm-sec^{-1} cm^{-2}, representing an eight-fold increase injection velocity. The increases in arc voltage is understandable if one considers the influence of the mass motion of injected gas on the ion drift current toward the cathode. Since the injected gas is in counterflux to the ion drift current, the latter can be expected to be slowed down by an amount depending on the injection velocity. Reduction of the ion drift velocity near the cathode can in turn be expected (on the basis of accepted cathode phenomena)[9] to cause an increased gradient in this region (subsequently verified by potential probe measurement) and therefore a higher arc voltage.

The surprising observation is the influence of injection velocity on the axial temperature, which jumps from 13,400 ^{o}K to 18,200 ^{o}K as ξ is increased from 2.5 to 5gm-sec^{-1} cm^{-2}, and then drops back to 12,600 ^{o}K as ξ is further increased to 20 gm-sec^{-1} cm^{-2}. Similar results were observed at various other axial stations encompassing virtually the entire cathode column. The temperature behavior is not so easily rationalized, but is probably the result of a fluid mechanical constriction of the column for which an optimum velocity could exist.*

With respect to its use in an arc system for a radioation source, it is significant that the source intensity

* The interpretation of this phenomenon as well as other features of forced cathode injection arc currently being treated in a doctoral dissertation on this subject by C. G. Stojanoff.

can be increased by a factor* of 3.4 for a corresponding increase of only 10.5% in arc voltage, all other factors remaining fixed.

As might be anticipated, the establishment of a high speed film of cold gas flowing along the conical cathode surface toward the tip helps to cool the body of the cathode by convecting away some of the waste heat conducted back from the cathode spot. During the preliminary study of cathode injection a few experiments were carried out to determine the effectiveness of this type of cooling. The cathodes were prepared with conical tips in the usual manner except that a 1 mm diameter flat was ground on the end of each cathode on which the cathode spot could form. These were then operated in the set-up sketched in Fig. 5 at very high current levels, and the ablation of the cathode tip was observed as ξ was varied. Fig. 7 shows two photomicrographs (magnification = 75 x) of cathode tips following runs at very low and very high values of ξ. The result of 20 mins. operation at 500 amps total current and ξ = 1 gm/sec-cm^2 is shown in Fig. 7a. Extensive ablation of the cathode tip is clearly evident. The "necking down" of the tip is considered to be due to fluid mechanical forces acting on the cathode material while in the molten or plastic state. During operation molten droplets were observed to fly off the cathode tip, most likely as a result of severe necking. After detachment of a droplet the necking process would begin again leading to further ablation, so that a considerable weight loss was suffered by the cathode tip after a relatively short period of operation.

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* Calculated from the 4th power of the temperature ratio: $(18{,}200/13{,}400)^4 = 3.4$

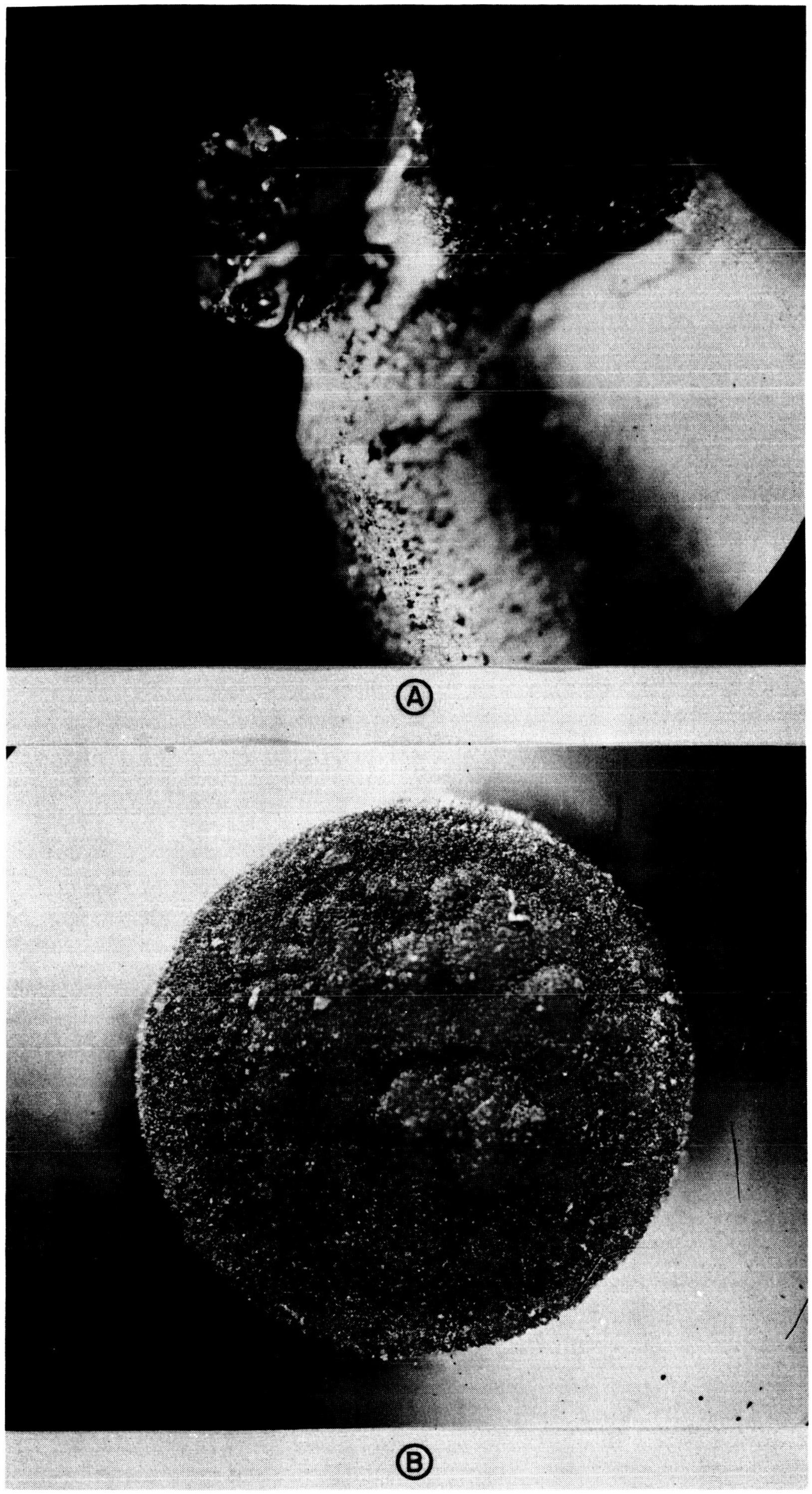

FIG. 7 PHOTOMICROGRAPHS (X75) OF CATHODE TIPS FOLLOWING OPERATION @ 500 amp. ARC CURRENT IN ARGON.

A - SIDE VIEW AFTER 20 min. WITH ξ = 1 gm/sec - cm^2

B - END-ON VIEW AFTER 7 hrs. WITH ξ = 65 gm/sec - cm^2

Fig. 7b shows an end-on view of a cathode identical to that of Fig. 7a and operated under the same conditions except that ξ was increased to 65 gm/sec-cm^2. Although emitting the the same arc current (500 amp.) as in the previous case, this cathode showed no evidence of melting or ablation of any kind. Nor was any weight loss detectable after 7 hrs. of continuous running time. The only difference in appearance before and after the run was a slight roughening of the emitting surface. This result demonstrates that injection of gas into the base of the cathode column, in the manner described, is effective in inhibiting cathode ablation for current densities at the cathode spot in excess of 60,000 amp./cm^2. This feature together with a similar result at the anode due to fluid transpiration, is of considerable importance in connection with long-term operating reliability of radiation sources such as required in solar simulation. At present the effect is being investigated more quantitatively to determine the conditions of operation for which ablation may be inhibited at values of ξ corresponding to optimum column brightness.

III. PROGRESS TO DATE

Although this report covers the first six months of the project, experimental work involving application of the FTA to an improved radiation source for solar simulation was performed only during the last seven weeks of this period. During the time between January 1, 1967 and May 1967, i.e., before activation of the contract, a detailed study was made of the background material relating to both the FTA and the FCCA* (see Sec. II) for the purpose of guiding the initial design of a radiation source. As a result of this study a new configuration was conceived having interesting potential characteristics for this application. Accordingly, the preliminary experiments as well as the design and procurement activity carried on toward the end of the report period were both concerned with the evaluation of this concept.

A. EXPERIMENTS

The original plan for this project contemplated the development of a radiation source employing the conical modification of the FTA, as illustrated in Fig. 3 and depicted in Fig. 4. During the early part of this year (February-March, 1967) some experiments were carried out in connection with the previous research program on the FTA to investigate the effect of cathode injection on the conical FTA. This was predicated in part on the assumption that effects similar

* "Forced cathode convection arc."

to those reported in Sec. II-C on the normal cathode column might also be observed for the conical FTA. If verified, the two features described above, relating to increased brightness of the column plasma and reduction of cathode ablation, would enhance the performance of the FTA as a radiation source.

The experiments were carried out by designing a special conical arc head which incorporated a thin annular nozzle between the cathode and the insulator (see Fig. 3) normally separating the cathode from the anode structure. This permitted the introduction of cathode injection gas in the manner of Fig. 5, independently of the main anode transpirant. Values of ξ from 0 to 100 gm/sec -cm^2 were tried at various total anode and cathode flow rates. The results of these tests were, in the main negative, at least insofar as increasing the plasma brightness is concerned. Also, to the limited extent investigated, it was clear that the conical configuration would not be so effective in reducing ablation as the cylindrical configuration of Fig. 5. This conclusion is understandable in view of the fact that, in the conical FTA, the column consists of a convergent flow of hot plasma, streaming parallel to the conical cathode surface towards the tip. The interposition of a layer of cold gas between the cathode surface and the main column would be expected to reduce somewhat the cathode surface temperature behind the spot, but not so effectively as if the cold gas were injected in the absence of an enveloping flow of hot plasma. The inevitable turbulent mixing of the two streams would act to vitiate, in part at least, the convection of heat from the cathode surface by the cathode gas. This reasoning was substantiated by the observation of some ablation even at high cathode injection rates.

The major effect of cathode injection on the bright plasma bubble (which is characteristic of the conical FTA in the absence of cathode injection), as observed in these experiments, was to decrease the diameter and increase the length (in the direction of flow) of the luminous zone, without any signifant increase in brightness. It is estimated that the total power radiated remained relatively independent of both $\mathring{m}$ and ξ for cathode injection* over a wide range. This observation is in direct contrast to the result described in Sec. III-C where a significant increase in plasma brightness was indeed observed. The basis for the difference between the two cases remains an open question. However, it is considered to be significant that in the cylindrical case, i.e., where the increase in brightness was observed, the injected gas is clearly in counterflux with the ion drift current of the column. In the conical case this situation does not obtain. Here, the current path (followed by positive ions) is at first, co-directional with the injected gas, and then, at some point downstream of the cathode tip, it reverses to flow back upstream toward the cathode spot near the axis. Thus the ion drift current is, first co-directional with, then orthogonal to, and finally in counterflux with the injected gas. Further it is conceivable that only a small fraction of the injected gas interacts with the ion drift current in counterflux. If, therefore, as postulated earlier (page 16), the causal phenomenon for the brightness increase is a local slowing down of the ion drift current by the injected gas, the failure to observe any significant increase in brightness in the conical case is readily rationalized. Further the stretching

* Since $\dot{m}$ (cathode) was always considerably less than $\dot{m}$(anode) significant cooling of the effluent jet by cathode gas was neither anticipated nor observed.

out of the luminous zone is also understandable, in view of the much larger collision cross-section between neutrals and ions as compared to neutral-neutral encounters, if we further postulate that a high plasma brightness requires a high ion (or free electron) density in a region of high potential gradient, or high current density, or both.

Following the line of reasoning suggested by the preliminary experiments on the conical FTA and the cylindrical FCCA, two requirements can be deduced for optimizing source performance:

1. The enhancement of plasma brightness (as well as the inhibition of cathode ablation) requires that the major portion of the gas injected at the base of the cathode enter the column in counterflux to the ion drift current.

2. Since maximum brightness also requires that the highest possible ion-electron density be maintained in the luminous zone near the cathode and since the positive column generated by the FTA is an extremely ion-rich plasma, the positive column must be directed into this zone, which in turn means that the flow from the anode must be co-directional with ion drift current, i.e., in opposition to the cathode flow.

The above conclusions suggest a source consisting of a cylindrical anode and cathode in a colinear geometry with opposing flow. If moreover, the flows are properly controlled a large stagnant zone will be created in the region of maximum plasma luminosity. The brightness of this zone should be enhanced near the cathode by injection of cathode gas in the required direction relative to the ion drift current. The continuum radiation from this zone should also be further enhanced as it is fed with ion rich plasma from the anode entering from the opposite direction. Finally, the collision of the two flows should augment the size of the zone by creating a larger stagnant bubble than otherwise possible in the region of the discharge most favorable to the emission of radiation. Thus the rate of dissipation of emitting centers will be slowed down, increasing the size as well as the brightness of the emitting zone, while both anode and cathode are operated under conditions of minimum erosion.

Several difficulties were also forecast for the postulated colinear, opposing flow configuration. For example, the creation of a large, stable stagnant zone would require accurately balanced, symmetrical, and radially uniform flows both cathode and anode. Also, since the flow cross-sections are unequal (the anode column having approximately twice the diameter of the cathode column at a given arc current) some difficulty was forseen in balancing the two flows, and in preventing excess hot plasma from the anode from impinging on the cathode structure. Both of these difficulties were actually encountered in the first trials of this concept, and both were overcome in the manner described below.

A sketch of the electrode system used to test the opposed geometry is shown in Fig. 8. A porous graphite* anode was used, with argon as the working fluid for both anode and cathode. It will be noted in Fig. 8 that the anode arc contact surface is concave instead of the planar surface used heretofore in the cylindrical FTA. The use of the concave surface was effective in compensating for the in-

* National Carbon Co. type NC- 60

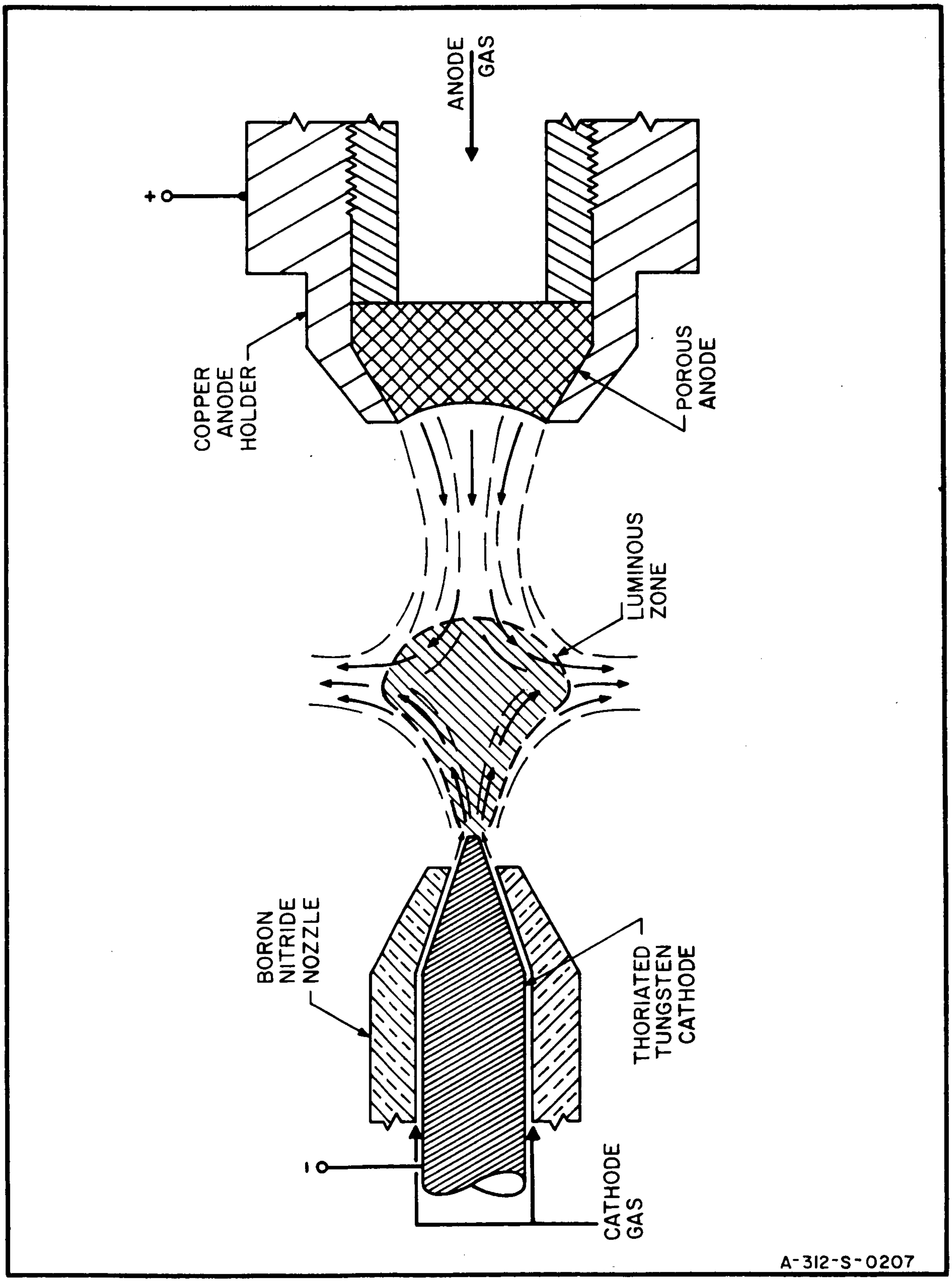

FIG. 8 SKETCH OF COLINEAR OPPOSING FLOW RADIATION SOURCE

equality in the radial dimensions of the cathode and anode flow fields mentioned above. In the first runs using flat anodes, it was found that the cathode jet was not effective in preventing the peripheral portions of the anode column from reaching the cathode structure and causing overheating, except at inconveniently large arc gaps (e.g., > 20 mm.). By using an anode with a concave surface whose radius of curvature was slightly less than the gap distance desired (15-18 mm) it was expected that the anode column could be "focussed down" to the natural cathode column diameter so that both flows could be properly balanced. This supposition was based on an earlier observation that effusive flow from a porous surface, containing a multitude of pores with random orientation, was essentially normal to the surface. The flow from a concave surface would therefore establish an axially directed radial pressure gradient thus reducing the cross-section of the flow field near the center of curvature. This effect was verified experimentally and was successful in providing adequately balanced flows at acceptable arc gaps(15 to 20 mm).

The problem of flow uniformity was solved by cold flow testing from each electrode, using a miniature pitot tube, and making adjustments until the flow probe indicated good uniformity. In the case of the cathode, the adjustment consisted of aligning the cathode and nozzle piece for accurate concentricity. In the case of the anode, careful selection of the porous anode material for uniform permeability was required. It was also found desirable to establish accurate colinearity of the cathode and anode axes. These adjustments were not over-critical, and, once properly made, permitted the source to operate in a stable manner for extended periods of time.

Although there was no opportunity for optimizing the operating conditions or make any quantitative radiometric measurements, qualitative observation left little doubt that a significant increase in source brightness had been achieved. For example, the conical FTA or cylindrical FTA with the offset geometry (Fig. 1), operating at the same power level,(~ 6 kW)were visually much less luminous. It is not known whether the apparent increase in luminosity was due to a higher temperature in the emitting plasma zone, or to the larger zone created, or both. From the fact that the light from the opposed geometry source appeared to have a more bluish cast than the others, it is predicted that subsequent measurements will show a higher temperature as well as the larger emitting zone.

A close-up photograph of the electrodes is shown in Fig.9, and a picture of the unit in operation, taken at the same magnification, is shown in Fig. 10. Conditions of the run were: $I = 150$ amps, $V = 40$ volts, gap = 17 mm, $\dot{m}$(anode) = 0.67 gm/sec-cm^2; $\dot{m}$(cathode) = 0.13 gm/sec-cm^2.

Several points of interest are observable from Figs.9 and 10. First, it is seen that the luminous zone is unusually large for a 6 kW arc, measuring some 8 mm long by 4 mm wide. This provides something like 4 or 5 times the emitting zone area of the other configurations at same power level. Secondly, we observe in the photo no trace of the luminous positive column from anode whose temperature is known from previous measurements (see Ref.3), to be 11,000°K. The absence of a positive column image is due to reduction of the film exposure until it was correct for the luminous zone near the cathode, which therefore must have had a temperature much higher than that of the positive

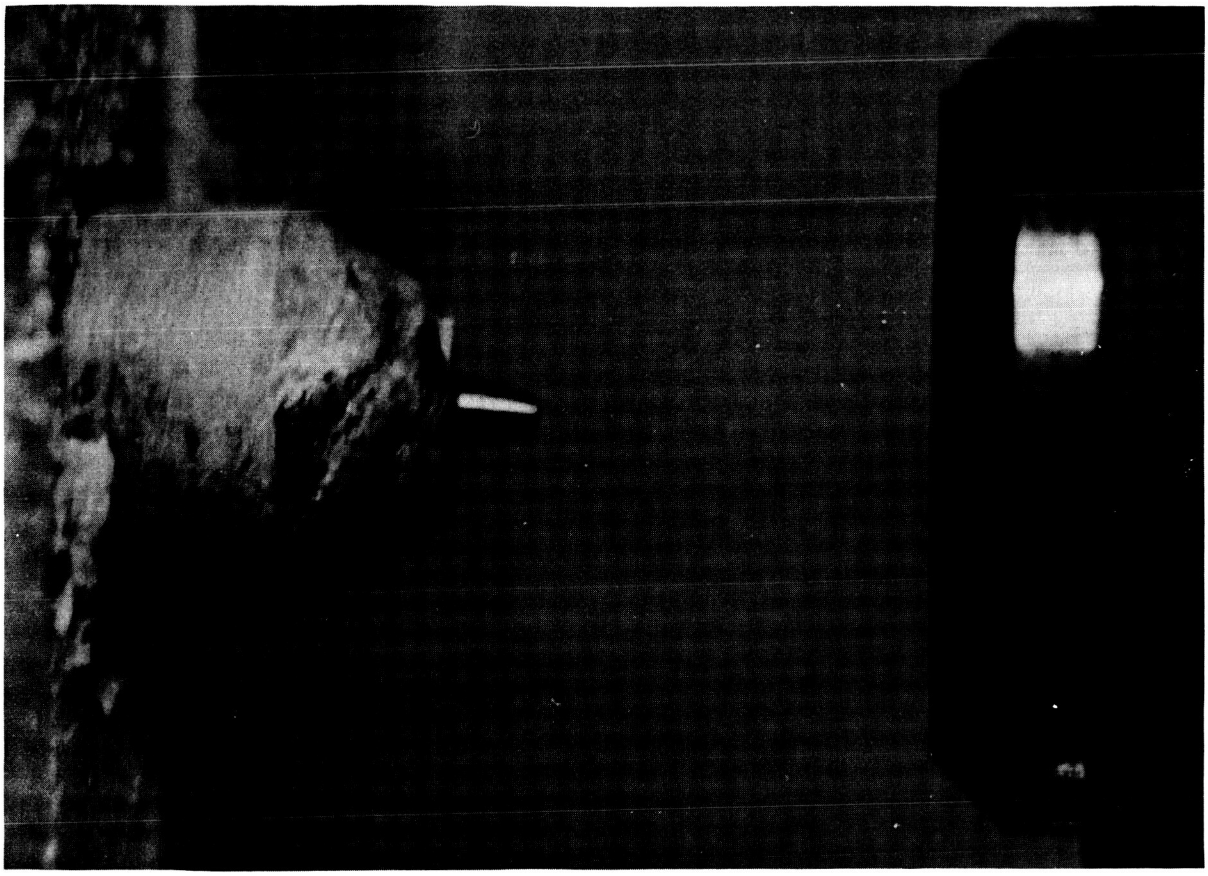

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FIG. 9 CLOSE-UP PHOTOGRAPH OF OPPOSED GEOMETRY FTA (x3)

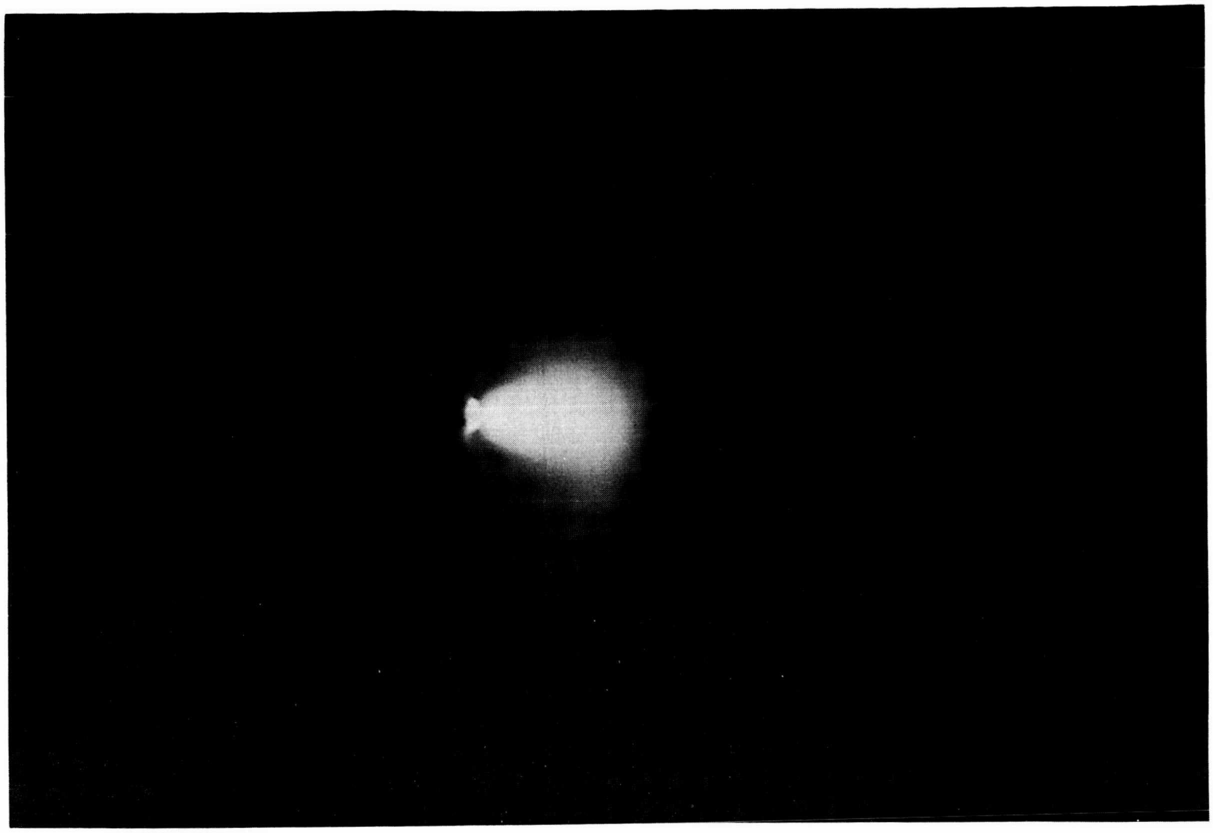

FIG. 10 OPPOSED GEOMETRY IN OPERATION
(SAME MAGNIFICATION AS FIG. 9)

column. Finally, the relatively low temperature of the cathode behind the spot, as noted in Fig. 10, presages inhibition of cathode ablation similar to that described previously.

B. DESIGN AND PROCUREMENT

1. Radiation Source

In view of the successful results of the initial experiments, particularly the promise of long operating life for the opposed geometry FTA, it was decided to proceed immediately with the design and construction of a radiation source based on this concept. For this purpose anode and cathode structures were designed for operation under pressure within a quartz enclosure. Because of the similarity in the electrode configuration of the opposed geometry FTA and the vortex-stabilized arc radiation source[10] the double quartz cylinder arrangement developed for the latter system was chosen for the FTA source. This system utilizes two concentric quartz cylinders with an auxiliary stream of cold gas, maintained at the same pressure as in the enclosure, flowing between the two cylinders. In this manner the inner cylinder bears the entire thermal gradient of the envelope but is under no mechanical stress, since the gas pressure is the same on both sides. The outer cylinder bears the entire mechanical stress but little or no thermal gradient owing to the cooling effect of the intercylindrical gas flow. In this manner maximum operating durability under high internal pressure is achieved.

An assembly diagram of the first design modification is shown in Fig. 11. The gas flow from the anode and cathode flare radially outwards from the arc zone and are zone and are caught up by a cold gas sweep, introduced aft

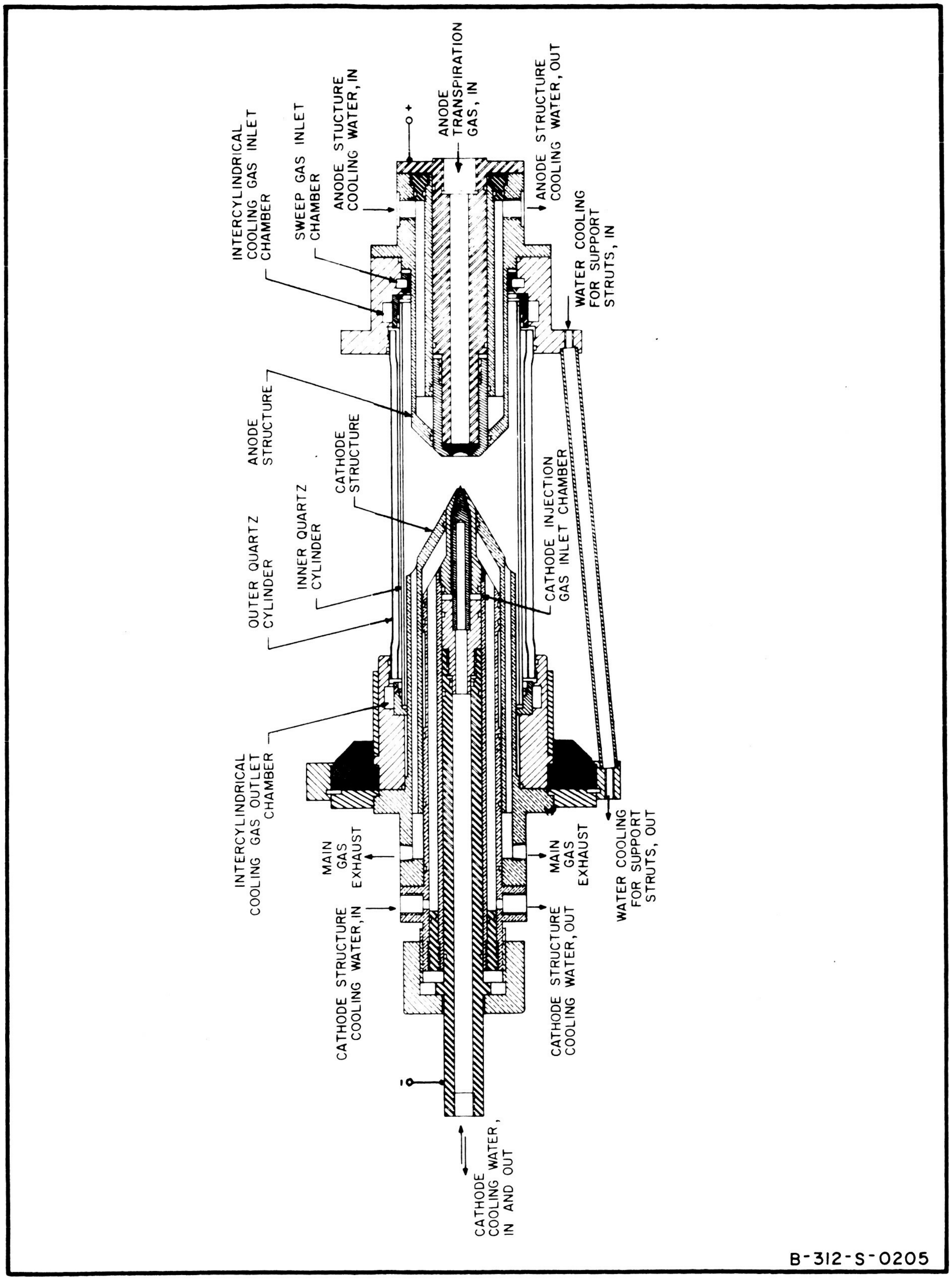

FIG. 11 ASSEMBLY SKETCH OF OPPOSED GEOMETRY FTA RADIATION SOURCE

of the anode structure, and flowing tangentially along the inside surface of the inner quartz cylinder. The sweep gas serves not only to keep the inside surface clear of accidentally dislodged particles or traces of electrode vapor, but also tempers the hot arc effluent, helping to lower its temperature before it enters the exhaust passages. The latter consist of a series of channels in the water cooled cathode structure, disposed radially about the cathode axis. After leaving the arc unit the exhaust gas is further cooled in an external heat exchanger and is then passed through the space between the two quartz cylinders so as to maintain a low temperature on inside surface of the outer cylinder and to reduce the pressure drop across the inner cylinder essentially to zero.

After emerging from the inter-cylindrical passageway the gas is again brought down to room temperature, filtered, repressurized, and fed to the inlet ports. This arrangement thus constitutes a completely closed recirculation system with adequate safeguards for reliable operation. A diagrammatic sketch of the entire system is presented in Fig. 12.*

At the present time, the electrode structures are in process of fabrication, and procurement of the lamp housing (quartz cylinders and end structures), as well as the gas recirculation system, has been negotiated with the Tamarack Scientific Co. of Orange, California. Included in this procurement is a calorimeter chamber which will enclose the the lamp during operation, and also permit measurements of the total radiated power to be made. Appropriate slits and

* The auxiliary cooling and recirculation of the gas through the intercylindrical passageway has not been detailed in Fig. 12.

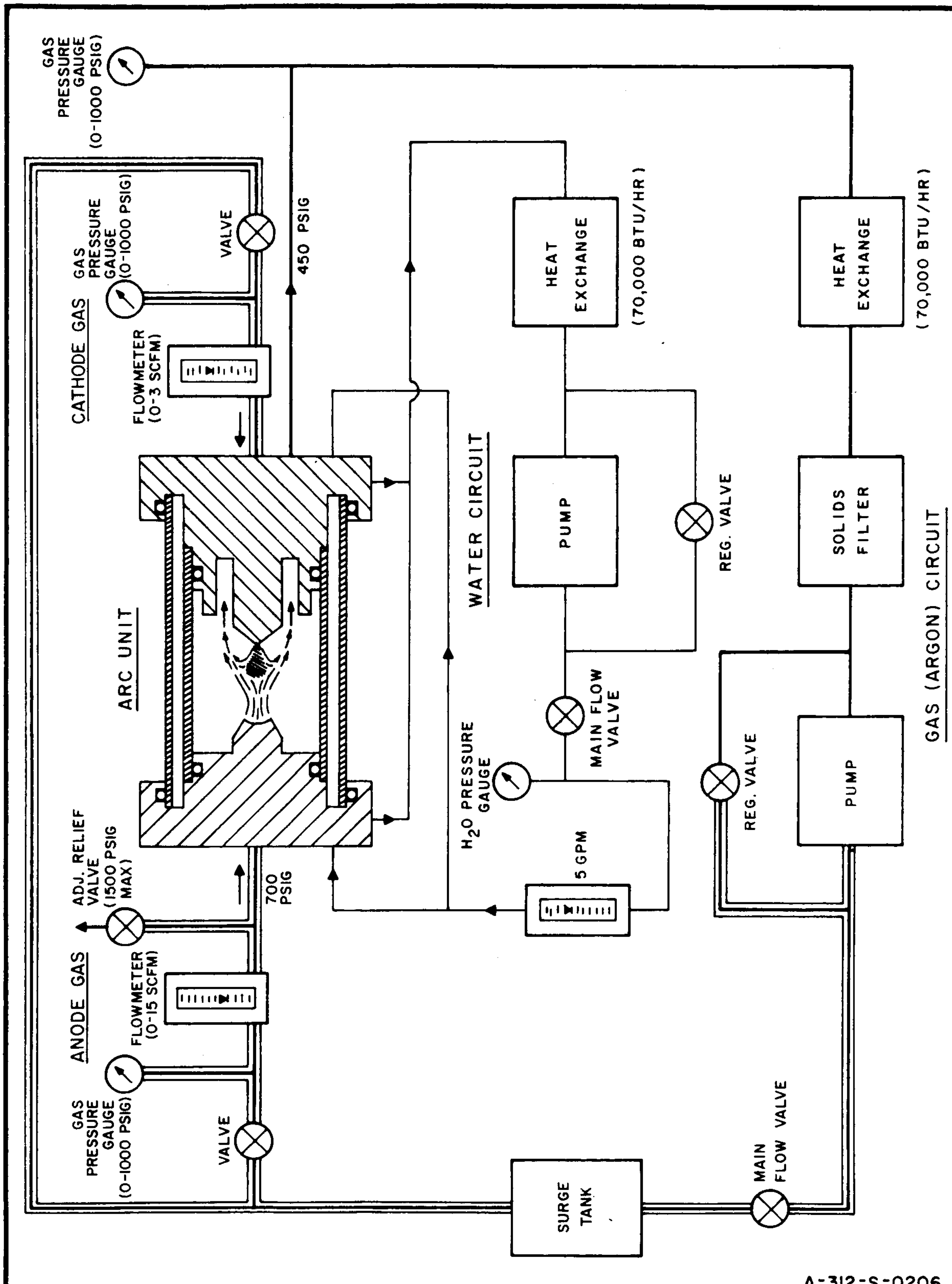

FIG. 12 DIAGRAM OF RECIRCULATION SYSTEM FOR FTA RADIATION SOURCE

apertures in the chamber are provided for viewing of the arc discharge and external measurements of spectral irradiance. It is anticipated that the completed lamp system will be received in November of this year.

2. Radiometry

The performance of the lamps as a source for solar simulation will be evaluated (in addition to operational reliability) chiefly by radiometric measurements of total radiated power and spectral irradiance. The former will be carried out by the Tamarack calorimeter chamber now under procurement. A complete radiometry system for measurement of the spectral irradiance is currently being procured. The radiometry system chosen for this purpose is that developed by Stair et al[11] and presently in use by the Radiometry Section, Thermophysics Branch, Spacecraft Technology Division of NASA at Goddard Spacer Flight Center.* The system involves comparison of the unknown source with a standard source, the latter consisting of a 1,000 watt quartz-iodine tungsten filament lamp, calibrated for spectral irradiance over the range 0.25 to 2.5 microns by the Eppley Laboratory, Inc., Newport, R. I. The radiation from a given (small) solid angle of either source is initially passed through a 4" diameter integrating sphere, so that the comparison is made on the basis of the radiant flux per unit solid angle (irradiance). The light emerging from the sphere is then passed through a Leiss double prism monochromator with slits adjusted to pass the radiation in 100 Å bands below 1 micron, and 1000 Å bands above 1 micron. A chopper wheel in front of

* The writers are indebted to Dr. Charles Duncan and his associates in the Thermophysics Branch, Messers Stanley Neuder, Ralph Stair, and Malcolm Lillywhite, for their kind assistance and helpful suggestions relating to radiometry.

the monochromator entrance slit interrupts the beam periodically so that subsequent detection and signal amplification is carried out at a frequency of 500 Hz. Two detectors are alternatively positionable at the exit slit. One consists of a pair of matched Eastman - Kodak Co. Ektron lead sulphide cells mounted in an evacuated, thermoelectrically cooled detection module, being built by the Edgerton, Germeshausen, and Grier Co. of Boston, Mass. It covers the range from 2.5 down to 0.7 microns. The second detector consists of an Ascop type 541E-05M-H low noise photomultiplier which covers the balance of the solar simulator range, i.e., from 0.7 to 0.25 microns. The output of either detector is fed to a Brower Laboratories lock-in type precision amplifier whose output is recorded on the Y-axis of a Houston Omnigraphic recorder. The X-axis of the recorder is indexed at 100 Å intervals by means of a special contactor drum attached to a motorized drive on the wave-length control of the Leiss monochromator.

All of the components for the above radiometry system have been ordered and it is expected that deliveries will have been completed by early October of this year. It is further anticipated that the radiometry system will be assembled and checked out by the time the lamp system is received.

IV. PLANS FOR THE SECOND SIX-MONTH PERIOD

The following tasks are scheduled for the second six-month period pf this project:

(1) Complete construction of the first modification of the FTA radiation source.

(2) Assemble lamp housing in calorimeter chamber; set up and check out calorimeter instrumentation for measurement of total radiant power.

(3) Assemble and check out gas recirculation system and auxiliary water-cooling circuits.

(4) Assemble and check out radiometry system for measurementof spectral irradiance.

(5) Begin tests on operating characteristics of FTA lamp at various pressure levels up to 20 atm.

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13. ABSTRACT

This report covers the period January 1, 1967 to June 30, 1967, during which time the project to develop a fluid transpiration arc radiation source for solar simulation was initiated. The background of the fluid transpiration arc, including a discussion of both the cylindrical offset and conical coaxial geometries, is presented. A description of certain features that offer possibilities of improved source performance is also included. In particular, the high ionization of the FTA anode column plus the effectiveness of high velocity cathode injection to enhance brightness and inhibit cathode ablation has led to a new concept for a plasma source. This involves a colinear opposing flow geometry to generate a large stagnant zone in the arc region of maximum excitation. A preliminary successful experiment on this configuration of 1 atm. pressure is described.

The report also described design and procurement of the first source of this type designed to operate at high pressures, including pressure vessel and recirculation system, as well as a complete system for radiometric and measurements.

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