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A SOURCE AND DETECTOR OF RADIATION IN THE WAVELENGTH REGION 1500-50 ANGSTROMS SUITABLE FOR RADIATION EFFECTS STUDIES ON MATERIALS IN VACUO

HORACE R. MOORE

ELECTRO-OPTICAL SYSTEMS, INC.

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FOREWORD

This report was prepared by Electro-Optical Systems, Inc., under USAF Contract No. AF 33(616)-6488. The contract was initiated under Project No. 7360, "The Chemistry and Physics of Materials", Task No. 73614, "The Physical Properties of Materials". It was administered under the direction of the Materials Central, Directorate of Advanced Systems Technology, Wright Air Development Division, (Presently designated Directorate of Materials and Processes, Aeronautical Systems Division) with Mr. Robert A. Winn acting as project engineer.

This report covers work conducted from 1 May 1959 to 30 June 1960.

ABSTRACT

This report describes a source and detector of vacuum ultraviolet radiation in the wavelength range 1500 - 50 angstroms which are being developed for radiation effects studies on materials in vacuo.

The principle of the radiation source is the repetitive pulsed discharge of capacitor stored energy into a ceramic discharge tube. A very hot plasma will thus be generated which will emit vacuum ultraviolet radiation by Bremsstrahlung - like processes.

The principle of the radiation detector is photoelectric emission from a photocathode exposed directly to the radiation in vacuo. The pulsed output current from the multiplier phototube will be measured with a finite integrator.

The radiation source and detector are designed to be finally incorporated in an environmental test chamber capable of being evacuated to a working pressure of 10^{-9} mm Hg.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Jules I. Wittebort

JULES I. WITTEBORT
Chief, Thermophysics Branch
Physics Laboratory
Materials Central

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The program carried out at Electro-Optical Systems under Contract AF 33(616)-6488 has been concerned with the research and development of methods and apparatus for the production and detection of radiation in the vacuum ultraviolet (V.U.V.) region of the electromagnetic spectrum with particular emphasis on the extreme solar ultraviolet including wavelengths from about λ1500 down to λ50*.

The contractor was to conduct research and development leading to a definite advancement in apparatus and techniques for the production and detection of radiation throughout the wavelength range indicated. The radiation source was to be of sufficient power and of a configuration suitable for its employment in radiation effects studies on materials. The contractor was not to limit his approach to the use of presently known techniques but was encouraged to develop new methods if such seemed advantageous.

With regard to the radiation source, it was anticipated that a suitable source of continuum radiation utilizing gas discharge phenomena might be developed to cover the wavelength range of interest. However, other possibilities were to be pursued if preferable. Again, with regard to the detector, it was indicated that photoelectric or photoionization methods of detection might be usefully pursued. While it was suggested that the ideal detector would be absolute, providing a response proportional to the incident energy flux, it was also anticipated that a secondary detector would be necessary, particularly for the measurement of low intensities.

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*The symbol λ represents a wavelength whose magnitude is expressed in Angstrom units. 1 Angstrom unit = 10^{-8} cm.

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The initial stage of the research program carried out at Electro-Optical Systems under the contract now being reported was concerned with a detailed evaluation and analysis of known methods of exciting and detecting radiation in the vacuum ultra-violet region of the spectrum. This initial survey led to the conclusion that a single source and a single detector of radiation probably could be developed to cover the wavelength range of interest. The type of source and detector selected for development under this program were a pulsed plasma discharge tube and an open photo-electron multiplier tube respectively.

The principle of the pulsed plasma V.U.V. radiation source being developed is the generation of a hot radiating plasma by the rapid discharge of capacitor stored energy into a confined volume of gas. This confinement is achieved by the use of a narrow bore ceramic discharge tube. The present source seeks to optimize the transfer of energy from the capacitor (which is repetitively charged from a power supply) to the discharge tube which is connected to the capacitor with a special co-axial electrode arrangement.

The principle of the open photo-electron multiplier detector being developed is simply that of an orthodox multiplier tube except that the photo-cathode is designed for direct exposure to the radiation, there being no window on the tube which is inserted into a vacuum chamber. Associated with the multiplier tube are the necessary electronic circuits for integrating the pulsed output which results from the pulsed operation of the radiation source.

In this report the reasons leading to the choice of these particular source and detector types are briefly reviewed and the progress achieved to date, in their development, is described.

1 The Solar Spectrum in Space

All stars emit electromagnetic radiation which might range from γ rays through the radio waves depending upon the effective temperature of the star. Of particular interest in our own solar system is the sun which is the primary source of radiation.

The sun emits radiation from about 1 Å in the X-ray region to longer wavelengths. No gamma radiation as yet has been detected from the sun (Ref. 1). The energy distribution in solar radiation is shown in Table 1 derived from the data of Brooks (Ref. 2).

The solar spectrum for the top of the atmosphere is shown in three figures, one extending from 1 Å to 2000 Å, another from 2000 Å to 5250 Å and the third from .525 microns to 3.0 microns (5250 Å to 30,000 Å) (Figures 1, 2 and 3 respectively).

The curve of Figure 1 showing the irradiance from 1 Å to 2000 Å is from rocket measurements made by Friedman (Ref. 1) as part of the International Geophysical Year (I.G.Y.) participation by the United States. This figure depicts x-rays from a "quiet" sun having radiation intensities characteristic of a 500,000 °K coronal temperature. Local temperatures within the corona may reach 2,000,000°K producing somewhat harder x-rays. The portion of the curve labelled 4,000,000°K was produced by a small flare and measured by Friedman. Still harder x-rays may be produced by the rare large flares, but no measurements have ever been made during one of these events. Friedman expects X-radiation corresponding to 10,000,000°K might be produced by such an event.

The most intense radiations below 1500 Å are characteristic line spectra, the most prominent of these being the hydrogen Lyman-α line at 1216 Å. About 100 such lines have been photographed during the I.G.Y. between the Lyman-α line and the region of x-rays. In this region, it appears that the ionized helium line at 304 Å has more energy than the rest of the region combined.

The ultraviolet spectrum of the sun between 2000 Å and 3000 Å was obtained by Tousey (Ref. 3) between 1949 and 1952, using

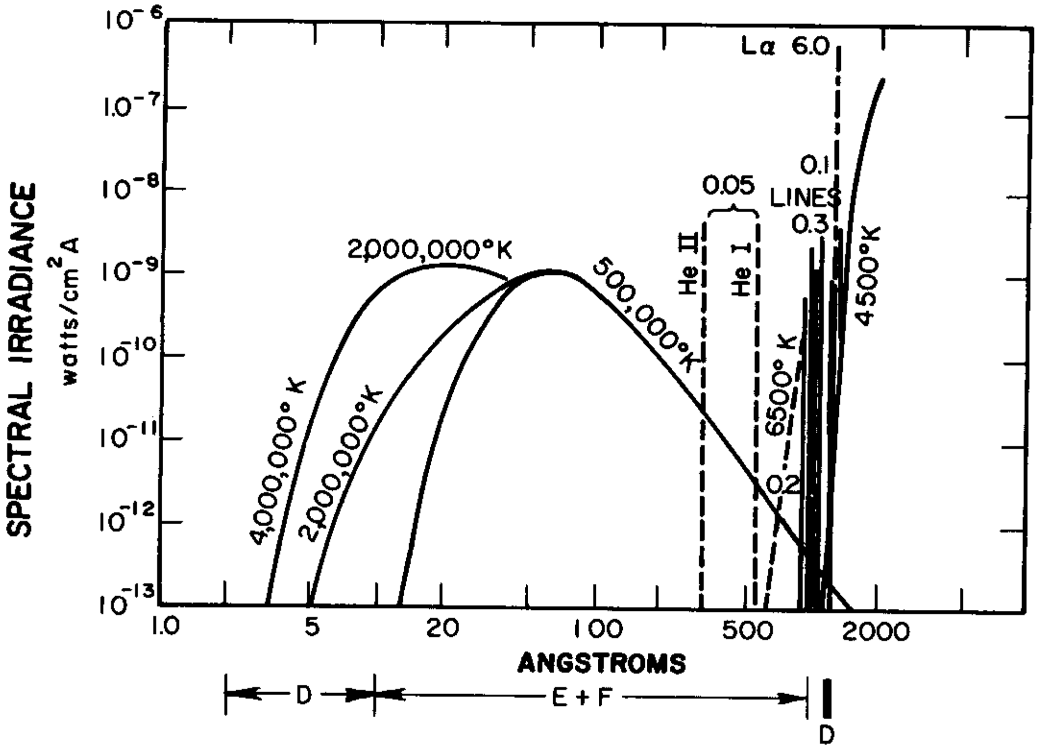

FIG. 1 THE SOLAR SPECTRUM AS MEASURED FROM ROCKETS

X-rays from a quiet sun have a distribution characteristic of a 500,000°K coronal temperature. Local condensations in the corona reach temperatures of 2,000,000°K and emit shorter wavelength X-rays. During a solar flare, the active region may reach temperatures as high as 10,000,000°K. The portion marked 4,000,000°K was observed during a small flare. In the ultraviolet, the continuum emission is very weak, and most of the energy is carried in a few strong lines, such as He II (304 Å) and Lyman - α (1216 Å).

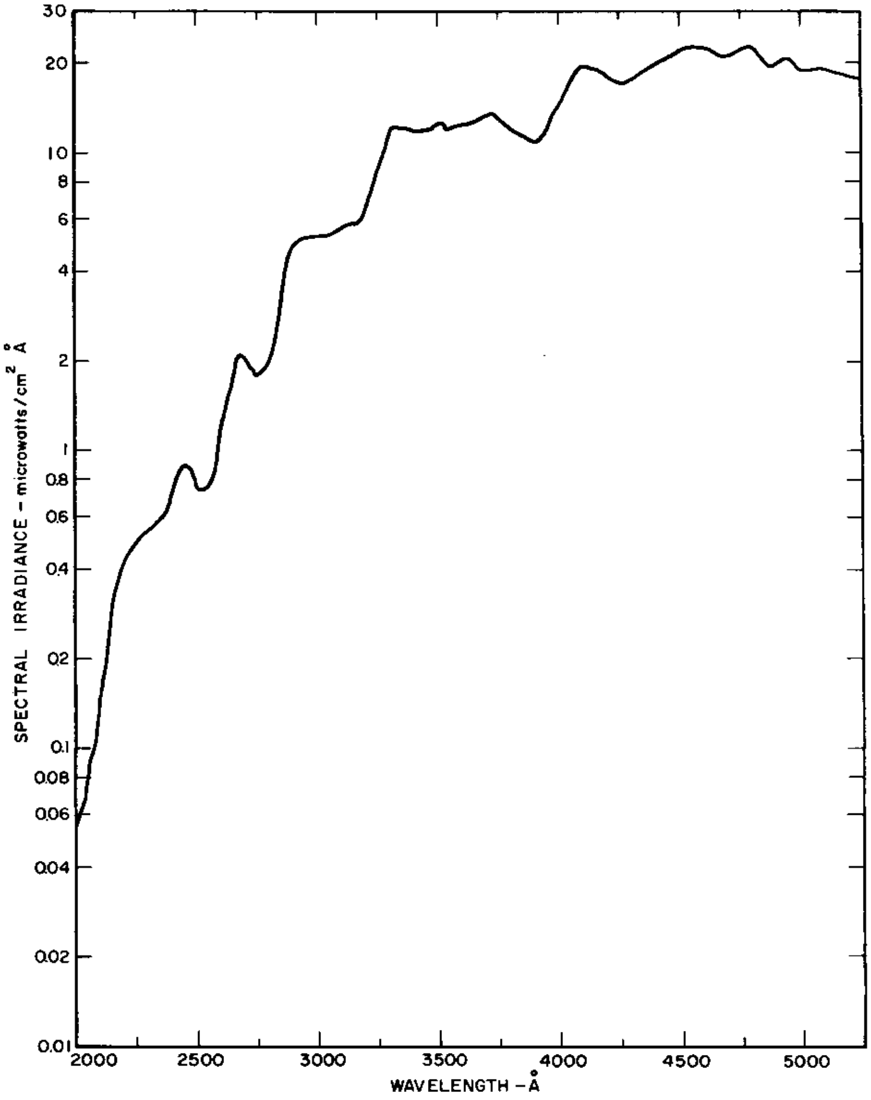

FIG. 2 SPECTRAL IRRADIANCE FROM 2000 - 5500 Å AT TOP OF ATMOSPHERE

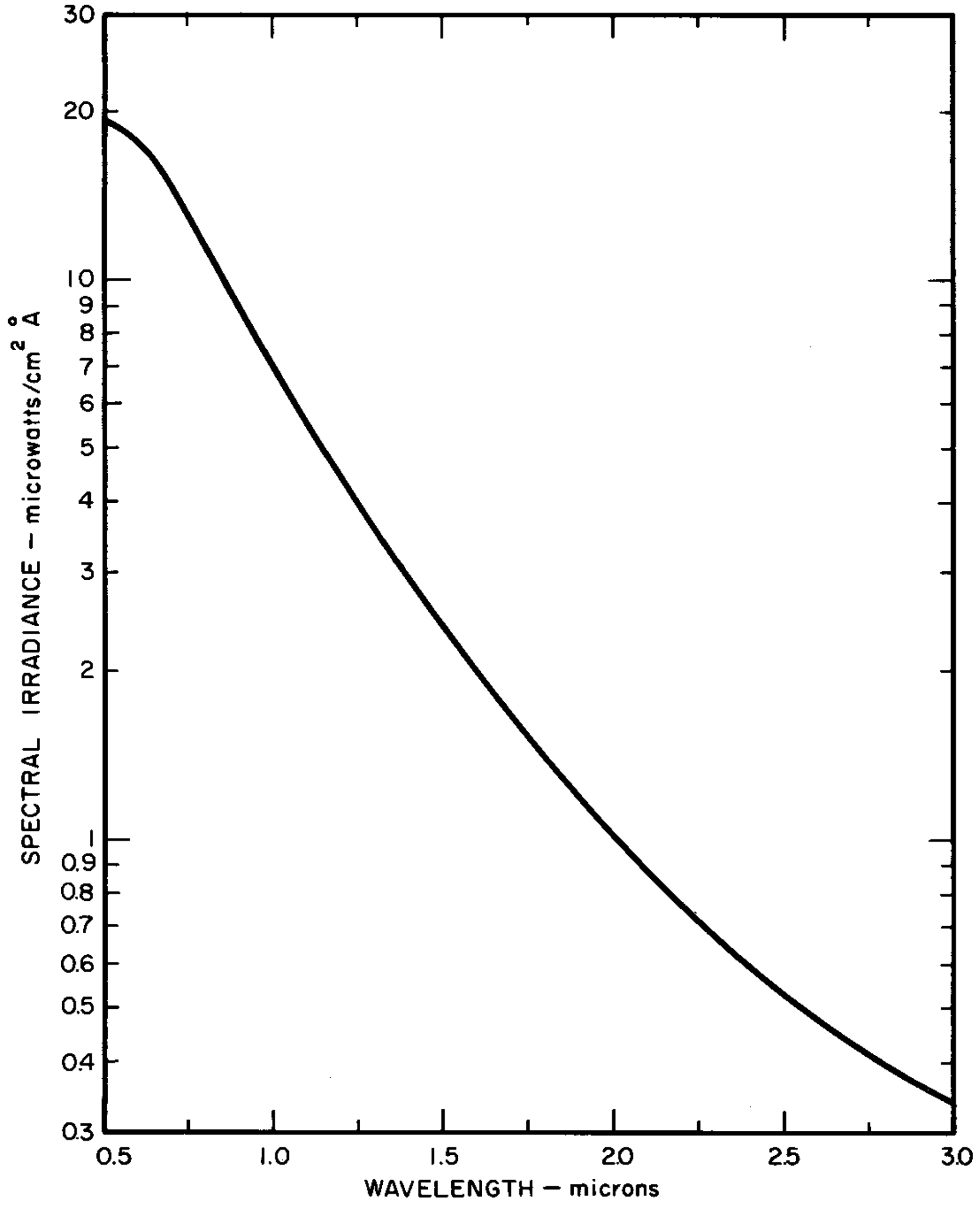

FIG. 3 SPECTRAL IRRADIANCE FROM .525 to 3.0μ

TABLE 1

ENERGY DISTRIBUTION IN THE SOLAR SPECTRUM

Wavelength Intervals (microns)	Percent Energy in Region	Percent Cumulative Energy
0.0 - 0.28	.51	.51
0.28 - 0.315	1.46	1.97
0.315 - 0.400	7.06	9.03
0.400 - 0.510	15.87	24.9
0.510 - 0.610	13.5	38.4
0.610 - 0.700	10.4	48.8
0.700 - 0.92	17.7	66.5
0.92 - 1.12	10.2	76.7
1.12 - 1.40	8.8	85.5
1.40 - 1.9	7.52	93.02
1.9 - ∞	6.98	100.

rocket borne spectrographs. At its short wavelength end this spectrum approaches a 4500°K blackbody curve; however, due to increased absorption in the atmosphere of the sun, such a comparison is rather meaningless.

The spectrum from 3000 Å to 5250 Å is that obtained by Dunkelman and Scolnik (Ref. 4). Their spectra were taken at Mt. Lemmon in Arizona, and were corrected for atmospheric absorption (altitude of observation 8015 ft.). Their results are in good agreement with curves obtained by Stair et al (Ref. 5) and Petit (Ref. 6). The spectra above 5250 Å are based on work done by Moon (Ref. 7) at the U. S. Naval Research Laboratory, which relies on observations by the Smithsonian Astrophysical Observatory.

The principal effects of solar electromagnetic radiation on matter in space will be in the γ, x-ray and u.v. region. The photons corresponding to visible and infrared wavelengths are not energetic enough to cause any effect other than heating. The γ's and hard x-rays act quite like particles giving effects characteristic of energetic primary particles.

2 The Origin of Vacuum Ultraviolet Radiation

Electromagnetic radiation in the approximate spectral range $\lambda 2000$ - $\lambda 100$ may be referred to as the vacuum ultraviolet. Shorter wavelengths are placed in the soft x-ray region while longer ones occur in the far (from the visible) ultraviolet. V.U.V. radiation is emitted when matter is excited into energy states between which transitions can occur and whose energy difference corresponds to the frequency involved.

Thus, using a kilovolt-angstrom conversion factor of 12.395 (Refs. 8,9), one may calculate that the range of V.U.V. wavelengths $\lambda 1500$ - $\lambda 50$ corresponds to an energy range of about 8 - 240 electron volts. The creation of excited states of matter with such high energies is equivalent to producing temperatures of order 10^6 degrees Kelvin.

Matter at such temperatures consists of excited atoms, ions in various stages of ionization, and free electrons. Line spectra arise from transitions involving electrons in bound atomic or ionic states. If one or both of the electronic states lie in the unbound continuum, continuous spectra are emitted by free-bound or free-free transitions. In a given emission source continuum and discrete radiative processes are competitive, although one process may be enhanced depending on the method of excitation and the radiative species involved. Whether the radiated spectrum is discrete or continuous in form, its intensity is determined by the population density of the upper excited state and the transition probabilities involved.

Matter in a sufficiently high state of excitation to radiate in the V.U.V. exists in nature only in high temperature stellar bodies such as the sun. Production of V.U.V. radiative conditions in the laboratory involves either generation of a very hot plasma or the acceleration of high energy electrons. Specific ways of achieving these conditions in practical sources will be described in Section 2.0.

3 The Absorption of Vacuum Ultraviolet Radiation

In considering the development of a source and detector of V.U.V, for simulating solar short wavelength radiation, special attention must be given to the high absorption suffered by such wavelengths in all materials. This prohibits the use of refractive optics or windows below about λ1100 which is the transmission limit of synthetic lithium fluoride. Further, even gaseous media absorb strongly throughout the wavelength range of interest.

λ1500 lies near the maximum of the continuous absorption band which adjoins the Schumann-Runge band system of O_2 between λ1950 and λ1759. Towards shorter wavelengths are further regions of absorption due to oxygen, as well as others due to nitrogen, carbon-dioxide, water-vapour and the rare gases (Ref. 10). Evacuation of air from all experimental apparatus is the only practical way to achieve transparency over these molecular absorption regions. Evacuation is also essential for observations at the short wavelength end of the spectrum of interest, since here the photon energy is such that photoelectric absorption and scattering absorption occur.

Quantitative absorption characteristics of gases for the V.U.V. are meagerly reported in the literature, although the need to work in a vacuum at wavelengths shorter than about λ2000 is well established. The degree of vacuum necessary for reasonable transmission can be calculated from an extension of Beer's Law which states that

$$I = I_o \exp. (-kx) = I_o \exp \left(\frac{-k\ T_o\ LP}{T\ P_o} \right)$$

where I_o is intensity of incident radiation, I is intensity of transmitted radiation, x is the thickness of the absorbing gas at normal temperature and pressure, P is the pressure of the absorbing gas, P_o is the atmospheric pressure, T is the absolute temperature of the absorbing gas, $T_o = 0^oC$, L is the actual thickness of the absorbing gas, and k is the linear absorption coefficient. Using nitrogen data from Weissler et al (Ref. 11) and Victoreen (Ref. 12) the operating pressures listed in Table 2 were calculated. These values illustrate the necessity of evacuating V.U.V. equipment to pressures at least as low as 10^{-4} mm Hg.

Related to the problem of absorption of V.U.V. by residual gas is the phenomena of self-absorption in the radiation source itself. Simply explained, this consists of the absorption of emitted radiation by regions of the source which are cooler, or in lower states of excitation, than the emitting region. The nature and degree of self-absorption will depend on particular source conditions and no generalized statement can be made in this regard.

TABLE 2

DEGREE OF VACUUM REQUIRED FOR 90 PERCENT TRANSMISSION THROUGH 50 CM NITROGEN GAS PATH

	TRANSMITTED WAVELENGTH, λ				
	1306	992	765	304	40
Pressure mm Hg	2.3×10^{-1}	2.2×10^{-2}	5.3×10^{-4}	1.4×10^{-2}	4.5×10^{-2}

4 Optical Techniques in Vacuum Ultraviolet Spectroscopy

The successful development of a source and detector of V.U.V. radiation implies the availability of spectrographic equipment for the discrimination and measurement of V.U.V. wavelengths. This is necessary for establishing both source emission characteristics and detector response characteristics. Leaving aside filter and crystal diffraction techniques, which are not applicable in the wavelength range of interest (λ1500 - λ50), dispersing systems involving prism or grating optics are left for consideration. General references in this area include Sawyer (Ref. 13), Boyce (Ref. 10), and Ditchburn (Ref. 14).

The only prism materials in practical thicknesses available for the V.U.V. region of the spectrum are natural (fluorite) or synthetic crystals of calcium fluoride and synthetic crystals of lithium fluoride. The absorption coefficient of fluorite increases rapidly below λ1250 although good samples of synthetic CaF may be more transparent. Synthetic LiF transmits as thin windows or lenses down to about λ1100 but it is not favored as a prism material due to a tendency for its transparency to decrease when irradiated with short wavelength radiation or when exposed to a gaseous discharge source. Fluorite prism spectrographs have, accordingly, been occasionally used down to about λ1250 (Ref. 15).

The normal incidence diffraction grating, which has the merit of a nearly constant dispersion, has been used quite extensively in the V.U.V. region down to λ500, and under special conditions down to about λ200 (Ref. 16). However, due to the low reflectivity of grating materials (glass, aluminum) at these short wavelengths a practical lower limit of usefulness at λ450 may be taken for normal incidence grating spectrographs. For recent work on reflectance increasing coatings for the V.U.V. reference should be made to the work of Berning et al (Ref. 17).

By taking advantage of the fact that the refractive index of materials for very short wavelengths is less than unity, 'total external reflection' may be achieved if a diffraction grating is illuminated at grazing incidence. The actual short wavelength limit of reflection which may thus be attained depends on the glancing angle of incidence and also on the material and groove form of the grating. Grazing incidence spectrographs are very astigmatic and have nonlinear dispersion. However, they are the only available instruments between about λ20 and λ450 and are often preferred up to λ1000 because of their superior reflectivity. The shortest wavelength recorded at grazing incidence is λ12 (Ref. 18) but the use of this technique below λ50 requires special skill and experience.

Two optical instruments were acquired,on the program being reported,for use in establishing the emission characteristics of the source and the response characteristics of the detector during their development. Both instruments were purchased from the Jarrell-Ash Company, Massachusetts. One of these is the 0.5 meter Seya-Namioka type vacuum monochromator shown in Fig. 4. Equipped with a 30,000 lines/inch replica grating blazed for λ1100 this instrument covers the wavelength range λ3000 - λ500 with a 12-speed reversible scanning drive. It is provided with a 35 mm film camera attachment for photographically recording spectra. The second instrument, shown to the right in Fig. 5, is a 1 meter grazing incidence vacuum spectrograph employing a 30,000 lines/inch original grating. It has a wavelength range from the central image to λ3000 and records spectra photographically with a 35 mm film strip camera.

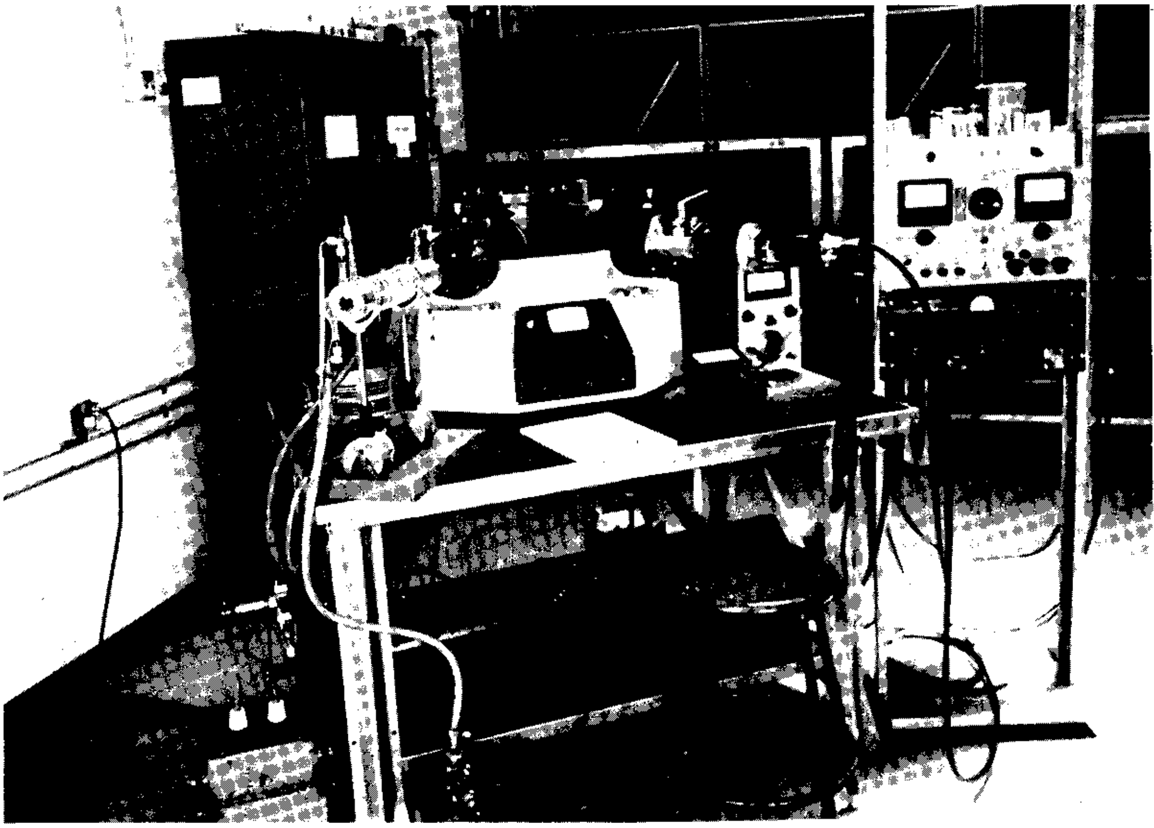

FIGURE 4 SEYA-NAMIOKA VACUUM MONOCHROMATOR AND RELATED EQUIPMENT

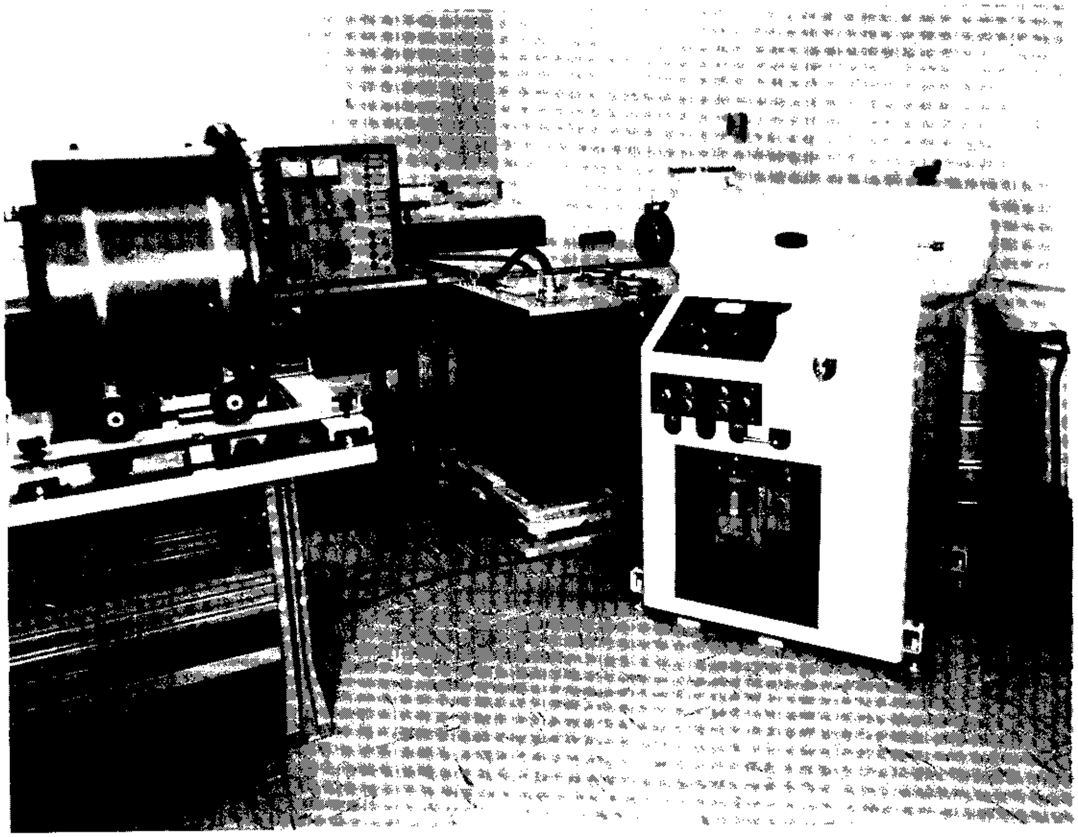

FIGURE 5 GRAZING INCIDENCE VACUUM SPECTROGRAPH AND RELATED EQUIPMENT

II. SOURCES OF VACUUM ULTRAVIOLET RADIATION

Various practical methods of generating the conditions in matter requisite for the emission of V.U.V. radiation have been developed, usually for spectral studies. Some of these, such as the gaseous discharge, are extensions of methods found useful with visible spectra. Others, such as the high voltage vacuum spark, were developed specifically for use at short wavelengths.

While no source-type is ideal, those in use have characteristics which make them acceptable for particular applications. This might be a preponderance of line or continuous radiation, or an enhancement of intensity in a limited spectral range. Various useful types of sources are described in the next sections.

1 The High Voltage Vacuum Spark

If a high voltage is applied between two adjacent metal electrodes in a good (10^{-6} mm Hg) vacuum no breakdown will take place until the electric stress is sufficient for field emission to occur. This is achieved between pointed electrodes at voltages of the order of 50 kV. If the electrodes are connected to a capacitor charged to such a voltage, the resultant spark is very violent and excites the vaporized electrode material into high states of multiple ionization. The resultant emission is predominantly discrete but so profuse that the individual lines coalesce into a pseudo-continuous spectrum. This type of source has been used, for example, by Skinner et al (Ref. 19) to study soft x-ray absorption edges between λ50 and λ500.

2 The Sliding Vacuum Spark

The sliding vacuum spark is essentially a modification of the high voltage vacuum spark in that an insulating material is inserted between the electrodes. Breakdown then occurs at lower voltages with the spark 'sliding' across the insulator surface.

The emitted radiation comes from the material of both the electrodes and the insulator. It is mainly line radiation with some underlying continuum and has been observed by Astoin (Ref. 20) over the range λ1100 - λ80. Further information on this source will be found in Refs. 21 and 22.

3 The Gaseous Discharge

The discharge of electricity through a rarefied gas is a common means of exciting radiation. The discharge may be unidirectional or alternating, continuously applied or pulsed. Line radiation can thus be generated by the excitation of atomic, ionic or molecular states throughout the V.U.V. and even into the region of soft x-rays (Ref. 23).

Of particular interest in the V.U.V. are the emission continua of molecules such as the well known continuum of the H_2 molecule which extends from λ5000 down to λ1600 (Ref. 24). This spectrum arises when the molecule dissociates following transition from a stable upper state to a lower unstable (continuous) state. The continuous spectra observed in rare gas discharges are probably similar in origin (Ref. 25). These continua extend to the long wavelength side of the resonance lines of the atoms concerned and together cover the range λ2300 - λ600.

4 The X-Ray Tube

Probably the best-known generator of short wavelength radiation is the x-ray tube wherein a solid metallic target is bombarded by high energy electrons (Ref. 26). This results in the emission of both line and continuous radiation, the former due to transitions between ionic states of inner ionization. The line radiation is observed from very short wavelengths up into the region of soft x-rays (Ref. 27). The continuous spectrum or Bremstrahlung arises from the deceleration of the bombarding electrons in the fields of the atomic nuclei. Its intensity is effectively limited to the shorter wavelengths (Ref. 28).

5 The Electron Synchrotron

When electrons are centripetally accelerated in an electron synchroton they radiate in the V.U.V. with a continuous distribution of frequencies. Tomboulian et al (Ref. 29) have observed such radiation in the range λ450 - λ60 and it has also been studied by Parratt (Ref. 30). This spectrum has almost ideal characteristics but its application is evidently limited to particular laboratories.

6 The High Current Pulsed Discharge

If a large amount of capacitor stores energy is rapidly discharged through a confined tube containing low pressure gas,a strong continuous emission results known in the V.U.V. as the Lyman continuum (Ref. 31).

Anderson (Ref. 32) studied this type of continuous emission in the visible region of the spectrum and showed that current densities of order 30,000 amps. per sq. cm. are required in the discharge tube. At shorter wavelengths the continuum has been observed by Rathenau (Ref. 33) and Worley (Ref. 34) to extend into the soft x-ray region at about λ100.

III. THE PULSED PLASMA VACUUM ULTRAVIOLET RADIATION SOURCE

Following a review of the various known sources of V.U.V. radiation, as outlined in the preceding sections, it was decided that the objective of the program would be best realized through the development of a high current pulsed discharge type of source.

As the previously referenced work shows, this type of source had been observed to emit through practically the entire wavelength range of interest $\lambda 1500$ - $\lambda 50$. The fact that its spectrum is predominantly continuous would give a greater freedom of choice if particular frequencies were required for radiation studies. The decision was also influenced by the then recent work of Garton (Ref. 35) who built such a source incorporating several new features, particularly in the electrical circuitry.

Accordingly, a design for a source was conceived wherein it is intended to maximize the rate of transfer of energy from the storage capacitor to the discharge tube. It is considered that the V.U.V. continuum emitted from a source of this type results from Bremstrahlung-like processes operative in the high temperature plasma generated in the discharge tube. The achievement of plasma temperatures of order 10^5 ^oK implies current densities in the discharge of order 100,000 amps. per sq. cm. This renders impractical a continuously operating source, a pulsed method being necessary to allow an extremely high rate of energy transfer to the discharge during the short period of the pulse. This, in turn, requires optimum matching of the discharge tube load to the energy storage capacitor which implies a coupling of low inductance between discharge tube and capacitor.

The essential feature of the source under development, referred to as a pulsed plasma V.U.V. radiation source, is that the cylindrical refractory discharge tube is a coaxial extension of the cylindrical storage capacitor. Details of the arrangement are shown in the diagram of Fig. 6, while Fig. 7 gives a general view of the partially completed source with some of its associated equipment.

The coaxial arrangement of source and capacitor ensures minimum inductance in the discharge circuit. It precludes the use of a series trigger such as a spark-gap, but this is desirable from the viewpoint of energy conservation. Instead, the source is triggered directly in the discharge tube in a manner to be described along with other details of the source in the following sections.

1 The Energy Storage Capacitor

The basic requirements for a capacitor to be used to supply energy rapidly to a discharge tube to generate V.U.V. radiation include sufficient voltage to create high energy states, high energy content and low internal inductance. Among the limited choice of capacitors available, that selected as an optimum compromise for the present application is a Model NRG 363-1A, designed by Tobe Deutschmann, and purchased from the Cornell-Dubilier Electric Corporation.

This unit has a capacitance of 2.2 μF and a maximum operating voltage of 60 kV. The maximum energy storage is accordingly 3,960 joules. The capacitor is specially wound to have a low internal inductance of 0.04μH.

The approximate physical size of this 500 lb. cylindrical unit is 18 in. long x 28 in. in diameter. Normally operated on its base, it has been provided with a special oil expansion bellows to allow side operation in the present application. The metal case of the capacitor acts as one terminal, the other terminal being a concentric ring bolt circle in the laminated bakelite front plate. As depicted in Figures 6 and 7, the discharge tube assembly is mounted from this front plate so that the case and its extension are at ground potential. The inner ring bolt circle is then at high positive potential and is connected to the discharge tube anode as later described.

According to the vendor's specifications, the lifetime, L, of the capacitor is 1000 discharges at the maximum operating

Reduce to 9"

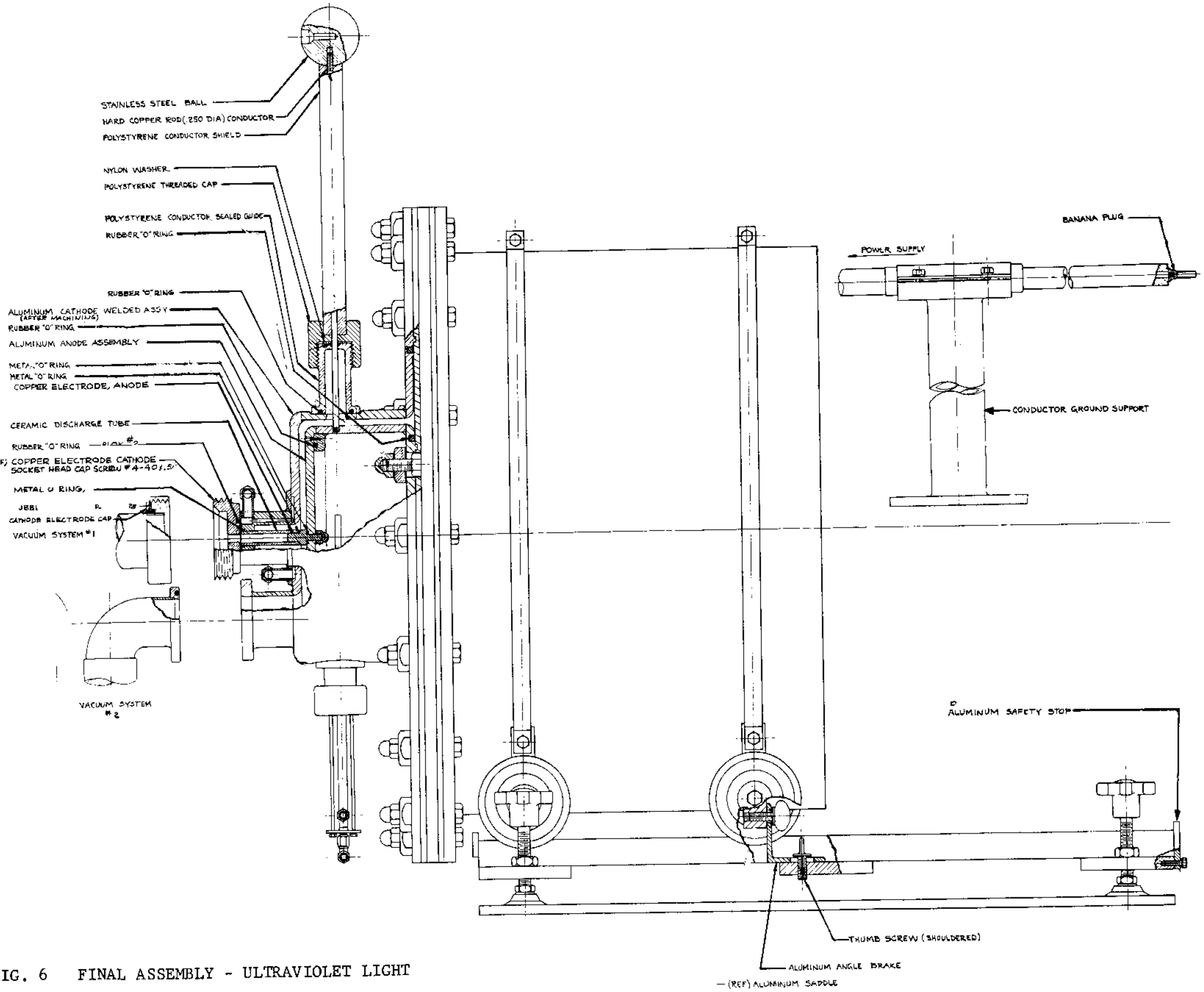

FIG. 6 FINAL ASSEMBLY - ULTRAVIOLET LIGHT

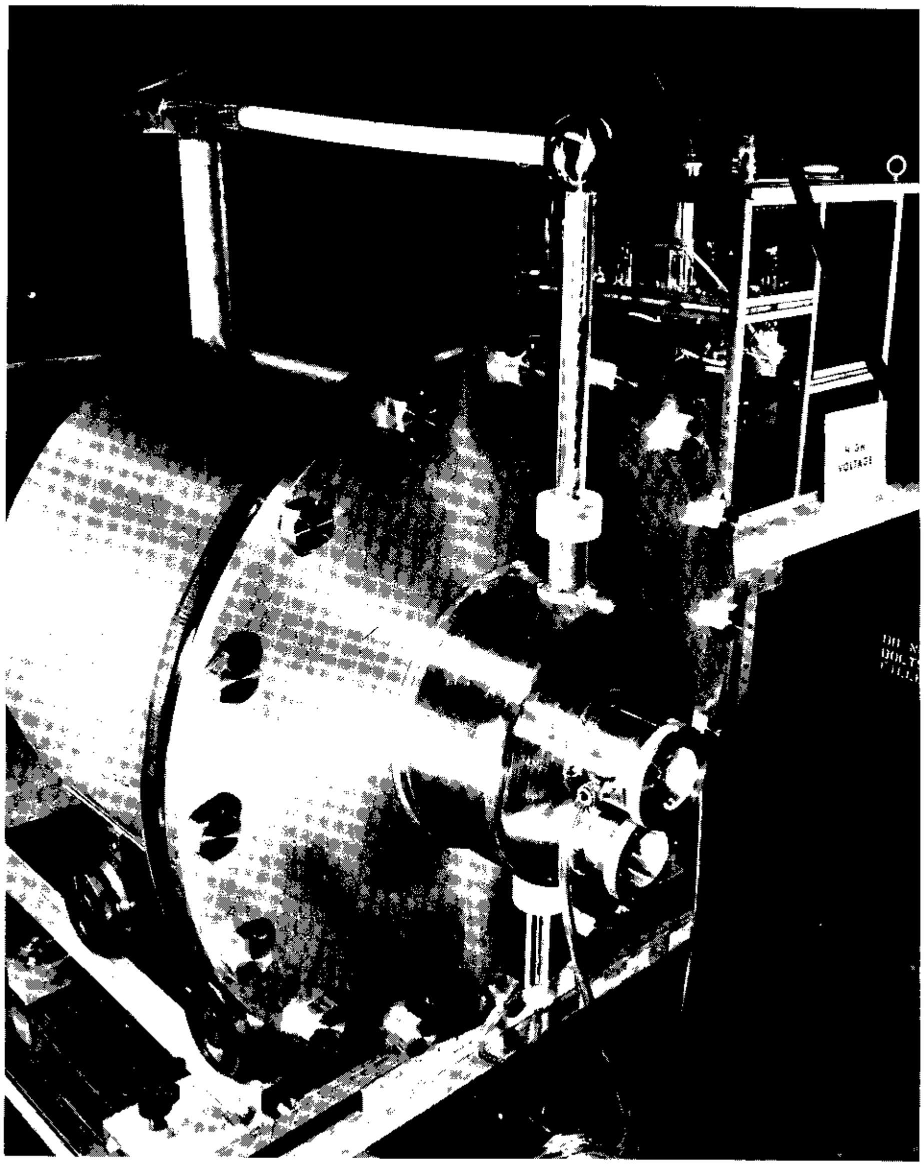

FIGURE 7 PULSED PLASMA VACUUM ULTRA-VIOLET RADIATION SOURCE (PARTIALLY COMPLETED)

voltage V_{max}. At lower operating voltages $V_{op.}$, the lifetime increases according to the relationship

$$L = 1000 \left(\frac{V_{max.}}{V_{op.}} \right)^{5}$$

For $V_{op.} = 50$ kV, which is the designed operating voltage of the pulsed plasma V.U.V. radiation source, L = 2,500 discharges.

2 The Discharge Tube

The internal dimensions of the refractory discharge tube wherein the radiating plasma is generated are about 1 cm. diam. x 5 cm. long. The tube was fabricated by the American Lava Corporation from their special ceramic formulation AlSiMag 614. This material was chosen because of its excellent mechanical, thermal, and electrical properties.

To avoid the consequences of impulsive mechanical shock and thermal expansion during operation, the tube is not rigidly attached to its associated anode and cathode electrodes but rides on expandable metal O-rings. This arrangement may be seen in Fig. 6. These O-rings also provide the necessary impedance to gas flow between the discharge tube vacuum and the insulating coaxial vacuum described in the next section. The high voltage anode electrode is seen to enter one end of the discharge tube while the grounded cathode electrode at the opposite end is of annular form. The radiation leaves the discharge region through the axial hole in the latter electrode.

3 The Co-Axial Structure and Insulating Vacuum

As noted previously, the essence of the present source design is that the discharge tube is a co-axial extension of the storage capacitor. This may be understood by reference to Fig. 6. The inner bolt circle on the capacitor face plate is covered with an anode assembly or cavity to which is attached the anode electrode proper. Concentric with, but spaced from, this anode assembly is a co-axial extension of the capacitor case which terminates on the annular cathode electrode. Evidently, these concentric conducting members carry the discharge current which flows to the discharge tube.

Minimization of inductance requires that the gap between these current carrying members should be closely spaced. Since, just prior to triggering the discharge, these conductors will be at a potential difference of about 50 kV, the lower limit of the inductance is determined by the nature of the dielectric inserted in the co-axial space. In the immediate region of the discharge tube this dielectric material will have to withstand equilibrium temperatures of several hundred degrees centigrade. This results from the high average power dissipation, discussed later. Consequently, it was not possible to find a solid dielectric with the requisite mechanical, thermal, and electrical characteristics to insulate the narrow co-axial gap.

Alternately, it was decided to insulate the gap by creating a vacuum in it. If the pressure in the gap were reduced to 10^{-6} mm Hg, or lower, breakdown can only occur by field emission (Ref. 36) and the effective dielectric strength becomes a property of the electrode material. For this reason, aluminum was chosen as the material of the co-axial members since it possesses an advantageous combination of properties such as high electrical and thermal conductivity, low sputtering rate and low density.

The breakdown fields for aluminum by the phenomenon of field emission range experimentally from about 300 kV/cm (Ref. 36) to 410 kV/cm (Ref. 37) depending on electrode condition, geometry, and spacing. In designing the co-axial structure, the lowest published value for the breakdown field was taken and a safety factor of 3 applied. The required gap sizes were then calculated for the various cross-sections of the conductor and found to have a maximum value of 0.75 cm.

The total inductance of the coaxial connection between capacitor and discharge tube was calculated to be approximately the same (0.04 μH) as that of the capacitor itself.

To evacuate the insulating gap between the co-axial members a pumping system consisting of a Veeco 2" diffusion pump and liquid nitrogen cold trap backed by a Kinney KC-8 will be provided. The volume of the insulating gap is 1.5 liters, the pumping speed at its evacuation port being about 25 liters per sec. at the designed operating pressure of 10^{-6} mm Hg.

4 The Cooling System

It is anticipated that approximately 2 kW of heat will be dissipated in the source when operating at its maximum duty cycle. This heat must be extracted via a cooling system in order that the equilibrium temperatures of the source elements do not exceed tolerable limits.

The cooling system consists of two separate sections which are shown in Fig. 6. One is simple water cooling fed through channels in the grounded cathode in the region of the discharge tube. The other area to be cooled is the anode assembly or cavity to which the anode electrode is attached. Since it is at high positive potential, the anode assembly will be cooled by circulating an insulating fluid such as transformer oil. This will be introduced and extracted from the field-free cavity interior via a coaxial double tube assembly which passes through seals in the walls of the insulating vacuum gap. The oil will be circulated by a 1/100 H.P. centrifugal pump and cooled externally before re-circulation with an oil-water heat exchanger.

5 The High Voltage Power Supply

The D.C. power supply selected for use in charging the energy storage capacitor is Sorenson and Company's Model 2050-50. This unit has an output of 50 mA at 60 kV, the rectifier section being oil immersed with a separate control panel. It is shown in the right foregound of Fig. 8.

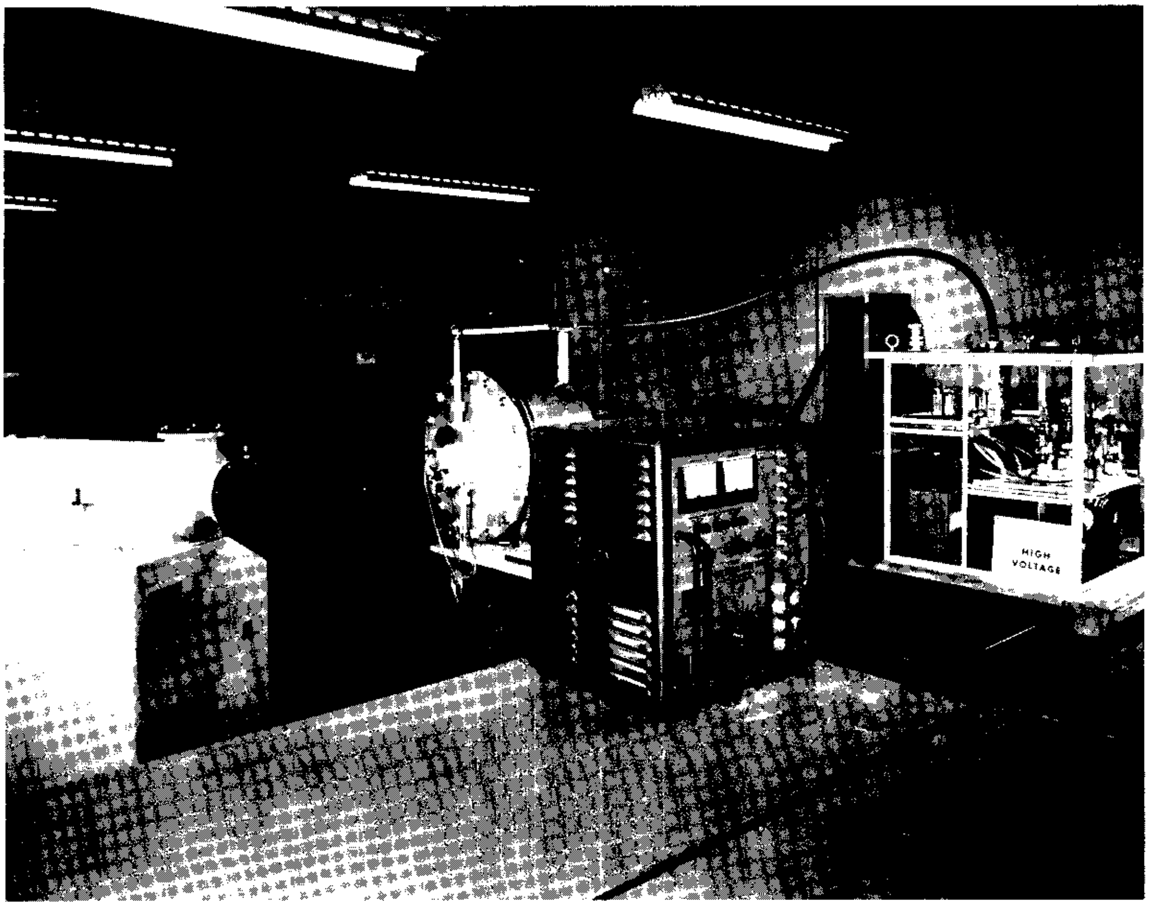

FIGURE 8 HIGH VOLTAGE POWER SUPPLY AND RELATED EQUIPMENT

The high voltage connection between the power supply and capacitor consists of an insulated high voltage cable which plugs into a 2 in. diameter stainless steel ball. This spherical termination is provided to eliminate the possibility of corona losses or air breakdowns and is effectively a connector between the high voltage cable and the rigid conductor which screws into the anode assembly (Figures 6 and 7). This conductor passes through a vacuum seal which is an integral part of a polystyrene stand-off insulating support attached to the grounded cathode assembly. Polystyrene was chosen as the insulator material, not only because of its excellent dielectric strength, but also because of its compatability with the 10^{-6} mm Hg vacuum in the insulating gap (Ref. 38).

6 The Pulsing Mechanism

Several methods of triggering or pulsing a high voltage discharge are known and have been used in past applications (Ref. 39). The simplest method is a series spark gap, but this is wasteful of energy and prohibits the achievement of a low inductance circuit. Alternately, a capacitor or pulse-forming network may be discharged through the primary of a step-up pulse transformer using a thyratron as switch. The pulse transformer is connected to a suitably located trigger electrode which initiates a spark between the main electrodes.

Two non-electrical triggers also have been considered, viz., ultraviolet irradiation of the cathode by an auxilliary source and gas injection. Initially, it has been decided to apply the latter method to the source under development. This decision was influenced by Garton's success with this method (Ref. 35) but also because it offers certain advantages in a source which will finally radiate into an ultrahigh vacuum.

The principle of the gas injection pulse method is simply to apply voltage to the electrodes with the discharge tube evacuated and then to inject sufficient gas into the discharge region to initiate ionization. For the designed electrode configuration, calculations from Paschen's curves (Ref. 36) show that pressures less than about 5×10^{-2} mm Hg are needed to prevent the discharge gap from breaking down.* It follows that, if the discharge region were evacuated to a pressure below 5×10^{-2} mm Hg during the capacitor charge cycle, then breakdown could be initiated at any desired subsequent instant by injecting sufficient gas into the discharge region to cause the necessary instantaneous pressure rise.

By evacuating the discharge volume continuously it is anticipated that the injected gas can be removed with sufficient speed to attain an insulating condition before the capacitor reaches breakdown voltage on the following charging cycle. The pumping system associated with the discharge region will consist of a 3 in. Kinney diffusion pump, with matching liquid nitrogen trap, backed by a Kinney KC-8 mechanical pump. This system will be capable of reducing the pressure from the expected breakdown value to well below that needed for insulation (approx. 10^{-4} mm Hg) in less than 1 second.

During experimental evaluation of the gas pulsing method, the gas will be injected into the discharge region via a narrow (hypodermic needle) tube. This will be connected to a gas tank with suitable control valves. These will be manually operated at first but, if the method is successful, later will be electrically controlled and electronically synchronized with the capacitor charging circuit.

It is important to note that the gas pulse method eliminates the necessity of maintaining a static gas pressure in the discharge volume. This may be a critical factor in enabling a differential pumping system to be designed by which the source could be connected to an ultra-high vacuum (10^{-9} mm Hg) irradiation chamber.

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*These calculations are based on the use of helium as the trigger gas.

7 The Source Pulse Rate

The upper limit on the pulse rate will be determined by the maximum tolerable average power losses in the various elements of the source circuit. These losses may be considered to be effectively localized in the power supply, the capacitor, and the discharge tube. As the pulse rate is increased the losses in these elements will cause a temperature rise which cannot exceed a certain limit without destruction of the element concerned.

Considering the power supply, it has a maximum power rating of 3 kW which is determined by losses in the oil-immersed transformer. It has been calculated that this limit is reached under optimum conditions when the power supply is delivering current at about 58 kV while the capacitor is being charged to 50 kV. The pulse rate under these conditions approaches 1 per sec.

It was indicated in Part III, Section 1 that the energy storage capacitor is rated for 1000 discharges at 60 kV. Discussions with the manufacturer have established that this is a conservative estimate and that 5,000-10,000 discharges are not uncommonly obtained. The lifetime is primarily a function of the electric stress rather than the discharge pulse rate. Little experimental data is available on capacitor discharge performance but the manufacturer has offered the following theoretical expectations of performance based on what data is available.

Operating Voltage	Discharge Pulse Rate	Lifetime
60 kV	1/2 min.	2500 discharges
50 kV	1/sec.	1000 discharges
30 kV	1/sec.	250 hours
15 kV	2/sec.	8000 hours

This data conveys the expectation that the maximum duty cycle for the source operation will not be limited by the capacitor provided a relatively short lifetime is accepted. They are based on the assumption of a 25°C ambient temperature and a 10 C°

temperature rise in the capacitor.

Upon discharge of the capacitor into the source tube most of the stored energy (2750 joules at 50 kV) will be dissipated as heat. If the pulse rate were 1 per sec. this would mean a power dissipation of about 2 kW in the discharge tube region. Since the ceramic tube is a good thermal insulator it is possible that the cooling system cannot prevent it from overheating. The refractory material AlMgSi 614 has a manufacturer's safe temperature rating of 1550°C at continuous heat. Whether this will impose a lower pulse rate than 1 per sec. cannot be pre-calculated but must be established experimentally when the source is operating.

IV. DETECTORS OF VACUUM ULTRAVIOLET RADIATION

When photons are absorbed by matter various interactions can occur leading to such phenomena as photo-conductivity or photo-luminescence. The nature of the interaction depends both on the photon energy and on the chemical and physical state of the material. Resultant phenomena which have been utilized in radiation detectors for the V.U.V. region of the spectrum include the photochemical, photoionic, photoluminescent, and photoelectric effects. The characteristics of such detectors will be described in the next sections.

1 The Photographic Plate

The photochemical effect in the silver halide salts occurs throughout the whole of the V.U.V. region leading to the widespread use of the photographic plate or film as a radiation detector. Due to the high absorption which these wavelengths suffer, the photographic materials must be specially prepared with practically no gelatin in the light path, the halide crystals being dispersed in the surface of the emulsion. V.U.V. emulsions such as Ilford Q and Kodak SWR are available commercially on both plate and film.

The photographic detector is deceptively simple since the spectral information contained in the developed image has to be extracted with some form of microdensitometer. Furthermore, because of their non-linear characteristics, they are difficult to use quantitatively although this is sometimes done (Refs. 27, 40).

2 The Ionization Chamber

Included in this category are both ionization chambers and photon counters since they are fundamentally the same. Their usefulness in the V.U.V. is limited to those regions where transparent windows are available since windows must be used to retain the gas in the sensitive region of the detector where the ionization occurs.

Rogers and Chalklin (Ref. 41) have used a xenon filled Geiger counter fitted with a thin cellulose nitrate window at wavelengths below λ200. Kupperian et al (Ref. 42) and Byram et al (Ref. 43) discuss the use of nitric oxide photon counters and ion chambers fitted with CaF_2 and LiF windows in the range λ1100-λ1350. Evidently there is no ionization detector available for a large part of the wavelength range of interest.

3 The Luminescent - Phototube

Luminescent phosphors are known which convert V.U.V. radiation to longer wavelengths which can then be detected with a photomultiplier tube. The combination is effectively a V.U.V. detector.

The responses of various phosphors to V.U.V. radiation down to λ200 have been studied (Ref. 44; Ref. 45). The most practical phosphor from the present viewpoint appears to be sodium salicylate which has a constant quantum efficiency down to λ850 (Ref. 46). The actual performance of phospor-phototube combinations down to λ900 has been studied by Johnson et al (Ref. 47) and their results indicate that this method has definite merit. However, for quantitative detection work, much more needs to be known about the response characteristics of phosphors to V.U.V. radiation.

4 The Open Phototube

The open photomultiplier tube has been developed specifically to fulfill the need for a direct sensitive detector of V.U.V. radiation. Probably the best summary description of this device is that of Tiutikov et al (Ref. 48) where references to more detailed descriptions are given. Briefly, it is a photo-electron multiplier tube in which the photocathode is exposed directly to the radiation without the use of a window. The photocathode and dynodes have high quantum and secondary-electron yields respectively and, due to their high work functions, they are insensitive to visible radiation. The materials employed for the electrodes are such that the spectral sensitivity to short wavelengths are sensibly unaffected by exposure to air. Platinum or nickel (Ref. 49) are suitable photocathode materials while light-heavy metal alloys such as beryllium-copper have been used for the dynodes (Ref. 50)

This type of detector has been used throughout the extensive wavelength range of λ10-λ2000 which includes the present range of interest.

V. THE OPEN PHOTO-ELECTRON MULTIPLIER DETECTOR

Among the various types of detector of V.U.V. radiation described in the preceding sections the open photo-electron multiplier was chosen for development under the present program.* It is a direct method of detection, sensitive to the entire wavelength range of interest, and one which utilizes well established electronic circuit techniques. Since the radiation source is pulsed the multiplier current output is pulsed. The radiation intensity will be determined by measuring the energy contained in an individual pulse from the multiplier by means of a finite integrator. The following sections describe the various elements of the detector system under development.

1 The Multiplier Tube

The basic multiplier structure consists of 14 dynodes, the first of which will act as the photocathode. This structure was fabricated by the Allen B. DuMont Laboratories, Inc., and is designated as part number SP-206.

Nickel was selected as the photocathode material following a consideration of the findings of Walker et al (Ref. 49) who investigated the photoelectric yields of various metals in the V.U.V. region between λ1400 and λ473. No information is available on the photoelectric

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*After work on the open multiplier detector had commenced Heroux and Hinteregger (Ref. 51) published results of their investigation of the performance of a different type of windowless photomultiplier for the V.U.V. This resistance strip magnetic photomultiplier was developed by the Bendix Aviation Corporation. After consideration of the results obtained by Heroux et al in the range λ304 - λ1250, and following correspondence with the Bendix Corporation, it was decided that this new variation of detector did not offer sufficient advantages to warrant a change in the planned program.

yield of nickel below λ473, a fact which must be taken into account when the detector is calibrated.

Beryllium-copper alloy was chosen for the dynodes because of its relatively high secondary electron yield (Ref. 50) and its high work function (4.2 ev) which makes it insensitive to radiation of wavelengths longer than λ3000 (Ref. 52).

The multiplier structure is held rigid with ceramic supports and, for initial evaluation of its response characteristics, it is mounted in a small vacuum chamber. The various electrical leads are brought out through suitable seals. This chamber is shown in Figure 4 mounted on the right hand exit slit of the vacuum monochromator preparatory to irradiation with light from the hydrogen discharge lamp mounted on the entrance slit.

2 The Finite Integrator

The electrical pulse generated by the multiplier tube will be amplified and passed via a switching circuit into a finite integrator (Ref. 53). This consists, basically, of a circuit whose RC constant is much longer in the reverse direction than in the forward direction allowing its capacitor to build up a net charge. The resultant capacitor voltage is a function of the energy in each pulse and will be measured with a high impedance Keithley Electrometer (Model 610A).

The switching circuit is included to prevent the integrator from integrating noise signals during the quiescent stage of the radiation source operating cycle. This switch will be synchronized electronically with the source pulsing mechanism referred to in Part III, Section 6.

The pulse length and shape delivered by the multiplier tube will determine the characteristics required of the detector amplifiers. These cannot be determined, nor the integrator system completed, until the radiation source is put into operation.

3 Calibration of the Detector

The detector under development is essentially a secondary detector which must be calibrated by comparison with an absolute detector. However, there is no presently known absolute detector of pulsed radiation for the wavelength range λ1500 - λ50.

At longer wavelengths thermal devices such as the thermocouple have been commonly used in detector calibration techniques. The use of a thermocouple technique in the V.U.V. involves the assumption that the thermocouple remains 'black' (i.e., absorbs all radiation and converts it to heat) within the entire region of measurement. Packer et al (Ref. 54) have thus used thermocouples to calibrate a steady source in the region λ2600-λ900. They claim 10 percent accuracy in the range λ1700 - λ1050 and 20-50 percent accuracy outside of it. Wainfan et al (Ref. 55) similarly have used a thermocouple to calibrate a luminescent - photomultiplier detector in the region λ1004 - λ436.

In the thermocouple calibration technique the thermocouple performs a transfer function since it in turn must be calibrated, in the visible region of the spectrum, against a primary radiation standard. The assumption of 'blackness,' or that the thermocouple sensitivity is independent of wavelength, ignores the energy loss due to photo-electron emission at the shorter wavelengths.

For the initial approximate calibration of the open photo-electron multiplier detector under development, advantage will be taken of the published data of Walker et al (Ref. 49) on the quantum yield of nickel in the V.U.V. Their data in turn derive their meaning from the previously mentioned detector calibration of Wainfan et al (Ref. 55).

The finite integrator concept of Part V, Section 2 allows determination of the energy per electrical pulse delivered by the multiplier tube. Let E(λ) be the energy contained in any such electrical pulse when the detector is exposed to radiation pulses at wavelength λ. Then, if Q(λ) is the quantum yield of the detector photocathode, it is permissible to write that

$$R(\lambda) = C \cdot Q(\lambda) \cdot E(\lambda)$$

where $R(\lambda)$ is the radiant energy per source pulse, and C is a proportionality constant involving the multiplier amplification, etc., and which is independent of λ. Since $Q(\lambda)$ is known (Ref. 49) for the material of the nickel photocathode, provided similar cleaning techniques are used, it follows that a relative intensity curve will be available from the product of the $Q(\lambda)$ and $E(\lambda)$ functions.

The outlined approximate calibration procedure will be valid down to λ400, but below this wavelength it will be necessary to extrapolate the $Q(\lambda)$ curve of Walker et al (Ref. 49).

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