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Investigations on the Direct Conversion of Nuclear Fission Energy to Electrical Energy in a Plasma Diode

Report No. 4

Authors

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Report for Period November 1, 1962 to October 31, 1963

General Motors Research Laboratories Warren, Michigan

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ABSTRACT

Experimental determinations are presented of the ion source rate generated by fission fragment ionization of noble gases. The effect of gas pressure (30 - 400 torr) and gas species (argon, neon, xenon and neon: argon) on ion source rate was studied inpile with ionization chamber tubes in which thin uranium foils served as a fission source. (Thermionic electron emission in these tubes was negligible.)

A theory was developed for the ion chamber current-voltage characteristic based on the assumption that the ion density in the plasma between the electrode sheaths was controlled by volume recombination loss. This theory accurately described the shape of the I-V curves. The values of ion source rate determined by the application of the theory to the experimental curves were in reasonable agreement with the values of source rate calculated independently from the ionization energy loss of fission fragments in the gas.

For the pure gases (neon, argon and xenon) the magnitude of ion source rate increased with increasing atomic mass and gas pressure. However for the neon:argon (1000:1) mixture the ion source rate was twice that for pure neon under the same conditions. This effect was attributed to fission fragment energy loss to metastable states of the parent gas (neon) which produced additional ionization of the trace gas (argon) by collisions of the second kind. For a 240 torr filling and a neutron flux of 1.2×10^{13} n sec⁻¹ cm⁻² the ion source rate was of order 10^{10} ions

Under these conditions, the ion density computed for the pure gases (dissociative recombination loss) was $\sim 1.5 \times 10^{11}$ ions cm⁻³. The ion density in neon:argon under the same conditions was estimated to be 8.3 x 10¹¹ ions cm⁻³ and therefore higher than in the pure gases. This was due to the fact that the conversion rate of A⁺ to A⁺₂, necessary to provide A⁺₂ for dissociative recombination loss, was slower in the neon:argon mixture than was the equivalent conversion rate of monatomic to diatomic ions in the pure gases.

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Investigations on the Direct Conversion of Nuclear Fission Energy to Electrical Energy in a Plasma Diode

Introduction

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The use of a fission fragment generated plasma as a space charge neutralizing medium in thermionic diodes has been described in earlier reports.(1) Previous work was limited to inpile experiments involving two gases at two pressures(neon:argon at 20 torr and xenon at 8 torr). Although the plasma generated by fission fragments did enhance electron transport in these tubes, important parameters such as ion source strength and the predominant ion loss mechanism and rates were not readily determinable from the data. An ion number density was inferred from the current-voltage characteristic, but this was obtained only for the two gas-pressure points.

In the last reporting period, ⁽¹⁾ work was begun on a glass ionization chamber (incorporating cold electrodes) which would more readily allow making ion source rate measurements over an extended pressure range and for several noble gases. The results of these experiments have led to the development of a ceramicmetal ionization chamber which has been operated extensively inpile with different gases at several pressures.

The present report discusses the results of these experiments along with a theory developed to explain the I-V characteristic. The theory also yields the magnitude of ion source rate from the data. An independent calculation of ion source rate from fission fragment energy loss considerations is given and comparison is made to the source rate obtained from the data.

The subsequent sections discuss the program Objectives, Conclusions and Future Plans.

Objectives

These were the initial objectives for this reporting period.

- 1. Measurements were to be made of ion number density in fission fragment generated plasmas using a glass ionization chamber. A plasma theory of the diode characteristic based on a random current model suggested that a saturated current characteristic would be observed from which ion density could be calculated.
- 2. The pulsed plasma diode experiment was to be continued to determine ion loss mechanisms from the decay of the discharge. These data were to complement the inpile studies.
- 3. An anomalous low voltage arc discovered in an earlier inpile experiment with a uranium bearing emitter and barium coated collector was to be studied by operating a noble gas diode inpile with a uranium emitter and bare collector to determine the influence or lack of influence of barium on the arc.

As the program developed it became evident that considerable effort was needed in the development, operation and analysis of the ion chamber tubes. It was agreed with the Office of Naval Research therefore to obtain as much data as possible on ion source rate by discontinuing work on items 2 and 3 and devoting maximum effort to the ion source measurements. After data were obtained, it was shown that the random current model did not explain the I-V characteristic of the ionization chambers. This led to increased effort on the development of a new theory that would explain the data. Thus the actual objectives of the work described in this report were the following:

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- 1. Current-voltage characteristics were to be measured with glass and ceramicmetal ionization chambers irradiated inpile. These chambers were to be designed to determine the individual ionization induced by fission fragments and gamma rays.
- 2. A theory was to be developed that would explain the measured current-voltage characteristic and would allow the calculation of ion source rate and ion number density from the data.

Conclusions

The following conclusions were based on the analysis of data from 6 glass ion chambers and 13 ceramic-metal ion chambers operated inpile. The former used neon:argon while the latter used neon:argon and pure gas fillings of argon, neon and xenon.

- 1. Data from the glass ion chamber in which the electrodes were immersed in the gas were difficult to analyze in detail due to the contribution to current from the ionization in the gas volume external to the electrodes.
- 2. The observed I-V characteristic for both types of tubes was not as predicted by the earlier random current plasma model. According to this model the current should saturate at less than one volt applied potential.
- 3. The use of a ceramic-metal tube structure immersed in an insulating oil (monoisopropylbiphenyl) allowed measurements of very low ionization currents (10-8 amps) with negligible leakage currents external to the diode volume.
- 4. A new theory of the I-V characteristic has been developed which accurately fits the data and yields an experimental value for an average ion source rate. The plasma was considered to be recombination controlled with current primarily collected from the sheath at the negative electrode.
- 5. The measured neutron flux dependency of current (at fixed voltage) fits that predicted by theory.
- 6. The saturation current observed in neon at low neutron flux was also predicted by theory. This corresponds to the negative electrode sheath extending across the entire diode gap.
- 7. The pure gases (argon, neon, xenon) did not show any electron multiplication effects out to 100 volts whereas the neon:argon tubes exhibited multiplication at 25 volts. The I-V theory in the latter case fit the data very well below 25 volts. The high multiplication rate in neon:argon was not surprising since the gas mixture used (0.1% A) has a high Townsend ionization coefficient at the values of E/p in the sheath.
- 8. The ion source rate due to gamma ionization (for the particular ratio of gamma to neutron flux in this experiment) was from 1 to 2% of that observed due to fission fragment ionization.
- 9. Values of ion source rate obtained from a least squares fit of theory with experiment are listed for 240 torr pressure and a neutron flux of 1.2 x 1013 n sec⁻¹ cm⁻².

Neon	-	0.75×10^{16} ions sec ⁻¹ cm ⁻³
Argon	-	1.7 x 1016
Xenon	-	4.0 x 1016
Neon:Argon	-	1.5×10^{16}

- 10. The higher ion source rate observed for the neon:argon tube compared to pure neon at the same pressure was attributed to the creation of neon metastable states by fission fragments and the subsequent generation of argon ions by neon metastables. This suggests that higher ion source rates can be generated in gas mixtures where the fission fragment energy loss to metastable states of the parent gas may be used to produce additional ionization of the trace gas.
- 11. The ion source rate as a function of position in the gas has been derived from fission fragment energy loss rate considerations. The earlier derivation for an average source rate was in error. Taking account of the finite geometry of the fissioning source in the ion chamber leads to a reasonable agreement between this independently computed value of source rate and that determined from the data.
- 12. Typical data at 240 torr pressure of the ion number density computed from the measured source rate and the appropriate recombination coefficient for the pure gases and a three body loss mechanism for neon: argon is tabulated for a neutron flux of 1.2×10^{13} n sec⁻¹ cm⁻².

Neon	-	1.8×10^{11} ions cm ⁻³
Argon	-	1.7×10^{11}
Xenon	-	1.4×10^{11}
Neon:Argon	-	8.3×10^{11}

These data for a fixed flux and gas pressure show that the neon:argon mixture provides the highest ion density.

Future Plans

- 1. Experiments will be continued inpile to measure ion source rate generated by fission fragments as a function of gas pressure and neutron flux. The ceramic ion chamber already developed will be used to complete the data now being taken for xenon, neon, argon and also for cesium. The theoretical analysis of the diode characteristics will be continued.
- 2. The electron transport through a noble gas plasma as a function of gas pressure will be measured inpile using a diode with thermionic electron emission from a uranium bearing electrode. A diode will be designed which would provide good control over important parameters such as collector area and electron emission of the emitter. The electron transport data in conjunction with the ion source rate data should provide a basis for developing a more complete analysis of the noble gas plasma thermionic energy converter concept.

References

 Investigations on the Direct Conversion of Nuclear Fission Energy to Electrical Energy in a Plasma Diode, 1962 Annual Report ASTIA AD No. 290 727; R. J. Donohue, F. E. Gifford, R. F. Hill, F. E. Jamerson (Editor), C. B. Leffert, R. F. Majkowski.

Acknowledgments

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Technical assistance in the design and fabrication of the tubes and inpile test system has been given by Messrs. R.Aikin, A.Dolenga, R.Dusman, R.Knoll and J. Palazzolo.

SECTION A

A STUDY OF THE FISSION FRAGMENT IONIZATION OF NOBLE GASES WITH THE G12x-R TUBES

ABSTRACT

A series of glass ionization tubes were operated in the University of Michigan nuclear reactor in an attempt to measure the ion source rate and the ion number density produced by the fission fragment ionization of neon gas seeded with 0.1%argon, as a function of gas pressure (30 torr) and with minimal thermionicemission from the electrodes. It was found that the observed current-voltage characteristics did not agree with the shape predicted from the random current-plasmasheath model developed previously.

The ion source rate calculated from the measured current (at a pressure of 220 torr and a neutron flux of $5 \times 10^{12} \text{ cm}^{-2} \text{ sec}^{-1}$) using this theory gave a value less than one half the source rate predicted for primary neon ionization (dNe⁺/dt = $9.8 \times 10^{15} \text{ cm}^{-3} \text{ sec}^{-1}$) using a fission fragment energy loss rate calculation. The source rate of neon metastable states (which can ionize argon atoms) is not known so that setting the estimated volume loss rate equal to the difference between the neon ion source rate and the collected current gave a minimum value of the ion density in the bulk of the plasma (N⁺) min = $3.65 \times 10^{11} \text{ cm}^{-3}$.

During operation in the reactor it was found that these glass ionization tubes were not well suited for a detailed experimental study of ion source rate. Two of the tubes failed internally from broken leads and, in addition, the analysis of the data was complicated (particularly at low neutron flux) by a weak gamma induced plasma in the gas outside the electrodes (but inside the tube).

Even so, it could be inferred from runs with a cadmium shield that the contribution to the ion source rate from gamma rays was small ($\sim 10\%$) compared to fission fragment ionization. Also, electrons released by fission fragment emission from (and penetration of) the electrodes were discovered to be the primary current component in the I-V data from a vacuum chamber.

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Previous studies on the thermionic direct conversion of heat to electricity using the concept of the fission fragment ionization of noble gases have used hot electron emitters.⁽¹⁾ While thermionic emission is basic to such a direct conversion device it complicates the analysis of the data when attempting to optimize such parameters as gas type and pressure. In order to make a parametric study of the gas pressure on the ion density produced by the fission fragment ionization of a noble gas, a specially designed ion chamber type glass tube, Gl2x-R, was constructed. The details of the tube and containment can design and the plasma-sheath theory pertaining to these studies have been described previously.⁽²⁾ A total of 6 tubes were constructed and tested in the University of Michigan reactor (see Table 1). This report presents the results and conclusions of the inpile runs on the Gl2x-R tubes.

TABLE 1

Listing of Gl2x-R Tubes

Tube No.	G12x-R No.	Gas and Pressure, Torr	Remarks
0	R.0	Не 760	Glass stem only
1	R.2	Vacuum	0.3 gm U-235
2	R.3	Ne:A 20	0.3 gm U-235
3	R.4	Ne:A 60	0.3 gm U-235
4	R.5	Ne:A 220	0.3 gm U-235
5	R.1	Ne:A 400	0.3 gm U-235
6	R.6	Ne:A 230	No U-235

DESCRIPTION OF TUBES AND CIRCUIT

The design of the Gl2x-R tube has been described in detail in a previous report $\binom{2}{2}$ and only a brief summary will be presented here. A drawing of the tube assembly in the aluminum containment can is shown in Fig. 1 and a photograph of the tube in Fig. 2.

Electrode Design

The electrode design consisted of parallel plane geometry with a guard ring to minimize fringing fields and a collection area large enough to give measurable ion currents. The pertinent electrode dimensions are shown in Fig. 3 and the electrode areas are listed in Table 2.

Electrode	Area, cm ²
1	6.75
'2	3.86
G (U covered)	3.44
G (peripheral)	2.90
G (total)	6.28

TABLE 2

Uranium-235 was applied uniformly to the inside electrodes to give equal and uniform work functions. The uranium was kept to a minimum thickness so that the maximum temperature would be such as to ensure negligible thermionic emission...

The electrodes were assembled as a unit on three sapphire rods and mounted on a 9 pin Corning 1720 aluminosilicate glass press. The electrodes were reactor grade zirconium with the uranium-tantalum foil combination bonded to the planar surfaces. Thermocouples of Ni-Mo were spot welded to each of the three electrodes. The nickel leg of the thermocouple also served as the electrode current carrying lead. The cold junction of these thermocouples was at the glass press temperature. The cold junction temperature was monitored by a Kulgrid-constantan thermocouple where the Kulgrid lead to a molybdenum feed through wire was used as one leg of this

Containment Can Design

The containment can (Fig. 1) was an all-heliarc-welded aluminum assembly with a ceramic-metal feed through soldered to the aluminum flange. The flange was copper plated to provide a good soldering surface. The containment can was heliarc welded to a 4 foot section of aluminum tubing which was connected to the 20 foot support tube by a gasketed flange (located 2 feet above the core and water shielded). This support tube carried all the electrical wiring and was pressurized with nitrogen gas as a further safeguard to prevent water leakage.

Cadmium Shield Design

In order to determine the gamma ray contribution to the ion production rate in the plasma, a cadmium shield was constructed to completely enclose the aluminum containment cans. This shield consisted of two parts as shown in the drawing in Fig. 4: (1) a cadmium basket which was lowered directly into the reactor grid and into which the aluminum containment can was lowered and (2) a set of cadmium cones which were attached to the 4' section above the containment can. Photographs of the cadmium basket and cones and containment can are shown in Fig. 5.













Figure 5(a) - 4 ft. aluminum containment can with lead weight on bottom.
 (b) - Cadmium basket and split cadmium cone.
 (c) - Cadmium basket and cone in place around 4 ft. aluminum can.

Electrical Circuit

The basic circuit used to obtain the reactor I-V data is shown in Fig. 6.

Figure 6 - Basic circuit for I-V Measurements.

Current meters I₁, I₂ and I₃ measure current to each electrode and I₃ measures the current to ground. In the first runs meters I₁ and I₃ were not used and in some runs V₂G was not connected. The floating circuit is illustrated by the open switch in Fig. 6.

Current meters I₂ and I_G were Hexem battery operated E-I-R meters, Model No. 110B, and measured the current to electrodes 2 and G. The maximum voltage drop across these meters was 100 mv at full scale. V_{12} and V_{2G} were Keithley battery operated electrometers, Model No. 600A, with an input impedance of 10¹⁴ ohms. V12 was used with a 10/1 voltage divider probe with an input impedance of 10¹⁰ ohms. The current meter, I₃, was a Hewlett Packard 425A milli-microammeter. The Keithley 600A electrometer was used as a current meter to electrode 1.

The battery operated meters I_2 , I_G and V_{12} together with the bridge circuit and battery power supply were placed in a shielded console to minimize ac pickup and shielded cable was used from this console to the top of the 20 foot tube on the reactor bridge.

Polarity convention for the data obtained using this circuit is shown in Fig. 7.

Figure 7 - Polarity convention with typical I-V curve.

Positive polarity: Voltage of 2 and G positive with respect to 1 (ions collected by 1, electron collected by 2 and G)

Current (conventional) flows from 2 and G to 1

Negative polarity:

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DATA SUMMARY

In this section typical inpile current-voltage curves are presented for each of the tubes tested. The general characteristics of these curves are discussed and a more detailed analysis of these data is presented in a later section.

Each of the tubes containing uranium was run with ("Cd shielded") and without ("Bare") the cadmium shield described previously and at the reactor power levels of 10, 100, 500, and 1000 kw. An absolute neutron flux measurement was made with a mockup of the tube assembly using a gold foil activation technique. The value of the thermal neutron flux at the uranium coated electrode position was 5×10^{12} sec⁻¹ cm⁻² at 1000 kw reactor power.

The curves selected for presentation include $I_2 vs V_{12}$ and $I_G vs V_{12}$ for both the bare and cadmium shielded runs at 1000 kw reactor power. Also presented for each power level are the curves for the fission fragment contribution to the total measured current versus the voltage, that is, $I_{AT} vs V_{12}$ where $I_{AT} =$ $I_T(Bare) - I_T(Cd)$ and $I_T + I_2 + I_G$. These data curves are compiled in the Appendix and discussed individually in the text.

Tube O (Leakage Test)

To obtain a measure of leakage currents between current carrying leads due to ionization of the gas (helium) in the containment can, a glass press was loaded into a containment can and operated under a variety of conditions. The ends of the press leads (envelope side) were cut and shorted corresponding to their condition in an actual tube. These leads were uncoated. The can was sealed with one atmosphere of helium identical to the other tubes. The mockup assembly is shown schematically in Fig. 8. One of the Kulgrid leads of the press was found to be in contact with the aluminum cap which itself was insulated from the can.

Figure 8 - Schematic of leakage test assembly.

The assembly consisted of four effective electrode surfaces whose areas were in the ratio:

$$A_{c} > A_{c} > A_{c} > A_{2} \sim A_{1}$$

where C = aluminum can, G = "guard" electrode + aluminum cap and 1 and 2 refer to electrodes "1" and "2".

Electrodes "1", "2" and "G" correspond to the wires on the evelope side of the press spot welded together as pairs corresponding to these electrodes. The current-voltage characteristics obtained for both positive and negative voltage polarities were found to be asymmetric for each electrode pair combination when the circuit was grounded and when it was floating. The magnitude of these leakage currents was negligible, however, compared to the ion currents measured at higher reactor power levels. Nevertheless, the asymmetry of the curves and the differences with circuit grounding could not be readily explained and consequently further work was undertaken with the leakage test assembly in an attempt to gain a fuller understanding of these I-V characteristics in terms of the weakly ionized plasma surrounding the assembly. Examples of the I-V curves are given in Figs. 0.1 to 0.4 in the Appendix.

The ratio of currents measured at + 100 volts on tube 0 are listed in Table 3. Each current ratio represents the mean of five determinations made at reactor power levels of source level (reactor in shut down conditions), 10, 100, 500 and 1000 kw.

TABLE 3

Average Current Ratios for T-O

Current Ratio at + 100 volts	Circuit Grounded	Circuit Floating
I.G. I.2.	5.9	16
$\left \frac{\mathbf{I}_{G+}}{\mathbf{I}_{2+}} \right $	39	35
<mark>I₂₋</mark> ₂₊	10	14
$\left \frac{I_{G-}}{I_{G+}} \right $	2.7	5.6
	1.9	4.5

It is seen from the above table that the values (39 and 35) of I_{G+}/I_{2+} are nearly the same for the gounded and floating connections. Likewise, the floating and grounded circuit values for $|I_{2-}/I_{2+}|$ are roughly equal, but the values for $|I_{G-}/I_{G+}|$ are significantly different. It was concluded that the current to electrode "2" was relatively insensitive to this change in circuit, and that the current, Ig., decreased when the connections were changed from the floating to the grounded circuit. Figure 9 illustrates the connections.

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Figure 9 - Schematic of current control for grounded and floating connections.

The connection to ground was made at the IG meter. The containment can C was always grounded in the water. For "G" negative, C is negative and ions are collected by both C and "G". However since $A_C > A_G$ more ions are collected by C and with the electrons returning through ground the net current through I_G is reduced. When "G" is positive, ions are collected by 1 and grounding the circuit has little effect on measured currents since the controlling ion collection surface area is not effected by this circuit change.

The floating circuit data at + 100 volts were used to determine approximate area ratios where it was assumed that the measured current was directly proportional to the ion collection area,

$$\frac{I_{G}}{I_{2-}} = \frac{A_G}{A_2} = 16$$

$$\frac{I_{T+}}{I_{T-}} = \frac{A_1}{A_G + A_2} = \frac{1}{4.5}$$

$$A_G = 16 A_2$$

$$A_G = 4.2 A_1$$

$$A_1 = 3.8 A_2$$

Area ratios of this magntiude are possible with the exposed surfaces in this assembly.

Tube 1 (Vacuum)

Tube 1	was	a vacuum	tube with	uranium	coated	electrodes.	Measured	electrode
temperature	s are	e given in	n Table 4,					

	T	ABLE 4		
Power Level, kw	Cold Junction on Stem - °C	Electrode 1 °C	Electrode 2 °C	Guard °C
100	100	263	257	244
500	113	503	500	446
1000	198	650	650	581
1000 with Cd	56	228	223	203

These temperatures indicate that thermionic emission from the uranium was negligible in comparison to the measured ion currents.

The I-V characteristics measured under bare and cadmium covered conditions are given in Figs. 1.1 and 1.2. The net current, due to thermal neutrons, is compiled for several power levels in Fig. 1.3.

The current measured can be readily explained by reference to Fig. 10. The arrows indicate that each uranium surface can contribute 3 components of current: IF due to fission fragments, IF due to electrons emitted simultaneously with the fission fragment⁽³⁾ and IS due to secondary electrons generated by the fragments striking the opposite electrode.

Figure 10 - Currents generated in vacuum from 2 fissioning uranium electrodes.

If the electrons produced have energies in the few electron-volt range, one pair of electron currents will be retarded for a given applied potential. The data of Fig. 1.3 agree with this model since the current is saturated beyond 30 volts indicating a relatively low energy spectrum from the neutron induced currents. That this current is primarily due to IF and IS is determined by calculating the expected fission fragment current. For a thickness greater than one fission fragment range, the current escaping from a uranium bearing electrode due to the remaining positive charge on the fragment is given by*

$$\mathbf{I}_{F}^{+} = (\Sigma_{f}^{FA}) \frac{1}{8} e \sum_{j=1}^{L} Z_{0j} R_{1j} = (\Sigma_{f}^{FA}) \frac{1}{4} e \bar{Z}_{0} \bar{R}_{1}$$
(1)

* See derivation in Section C of this report.

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where $e\overline{Z}_{e}$ = average initial charge for a fission fragment

 $\Sigma_{f} = \text{fission cross section, 23.1 cm}^{-1}$ $\overline{R}_{1} = \text{average range of the fragment in U-Ni foil, 6.75x10}^{-4} \text{cm}.$ $F = \text{thermal flux, 4 x 10}^{12} \text{ sec}^{-1} \text{ cm}^{-2}$ $A = \text{electrode area, 7 cm}^{2}$

These values yield a current for I_F of 3.67×10^{-7} amps for a 1000 kw power level. From Fig. 1.3 saturated currents of 6.8×10^{-6} and 7.8×10^{-6} amps were measured. Thus the I_F components from Fig. 10 are small compared to the saturated currents from Fig. 1.3 and thus the current measured is primarily due to I_F and I_S . The currents for positive, I(+), and negative, I(-), polarities of Fig. 1.3 are

$$I(+) = I_{F}^{-}(1) + I_{S}^{-}(2 + G)$$

$$I(-) = I_{F}^{-}(2 + G) + I_{S}^{-}(1)$$
(2)

and

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The 1 and (2 + G) refer to the electrode designations defined earlier. For the 1000 kw data the ratio of $I(-) = \frac{7 \cdot 8}{1(+)} = 1.15$. This ratio should be > 1 providing $I(+) = \frac{1}{6.8} = 1.15$.

that $I_{F} > I_{S}$, since the uranium loading is larger on (2 + G). The appropriate area (or uranium) ratio is 7.24 = 1.07.

The saturated current characteristic for the electrons from fission fragment ejection and bombardment (Fig. 1.3) is indicative of an electron energy distribution, where most electrons have less than 40 volts kinetic energy. The saturated currents are a measure of electron sources independent of space charge effects since space charge limited currents for the diode would be of order 15 ma. To evaluate the $I_{\overline{F}}$ and $I_{\overline{S}}$ components independently, a single uranium electrode is required (as presently being studied with ceramic-metal diodes).

The data of Fig. 1.2 do not exhibit any saturation over the voltage range of + 100 volts and show that the photoelectrons produced by gammas have an energy distribution which exceeds the maximum of 100 volts applied to the tube. Photoelectrons can of course have kinetic energies of many Mev. The small inflexion near zero volts may be indicative of a secondary electron distribution from the electrodes caused by Mev electron collisions with the electrode.

Tube 2 (20 Torr)

This tube was filled to a pressure of 20 torr with Ne:A (1000:1). Temperature data are given in Table 5. The thermocouple to the guard electrode was open inside the tube and could not be used.

Power Level, kw	Cold Junction on Stem - °C	Electrode 1 C	Electrode 2 °C
100	48	128	145
1000	172	337 502	400
1000 with Cd	71	159	160

Typical characteristics of this tube are shown in Figs. 2.1 - 2.3. The currents are asymmetric for both bare and cadmium covered conditions as well as for the net current data.

The asymmetry can be attributed to electrode 1 collecting only a small fraction of the ion current relative to the 2 + G combination. It was initially felt that a leakage to ground or a 'dirty' electrode 1 were the cause of the asymmetry.

Measurements were subsequently repeated with a current meter to ground (I_3) . These data are shown in Fig. 1.4 which shows a more pronounced breakdown in the negative quadrant. The current to ground (I_3) is seen to be small in this case.

An attempt was made to clean up a possible 'dirty' electrode using a discharge created in the interelectrode gap with a current of 4 amps at 100 volts. Electrode 1 temperature increased to around 900°C. The I-V data after breakdown, however, were again asymmetric similar to Fig. 1.4.

Additional operation indicated that a short had developed between electrodes 2 and G and measurements were terminated on this tube.

Subsequently the tube was disassembled in a hot cell where an open connection was discovered between electrode 1 and its thermocouple, one side of which also served as a current carrying lead. The thermocouple was still intact, although disconnected from electrode 1, and was sufficiently close to the electrode to provide a fairly high temperature reading. A mockup test had been made in the laboratory with a thermocouple suspended just above an electrode but the results were inconclusive.

At positive polarity of the I-V data, the thermocouple wire served as an ion collector. Since it had a small area and resided in the region of the plasma created primarily by gamma radiation, the currents in this quadrant were small. In the negative quadrant the free thermocouple collected electrons which had a much higher mobility than the ions collected by electrodes 2 and G. Thus electrodes 2 and G controlled current flow. Breakdown subsequently occurred possibly from the sharp ends of the thermocouple.

Tube 3 (60 Torr)

This tube was filled to a pressure of 60 torr with Ne:A (1000:1). Temperature data are given in Table 6.

TABLE	6
	U.

Power Level, kw	Cold Junction on Stem - °C	Electrode 1	Electrode 2 °C	Electrode G °C
100	40	127	137	133
500	103	351	383	354
1000	160	516	561	510
1000 with Cd	70	186	199	194

Typical data for this tube are shown in Figs. 3.1 to 3.3. An asymmetry of current is again apparent similar to that found using tube 2 (20 torr). Although tube 3 was not disassembled after inpile operation, it was considered that the marked similarity in the data between tube 2 and tube 3 was sufficient evidence to conclude that a connection to electrode 1 had also broken loose on tube 3 and was the cause of the current asymmetry. The I-V characteristics obtained using tube 3 are discussed below with reference to Fig. 11.

Figure 11 - Equivalent circuit for tube-3.

With a broken lead above electrode 1, the current measured to $l(I_1)$ must be traced through the weak gamma induced plasma at the end of the broken lead as well as through the interelectrode plasma. The I-V characteristics taken with electrode G floating are shown in Fig. 3.4. In this case the value of $I_1(=I_2)$ was about 20% less than the value of $I_1(=I_2+I_G)$ when both 2 and G were collecting current $(V_{12} = 0)$. When electrode G was floating, the potential of G followed closely the potential of 2. When electrode 2 was positive (with respect to 1) and collecting electrons, G was slightly negative with respect to 2; thus the low electron field between G and 2 would be capable of diverting some of the plasma electron from G to 2. When electrode 2 was negative (with respect to 1) and collecting ions, G was positive with respect to 2; this would have the effect of diverting some of the plasma positive ions from G to 2.

The voltage across this tube was raised until electrical breakdown occurred with high currents similar to the breakdown studies on Tube 2. The characteristics observed before and after breakdown are shown in Figs. 3.5 and 3.6 respectively. The current to I_1 appeared the same before and after bombardment; however, I_2 and I_G were bigger in magnitude corresponding to a substantial increase in circulating

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current. In order to measure this circulating current, a resistive load was placed across electrodes 2 and G and the characteristic of Fig. 3.7 was observed. This circulating current between electrodes 2 and G was possibly due to evaporation of uranium from one of the electrodes. This could provide a substantial dissimilarity in plasma source in the vicinity of the small gap between 2 and G.

To determine the effect of electrode 1 on current collected between electrodes 2 and G, the currents I_2 and I_G were measured as a function of V_{2G} with the circuit floating and, $V_{12} = 0$, and at $V_{12} = +20$ volts. These data are shown in Figs. 3.8 and 3.9 which are identical. I_2 and I_G are symmetric around V = 0 and $I_2 = -I_G$ indicating that plasma current was being collected between electrodes 2 and G and that the potential to electrode 1 did not affect the current collection between electrodes 2 and G (because of broken lead to 1). Similar results were observed in Fig. 3.10 which was taken with the tube covered with the cadmium shield and consequently at lower current levels. These data also support the earlier statement that the connection to electrode 1 was broken in similar fashion to that of Tube 2.

Tube 4 (220 Torr)

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This tube was filled to 220 torr of Ne:A (1000:1). The electrode temperature data from the inpile runs are given in Table 7.

Power Level, kw	Cold Junction on Stem - °C	Electrode 1 °C	Electrode 2 °C	Electrode G
10	23	35	35	35
100	53	151	144	137
500	118	392	361	333
1000	158	572	532	478
1000 with Cd	75	168	165	165

TABLE 7

At these temperatures thermionic emission from the uranium is negligible compared to the measured currents.

Variation of V_{12} The measured I- V_{12} curves at 1000 kw reactor power are

shown in Fig. 4.1 for the bare tube and in Fig. 4.2 for the cadmium shielded tube. The fission fragment contribution to the ion generation rate $(I_{Bare}-I_{Cd})$ is shown for each of the reactor power levels in Fig. 4.3.

In general the $I_T - V$ (where $I_T = I_2 + I_G$) curves at this higher pressure were symmetrical about the origin as shown in Fig. 12.

Figure 12 - Typical I_{m} -V characteristic for 220 torr.

The current tended to saturate at $10 \le |V| \le 20$ volts and then increase with increased voltage. The currents were about 30% higher in the negative quadrant but in fair agreement with the area dependence in the plasma sheath theory(2)___ that is

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$$|\mathbf{I}_{Sz}| = \mathbf{J}^{+}\mathbf{A}_{z}$$
(3)

where I_{SZ} is the saturated ion current to electrode z with area $A_z(2)$ that is at a negative potential with respect to the plasma. It has been shown (2) that the plasma potential at saturated current is about 0.4 volt above the most positive electrode. In the correlation of the data to follow it was found that when A_z included the guard ring, the data were better fit by equation (3) if the total (inside) area of the guard ring was taken as the area of the uranium coated surface plus only one half of the peripheral area, i.e.

$$A_{G} = A_{G}(U) + .5 A_{G}(P) = 4.89 \text{ cm}.$$
 (4)

This reduced effective collection area could be explained by a decrease in the ion number density near the uncoated surface at the outer edge of the plasma. The correlation of various I-V data with Eq.(3) is given in Table 8. From Table 8 for Run 22.8 (see Fig. 4.1) I_T (+20 v)/ I_T (-20v) = .80, I_T (+100 v)/ I_T (-100 v) = .72 in good agreement with equation (3) where $A_1/(A_2 + A_G) = .77$. In contrast to the use of A'_G , $A/(A_2 + A_{GU}) = .93$ and $A_1/(A_2 + A_{GT}) = .65$

The individual I-V curves as illustrated in Fig. 13 were not as symmetric as the I_{T-V} (see Fig. 12).

Figure 13 - I-V characteristics for 220 torr.

This behavior can be explained in the following manner. When V < 0 electrodes 2 and G are negative with respect to electrode 1 (see Fig. 7) so that the distribution of the current between 2 and G is fixed by the ion collection to surfaces 2 and G. Since the ions are much less mobile than the electrons the distribution of the current is fixed by the area ratios. From Table 8 for Run 22.8 $I_2(-20v)/I_G(-20v) = .96$, $I_2(-100v)/I_G(-100v) = .81$ in fair agreement with Eq.(3). In contrast to using A'_G , where $A_2/A_G = .79$, $A_2/A_G = 1.14$ and $A_2/A_G = .618$.

On the other hand when V > 0, ions are collected on the single electrode 1 and the distribution of the internal electron current between 2 and G can readily take the less resistive path to the nearest electrode, G. It was observed that the distribution of current was very sensitive to V_{2G} when $V_{12} > 0$ in accord with this explanation. The sum of the two currents, however, is symmetrical as depicted in Fig. 12.

The individual I-V curves for the cadmium shielded run are shown in Fig. 4.2. The asymmetry of the I_2 and I_G curves is similar to the asymmetry observed for the bare run (see Fig. 13 also) but the measured currents with the cadmium shield were about 0.1 of the currents due to the fission fragments.

For the cadmium shielded runs, the plasma density outside the electrodes should be comparable to that inside the electrodes so that it is more difficult to assign the effective ion collecting areas. Nevertheless, as seen from Table 8 the distribution of ion current follows closely that for the bare runs.

Variation of V_{2G} In order to investigate the sensitivity of the current distribution to a variation of V_{2G} , two runs (100 kw reactor power) were made with V_{12} fixed. These data are presented in Fig. 4.4 for $V_{12} = 0$ and in Fig.4.5 for $V_{12} = +20$ volts. The data for I_2 , I_G and I_T vs V_{12} are given in Fig. 4.6.

The shape of these I-V characteristics can be explained by plasma sheath considerations. In terms of conventional current, referring to Fig. 6,

$$\mathbf{I}_{1} = \mathbf{I}_{2} + \mathbf{I}_{G} = \mathbf{I}_{T}$$
 (5)

The motive diagrams for Fig. 4.4 with $V_{12} = 0$ volts would take the shapes shown in Fig. 14.

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Figure 14 - Motive diagrams for Fig. 4.4 with $V_{12} = 0$ volts.

For $V_{2G} > + 10$ volts in Fig. 14 ions would be collected by 1 and 2 and electrons by G. Electrons moving externally from G to 1 would be measured positive on A_G and electrons moving externally from G to 2 would be measured positive on A_G and negative on A₂. From Table 8, $I_2(+20v)/I_1(+20v) = .67$, $I_2(+100v)/I_1(+100v)$ = .62 in fair agreement with Eq. (3) where $A_2/A_1 = .57$.

For $V_{2G} < -10$ volts in Fig. 14 ions would be collected by G and electrons would be collected by 1 and 2. Electrons moving externally from 1 back to G would be measured negative on A_{C} while electrons moving externally from 2 back to G would be measured positive on A_{C} and negative on A_{C} . From Table 8, $I_{2}(-20\nu)/I_{1}(-20\nu)$ = .345 and $I_{2}(-100\nu)/I_{1}(-100\nu) = .109$ which is much less than $A_{2}/A_{1} = .57$ and shows that Eq.(3) does not apply when the two competing surfaces are collecting electrons instead of ions. These data indicate that the plasma may provide a minimum resistive path at the edge of 1 near G for the internal flow of electrons to 1 and then externally to G.

The motive diagrams for Fig. 4.5 with $V_{12} = +20$ volts would take the shapes shown in Fig. 15.

Figure 15 - Motive diagrams for Fig. 4.5 with $V_{12} = +20$ volts.

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The I-V curves in Figs. 4.4 and 4.5 are similar and the analysis of the internal flow of ions and electrons would be similar to the above for V = 0 in Fig. 14 except for the following differences. Electrode 1 is now biased 20 volts negative with respect to 2 so that when $V_{23} < -20$ volts the electrons flow from the plasma to electrode 2 against less retarding potential than to electrode 1 the plasma to electrode 2 against less retarding potential than to electrode 1 and therefore I₂ is much greater when $V_{12} = +20v$ than for $V_{12} = 0$ volts. Indeed, using Eq. (5) to obtain I₁ indicates that I₁ is now 0.1 ma positive (when $V_{23} < 0$) or that electrode 1 is collecting more ions due to the negative potential relative to electrode G. In Fig. 4.4, I₁ = + 0.1 ma at $V_{23} = V_{13} = +20$ volts and in Fig. 4.6, I₁ = 0.1 ma at $V_{12} = +20$ volts in agreement with this plasma sheath model. For $V_{23} > +10$ volts the curve for I₁ in Fig. 4.5 is identical to I₁ in Fig. 4.4 except that it is shifted 20 volts to the left as would be expected from a comparison of the motive diagrams in Fig. 15.

Table 8 G12x-R Ion Current Distribution

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leactor	k. .	ma	I, ,	ma	Ix/Iy	Ax/Ay
1000	$I_{T}^{(+20v)}$ $I_{T}^{T}^{(+100v)}$ $I_{2}^{(-20v)}$ $I_{2}^{(-100v)}$ $I_{2}^{(+20v)}$.82 3.8 .51 2.35 .31	$\frac{I_{T}(-20v)}{I_{T}(-100v)}$ $\frac{I_{T}(-20v)}{I_{G}(-100v)}$ $\frac{I_{G}(-100v)}{I_{G}(+20v)}$ $\frac{I_{G}(+20v)}{I_{G}(+100v)}$	1.03 5.25 .53 2.9 .51 2.3	.80 .72 .96 .81 .61	$A_{1}/(A_{2}+A_{G}) = .77$ $A_{2}/A_{G}' = .79$
1000 r)	$I_2(+100v)$ $I_1(+20v)$ $I_1(+100v)$ $I_2(-20v)$ $I_2(-100v)$ $I_2(+20v)$ $I_2(+20v)$.073 .475 .049 .320 .015	$\frac{I_{G}(-20v)}{I_{T}(-100v)}$ $\frac{I_{T}(-20v)}{I_{G}(-20v)}$ $\frac{I_{G}(-100v)}{I_{G}(+20v)}$ $\frac{I_{G}(+20v)}{I_{G}(+100v)}$.102 .680 .053 .360 .058 .400	.72 .70 .925 .89 .259 .188	(Ion collec- tion on outside surface of elec trodes also sig nificant.)
100	$I_2(+100v)$ $I_T(+20v)$ $I_T(+100v)$ $I_2(-20v)$ $I_2(-100v)$ $I_2(+20v)$ $I_2(+20v)$ $I_2(+20v)$.104 .728 .064 .430 .020	$I_{T}(-20v)$ $I_{T}(-100v)$ $I_{T}(-20v)$ $I_{T}(-20v)$ $I_{T}(-20v)$ $I_{T}(-20v)$ $I_{T}(-20v)$ $I_{T}(-20v)$ $I_{T}(-20v)$ $I_{T}(-20v)$.134 .960 .070 .530 .084 .660	.78 .76 .915 .81 .238 .103	$A_{1}/(A_{2}+A_{G})$.77 A_{2}/A_{G} .79
100 (V ₁₂ =0)	$I_2(+100v)$ $I_G(-20v)$ $I_G(-100v)$ $I_G(+20v)$ $I_2(+100v)$ $I_2(+100v)$ $I_2(-20v)$.074 .55 .069 .480 .019	G I _G (+20v) I ^G (+100v) I ^G (+20v) I ¹ (+100v) I ¹ (+100v) I ¹ (-20v) I ¹ (-20v)	.172 1.25 .103 .770 .055	.43 .44 .67 .62 .345 .109	$A_{g}'/(A_{1}+A_{2})$.46 A_{2}/A_{1} .57
	eactor <u>ower,kw</u> 1000 1000 r) 100 (V ₁₂ =0)	eactor wer, kw $ _x $, 1000 $I_T(+20v)$ $I_T(-20v)$ $I_2(-20v)$ $I_2(-100v)$ $I_2(+20v)$ $I_2(+100v)$ $I_2(+20v)$ $I_2(+100v)$ $I_2(+20v)$ $I_2(-100v)$ $I_2(-20v)$ $I_2(-100v)$ $I_2(+20v)$ $I_2(+100v)$ $I_2(+20v)$ $I_2(+100v)$ $I_2(-20v)$ $I_2(-20v)$ $I_2(-20v)$ $I_2($	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $

Tube 5 (400 Torr)

This tube was originally constructed as a mockup tube to check out construction and processing steps. It had been backfilled to 400 torr of Ne:A for experiments using a cobalt-60 source to check current measurement technique during gamma ionization. After analysis of the first series of inpile experiments it was decided to install Tube 5 in an aluminum containment can and run it in the reactor to provide data at the higher gas pressure.

The electrode temperature data from the inpile runs are given in Table 9.

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Level, kw	Cold Junction on Stem, °C	Electrode 1 °C	Electrode 2	Electrode G
10	20	27		<u>•°C</u>
100	34	=1	27	26
500	J +	98	98	80
500	98	281	200	
1000	138	400	290	244
1000 with	Ca 56	130	413	326
			130	120

Thermionic emission from the uranium surfaces would be negligible at these temperatures.

The measured $I-V_{12}$ curves at 1000 kw reactor power are shown in Fig. 5.1 for the bare tube and in Fig. 5.2 for the cadmium shielded tube. The fission fragment contribution to the ion generation rate $(I_{bare}-I_{cd})$ is shown for each of the reactor power levels in Fig. 5.3.

In general the I-V curves at this pressure were symmetrical about the origin as for Tube 4 (220 torr). The significant difference between the data from Tube 5 (400 torr) and Tube 4 (220 torr) is that the currents were about 50 percent lower for Tube 5. This was a mockup tube and there is some doubt as to whether all of the internal surfaces were covered with a thickness of one fission fragment range of uranium. The current data, if it were to vary with pressure would indicate that almost one half of the uranium was left out. It is more likely that a combination of poor uranium coverage and perhaps an error in the gas filling technique would account for this smaller current.

Tube 6 (230 Torr - No Uranium)

This tube was constructed to provide a check on the level of ionization produced by the gamma background in the reactor. The tube was built identical to Tube 4 (220 torr with uranium), except that no uranium was bonded to the inside surface of the electrodes. It was backfilled to 230 torr of Ne:A (1000:1). The tube was run first bare at various reactor power levels and then was run in the cadmium shield just at 1000 kw reactor power level to see if the cadmium shield reduced the level of ionization even though there was no uranium in the tube. With no uranium present the electrode temperatures were at reactor water temperature (25°C). The measured I vs V_{12} curves at 1000 kw reactor power are shown in Fig. 6.1 for the bare tube and in Fig. 6.2 for the cadmium shielded tube. The difference between $I_m(bare)$ and $I_m(Cd)$ is shown in Fig. 6.3. Since there was no uranium present in this tube, the current difference in Fig. 6.3 is attributed to the absorption of lower energy gamma rays in the cadmium shield.

The current levels from this tube were about 0.1 of the current levels for Tube 4 (bare) at the same reactor power levels in agreement with the cadmium covered data of Tube 4.

The currents for $-V_{12}$ were about twice the currents for $+V_{12}$. This was explained by the greater collection of ions on the outside surfaces of the electrodes where $(A_2 + A_C) \simeq 2A_1$. When V_{12} was negative, A_2 and A_C were the controlling ion collecting areas. As V_{12} was made more negative (<-10 volts), $|I_C|$ increased more rapidly than $|I_2|$ and is explained by the greater multiplication of ions due to the sharp edge and consequent intense electron field on the outside of electrode G near electrode 1.

Mode Change when $V_{12} > 0$. A "splitting" of the I-V curves was obtained with this tube when V_{12} was positive at reactor power levels of source power, 10 kw and 100 kw as shown in Figs. 6.4 and 6.5 and in the sketch in Fig. 16.

Figure 16 - Mode change at V in I-V curves for Tube 6.

The critical voltage ($V_{12} = V$) at which this mode change occurred was also a function of reactor power. At 10 kw, V was 30 volts while at 100 kw, V was 80 volts. The "splitting" was not observed at 500 and 1000 kw power.

Both curves I_{G} and I_{2} go through the origin so that there seemed to be no "circulating current" between 2 and G for $V_{12} < V_{c}$. $I_{T} = I_{2} + I_{G}$ is a smooth curve through V so that the depression of I_{2} and the equal increase of I_{G} is in agreement with the onset of a circulating current from G to 2 at V.

ANALYSIS OF DATA

Theoretical Ion Source Rate

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The expression derived for the ion generation rate from fission fragment ionization of a noble gas (for one fission fragment and one uranium surface)* reduces to the following expression when the interelectrode gap width, d, is much less than the fission fragment range in the gas, R_0 :

$$\frac{dn}{dt} = \frac{1}{2} \left(\frac{\Sigma_{f} F_{f} R_{1}}{W R_{2}} \right)$$
(6)

where dn/dt is the ion generation rate per unit volume in ions sec⁻¹ cm⁻³, Σ_{f} is the fission cross section in cm⁻¹, F is the thermal neutron flux in sec⁻¹ cm⁻², R₁ is the range of the fragment in the electrode surface in cm, R₂ is the range of the fragment in the gas in cm, E_f is the fission fragment energy in ev and W is the average energy loss in ev per ion pair produced.

Computations are made at 220 torr and 1000 kw for comparison to the data of Tube 4 which provided the best current measurements. The range of the fission fragment in a gas is dependent on gas temperature and pressure. (18) For this calculation the neon gas temperature was set equal to the electrode temperature ($550^{\circ}\dot{C}$) and the tube pressure corrected to 300 torr to obtain

$$R_2 = R_{air} \left(\frac{\rho_{air}}{\rho}\right) \sqrt{\frac{A}{A_{air}}} = 26.2 \text{ cm}$$
(7)

In the bonding of the uranium to the zirconium electrode, the uranium foil thickness was 19×10^{-4} cm with a density of 18.7 gm cm^{-3} and the nickel foil thickness was 2.5×10^{-4} cm with a density of 8.3 gm cm^{-3} . After melting, the density of the U-Ni alloy is $\rho_{U_Ni} = 17.54 \text{ gm cm}^{-3}$. For an average energy of the two fission fragments ($E_f = 77 \text{ Mev (av)}$), the fission fragment range in uranium is $R_u = 6.7 \times 10^{-4} \text{ cm}^{-5}$ and the range for Ni was taken equal to be that for Cu or $R_{Ni} = R_c = 5.8 \times 10^{-4} \text{ cm}^{-5}$. The range in the U-Ni alloy is then given by

$$R_{U-Ni} = R_{u} \frac{\rho_{U} t_{U}}{\rho_{U-Ni} t_{U-Ni}} + R_{Ni} \frac{\rho_{Ni} t_{Ni}}{\rho_{U-Ni} t_{U-Ni}}$$
(8)

and is equal to 6.65×10^{-4} cm. The U foil was 93% enriched in U235 so the total fission cross section for the U-Ni alloy is 23.1 cm⁻¹. The average energy loss per ion pair was taken from measurements on α particles(6) (W = 36.8 ev/ion pair) which are equivalent to fission fragments in energy loss properties. Using these values of the constants, $dn/dt = 2.46 \times 10^{15}$ ions sec⁻¹ cm⁻³ for 1 fragment from 1 uranium coated surface. Summing over both fragments and both surfaces the theoretical ion source rate for tube 4 at 220 torr and 1000 kw power is

$$5 = \left(\frac{\mathrm{dn}}{\mathrm{dt}}\right)_{\mathrm{T}} = 9.84 \times 10^{15} \frac{\mathrm{ions/sec}}{\mathrm{cm}^3}$$
(9)

* See derivation in Section C of this report.
From Eq. (8) reference (2) and neglecting the diffusion loss term and the ion loss term due to volume recombination, the predicted total saturated currents are

$$\mathbf{I}_{S+} = \left[\frac{A_{1}}{A_{1} + (A_{2} + A_{G}^{*})}\right] S \in U$$
(10)

and

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$$I_{S-} = \left[\frac{(A_2 + A_G')}{A_1 + (A_2 + A_G')}\right] S e U$$
 (11)

where $e = 1.6 \times 10^{-19}$ coulomb and U_i is the interelectrode volume = .3 cm x 6.75 cm² = 2.0 cm³.

Solving these equations for S and using $I_{s} = .61$ ma and $I_{s} = .75$ ma from the difference between the bare - cadmium runs (22.8 - 21.6) at 1000 kw and at + 10v, the measured ion source rate was computed as shown in Table 10

Table 10

S (from I _{St})	=	4.39×10^{15} ions cm ⁻³ sec ⁻¹
S (from I _{S-})	=	4.15×10^{15} ions cm ⁻³ sec ⁻¹
S (Experimental average)	=	4.27×10^{15} ions cm ⁻³ sec ⁻¹
S (Theoretical)	=	9.84×10^{15} ions cm ⁻³ sec ⁻¹

The source rate values computed from the measured currents are less than one half the source rate calculated from the fission fragment energy loss rate. These data indicate that the ion loss rate due to processes such as volume recombination in the bulk of the plasma are of the same order of magnitude as the measured ion collection rate to the electrodes. In Eqs. (10) and (11) volume recombination loss is neglected and it is assumed that the measured current is made up of ions produced throughout the gas volume. These data and the differences between measured and predicted shape of the I-V characteristics show that the plasma sheath theory is inadequate to describe satisfactorily the operation of these ionization

Ion Currents Versus Neutron Flux (Reactor Power)

In order to show the effect of neutron flux (reactor power) on the measured current, the sum of the measured currents to electrodes 2 and G at V_{12} = -10 volts is plotted versus reactor power in Figs. 12 and 18 for each of the tubes. Data at -10 volts is well below ionization potential and on a reasonably flat part of the I-V curve. The data from the runs with the tubes cadmium shielded are plotted in Fig. 18 and therefore represent the gamma contribution to the ionization. In Fig. 17 the difference in total currents between the bare runs and the cadmium shielded runs is plotted and therefore represents the fission fragment contribution to the ionization.

The gamma contribution to the ion current in Fig. 18 is roughly proportional to reactor power 1/2. The fission fragment contribution to the ion current is approximately proportional to reactor power at the higher power levels but to a smaller exponent of the reactor power at lower levels. As the reactor power is increased the temperature of the electrode increases. In addition, the temperature of the gas in the interelectrode volume increases whereas the gas outside the electrodes remains at the tube wall temperature. Consequently the gas density in the interelectrode volume decreases. Each curve in Fig. 17 (and to a lesser extent in Fig. 18 where temperatures are lower), therefore, does not represent a constant gas density even though the pressure is constant.

Ion Number Density From Random Current Considerations

The ion number density was computed from the random ion current density expression $J^+ = n^+ \in \langle v \rangle_{av}/4$ where **c** is the electronic charge in coulombs and $\langle v \rangle_{av}$ is the average ion velocity, cm sec⁻¹. In the plasma sheath model the random ion current density is related to the measured saturated current, $I_{Sz} = J^+ A_z$ where A_z is the area of the ion collecting electrode which is at negative potential. The I-V curves for the gas filled tubes exhibited no well defined saturated current so current values were taken at -10 volts which is below the ionization potential. The expression for the ion density in more complete form is

$$N^{+} = \left[\frac{(2\pi M)^{1/2}}{100 \ e^{3/2}}\right] \frac{|I_{Sz}|}{A_{z} \ (T^{+})^{1/2}} , cm^{-3}$$
(12)

where $A_z = A_1$ for $I_{Sz} = I_{S_z} = I(+10v)$ and $A_z = (A_2 + A_3)$ for $I_z = I_z = I(-10v)$. As an example from Fig. 4.3 at 1000 kw the average temperature of the electrodes was 527°C and using this as the ion temperature, $T^* = (527 + 273)/11,600 = .069$ ev. Choosing neon as the predominant ion in the plasma M = 3.35 x 10⁻²⁶ kg and

$$n^{+} = \left[\frac{(2\pi \times 3.35 \times 10^{-26})^{1/2}}{100 \times (1.6 \times 10^{-19})^{3/2} \times (.069)^{1/2}} \right] \left(\frac{|\mathbf{I}_{Sz}|}{A_{z}} \right)$$
$$= 2.71 \times 10^{14} \left(\frac{|\mathbf{I}_{Sz}|}{A_{z}} \right), \text{ cm}^{-3}.$$
(13)

For the run in Fig. 4.3 $I_{S_{+}}(Tot) = .66$ ma and $I_{S_{+}}(Tot) = .82$ ma. Using these values together with the electron areas from Table 2 and $A_{c} = A_{U} + 1/2 A_{p}$, the ion number densities at 1000 kw were computed using Eq. (13) and the results are shown in Table 10.



but to a smaller exponent of the reactor power at lower levels. As the reactor power is increased the temperature of the electrode increases. In addition, the temperature of the gas in the interelectrode volume increases whereas the gas outside the electrodes remains at the tube wall temperature. Consequently the gas density in the interelectrode volume decreases. Each curve in Fig. 17 (and to a lesser extent in Fig. 18 where temperatures are lower), therefore, does not represent a constant gas density even though the pressure is constant.

Ion Number Density From Random Current Considerations

The ion number density was computed from the random ion current density expression $J^+ = n^+ \in \langle v \rangle_{av}/4$ where \bullet is the electronic charge in coulombs and $\langle v \rangle_{av}$ is the average ion velocity, cm sec⁻¹. In the plasma sheath model the random ion current density is related to the measured saturated current, $I_{S_2} = J^+ A_v$ where A_v is the area of the ion collecting electrode which is at negative potential. The I-V curves for the gas filled tubes exhibited no well defined saturated current so current values were taken at -10 volts which is below the ionization potential. The expression for the ion density in more complete form is

$$N^{+} = \left[\frac{(2\pi M)^{1/2}}{100 \ e^{3/2}} \right] \frac{|\mathbf{I}_{Sz}|}{A_{z} \ (\mathbf{T}^{+})^{1/2}} , \text{cm}^{-3}$$
(12)

where $A_z = A_1$ for $I_{Sz} = I_{Sz} = I(+10v)$ and $A_z = (A_2 + A_G^{'})$ for $I_{Sz} = I_S = I(-10v)$. As an example from Fig. 4.3 at 1000 kw the average temperature of the electrodes was 527°C and using this as the ion temperature, $T^{+} = (527 + 273)/11,600 = .069$ ev. Choosing neon as the predominant ion in the plasma M = 3.35 x 10⁻²⁶ kg and

$$n^{+} = \left[\frac{(2\pi \times 3.35 \times 10^{-26})^{1/2}}{100 \times (1.6 \times 10^{-19})^{3/2} \times (.069)^{1/2}} \right] \left(\frac{|\mathbf{I}_{Sz}|}{A_{z}} \right)$$
$$= 2.71 \times 10^{14} \left(\frac{|\mathbf{I}_{Sz}|}{A_{z}} \right), \text{ cm}^{-3}.$$
(13)

For the run in Fig. 4.3 $I_{S+}(Tot) = .66$ ma and $I_{S}(Tot) = .82$ ma. Using these values together with the electron areas from Table 2 and $A'_{S} = A_{U} + 1/2 A_{p}$, the ion number densities at 1000 kw were computed using Eq. (13) and the results are shown in Table 10.

Ion Source	Run	Table 10 n ⁺ (cm ⁻³) from I _{S+} (Tot)	n ⁺ (cm ⁻³) from I _{S-} (Tot)	
γ	21.6	.10 x 10^{10}	.11 x 10^{10}	
FF	22.8 - 21.6	2.45 x 10^{10}	2.33 x 10^{10}	
FF and γ	22.8	2.65 x 10^{10}	2.56 x 10^{10}	



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Figure 17 - Fission fragment contribution to ionization vs reactor power. In this plot the gas density in the interelectrode gap varies with reactor power.

Reactor Power, KW



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Volume Recombination

The theoretical neon ion source rate which was computed from the direct fission fragment ionization of neon atoms was found to be about twice the source rate calculated from the measured current assuming no volume recombination. If the theoretical calculation of ion source rate is assumed correct, these data show that volume recombination loss of the ions is appreciable and cannot be neglected in the theoretical model.

If the volume recombination loss is of the order of the collected current loss, the ion density in the bulk of the plasma must be greater than the values computed from the previous random current considerations. This is readily shown by a calculation of the volume recombination loss rate using the ion density from Table 10 (8) The neon ion loss rate by dissociative recombination ($\alpha_D = 2.2 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$)(8) using Ne⁺ = n⁻ = 2.33 x 10¹⁰ cm⁻³ is

$$\frac{dNe^{+}}{dt}\Big|_{D} = -\alpha(n^{-})^{2} = -2.2 \times 10^{-7} \times (2.33 \times 10^{10})^{2} = -1.19 \times 10^{14} \text{ sec}^{-1} \text{ cm}^{-3}.$$
 (14)

This loss rate is much smaller than the difference between the theoretical neon ion source rate and the collected current loss rate and shows that the ion density in the bulk of the plasma must be considerably higher to account for the balance of the ion loss rate. The ion density in the bulk of the plasma cannot be calculated directly by setting the dissociative recombination loss rate of neon ions equal to the difference between the neon ion source rate and collected current rate, for the following reasons:

- (a) The dissociative recombination loss of neon ions does not necessarily represent a net loss of ions from the plasma since metastable states of neon may be formed during dissociative recombination which can then ionize the argon atoms.
- (b) Argon ions can also be produced in the plasma by metastable states of neon which are formed directly from collisions of the fission fragments with neutral neon atoms. This represents a source term in addition to the direct fission fragment ionization of neon.
- (c) If the predominant ion in the plasma is argon, the reaction controlling loss rate is not at once evident since the dissociative recombination loss rate of argon ions should be small because of the low concentration of argon atoms.
- (d) If volume recombination is appreciable, Eqs. (10) and (11) are no longer valid since ions produced over the entire volume can no longer be expected to be collected at the electrodes.

A review of some of the more important reactions in this complex plasma was made to decide which is the predominant ion in the plasma and which reaction limits the ion loss rate.

Consider first a low density (n $\leq 10^{15}$ ions cm⁻³) Ne:A(1000:1) plasma in which the electric field E is uniform and the excitation and ionization processes sustaining the plasma arise initially from electron-atom collisions. At low values of $E/p_{\sim} 3 \text{ v}$ (cm torr)⁻¹, the primary ionization coefficient η for Ne:A(1000:1) is $\sim 4 \text{ x}$ 10⁻² ion pairs volt⁻¹, while for pure neon at the same value of E/p, η is only $\sim 6 \text{ x}$ 10⁻⁴ ion pairs volt⁻¹. The marked increase in the value of η in neon seeded with 0.1% A can be explained in terms of the Penning effect, (10) and the energy distribution of the electron swarm.

For values of $E/p \sim 3$ in pure neon, the electron energy distribution is such that for each ionizing collision about 60 exciting collisions occur.(11) (The ionization potential of neon, $V_1(Ne)$ is 21.56 v, and the first excitation potential of neon is 16.5 v.) (12) A large proportion of these exciting collisions yield neon

metastable atoms in the $3P_{2}(16.62 \text{ v})$ and $3P_{0}(16.71 \text{ v})^{(12)}$ states. When the neon contains traces ($\leq 0.1\%$) of argon, the relatively large number of high energy long-lived neon metastable states can produce appreciable ionization of the argon atoms, ($V_{1}(A) = 15.76 \text{ v}$), thereby significantly increasing the value of the ionization coefficient, N. The electrons which produce the neon metastable states evidently have sufficient energy to ionize the argon atoms directly, but when the concentration of argon ions in neon is small ($\leq 0.1\%$), the probability of ionizing argon atoms directly by electrons is much less than the probability of ionizing argon atoms by metastable states of neon.⁽¹³⁾

At higher values of $E/p \ge 100$ volts $(cm \text{ torr})^{-1}$ the ionization coefficient of the (1000:1) neon:argon mixture is essentially the same as for pure neon $(\eta \ge .015 \text{ ion pairs volt}^{-1})^{(0)}$ because sufficient energetic electrons are available to ionize the neon directly.

The influence of the Penning effect in nuclear generated plasmas then depends upon the relative production rate of the metastable states of neon to the production rate of primary ions which may in turn depend upon the energy distribution of the electrons in the plasma.

In the neon:argon nuclear generated plasma, the Mev fission fragments would be expected to produce first generation ions of neon and argon in the ratio (1000:1) of their concentration in the gas. It is known that neon ions in neon gas recombine by dissociative recombination. (14) The dissociative recombination coefficient for neon is $\alpha_{\rm D}(\rm Ne) = 2.2 \times 10^{-7} \rm \ cm^3 \ sec^{-1}(8)$. In this process it has been postulated that a molecular neon ion is formed by the three body reaction (15)

$$Ne^+ + 2Ne^- Ne_2^+ + Ne$$
 (15)

and the molecular ion then recombines with an electron in a non-radiative capture to produce one or more excited states of the neon(16)

$$Ne_2^+ + e^- - Ne_2^* - Ne^* + Ne.$$
 (16)

This reaction is thought to be much more probable than the radiative recombination of the atomic ion $(\alpha_R \simeq 10^{-10} \text{ cm}^3 \text{ sec}^{-1})$

$$Ne^+ + e^- Ne^+ Ne^+ hv$$
 (17)

since in the former the dissociation of the molecule occurs very rapidly ($\tau = 10^{-13}$ sec)(11) while the lifetime of the excited state in the later reaction is of order 10^{-8} sec.(16)

The dissociative recombination loss of the neon ion does not necessarily represent a net loss of ions from the plasma because the metastable excited states of neon can be produced by the process given in Eq. (16) and the probability of destruction of the metastable neon ion by ionization of an argon atom approaches unity (17)

$$Ne^{M} + A \longrightarrow Ne + A^{+} + e^{-}$$
. (18)

Not all of the excited states produced in (16) decay to a metastable state and, of course, (16) is not the only source of neon metastable states. The argon atoms are so dilute that the probability of dissociative recombination ($\alpha_{\rm L}(A) = 6.0 \times 10^{-7} \, {\rm cm}^3 \, {\rm sec}^{-1}$)(7) loss of argon ions (involving first a three body collision between an argon ion and two argon atoms) is negligible. Furthermore, the radiative recombination loss of argon ($\alpha_{\rm R}(A) = 2 \times 10^{-10} \, {\rm cm}^3 \, {\rm sec}^{-1}$)⁽⁸⁾ is also negligible for the number densities expected in this study.

The molecular argon ion can be formed, however, by the three body reaction $A^{+} + A + Ne - A_{2}^{+} + Ne$ (19)

which would then rapidly recombine similar to (16)

 $A_2^+ + e^- A_2^* - A^* + A.$ (20)

In the afterglow studies of neon:argon plasmas by microwave techniques, H. J. Oskam has measured the electron density decay rate and the collision frequency was found to be $v = 315 [p(Ne) p(A)]^{(14)}$ where p is the partial pressure of the gas constituent. Oskam attributed the rate controlling reaction to be that given in (19). In order to obtain the ion number density using this decay rate, it is necessary to know the total ion source rate including the production rate of those ions resulting from the fission fragment production of the metastable states of neon. Very little is known about the production rate of metastable states by fission fragments but a minimum value on the ion number density in the bulk of the plasma may be obtained be setting the difference between the computed fission fragment production rate of neon (S_{Ne}^{+}) ions and the collected ion current density (S_{Coll}) equal to Oskam's decay rate.

$$(n^{+})_{\min} = \frac{S_{Ne} - S_{C}}{v} = \frac{(9.84 - 4.27) \times 10^{15}}{1.52 \times 10^{4}} = 3.65 \times 10^{11} (cm^{-3})$$
 (21)

This value is a factor of about 15 times the value obtained from random current considerations in Table 10.

SUMMARY AND CONCLUSIONS

The current-voltage characteristics from the Ne:A filled glass ionization tubes did not exhibit a pronounced current saturation as predicted from the random currentplasma sheath model. With the thermionic emission of electrons made negligible in the glass ionization tubes this theory predicted current saturation at an applied potential less than 1 volt. The experimental I-V curves showed only a tendency towards current saturation around 10 volts and then multiplication caused the current to increase rapidly with higher voltage. Furthermore, the ion source rate calculated from the measured current using this theory gave a value less than one half that predicted for primary neon ionization using the fission fragment energy loss rate calculation. It was concluded from these data that volume recombination must be a major ion loss mechanism in these plasmas.

The ion density in the plasma calculated from random current considerations gave a value of 2.3×10^{10} cm⁻³ for the 220 torr tube at 1000 kw reactor power. It was shown, however, that the ion density must be considerably higher than this $(n_{min} = 3.7 \times 10^{11} \text{ cm}^{-3})$ just to balance the source rate from the neon ion production rate from fission fragments. The production rate of neon metastable states by fission fragments is not known but could be a significant additional source of argon ions which would result in an even higher number density in the plasma.

Using various circuit configurations the differences in measured currents from the electrodes were explained in terms of the random ion current collected at the negative electrodes. Ion current distribution between dual ion collecting electrodes was proportional to the electrode areas but electron current distribution between dual electron collecting electrodes was not proportional to the respective electrode areas. This difference in charge behavior was explained by the higher electron mobility which permitted electrons to respond more readily to slight differences in the electric field near the electrodes.

The tubes were also run in a cadmium shield to measure the ionization rate induced by gamma rays (ionization from photoelectrons produced on the tube parts). Gamma induced ionization also occurred outside the electrodes so that it was not possible to obtain a direct comparison of gamma induced and fission fragment ionization within the interelectrode volume. The total gamma induced ionization, however, was only a small fraction of the contribution from the fission fragments.

The two low pressure tubes (20 torr and 60 torr) showed asymmetrical I-V curves and subsequent disassembly of the 20 torr tube showed that a lead had broken free from one of the electrodes. From the data it was concluded that an identical wire had broken free in the 60 torr tube. The ion currents measured in the 400 torr tube were slightly lower than the 220 torr tube. This unexpected result was attributed to the fact that this tube had originally been made as a mockup tube and either poor surface coverage of uranium or an error in the gas backfilling step led to a reduced ion generation rate.

The current from the vacuum tube exhibited a pronounced saturation. Analysis showed this to be an electron current produced by the combination of electrons emanating from a uranium foil along with the fission fragments and electrons ejected from the opposite uranium surface by fission fragment bombardment. From the shape of the characteristic it was observed that most of these electrons have kinetic energies less than 40 volts.

Sufficient data were not taken with these tubes to establish the relationship of the ion source rate on gas pressure. The continuation of this program using the new ceramic-metal tube design is discussed in the next Section (B) of this report.

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Fig. 1.2 - I2, IG vs. V $_{12}$ for T1 (vacuum) in the cadmium shield at 1000 kw reactor power.





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Fig. 2.2 - I_2 , I_G vs. V $_{12}$ for T2 (20 torr Ne:A) in the cadmium shield at 1000 kw reactor power.





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Fig. 3.6 - I_2, I_G and I_1 vs. V_{12} for T3 (60 torr Ne:A) at 1000 kw reactor power.





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Fig. 5.3 - 1 ΔT • 1 (Bare) - 1 (Cd Shield) vs. V₁₂ for T5 400 torr Ne:A) with reactor power as parameter.

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Fig. 6.2 - I_2 , I_G vs. V_{12} for T6 (230 torr Ne:A, no U) in the cadmium shield at 1000 kw reactor power.



Fig. 6.4 - I_2 , I_G vs. V_{12} for T6 (230 torr Ne:A, no U) at 10 kw reactor power.

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Fig. 6.5 - I_2 , I_G vs. V_{12} for T6 (230 torr Ne:A, no U) at 100 kw reactor power.

SECTION B

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NOBLE GAS IONIZATION BY FISSION FRAGMENTS -THEORY AND CERAMIC-METAL DIODE EXPERIMENTS

ABSTRACT

Inpile studies on the fission fragment ionization of noble gases are presented in which an ion chamber of ceramic-metal design was employed. This tube had three planar electrodes forming a double diode. One diode was gamma sensitive only, whereas the other had a uranium foil on one electrode. These double diodes were operated in monoisopropylbiphenyl oil to eliminate the ion source external to the electrodes. Initially a diode was run under vacuum conditions in order to measure the energy distribution of electrons accompanying fission. These measurements indicated that most of the electrons had energies less than 40 volts. Detailed studies were then undertaken with gas filled diodes and it was found from these tubes that the current contribution resulting from gamma ionization was, in general, only $\sim 1\%$ of that resulting from ionization due to fission fragments. Ion source rates for various gas pressures of neon, argon, xenon and neon: argon (1000:1) were determined from the experimental currentvoltage data using a plasma theory based on the assumption that the ion number density in the plasma between the two electrode sheaths was limited by volume recombination loss. The theory accurately described the shape of the current-voltage curves, $(I = k V^{1/2})$ and enabled values of source rate to be determined by a one parameter fit of the theory to the experimental curves.

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INTRODUCTION

A ceramic-metal ion tube has been designed and operated in order to extend the data on ion source rate measurements taken earlier with the glass ion chamber tube. The construction problems involved with the glass tube and the deleterious effect of the plasma created external to the electrodes of this chamber, were satisfactorily eliminated in the new design by the use of ceramic-metal construction techniques and oil insulation external to the electrodes.

Current-voltage data have been obtained on thirteen tubes (to date). These tubes have been operated at 240 torr with gas fillings of neon, argon, xenon, and the (1000:1) neon:argon mixture. In addition, the neon:argon mixture has been run at 30, 60, 120 and 400 torr pressure, xenon has been run at 400 torr and a tube constructed identical to these gas filled tubes has been operated under vacuum conditions. In order to measure leakage currents in the reactor environment a vacuum tube was used which contained no uranium.

The current-voltage data from the glass tubes did not follow that predicted from the model which considered tube current to be controlled by random currents flowing to the electrodes from a uniform plasma.⁽¹⁾ Therefore a new model has been developed which considers the ion density in the plasma to be controlled by volume recombination loss and considers the tube current to be dependent only on the loss rate to the electrodes of the charges initially generated in the electrode sheaths. The form of the I-V relationship predicted by this theory is in good agreement with the experimental I-V data and this enabled the ion generation rate to be accurately determined by the application of the theory to the experimental data.

The report that follows describes the construction details of the ceramicmetal ion chamber (hereinafter referred to as ion chamber or tube only), the measuring circuits, the plasma theory and the analysis of the data that have been carried out so far.

DESCRIPTION OF TUBE AND MEASURING CIRCUIT

A drawing of the ion tube is shown in Fig. 1. This is a double diode design which allows the simultaneous measurement of gamma induced current (in the upper chamber) and the current induced by fission fragments plus gamma radiation in the lower chamber which contains uranium. The current resulting from fission fragment ionization alone can thus be measured directly.

The bottom electrode subassembly was made in a one step vacuum brazing operation. The enriched uranium foil (~ 0.0005 in. thick) was bonded to the tantalum disc as a uranium-nickel alloy. This tantalum support disc and the tantalum backup disc were copper brazed to the Kovar electrode in vacuum. The high density alumina to Kovar brazes (copper) were made in hydrogen and the two subassemblies were joined by a heliarc weld. After bakeout on an ultra-high vacuum system ($p \sim 10^{-9}$ torr) the tubes were back-filled to the desired pressure with Airco reagent grade noble gases. The six small holes in the center electrode permitted equalization of the pressures in the two volumes. A photograph of the completed tube is shown in Fig. 2.

For the inpile runs four tubes were mounted on one lava block as shown in Fig. 3 which in turn was supported from a flange at the top of the 4 foot aluminum containment chamber. The entire assembly was immersed in oil (monoisopropylbiphenyl) in this chamber. A value on the flange was connected to 1/4 inch poly flow tubing which extended, with the lead wires, to the top of the 20 foot



Figure 1 - Ceramic-Metal Ionization Tube Design.



Figure 2 - Completed Ceramic-Metal Ionization Tube.





support tube. A gauge and values at the top of the 20 foot tube permitted monitoring of the gas pressure above the oil and also permitted pumping out the gas formed from the radiolytic decomposition of the oil. A calculation of the radiolytic gas release and experimental measurements on gas evolution are presented in Appendix A.

The circuit originally conceived for this tube was the dual bias circuit of Fig. 4. The intent was to measure a current induced by fission fragment ionization alone from the difference between the currents in the uranium coated chamber and gamma sensitive chamber. Thus a dual power supply with a coupled variable speed motor drive unit was employed to vary the voltage from -100 volts to +100 volts across both chambers. Battery operated ammeters and voltmeters were used in this circuit to minimize ac pickup. The outputs of a given voltmeter and ammeter were connected to an x-y pen recorder for recording an I-V characteristic. Thus any single chamber current, (A_1, A_2) or a net current, (A_3) could be swept out on the x-y recorder.

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The initial data taken with this circuit (Fig. 4) indicated a marked asymmetry in the I-V characteristic for both chambers for the neon-argon filling. This was considered to be due to plasma coupling between diode volumes (to be discussed later). With the center electrode negative with respect to the uranium electrode, plasma coupling was not observed and under these conditions the current from the gamma chamber was only of order 1% of the neutron chamber current. These data indicated that the need for measuring a net current in order to determine the individual fission fragment contribution to current was not necessary in the present experiment and consequently A_2 served only as a check on circuit behavior. Also it was observed that plasma coupling could be reduced or in most cases eliminated by operating the tube with a single bias power supply. This is shown in Fig. 5 where the outer electrodes had a common potential. For this



Figure 5 – Single Bias Circuit for Ion Chamber Experiments.

circuit the current from the neutron chamber and the gamma chamber were recorded independently on the x-y recorder. Meter A₂ was read to check on circuit continuity and leakage. The polarity conventions for the data presented in this report for each of these circuits are shown in Fig. 6.





Figure 6 - Circuit polarity convention for I-V data.

THEORY

The ionizing source rate S is obtained from the experimental I-V data by using a plasma theory which predicts I-V curves in monatomic noble gases for different values of S. The theoretical model is based on the assumption that the source rate S is uniform throughout the interelectrode volume and that the ion number density in the plasma $(n^{+} \simeq n^{-} = n_{p})$ between the two electrode sheaths is limited by volume recombination loss (α). Therefore,

$$S = \alpha n_p^2 .$$
 (1)

In the electrode sheaths it is assumed that the volume recombination loss can be neglected. That is, the average time spent by the charge carriers in the sheaths is very much less than the average recombination time. The electrons and ions which are lost to the electrodes are considered to be only those initially generated in the sheaths, and the rate at which these charges are transported to either electrode depends on the applied potential.

The factor limiting current output is expected to be the rate at which ions can be moved to the cathode.* This results from the fact that electrons have a mobility much higher than that of ions and are consequently more readily moved to the anode. The ion and electron loss rates from both sheaths must, however, equalize and this is achieved by the creation of an electron space charge field at the anode which retards the flow of electrons from the plasma to the anode. A potential drop of the order of a few tenths of a volt across the anode sheath(1) $(0 \le x < a, Fig. 7)$ would be sufficient to equalize the electron and ion loss rates to the electrodes for the currents \sim ma, and to a first approximation, this potential drop may be neglected in comparison with the applied potentials (5 -100 volts) used in the experiment. Furthermore, it can be shown that the electric field in the plasma, E_p , is small for currents \sim ma, and the potential drop V across the plasma may be neglected without much error.

* Cathode is used to define the cold electrode with negative polarity whereas anode refers to the cold positive electrode.



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Under these conditions, the external potential V applied to the electrodes is very nearly the potential drop V_b across the cathode sheath (d - b < x \leq d, Fig. 7), and therefore the I-V characteristic for the ionization tube can be approximately derived as shown below by a study of the I-V_b relationship in the cathode sheath.

Consider the region $0 \le z \le b$ (where z = x - (d - b), Fig. 7) between plane parallel electrodes of infinite extent. The basic particle equations for electrons (-) and ions(+) are

$$\int = -D - \frac{dn}{dz} - \mu E n$$
 (2)

$$\int^{n^+} = -D^+ \frac{dn^+}{dz} + \mu^+ E n^+$$
(3)

$$\frac{d}{dz} = \frac{d}{dz} = S \qquad (4), (5)$$

where | is the current density of particles, D the diffusion coefficient and μ the mobility coefficient. It is assumed that ions generated in the anode sheath do not significantly contribute to the ion current at the cathode. (The field across the anode sheath tends to drive the ions produced in the sheath into the anode.) For the values of E(z)/p (p the gas pressure) which occur in the experiments considered here ($\langle E(z)/p \rangle \sim 3 V(\text{cm torr})^{-1}$) the ion diffusion term in Eq.(2) is small in comparison with the mobility term and will therefore be neglected. Using Eqs. (3) and (5) and integrating yields immediately

$$t^{+} = \frac{Sz}{\mu^{+}E}$$
 (z > 0) (6)

which evidently can satisfy the approximate boundary condition $E \longrightarrow E_p \simeq 0$ when $z \longrightarrow 0$ for finite n. (For $z \le 0$, $n = \left(\frac{S}{\alpha}\right)^{1/2}$).

Substituting this value of n in Poisson's equation

$$\frac{dE}{dz} = \frac{e}{\varepsilon_0} \left(n^+ - n^- \right) = \frac{e}{\varepsilon_0} n^+ \left(n^+ - n^- \right)$$
(7)

and integrating with the boundary conditions $E - E_p \simeq 0$ when z - 0 gives the field distribution in the sheath:

$$E = \left(\frac{e S}{\epsilon_0 \mu}\right)^{1/2} z.$$
 (8)

Now at z = b, $n - \ge 0$, and thus the net particle current $\bigcap (= \bigcap^+ - \bigcap^-)$ is $\ge S.b$ provided $b \le d$. Using $b = \prod_{s} = j$ (j in amps cm⁻²) and Eq.(8), the potential

drop V_h across the cathode sheath is found to be

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$$\mathbf{v}_{b} = \left[4 \ \mathrm{s}^{3} \ \mu^{+} \ \mathbf{E}_{o} \ \mathrm{e}^{3}\right]^{-1/2} \ \mathrm{j}^{2} \tag{9}$$

which is approximately equal to the potential drop V across the ionization tube. If the source rate S is written in the form $S'F^{(2)}$ where F is the neutron flux and S' the ionizing source rate per unit neutron flux, then from Eq. (9)

$$I = A(4\mu^{+} \ \boldsymbol{\epsilon}_{o} \ e^{3})^{1/4} \ (s')^{3/4} \ F \ \boldsymbol{v}, \qquad (10)$$

where I(amps) is the current measured over an electrode surface of area A. This equation will, of course, be valid only as long as the sheath thickness b is less than the gap separation d. When b becomes equal to d at a value of V = V say, the current I saturates at a value I which is independent of V for values of $V > V_s$. From Eqs. (8) and (9) the values of I and V are evidently

$$I_{e} = e d A S.$$
(11)

$$V_{s} = \left(\frac{e s}{4 \epsilon_{0}\mu^{+}}\right)^{1/2} d^{2} . \qquad (12)$$

For a given value of S, the ion number density in the plasma (b < d) can be determined using Eq. (1). The ion density in the cathode sheath (n') for b < d can also be readily found in terms of S from Eqs. (6) and (8):

 $n^{+} = \left(\frac{s \epsilon_{o}}{e \mu^{+}}\right)^{1/2}$ (13)

When the current saturates (b = d) at low values of source rate, then the ion number density (n^+) across the diode can be determined directly from the value of the saturation current by combining Eqs. (11) and (13) to give

$$n_{s}^{+} = \frac{1}{e} \left(\frac{\epsilon_{o} I_{s}}{\mu^{+} Ad} \right)^{1/2}$$
(14)
The parabolic dependence of current upon voltage given in Eq. (10) (when $V < V_s$) will break down when V becomes small and diffusion terms become significant. In addition, for large values of E(z)/p in the sheath, the electrons can acquire sufficient energy to cause appreciable multiplication of the current by electron-atom collisions and this effect is likely to be of particular importance in a (1000:1) neon:argon mixture.⁽³⁾ Attempts are currently being made to include these effects and generalize the theory.

DATA ANALYSIS

The data on all tubes were obtained in the same reflector position of the University of Michigan reactor. An absolute neutron flux calibration for each tube position was made in a mockup of the four tube assembly using gold foil activation techniques. Current-voltage data were obtained at reactor power levels of 10, 100, 1000 kilowatts for all tubes and also at 2000 kilowatts for the last two sets of four tubes (the maximum reactor power level was increased during this program). Table I gives the neutron flux values at the four tube positions along with a summary of the ion chambers as they were located in the four foot aluminum (Al) containment tube. Gas pressure is given in torr units (1 torr = 1 mm Hg). The designation Ne:A is for the mixture of neon and argon containing 0.1% argon.

Position	Neutron Flux n/sec cm ² at 2000 kw	Al Tube 1	Al Tube Torr	e 2 - Gas	Al Tub Torr	e 3 - Gas	Al Tul Torr	- Gas
Tl (top)	1.23 x 10 ¹³		60	Ne :A	30	Ne :A	240	A
T2	1.29×10^{13}		60*	Ne :A	120	Ne :A	240	Xe
ТЗ	1.27×10^{13}	Vacuum (no uranium)	Vacuum uran	(with nium)	400*	Ne:A	400	Xe
T 4	1.19×10^{13}		240	Ne :A	240*	Ne:A	240	Ne

Neutron Flux and Ion Chamber Summary

Table 1

The tubes marked * were processed together and may have become slightly contaminated with air from the breakage of a glass-covered iron slug within the manifold during gas filling. New tubes at 60 and 240 torr were built to see if the data in the * tubes were affected by this incident. There was no marked difference between I-V characteristics so the data from the * tubes are considered equally valid. Operation of two 60 torr tubes in one Al tube and two 240 torr tubes at the same position in different Al tubes checked reproducibility of different tubes filled to the same pressure and also checked neutron flux reproducibility between reactor runs.

The overall leakage resistance of the ion chambers mounted in the Al tube and attached to the 20 ft support tube was measured prior to operation inpile. This resistance was of order $10^{10} - 10^{11}$ ohms.

A check on leakage current inpile at 1000 kw was made by running a vacuum ceramic-metal tube with no uranium. This varied from 10^{10} ohms to 2.5 x 10^{8} ohms over a period of several hours and was observed to be influenced by the presence of radiolytic gas above the oil in which ionization from radiation could take place. Pumping out this gas increased the resistance. These tests indicated that for the current levels observed in the gas-filled tubes the current

leakage external to the diode was negligible. Radiolytic gas was pumped out only when it approached atmospheric pressure - initially the space above the oil was evacuated.

The gamma radiation intensity at the position of the ion chambers was $3.4 \times 10^7 \text{ Rad/hr}$ at 2000 kw. This value can be scaled directly at 100 and 1000 but not necessarily at 10 kw where gamma flux from residual activity due to previous operations at high reactor power may be appreciable.

The nuclear heat generated in the uranium foil was computed to be 77 watts for an average neutron flux of 1.25×10^{13} n gec⁻¹ cm⁻² at 2000 kw reactor power. This heat was generated over a foil 2.85 cm² area. The temperature of the uranium bearing electrode of the lower ion chamber was monitored with a chromelalumel thermocouple. In addition a thermocouple was placed several inches above the ion chamber assembly to monitor reservoir oil temperature. Table 2 gives the average measured values of electrode and oil temperature at 1000 and 2000 kw for the 3 tube assemblies employed (the individually recorded temperatures did not differ significantly from these average values). Evidently these temperatures were sufficiently low to assure negligible thermionic electron emission in the tubes.

Tab	le	2
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Tem	ber	at	ure	Da	ta

Reactor Power	Uranium Electrode	Oil Reservoir		
1000 kw	183°C	97°C		
2000 kw	205 °C	105°C		

Fission Chamber Data

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In order to apply the one-dimensional model discussed in the preceding section to the analysis of the experimental I-V data from the ionization tube, the ion collection area, A, was taken to be the total area of the 1 inch diameter electrodes. The uranium was bonded to a 3/4 inch diameter disc in the center of the electrode 1 (see Fig. 1) and the source rate would not be expected to be uniform throughout the interelectrode volume. Using the one dimensional model and the total collection area results in the determination of an "average source rate, S," which should have the same functional dependence as Eq. (10). The average source rates obtained for the various gases can be compared directly since the geometry was the same for all the tubes tested.

The plasma model predicts that when the sheath thickness b is less than the gap separation d (Eq.(10)), the current I is (i) dependent on $V^{1/2}$ for a constant value of F, or (ii) dependent on $F^{3/4}$ for a constant value of V. In addition, the theory gives the value of the potential at which the current saturates (Eq.(12)), when b becomes equal to d, and also gives the value of this saturated current (Eq.(11)), in terms of F (or S'F) and d. The following data (Figs. 8, 9, 10 and 11), obtained with the positive quadrant configuration of the single bias circuit (right hand side of Fig. 6(a)), are presented to show that the above predictions were accurately verified experimentally in the fission chamber. The value of the average source rate S(=S'F) could, therefore, be determined by adjusting this one parameter in Eq. (10) to give a least-mean-square fit to the experimental I-V data.

The fit of the experimental I-V data to Eq. (10) for neon, argon and xenon at a neutron flux of $1.2 \times 10^{13} \text{ sec}^{-1} \text{ cm}^{-2}$ is shown in Fig. 8. (The values of ion mobility for these pure gases and the neon:argon mixture discussed below were taken from Brown.)⁽⁴⁾. The fit to Eq. (10) is good for neon and argon over the entire voltage range ($5 \leq V \leq 100$) while for xenon the theoretical curve is about 10% low for V less than 20 volts. The increasing current values (at constant voltage) for the gases in the order neon, argon and xenon reflect the increase of fission fragment energy loss and average source rate with higher atomic mass.

The experimental I-V curve for the neon-argon mixture at 240 torr and $F = 1.2 \times 10^{13} \text{ sec}^{-1} \text{ cm}^{-2}$ is compared with the pure neon experimental and theoretical data in Fig. 9. For V less than 25 volts the current for the neon:argon is about twice that for pure neon. The rapid increase in the current with voltage for neon:argon above 25 volts is attributed to electron impact ionization in the sheath. The neon:argon curve below V = 25 volts was fitted to Eq.(10) with a value of $\bar{S} = 1.6 \times 10^{16} \text{ sec}^{-1} \text{ cm}^{-3}$. The increase in \bar{S} for neon:argon over that for pure neon ($\bar{S} = 0.75 \times 10^{16} \text{ sec}^{-1} \text{ cm}^{-1}$) is attributed to ionization of the argon atoms in collisions of the second kind with metastable states of neon.

The fit of the experimental data with theory at lower neutron flux is shown in Fig. 10 for the pure gases. Using current values at a constant value of potential V = 50 volts and reactor power levels of 10, 100, 1000 and 2000 kw, the current is shown versus the neutron flux on a log-log plot. The theoretical curves were obtained from Eq.(10) using a value of S'(=S/F) for each gas determined from the previously found value of S at $F = 1.2 \times 10^{13} \text{ sec}^{-1} \text{ cm}^{-2}$. It is seen from this plot that the predicted dependence of current on the three quarters power of neutron flux is in good agreement with experiment (for the arbitrarily chosen value of V = 50 volts) at these lower values of neutron flux.

A comparison of predicted and measured saturated current at a low source 10 rate as shown in Fig. 11 for pure neon at 240 torr and neutron flux of 6.2 x 10¹⁰ sec-1 cm-2. Using the experimentally determined value of source rate and the diode spacing of d = 0.274 cm, the predicted saturated current was $I_S = 8.36 \times 10^{-6}$ for V > V_S = 85.5 volts. The measured saturated current was 8.1 x 10⁻⁶ amps for V > ~83 volts. Thus the agreement between the measured and predicted saturation currents was within 3%.

It was concluded from these results (Figs. (8), (9), (10), (11)) that the plasma theory could adequately account for the observed experimental data. Consequently, the average fission fragment source rates for neon, argon, xenon and the neon:argon mixture were determined by fitting the theoretical I-V expressions to all the experimental I-V data as indicated in Figs. (8), (9), and (11). The results are shown in Table 3 for experimental I-V data obtained using both the positive and negative quadrant configurations of the single bias circuit (Fig.6(a)). Additional experimental data with fit to theory are exhibited at the end of this report. Figures (12) to (20) represent typical fits of theory to experiment for various values of gas pressure (30 - 400 torr) and reactor power (10, 100, 1000, 2000 kw) for neon, argon and xenon over the potential range -100 < V < 100 volts, and for the neon:argon mixture over the potential range -25 < V < 25 volts, where the additional electron ionization rate due to the electric field across the cathode sheath was considered negligible in comparison with the fission fragment ionization rate.

For a constant value of neutron flux it may be seen from Table 3 that the source rate for a given gas increases with pressure, and that for a given pressure in the case of the pure gases (240 torr), the source rate increases with increasing atomic mass. This dependence of source rate on gas pressure and



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Figure 8 - Comparison of Experimental Current-Voltage Data With Theory for Xenon, Argon and Neon.



Figure 9 - Comparison of Experimental Current-Voltage Data With Theory for the (1000:1) Neon: Argon Mixture.



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Figure 11 - Comparison of Predicted and Measured Saturated Current at Low Source Rate.

TABLE 3

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Average Ion Source Rate from Fission Fragment Ionization

S- Positive Quadrant I-V fit to Theory

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S.	10 ¹³		3.41 ~ 10 ¹⁵			9.03 × 10 ¹⁵	9101 - 14.1		9101 ~ 11 0	7.51 × 10 ¹⁵	91.01 × 52.1	3.4 × 10 ¹⁶	5.43 × 10 ¹⁶
to	1.25 x :		3.92 × 10 ¹⁵			1.09 × 10 ¹⁶	1.62 × 10 ¹⁶		3.02 × 10 ¹⁶	7.51 × 10 ¹⁵	1.83 × 10 ¹⁶	4.63 × 1016	9.5 × 10 ¹⁶
s-	0 ¹²		1.5 x 10 ¹⁵	3.00 × 10 ¹⁵	2.5 × 10 ¹⁵	4.52 x 10 ¹⁵	6.84 × 10 ¹⁵	8.04 × 10 ¹⁵	91.05 × 10 ¹⁶	3.8 × 10 ¹⁵	8.62 × 10 ¹⁵	1.74 × 10 ¹⁶	2.8 × 10 ¹⁶
111 to The	6.23 × 1		1.72 × 10 ¹⁵	3.62 × 10 ¹⁵	3.13 × 10 ¹⁵	5.47 × 10 ¹⁵	8.43 × 10 ¹⁵	8.86 × 10 ¹⁵	1.44 × 10 ¹⁶	3.9 × 10 ¹⁵	9.92 × 10 ¹⁵	2.36 × 1016	4.66 × 10 ¹⁶
-S	1101		⁴¹ 01 x 2.1	2.62 x 10 ¹⁴	2.2 × 10 ¹⁴	3.63 × 10 ¹⁴	6.55 x 10 ¹⁴	7.08 × 10 ¹⁴	1.03 x 10 ¹⁵	3.88 × 10 ¹⁴	4101 x 20.9	1.81 × 10 ¹⁵	2.81 × 10 ¹⁵
to	6.23 × 1		1.3 × 10 ¹⁴	2.64 × 10 ¹⁴	2.31 × 10 ¹⁴	4.15 × 10 ¹⁴	7.36×10^{14}	7.85 × 10 ¹⁴	1.33 × 10 ¹⁵	4.12 x 10 ¹⁴	1.08 × 10 ¹⁵	2.49 × 1015	4.88 × 10 ¹⁵
ιω	1010		1.01 × 10 ¹³	2.11 × 10 ¹³	1.8 × 10 ¹³	3.6 × 10 ¹³	6.75 × 10 ¹³	7.14 × 10 ¹³	⁴¹ 01 x 60.1	3.67 × 10 ¹³	7.33 × 10 ¹³	1.51 × 10 ¹⁴	2.62 × 10 ¹⁴
tos	lux(a) 6.23 x		1.04 × 10 ¹³	2.13 × 10 ¹³	1.85 × 10 ¹³	4.02 x 10 ¹³	8.78 × 10 ¹³	8.0 × 10 ¹³	1.35×10^{14}	3.78 × 10 ¹³	8.65 × 10 ¹³	2.07 × 1014	4.28 × 10 ¹⁴
rce Rate n-3 sec-1)	Reutron F L cm-2)	Pressure (torr)	30	60*	60	120	240*	240	400 +	240	540	540	007
Ion Sou (ions cu	Average (n sec	Gas	Neon: Argon			3				Neon	Argon	Xenon	

(a) The actual neutron flux at each tube is given in Table 1, page 10

atomic mass can evidently be attributed to the increase in fission fragment energy loss in the gas with increasing pressure and atomic mass.

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Table 3 also shows that the values of source rate determined from the negative quadrant I-V data (5-) are, in general, less than the values of source rate determined from the positive quadrant I-V data (S^+) . The values of S^+ and $S^$ are approximately equal only at the lowest pressures for the neon: argon mixture and for the 240 torr pure neon data. Now the application of the present theory to a particular set of experimental I-V points enables a determination to be made of the value of the average source rate in the cathode sheath only and in most cases the cathode sheath thickness is small compared with the electrode separation d. If the average source rate changes with distance from the uranium surface, due for example to the attenuation in the gas of fission fragments from the uranium-coated electrode, then the average source rate near the surface of the center electrode can be measurably less than the average source rate near the uranium surface. (The influence of geometric factors which can give rise to dif-ferences in the values of S^+ and S^- is discussed in Section C of this report.) Reference to Fig. 6(a) indicates that in the positive quadrant (S^+) , the cathode sheath is adjacent to the uranium surface, and in the negative quadrant (5-) the cathode sheath is adjacent to the center electrode surface. Thus, on the basis that the source rate is non-uniform only because of the partial attenuation of the fission fragments in the gas, it would be expected that $S^+ > S^-$ as shown in Table 3. This table also indicates that when the attenuation of fission fragments is expected to be least, i.e. for low pressures (neon:argon) and low atomic mass (pure neon), the percentage difference between S^+ and S^- is least, whereas when the attenuation of fission fragments is expected to be largest for high pressure and high atomic mass (xenon at 400 torr) the percentage difference between S+ and 5- is largest.

For the purpose of evaluating the ion number density in the plasma under given conditions, the value of source rate used is $S_E = \underline{S^+ + S^-}$. The values of SE for xenon, argon, neon and neon:argon at 240 torr and a neutron flux of 1.2×10^{13} sec⁻¹ cm⁻² are shown in Table 4.

TABLE 4

Ion Source Rate and Ion Number Density

p = 240 torrF = 1.2 x 10¹³ sec⁻¹ cm⁻²

		Xenon	Argon	Neon	(1000:1) Neon:Argon
S _E (x 10 ⁻¹⁶) sec ⁻¹ cm ⁻³	Experimental (application of plasma model to I-V data)	4.0	1.7	0.75	1.5
n^{+} (x 10 ^{-1.1}) cm ⁻³	From $(S_E^{\alpha})^{1/2}$	1.4	1.7	1.8	
n^+ (x 10 ⁻¹¹) cm ⁻³	From S_E/ν (A ⁺ +A+Ne \rightarrow A ⁺ ₂ + Ne)				8.3

For the pure gases, the number density in the $plasma(n^+=n_p)$ is determined using Eq.(1) where the values for the recombination coefficient (dissociative) in xenon ($\alpha = 2 \times 10^{-6} \text{ cm}^3 \text{ sec}^{-1}$), $argon(\alpha=6 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1})$ and neon ($\alpha = 2.2 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$) are taken from Richardson, (5) Biondi(6) and Connor and Biondi(7)

respectively. It is seen from Table 4 that the values for n⁺ in the pure gases under the same experimental conditions are not markedly different (1.4 to 1.8 x 10ll ions cm⁻³). For the neon:argon mixture, the ion loss mechanisms are more complicated and these have been previously discussed in detail in Section A of this report. It was concluded there that the reaction controlling the net rate of disappearance of ions from the plasma was the three body reaction, A⁺+A+Ne ----A₂ + Ne, the molecular argon ions then rapidly disappearing by dissociative recombination with electrons. The collision frequency for this reaction has been measured by Oskam⁽⁸⁾ and was found to be $v = 315 p(Ne) p(A) \sec^{-1}$ where p represents the partial pressure (torr) of the constituent gases. The ion number density in this case is therefore given by h⁺-Sg/v which, under the conditions listed in Table 4, yields a value of 8.3 x 10¹¹ ions cm⁻³. This demonstrates that plasmas of higher number density can be generated a Fenning-type mixture than in the pure noble gases alone.

The next section of this report (Section C) outlines how the source rate may be computed theoretically from a study of fission fragment energy loss in a gas. For infinite parallel plane geometry, with complete coverage of uranium on one electrode, the source rate at each point in the gas can be readily calculated. However, for the purpose of comparing theory with the average value of source rate determined experimentally, it is essential to take into account the finite geometry of the diode and partial coverage of the electrode surface with uranium, and this study has not yet been completed. Section C indicates how the theoretical problem of determining source rate is being undertaken.

Gamma Chamber Data

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The data from the gamma sensitive volume of the ion chamber exhibited current magnitudes that were generally of order 1% of the neutron chamber current. The shape of the I-V characteristic varied considerably between the various gases and depended on the circuit employed.

That data from the single bias circuit (Fig. 6(a)) which appeared to have I $\alpha \sqrt{1/2}$ were used in a least-square-fit to theory to obtain the ion source rate. These source rates are given in Table 5 and the I-V data for these results are shown in Figs. 21, 22 and 23. The source rate is symmetric in that both quadrants give approximately the same value for \bar{S} . The magnitudes of these source rates are from 50 - 100 times smaller than those obtained from the previous analysis of the neutron chamber data for the same pressures and reactor power levels.

TABLE 5

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Average Ion Source Rate from Gamma Ionization

S Positive Quadrant I-V fit to Theory

S- Negative Quadrant I-V fit to Theory



The data obtained for the double bias circuit (Fig. 6(b)) were very sensitive to the relative potential of the third electrode (in the case of the uranium electrode). The current in the gamma chamber was very asymmetric and is schematically exhibited in Fig. 24.



Figure 24 - Gamma chamber current for 60 torr neon-argon at 1000 kw.

The current in the neutron chamber under these conditions also exhibited an asymmetry as shown in Fig.25. where the dashed line shows the data with meter A_2 open.



Figure 25 .- Neutron chamber current for 60 torr neon-argon at 1000 kw.

This anomalous current behavior was explained qualitatively in the following way. For the polarity applied in the positive quadrant, it is possible for electrons from the high density plasma in the neutron chamber to leak through the 'weep' holes in the center electrode into the gamma chamber under the influence of the electric field in the gamma chamber. At a sufficiently large positive potential (now the sum of both chambers) these electrons can cause multiple ionization in the gamma chamber with a subsequent large increase in plasma density in this volume. The additional current extracted from this plasma can divide itself between current in the gamma chamber (increase in A₂) and current in the neutron chamber through leakage in the holes (increase in \tilde{A}_1). This observation shows a feature similar to the Gabor triode(9) in which a collector grid is located between an emitter and plate in a gas filled tube. Thermionic electrons in this case leak through the grid and are accelerated in the grid collector space to produce ions which leak back to the emitter grid space to neutralize space charge. In our present experiment the electron source for this multiplicative ionization effect is a fission fragment generated plasma rather than thermionic electrons.

Vacuum Tube Data

The vacuum tube I-V data obtained with the single bias circuit is shown in Figs. 26 and 27 for 1000 kw. Data at 100 kw and 10 kw showed a similar shape to these I-V characteristics. The neutron chamber data of Fig. 26 exhibits a saturation similar to that of the glass ion chamber (Section A). The asymmetry in current is attributed to the difference in yield between the secondary electrom emission generated by the fission fragments in the uranium and Kovar electrodes.

The current components measured in Fig. 26 are depicted in Fig. 28. These are: I_F due to fission fragments, I_F due to secondary electrons emitted simultaneously with the fission fragment and I_S due to secondary electrons generated by the fragments striking the opposite Kovar electrode.





Kovar Electrode

Uranium on Kovar Electrode

Figure 28 - Currents generated in vacuum from one fissioning electrode.

The current I_F^+ can be computed as before from Eq. (1) of the glass ion chamber, Section A. This yields a value of 1.5 x 10-7 amps for 1000 kw reactor power. The saturated currents in Fig. 26 are 3.1 x 10⁻⁶ and 1.9 x 10-6 amps so that I_F^+ is a small contribution to the measured current. The saturated current for positive, I(+), and negative, I(-), polarities of Fig. 26 thus approximately correspond to

 $I(+) = I_{F}^{-}$ $I(-) = I_{S}^{-}$

The yield of secondary electrons per fission fragment can be obtained by computing I-/eN_{FF} where e is electronic charge and N_{FF} is the fission fragment emission from the surface. For a one range thick foil N_{FF} = $1/2\Sigma_{\rm f}$ FV where $\Sigma_{\rm f}$ is the fission cross section (cm⁻¹), F is neutron flux (sec-1 cm⁻²) and V is the volume of uranium (cm³). At 1000 kw, the fragment emission is computed to be 1.37 x 10¹¹ fission sec⁻¹. Scaling this value with neutron flux, the secondary ratios are tabulated in Table 6 for data obtained at three power levels for both surfaces. The saturated electron current data at 50 volts are used for this calculation and the data at 10 kw were corrected for a gamma component as measured with the gamma chamber.

TABLE 6

Secondary Electron Yield per Fission Fragment (Electrons/Fission Fragment)

Power Level	Uranium Electrode	Kovar Electrode
(KW)	194	103
10	150	96
100	1)0	86
1000	142	

This variation of secondary yield with reactor power (neutron flux) is not explained at this time. The major assumption in this calculation is that the fragment emission is proportional to flux and that the flux is accurately given by the reactor power measuring system.

These values of electron yield for uranium are consistent with electron yield data reported for uranium less than 1 range thick and extrapolated to 1 range.(10) The electron current observed in the gamma chamber (Fig. 27) arises from the photoelectric emission of electrons by the interaction of gamma radiation with the diode electrodes. The asymmetry in the I-V characteristic (more current in the negative quadrant) may be due to an asymmetric electron source distribution within the gamma chamber.

Summary and Conclusions

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A method has been developed for the measurement of the average ion source rate in a noble gas plasma generated by fission fragment ionization.

A theoretical current-voltage characteristic has been derived from a model which considers the plasma to be recombination controlled except in the sheaths at the electrodes. The theory fits current-voltage data well in neon, argon and xenon out to 100 volts and in neon:argon (1000:1) out to 25 volts (ionization by electron impact is significant in neon:argon beyond this voltage.)

The experimental data also follow the predicted variation of current with neutron flux which gives further credence to the theoretical plasma model developed.

The least-mean-square fit of the theory to the experimental current-voltage data was used to evaluate an average value of ion source rate. The ion source rate for the (1000:1) neon-argon mixture was higher than for pure neon by a factor of about 2. This increase in ion source rate was attributed to argon ionization by collisions of the second kind with metastable neon states. The ion density ascribed to the neon:argon tube at 240 torr was 8.3×1011 ions cm⁻³ in a neutron flux of 1.2 x 10^{13} sec⁻¹ cm⁻². The ion densities in the other gases under the same pressure and flux conditions were significantly less, viz., argon: 1.7×10^{11} cm⁻³ neon: 1.8×10^{11} cm⁻³ and xenon: 1.4×10^{11} cm⁻³.

Concurrent with the investigation of fission fragment ionization rates, a study was made of the noble gas ionization rate due to gamma radiation. It was found that for gamma radiation intensities in the range $\sim 10^5$ to 10^7 Rad/hr (the corresponding neutron flux range was $\sim 10^{11}$ to 1013 sec⁻¹ cm⁻²), the source rate due to gamma induced ionization was in the region of 50 to 100 times less than the source rate due to fission fragments.

Using a vacuum chamber containing uranium, an approximate determination was made of the yield of secondary electrons per fission fragment emitted from the uranium. For reactor power in the range 10 - 1000 kw, the electron yield per emitted fission fragment was $\sim 140 - 200$. An estimate of the secondary electron yield from a Kovar surface due to the incidence of fission fragments over the same range of reactor power, gave $\sim 80 - 100$ electrons per incident fission fragment.

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APPENDIX A

Radiolytic Decomposition of Oil

The radiolytic gas generation rate for monoisopropylbiphenyl (Monsanto Chemical Company) oil was reported to be 0.76 ml of gas (STP)/ml of fluid exposed for a radiation dose of 10° Roentgen (Monsanto Bulletin AD 36). A gamma dose of 10¹⁹ Roentgen is equivalent to 1×10^{10} NVT of thermal neutrons or 2.5 x 10¹⁷ NVT of fast neutrons. The radiolytic gas generation rate was calculated for a thermal neutron flux of 5 x 10¹² cm⁻² sec⁻¹ (approximate average over the oil volume 1 MW reactor power) with a cadmium ratio of 4 for a 1 hour exposure of 250 ml of this oil (in a 570 ml volume) as follows:

 $\frac{\text{Thermal Neutron Contribution}}{5 \times 10^{12} (\text{NV}) \times 3600 (\text{T})} \times \frac{.76 \text{ ml gas}}{\text{ml oil}} \times 250 \text{ ml oil} \times \frac{760 \text{ torr}}{320 \text{ ml gas}} = 8.5 \text{ torr}$

Fast Neutron Contribution

Total pressure change = 19.4 torr in 1 hour.

A six hour irradiation was made of 250 ml of oil while pressure was monitored. The pressure gauge reading changed linearly with time from 29 in. Hg (vacuum condition on starting) to 25 in. Hg or a change of 4 in. Hg. The predicted change for this period was $6 \times 19.4 \times 30/760 = 4.6$ in. Hg which is in reasonably good agreement.

The support tube was initially evacuated at the start of a run and build up to one atmosphere radiolytic gas pressure took about 6 hours (the oil volume is greater than in the test run above). This gas was evacuated into a balloon for storage and subsequent release when the gas activity decreased to a tolerable level.

Explanatory Note for Figures 12 - 23

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These figures show the comparison of the theoretical current-voltage curve (0) with experimental data (X) for a particular ion chamber and neutron flux. Pertinent data on the chamber along with the source rates computed from the fit of theory to experiment (in each quadrant) are listed in the following order on each figure.

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Run M	umber Tube	Position	Neutron Flux	Source Rate Computed for Negative Quadrant
Gas	Pressure	Source for Pos	Rate Computed	Reactor Power

The data for Figures 12-20 are for neutron chambers whereas Figures 21-23 are for gamma chambers (in this case the word Gamma is substituted for the Neutron Flux in the tabulation).

Summary

Figure	Gas	Pressure (torr)	Reactor Power (kw)
12	Ne :A	30	2000
13	Ne :A	60	100
14	Ne :A	120	1000
15	Ne :A	400	2000
16	Ne :A	240	10
17	Neon	240	10
18	Argon	240	1000
19	Xenon	240	100
20	Xenon	400	2000
21	Argon	240	10
22	Xenon	240	10
23	Xenon	400	10



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Figure 13



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Figure 15



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Figure 17







SECTION C

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ION SOURCE RATE FROM FISSION FRACMENT ENERGY LOSS

ABSTRACT

The ion source rate in a gas film adjacent to a uranium bearing electrode was computed from the energy loss rate of the fission fragments that penetrate this gas film. The fission fragment energy loss was linearized with path distance to obtain first a one-dimensional solution for the ion source rate. Then, for the geometry of the ceramic-metal ionization tube, an analytic solution was obtained for the ion source rate along the axis of the tube and an approximate solution was obtained for the source rate at the edge of the uranium disc. The values of source rate computed using this latter solution were compared with the experimental values of ion source rate. The agreement was good in view of the fact that the comparison was made between an experimental average source rate and a value computed at one point in the cathode sheath. A general expression for the ion source rate for all points within the interelectrode gap is being programmed for solution on an IEM 7090 computer.

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INTRODUCTION

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Studies have been carried out in the University of Michigan reactor to determine experimentally the ion source rate from the fission fragment ionization of noble gases.* From the current-voltage characteristics of the ionization tube and a one-dimensional-plasma model it was possible to make a one parameter fit to the I-V data and obtain an average ion source rate (S, cm⁻³ sec-1). The ion source rate can also be obtained from an entirely independent approach; namely, from the energy loss rate of the fission fragments as they penetrate the gas in the interelectrode gap. A one-dimensional treatment of the energy loss rate in a gas medium was reported previously.(1) In that treatment, the total - fission fragment loss rate in the gas was determined from the difference between the fission fragment kinetic energy emitted from the uranium surface and that lost to the opposite electrode. The total energy loss rate in the gas was then set equal to the product of the average ion source rate in the interelectrode volume and the energy to produce an ion pair in the interelectrode gas. The expression derived for the source rate was found to give values in fair agree-ment with experimental measurements(2) but it was found later that this was due in part to partially compensating errors that had been made in the derivation.

In re-examining this problem it was decided not only to treat the onedimensional case but also the three-dimensional case so that the source rate derived from fission fragment energy loss rate considerations might be more readily applied to the particular geometry of the experimental ionization tube (Fig. 1).



Figure 1 - Expected influence of geometry of the ceramic-metal ionization tube on shape of cathode sheath.

Because of the geometry of the ionization tube and the finite range of fission fragments the actual source rate in the interelectrode volume S (r_2, y_2) would be expected to decrease with increasing distance from a point $(r_2, y_2 = 0, 0)$ on the surface at the center of the uranium disc. In the one-dimensional plasma model a uniform ion source rate was assumed and the cathode sheath thickness was given by b = $J/eS = (4 \ \mu^+ \epsilon_0/eS)^{1/4} \ v^{1/2}$. Considering the three-dimensional geometry in Fig. 1, and by analogy to the one-dimensional treatment, the cathode sheath thickness, $b(r_2)$, is given by the solution to the integral equation

* See Sections A and B of this report.

$$J(r_{2}) = e \int_{y_{2}=0}^{b(r_{2})} S(r_{2}, y_{2}) dy_{2} = (4\mu^{+} \epsilon_{0}e^{3})^{1/4} v^{1/2} \left\{ \frac{1}{b(r_{2})} \int_{y_{2}=0}^{b(r_{2})} S(r_{2}, y_{2}) dy_{2} \right\}^{3/4}$$
(1)

and the measured current, I, is given by

$$I = 2\pi e \int_{0}^{P_2} r_2 dr_2 \int_{0}^{b(r_2)} S(r_2, y_2) dy_2$$
(2)

The problem to be treated in this report is the derivation of an expression for the ion source rate $S(r_2, y_2)$ in terms of the fission fragment energy loss rate in the gas, the diode geometry and the properties of the uranium bearing electrode.

ENERGY LOSS RATE OF FISSION FRAGMENTS

In the derivation of the ion source rate from fission fragment energy loss rate in the next section the fission fragment energy loss has been linearized with path length. This approximation to a complex physical phenomenon greatly simplifies the mathematical treatment. In order to provide a basis for qualitative evaluation of the assumptions made, the full expression for fission fragment energy loss is presented in this section together with pertinent relationships that have been derived by various investigators.

The energy loss of fission fragments has been treated theoretically by Bethe and Ashkin⁽³⁾ and the total energy loss per centimeter of path is given by

$$\frac{dE}{dX} = \frac{4\pi e^4}{m v^2} \frac{(Z_1^{eff})^2 Z_2 \log \frac{1.123 m v^3}{\omega e^2 Z_1^{eff}}}{\omega e^2 Z_1^{eff}} + \frac{4\pi e^4}{M_2 v^2} Z_1^2 Z_2^2 \log \left(\frac{M_1 M_2}{M_1 + M_2} \frac{v^2 a_{12}^{scr}}{Z_1 Z_2 e^2}\right)$$
(3)

where: dE/dX = energy loss/cm = - ("stopping power" of medium) N = number of atoms of stopping medium

- m = mass of electron
- $M_1 = mass of fragment$

1 N

- M_2^{\dagger} = mass of a nucleus of the medium
- e = charge of electron
- v = velocity of fragment
- Z_1 = nuclear charge of the fragment
- Z₁^{err} = effective charge of the fragment shielded by the captured electrons surrounding it
 - Z_2 = number of electrons in one of atoms of stopping material

 $\omega = I/n$ = average oscillation frequency of the electrons in the atom and

I = average excitation potential of the atom

The first term on the right represents the energy loss due to electronic excitation and ionization processes and the second term represents the energy loss due to nuclear collisions which predominate at the end of the fission fragment track.

The range, R, of a fragment with initial velocity corresponding to energy E_1 in a medium with a stopping power of (-dE/dx) is given by the expression⁽⁴⁾

 $R = \int_{0}^{R} dx = \int_{E=0}^{E_{1}} (-dE/dx)^{-1} dE$ (4)

The standard medium for ranges for high velocity charged particles is dry air at 15°C(288°K) and 760 torr.⁽⁵⁾ An often used unit of measure of range is the "airmm" which is the path equivalent to one mm of air at the above standard conditions.

The variation with velocity of some of the variables in Eq.(3) is not well known so that the usefulness of Eq. (4) for the determination of the range $(E_1 \longrightarrow E = 0)$ of fission fragments in various media is limited.

Fission fragments are created with large kinetic energies and a large positive charge (see Table 1).

TABLE 1

Group Properties of Fission Fragments

	Symbol	Light Fragment	Heavy Fragment	Average
Average Energy, Mev (5)	Ef	98	67	82.5
Average Mass, Amū ⁽⁶⁾	мј	95	139	117
Average Charge ⁽⁶⁾	Zoj	20	22	21
Average Range in Air, cm ⁽⁵⁾	R _{airj}	2.5	1.9	2.2

As the fragments slow down in their passage through matter electrons are captured and the charge is continually decreased (see Z_1^{eff}). The dependence of Z_1^{eff} on the fragment velocity is not well established but for the heavier fission fragments Z_1^{eff} varies almost linearly with v according to Fermi-Thomas statistical model(3)

$$Z_1^{\text{eff}} = Z_1^{1/3} \frac{1}{h} v/e^2$$
 (5)

A variation as $v^{1/2}$ is indicated for the lighter fragment. Using the dependence in Eq. (5) Bohr obtained an expression for the ratio of the ranges for a fission fragment and an α particle.

$$\frac{R_{f}}{R_{\alpha}} \simeq 7 \frac{A_{1}}{(Z_{\gamma}^{eff})^{2}} \simeq 7 \frac{A_{1}}{Z_{\gamma}^{2/3}} \left(\frac{e^{2}}{\hbar v}\right)^{2}$$
(6)

This expression is independent of the medium so that the stopping power of various materials for fission fragments varies in the same way as for alpha particles.

Experimental measurements of the range of heavy particles have been cor -lated with some success by a semi-empirical Bragg-Kleeman rule (7)

 $R = R_{air} \left(\frac{\rho_a}{\rho}\right) \sqrt{\frac{A}{A_a}}$ (7)

where

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R = range in material of density, ρ . R_{air} = range in air of density, ρ_a . A = mass number of material A_a = mean mass number of air

When the material is a gas at temperature, T, and pressure, p, Eq.(7) can be written in terms of the range in standard air, $R_{\rm a}$, and the molecular weights, M,

$$R = R_{a} \left(\frac{760}{288} \right)^{M} \frac{A}{M} \sqrt{\frac{A}{A_{a}}} \frac{T}{p} = 20.1 R_{air} \frac{\sqrt{A}}{M} \frac{T}{p}$$
(8)

As the velocity of the fission fragment decreases the charge also decreases (see Eq. (4)) and the specific ionization, $\frac{dT}{dX} \left(\simeq K \frac{dE}{dX} \right)$, decreases almost linearly with range as shown in Fig. 2.



Figure 2 - Rate of energy loss as a function of range. (5)

After the fission fragment reaches a residual range of ~ 4 air-mm nuclear collisions become increasingly important (Eq. (1)) which results in the rapid increase in dT/dX as the fragment comes to thermal equilibrium with the material.

In the treatment of the fission fragment energy loss in the next section it is assumed that the energy loss is linear with path length in the absorber or

$$-\frac{dE}{dx}_{ij} = \frac{E_{fj}}{R_{ij}}$$

(9)

E_{fj} = Initial kinetic energy of the fission fragment, j(i.e. most probable fragment of group j, see Table 1)

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R_{ij} = range of fragment, j, in absorber, i.

As shown in Fig. 2 this approximation is only fair but it greatly simplifies the mathematical treatment. Expressing distance in the absorber in terms of range units in the absorber $(\xi_{i,j} = x_i/R_{i,j})$, Eq. (9) can be written for the passage of one fission fragment through a number of successive absorbers as (see Fig. 3)

$$\frac{dE}{d\xi_{ij}} = -E_{fj} = \frac{dE}{d\xi_{nj}}$$
(10)

1 .

providing



Figure 3

The ion source rate in the gas, S, is related to the energy loss rate by (using (9))

$$S = \frac{(-dE/dx)\Delta x}{W}$$
(12)

where

 Δx = distance traveled by the particle in the gas

✓ = is the total amount of energy expended in the gas per ion pair produced.

The energy loss per ion pair produced is very nearly independent of the energy of the primary particle(3) and is also nearly the same for alpha particles, protons, and fission fragments.⁽⁷⁾ In the treatment to follow the measured values for w for alpha particles are used for the fission fragments.

ONE-DIMENSIONAL SOLUTIONS

Assumptions

The assumptions made in the following treatment are listed below:

- 1. Fission rate Uniform through a depth of one fission fragment range in the uranium bearing surface.
- 2. Fission fragments Two emitted isotropically per fission with average group properties listed in Table 1.
- 3. Charge loss rate Linear with path (See Eq.(5))
- 4. Energy loss rate Linear with path (See Eqs. (9) and (10))

5. Range of fragments - See Eq. (8)

6. Ionization - See Eq. (12)

where

(11)

Fission Fragment Emission

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The particle current of fission fragments, Γ , escaping from the surface of a planar fissioning film depends upon the thickness and properties of the film.



The fragments of group j initially generated in dV_1 that would penetrate dA_2 , dN_1/dt , is given by

$$\begin{pmatrix} dN_{i} \\ dt \end{pmatrix} = \Sigma_{f} F dV_{i} \begin{pmatrix} dA_{2} \cos \theta \\ \hline 4\pi (y_{i} / \cos \theta)^{2} \end{pmatrix}, \quad (0 \le \theta \le \Theta_{M_{i}})$$
(13)

where $\sum_{i=1}^{n}$ is the macroscopic fission cross section (cm^{-1}) and F is the thermal neutron flux $(cm^{-2} \sec^{-1})$. For dV_1 at a depthy cm in the uranium film, the maximum angle (Θ_{Mj}) at which fragments can reach the area (dA_2) is given by

$$\Theta_{m_3} = \cos^{-1}(y_1/R_{13}) = \cos^{-1}X_{13}, (X_{13} \leq 1).$$
 (14)

For $x_{1j} > 1$, dN_j/dt is, of course, zero.

The current through dA_2 is $\partial^2 \Gamma_j = (dN_j/dt)/dA_2$

$$\partial^2 \Gamma_i = \left(\frac{\sum_{f} F R_{ij}}{2}\right) dx_{ij} \sin \theta d\theta$$
 (15)

The total particle current, \prod_{j} , due to all the fissions to a depth $y_1(cm)$ in the uranium is

$$\begin{aligned}
 f_{j} &= \frac{\Sigma_{f} F R_{ij}}{2} \int d \left(\frac{y_{i}}{R_{ij}} \right) \int \sin \theta \, d\theta \\
 y_{i} &= 0 \quad \theta = 0
 \end{aligned}$$

$$f_{j}^{*} &= \left(\Sigma_{f} F y_{i} \right) \left[\frac{j}{z} \left(l - \frac{y_{i}/R_{ij}}{z} \right) \right].$$
(16)

or

The fission fragment emission due to both fragments is

$$\int -\sum_{j=1}^{2} \int_{j} \int_{j} \dots \quad (17)$$

For a fissioning film of one range thickness $\int_{1}^{1/4} \sum_{r} \tilde{R}_{r}$ and $\int_{2}^{1/4} \sum_{r} \tilde{R}_{r}$ and \tilde{R}_{r} and \tilde{R}_{r} is the average range for the light and heavy fragments.

Current of Positive Charge from Fission Fragment Emission

Referring again to Fig. 4, the initial charge generation in dV_1 due to the jth fission fragment that would penetrate dA_2 if there were no absorption in region 1 is

$$\partial dI_{3} = \left(\Sigma_{4} Fe Z_{0}\right) dV_{1} \left(\frac{dA_{2} \cos \Theta}{4\pi (\gamma / \cos \Theta)^{2}}\right), \left(0 \le \Theta \le \Theta_{m_{0}^{2}}\right)$$
(18)

where Θ_{M_j} is given by (14) and $\partial dI_j = 0$ for $X_{1j} > 1$. The fraction of ∂dI_j that is not absorbed and penetrates dA_2 is $1 - y_1/(R_{1j} \cos \theta)$ (see Eq.9). Substituting into (18), the current density is

$$\partial dJ_{j} = \frac{\partial dJ_{j}}{\partial A_{2}} = \left(\frac{\sum_{f} Fe Zo_{j}}{2}\right) dy \left(I - \frac{\chi_{ij}}{\cos\theta}\right) \sin\theta d\theta.$$
 (19)

The total current density due to fissioning to a depth y_1 in the uranium film is

$$J_{j} = \left(\frac{\sum_{i} Fe Z_{ij} R_{ij}}{2}\right) \int d\left(\frac{y_{i}}{R_{ij}}\right) \int \left(1 - \frac{x_{ij}}{\cos\theta}\right) \sin\theta d\theta$$

$$y_{i} = 0$$

or

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$$U_{j} = \left(\Sigma_{4} Fe Z_{oj} Y_{i}\right) \left[\frac{1}{2} \left(I - \frac{3}{4} X_{ij} + \frac{X_{ij}}{2} \ln X_{ij}\right)\right]$$
(20)

The total positive charge current is $J = \sum_{j=1}^{L} J_j$. As $y_1 \rightarrow 0, J_j \rightarrow 1/2$ the initial charge generation rate $(\sum_{f} Fe Z_{oj} y_1)$ and as $y_1 \rightarrow R_{1j}$, $J_j \rightarrow 1/8$ the initial charge generation rate.

The average charge per fission fragment (of group j) on leaving a surface film of depth $y_1(cm)$ is given by

$$\langle Z_{j} \rangle_{av} = \frac{V_{j}}{T_{j}} = Z_{oj} \left[\frac{1 - 3/4 \chi_{ij} + (\chi_{ij}/2) lm \chi_{ij}}{1 - \chi_{ij}/2} \right], (\chi_{ij} \leq 1)$$
 (21)

For $y_1 \ge R_{1j}$, $\langle Z_j \rangle$ av = $Z_{oj}/2$.

Kinetic Energy of Fission Fragments Emitted from an Electrode

Using assumption 4 and the same logic as discussed above, a similar expression may be obtained for the escape of fission fragment kinetic energy from the surface of a uranium bearing film; viz.,

$$\left(\frac{dE}{dt}\right)_{j} = \left(\Sigma_{f}FE_{fj}y_{i}\right) \left[\frac{1}{2}\left(1 - \frac{3}{4}X_{ij} + \frac{X_{ij}}{2}\ln X_{ij}\right)\right], \left(X_{ij} \leq 1\right). (22)$$

Also, $(dE/dt)_j \longrightarrow 1/2 (\Sigma_f F E_{fj} y_1)$ as $x_{ij} \longrightarrow 0$ and at $y_1 = R_{ij}$, $(dE/dt)_j \longrightarrow 1/8 (\Sigma_f F E_{fj} R_{ij}).$

The average kinetic energy of the fission fragments (of group j) escaping from a surface film of depth y (cm) is given by

$$\langle E_{fj} \rangle_{w} = \frac{(dE/dt)_{ij}}{P_{ij}} = E_{fj} \left[\frac{1 - 3/4 \chi_{ij} + (\chi_{ij}/2) lm \chi_{ij}}{1 - \chi_{ij}/2} \right], (\chi_{ij} \leq 1)$$
(23)

For $y_1 \ge R_{i,j}, \langle E_{f,j} \rangle_{av} = E_{f,j}/2$. Referring to Fig. 2 this treatment using assumption 4 (and $y_1 \ge R_{i,j}$) will overestimate the amount of kinetic energy entering the gas from the uranium film.

Ion Source Rate in the Gas

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For this derivation assumptions 1, 2, 4, 5 and 6 are used.



Figure 5

Consider the volume element $dV_2=dA_2 dy_2$ in the gas at a distance y_2 above the uranium disc and the volume element, dV_1 , in the uranium at a depth of y_1 cm and at a distance of r_1 cm from the normal through dV_2 .

The kinetic energy generated in dV, from fragments of group j is $(\Sigma, T E, dV_{i})$ and the fraction of this energy that would penetrate $(dV_{i} = dA_{i} dy_{i})$ if there was no absorption in either regions 1 or 2 is $dA_{i} \cos \frac{\partial}{4\pi} (y_{i} + y_{i})/\cos \frac{\partial}{2}$. With absorption in both the gas and uranium and dV_{i} at a depth of y, ca in the film, the volume element dV_{2} can receive fragments from dV_{1} from a maximum angle, Θ_{KJ} , given by

T

or

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$$\Theta_{m_{ij}} = \cos^{-1}(y_{i}/R_{ij} + y_{i}/R_{kj}) = \cos^{-1}(x_{ij} + x_{kj}).$$
 (84)

The maximum depth of dV_1 at which dV_2 can receive fragments is given for $\Theta = 0$ by

$$\frac{(Y_{ij})_{M}}{R_{ij}} = (X_{ij})_{M} = 1 - X_{2j} .$$
(25)

The fraction of the kinetic energy entering dV_2 that is absorbed in dV_2 is $(dy_2/R_{2j} \cos \Theta)$. The energy absorption in dV_2 from dV_1 is then

$$\left(\frac{dE_{z}}{dt}\right)_{j} = \frac{(E_{c}F E_{fi})}{(4TR_{z})} dA_{z} dy_{z} dy_{z} d\psi \tan \Theta d\Theta. \qquad (26)$$

Using $dy_1 = R_1$, dx_1 , and integrating over ψ , the energy absorption rate per unit volume in dy_2 in the gas (at y_2) from all (j) fragments arriving in $d\Phi$ at Θ and from dy_1 at y_1 is

$$\frac{\left(\frac{dE_{1}}{dt}\right)_{j}}{\left(\frac{dE_{1}}{dt}\right)_{j}} = \left(\frac{\sum_{i} FE_{ij}R_{ij}}{R_{2j}}\right) \left[\frac{1}{2} dx_{ij} \tan \theta d\theta\right] .$$
 (27)

Integrating our Θ from 0 to $\Theta_{i,j}$ and over y_1 to the maximum depth $(x_{1,j} = 1 - x_{2,j})$ is the uranium to obtain all contributing j fragments and setting the energy absorption rate equal to w times the ion source rate, fields

$$S_{j}(t_{j2}) = \left(\frac{\sum_{i} F E_{ij} R_{ij}}{W R_{2j}}\right) \frac{1}{2} \int dX_{ij} \int d\theta d\theta \qquad (28)$$

$$S_{j}(y_{2}) = \left(\frac{\sum_{f} F E_{fj} R_{ij}}{W R_{sj}}\right) \left[\frac{1}{2} \left(1 - X_{2j} + X_{sj} \ln X_{sj}\right)\right].$$
 (29)

The ion source rate at y_2 due to both fragments is $S(y_2) = \sum_{j=1}^{\infty} S_j(y_2)$. As $y_2 \longrightarrow 0$, $S_j(y_2) \longrightarrow 1/2$ ($\sum_{f} F E_{fj} R_{ij} / W R_{2j}$) and as $y_2 \longrightarrow R_{2j}$ or as $x_{2j} \longrightarrow 1$, $S_j(R_{2j}) \longrightarrow 0$ as all are absorbed before reaching $y_2 = R_{2j}$.

The average ion source rate in a gas layer of thickness $(y_{22} - y_{21})$ is given

$$457 m r_{12} - \sum_{j=1}^{2} \int dy_2 S_j(y_2)$$
, (30)
 $y_3 - y_{21}$

For the gas layer next to the uranium of thickness y_2 cm Eq. (30) gives

$$\langle S \rangle_{aw} = \sum_{j=1}^{2} \left(\frac{\sum_{i} F E_{i} R_{ij}}{W R_{aj}} \right) \left[\frac{1}{E} \left(1 - \frac{3}{4} X_{aj} + \frac{X_{aj}}{E} \int_{aw} X_{aj} \right) \right] (31)$$

as $y_2 \longrightarrow R_{2,1} < S_2 > \dots -1/8$ ($\Sigma_r F E_r R_{1,1}$)/($v R_{2,1}$) which represents the 1/8 fraction of the kinetic energy escaping from the uranium surfaces (see Eq.(22)) distributed uniformly over a gas thickness of $R_{2,1}$, cm to produce ionization.

FINITE GEOMETRY SOLUTIONS

As seen from the geometry of the experimental ionization tube in Fig. 1, the previous one-dimensional solutions could not be expected to apply to the collection of ions over the entire electrode surface particularly when the uranium covers only a fraction of that surface. From Eqs. (1) and (2) the I-V characteristic for an ionization tube can be predicted entirely from theoretical considerations if the ion source rate at each point in the gas, $S(r_2, y_2)$, can be derived from energy loss rate considerations. This problem is being programmed for solution on the 7090 IEM computer but analytic solutions have been obtained for the source rate $S(r_2, y_2)$ along the axis of the diode $(r_2=0)$ and at the outer edge of the uranium disc $(r_2=\rho_1)$. These two solutions are presented below and the latter is then used in the last section to give a preliminary correlation with the experimentally measured ion source rates.

Ion Source Rate Along the Axis of a Circular Disc

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Consider the ion source rate at a distance y_2 from—and along the axis of a circular uranium bearing disc of radius ρ_1 .



The derivation of the ion source rate for this case follows the previous derivation for an infinite plane except for the limits of integration. For $0 \le x_{ij} \le (x_{ij})_{OM}$ the upper limit on Θ is given by

$$\Theta_{\text{PM}_{j}} = \cos^{-1} \frac{y_{1} + y_{2}}{\sqrt{e_{1}^{2} + (y_{1} + y_{2})^{2}}} \simeq \cos^{-1} \frac{y_{2}}{\sqrt{e_{1}^{2} + y_{1}^{2}}} = \cos^{-1} \frac{x_{2}}{\sqrt{e_{1}^{2} + (y_{1} + y_{2})^{2}}} (32)$$

For $(x_{ij})_{\rho M} \leq x_{ij} \leq 1 - x_{2j}$, the upper limit on Θ is given, as before, by Eq.(24). The $(x_{ij})_{\rho M}$ limit is given by the value of x_{ij} when $\Theta_{Mj} = \Theta_{\rho Mj}$ or

$$(X_{ij})_{em} = \frac{X_{zj}}{\sqrt{(R_i/R_{zj})^2 + X_{zj}^2}} - X_{zj},$$
 (33)

The ion source rate $S_1(r_2, y_2)$ at $r_2 = 0$ is

$$S_{j}(0,y_{2}) = \left(\frac{\sum_{f} FE_{fj} R_{ij}}{WR_{2j}}\right) \left(\begin{array}{c} (X_{ij})_{PM} \quad \Theta \in M_{j} \\ \int dX_{i} \quad tan \quad \Theta d\Theta \\ \int dX_{i} \quad tan \quad \Theta d\Theta \\ X_{i} = 0 \quad \Theta = 0 \quad X_{1} = (X_{ij})_{PM} \quad \Theta = 0 \end{array} \right)$$
(34)

which integrates to

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$$S_{j}(0, y_{2}) = \left(\frac{\sum_{e} F E_{fj} R_{ij}}{W R_{2j}}\right) \left[\frac{1}{2} \left[1 - \frac{X_{2j}}{\sqrt{(R_{i}/R_{1j})^{2} + X_{2j}^{2}}} + \frac{X_{2j} l_{m} X_{2j}}{\sqrt{(R_{i}/R_{1j})^{2} + X_{2j}^{2}}}\right]\right]. (35)$$

The total ion source rate due to both fragment groups is

$$S(0,y_2) = \sum_{j=1}^{2} S_j(0,y_2).$$
 (36)

Ion Source Rate at the Edge of a Circular Disc

Consider a circular uranium bearing disc of radius, ρ_1 . Along a line normal to the surface and at the edge of the disc $(r_1 = \rho_1)$, consider the point $p = (r_2 = \rho_1, y_2)$ in the gas at a distance y_2 from the disc (Fig.7).



Figure 7

The complete expression for $S_1(\rho_1, y_2)$ is not readily integrated analytically so that an approximate solution was found when $y_2 <<\rho_1$ using the previous expression(35) derived for the source rate along the axis of a circular disc.

For the point $p = (r_2 p_1, y_2) = (r_2 = 0, y_2 = y_2)$ consider the "equivalent" segment (f_{π}) of a hypothetical disc of radius $r_2 = p_1$ which would produce the same ion source rate at p. For $y_2 << \rho_1$ the fission fragment path from dV_1 to dV_2 is $\tau_2' = \tau_2'$. The hypothetical segment equivalent to the disc should have (1) an area equal to that of the disc and (2) a first moment about p equal to that of the disc about p(Fig.8).



Figure 8

Setting the area of the disc $(\pi/4 \rho^2)$ equal to the area of the segment $(f \pi/4 \times (\rho')^2)$ gives $\rho' = (1/\sqrt{f'})\rho$. For the disc, the first moment about p is (Fig.8)

 $\int d\theta \int r^{3} dr = \frac{32 \rho^{3}}{9}$

and the first moment for the segment is



Setting the first moments equal gives f = .346 and $\rho' = 1.70 \rho$. Substituting ρ' into Eq.(35) and multiplying by f for the contribution from the segment gives

$$S_{i}(P_{i}, y_{2}) \simeq \left(\frac{\sum_{f} F_{f_{i}} R_{i}}{W R_{2}}\right) \left\{ \cdot 173 \left[I - \frac{\chi_{2j}}{\sqrt{(I,7P_{i}/R_{2j})^{2} + \chi_{2j}^{2}}} + \chi_{2j} \int \frac{\chi_{2j}}{\sqrt{(I,7P_{i}/R_{2j})^{2} + \chi_{2j}^{2}}} \right\} (37)$$

for $y_2 \ll \rho_1$.

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The total ion source rate at (ρ_1, y_2) is

$$S(\rho_{1}, y_{2}) = \sum_{j=1}^{2} S_{j}(\rho_{j}, y_{2}).$$
 (38)

In terms of the average (designated \sim) of the two group constants (see Table 1), the total ion source rate at (ρ_1, y_2) is

$$\widetilde{S}(P_{1}, y_{2}) \simeq \left(\frac{\mathbb{E}_{+} F \widetilde{E}_{+} \widetilde{R}_{1}}{W \widetilde{R}_{2}}\right) \left\{ \cdot 346 \left[1 - \frac{\widetilde{X}_{a}}{\sqrt{17} (17 \sqrt{R}_{a})^{2} + \widetilde{X}_{2}} + \widetilde{X}_{2} \ln \frac{\widetilde{X}_{a}}{\sqrt{17} (17 \sqrt{R}_{1})^{2} + \widetilde{X}_{2}} \right]$$
(39)

COMPARISON OF COMPUTED AND EXPERIMENTAL VALUES OF ION SOURCE RATE

The experimental average source rate \bar{S} was obtained from a fit to the measured I-V data using (rewriting Eq.(10) Section C)

$$I = \pi \rho_2^2 e \overline{b(v)} \overline{S}$$
 (40)

where the cathode sheath thickness $\overline{b(v)}$ was obtained from the one-dimensional plasma model. In order to provide a qualitative comparison of the values of the measured (\overline{S}) and predicted (\overline{S}) ion source rates, Eq.(39) was solved for the average ion source rate in the cathode sheaths at the outer edge of the uranium disc ($\rho_1 = .75 \ \rho_2 = .952 \ cm$, see Fig. 1).

Pertinent information on the runs selected for comparison are given in Table 2.

TABLE 2

Experimental Data

(Superscript + for $V = +50V$ and	- for	$\mathbf{V} = -50$	(VC
Gas	Neon	Argon	Xenon
Run Number	41.26	41.28	41.27
Gas Pressure, torr	240	240	240
Neutron Flux, $(cm^{-2}sec^{-1})(x \ 10^{-13})$	1.19	1.23	1.29
b* (Experiment), cm	.054	.036	.022
b (Experiment), cm	.055	.038	.024
S^{+} (Experiment), (cm ⁻³ sec ⁻¹)(x 10 ⁻¹⁶)	0.75	1.83	4.63
S - (Experiment), $(cm^{-3}sec^{-1})(x \ 10^{-16})$	0.75	1.53	3.40

When V > 0 the cathode sheath is next to the uranium surface (+ superscript) and when V < 0 the cathode sheath is next to the Kovar electrode opposite the uranium (- superscript).

Theoretical ion source rates were calculated from (39) using the average of the two group constants listed in Table 1. The average fission fragment range in the uranium bearing disc was $R_1 = 6.65 \times 10^{-4}$ cm and the macroscopic fission cross section was $L_r = 23.1$ cm⁻¹. The distances of the midpoint of the cathode sheath from the uranium disc are given by $x_2 = (b^{+}/R_2)/2$ and $x_2 = d/R_2 - (b^{-}/R_2)/2$ where d = .274 cm (see Fig. 1). The values of x_2 together with the calculated values of the ranges in the gas from Eq.(8) are given in Table 3.

TABLE 3

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Values of Constants Used in Equation (39)

Gas	Neon	Argon	Xenon
W, ev	36.8	26.4	21.9
R ₂ , cm	11.88	8.40	4.62
d/R2	.0231	.0326	.0593
X2	.00227	.00215	.00238
x2	.0208	.0303	.05675

The calculated values of $S(R_1, b/2)$ using Eq.(39) and the constants in Table 3 are presented in Table 4 together with the average experimental source rate values, S, obtained previously* from the experimental data (see Eq.(41)).

TABLE 4

Comparison of Computed and Experimental Values of Average Ion Source Rate (Units of $cm^{-3} sec^{-1} x 10^{-16}$)

	Computed from Energy Loss	Computed from Experimental Data Š	Ratio S/S
Neon			
s ⁺	1.16	•75	1.55
s	•965	•75	1.29
s ⁺ /s ⁻	1.20	1.00	
Argon			
s ⁺	2.37	1.83	1.29
s ⁻	1.91	1.53	1.25
s ⁺ /s ⁻	1.24	1.20	
Xenon			
s ⁺	5.50	4.63	1.19
s	4.12	3.40	1.21
s ⁺ /s ⁻	1.34	1.36	

See Section B of this report.
The agreement is considered good in view of the fact that the experimental average ion source rate values, \tilde{S} , are compared to the values, \tilde{S} , computed at one point in the gas. Except for neon, the ratio $(\tilde{S}^+/\tilde{S}^-)$ is correctly predicted by $(\tilde{S}^+/\tilde{S}^-)$. The constancy of the ratio (\tilde{S}/\tilde{S}) indicates that the geometrical correction (over one-dimensional solution) is significant and approximately correct. The magnitude of $(\tilde{S}/\tilde{S}) = 1.25$ is thought to reflect the nonlinearity with distance of the actual source rate along the radius of the tube. Work is progressing on the solution of the generalized three-dimensional ion source rate function on the IBM computer.

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	 Direct energy conversion Thermionics Gaseous electronics Plasma physics 	I. C. B. Leffert II. F. E. Jamerson III. D. B. Rees	IV. General Motors Research Laboratories V. Nonr-3109(00)	UNCLASSIFIED	on that the ion density in the by volume recombination loss. V curres. The values of ion ory to the experimental curres are rate calculated independently in the gas.	megnitude of ion source rate re. However for the neoniargon for pure meon under the same con- ment remergy loss to metastable ional ionization of the trace gas torr filling and a neutron flux t order lo ¹⁰ ions sec-1 cm ⁻³ .	d for the pure gases (dissocia- The ion density in meoniargon 10 ¹¹ ions cm ⁻³ and therefore fact that the conversion rate re recombination loss, was alower mversion rate of monatomic to
eneral Motors Research Laboratories 2 Mile and Mound Roads, Warren, Michigan	NVESTIGATIONS ON THE DIRBUT CONVERSION OF MUCLEAR ISSUEN ENTROY TO ELECTRICAL ENERGY IN A FLASMA IODE, by C.B. Leffert, F.E. Jamerson and D.B. Rees 05 pp incl. figs.	umual Technical Bummary Report, Movember 1, 1962 to October 31, 1963 (Report No. 4) Contract Nonr-3109(00)	Experimental determinations are presented of the ion source rate generated by fission fragment ionization of noble gases. The effect of gas pre- sure (30 - 400 torr) and gas species (argon, neon, kenon and neoniargon) on ion source rate was studied inpile with ionization chamber tubes in which thin inpile with ionization chamber tubes in which thin inpile vich ionization chamber tubes in which thin inpile served as a fission source. (Therm- ionic electron emission in these tubes was negli- gible.)	A theory was developed for the ion chamber	current-voltage characteristic based on the assumption plasma between the electrode sheaths was controlled by This theory accurately described the shape of the I-V source rate determined by the application of the theory were in reasonable agreement with the values of source from the ionization energy loss of fission fragments	For the pure gases (neon, argon and xenon) the sincreased with increasing atomic mass and gas pressus (1000:1) mixture the ion source rate was twice that i ditions. This effect was attributed to fission fragistates of the parent gas (neon) which produced additistates of the parent gas (neon) which produced additistates of 1.2 x 10 ¹³ n sec ⁻¹ cm ⁻² the ion source rate was of of 1.2 x 10 ¹³ n sec ⁻¹ cm ⁻² the ion source rate was of the second kind.	Under these conditions, the ion density compute tive recombination loss) was $\sim 1.5 \times 1011$ ions cm ⁻³ . under the same conditions was estimated to be 0.3×1016 the figher than in the pure gauses. This was due to the of A^+ to A_2^+ , necessary to provide A_2^+ for dissociative in the neoniargon mixture than was the equivalent co diatomic ions in the pure gases.
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General Motors Research Laboratories	INVESTIGATIONS ON THE DIRECT CONVERSION OF WUCLEAR FISSION EMERGY TO ELECTRICAL EMERGY IN A FLASMA DIODE, by C. B. Leffert, F. E. Jamerson and D.B.Rees	Annual Technical Summary Report, November 1, 1962 to October 31, 1963 (Report No. 4)	Experimental determinations are presented of Experimental determinations are presented of the ion source rate generated by fission fragment ionization of noble gases. The effect of gas pres- sure (30 - 400 torr) and gas species (argon, neon, term and neonization chamber tubes in which thin inplie with ionization chamber tubes in which thin uranium foils served as a fission source. (Therm- ionic electron emission in these tubes was negli-	gible./ A thank we developed for the ion chamber	This theory accurately described the sasumption plasma between the electrode sheaths was controlled by This theory accurately described the shape of the L-V source rate determined by the application of the theory were in reasonable agreement with the values of source from the ionization energy loss of fission fragments	For the pure gases (neon, argon and xenon) the = increased with increasing atomic mass and gas pressui (1000:1) mixture the ion source rate was twice that i ditions. This effect was attributed to fission frag- states of the parent gas (neon) which produced addity (argon) by collisions of the second kind. For a 240 (argon) by collisions of the second kind. For a 240 of 1.2 x 1013 n sec ⁻¹ cm ⁻² the ion source rate was of	Under these conditions, the ion density compute tive recombination loss) was $\sim 1.5 \times 10^{11}$ ions cm ⁻³ . tive reterms the same conditions was estimated to be 9.3×10^{11} than in the pure gases. This was due to the higher than in the pure gases. This was due to the of A+ to A ² , necessary to provide A ² for dissociative in the neoniargon mixture than was the equivalent co diatomic ions in the pure gases.

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General Motors Research Laboratories 12 Mile and Mound Roads, Warren, Michigan	INVESTIGATIONS ON THE DIRECT CONVERSION OF NUCLEAR FISSION ENERGY TO ELECTRICAL ENERGY IN A PLASMA DIODE, by C. B. Leffert, F. E. Janerson and D.B.Rees 105 pp. incl. figs. Annual Technical Summary Report, November 1, 1962 to October 31, 1963 (Report No. 4) Contract Nonr-3109(00)	Experimental determinations are presented of the ion source rate generated by fission fragment ionization of noble gases. The effect of gas pres- sure (30 - 400 torr) and gas species (argon, neon, xenon and neon:argon) on ion source rate was studied inpile with ionization chamber tubes in which thin uranium foils served as a fission source. (Therm- ionic electron emission in these tubes was negli- gible.)	A theory was developed for the ion chamber	rent-voltage characteristic based on the assumption t sma between the electrode sheaths was controlled by v s theory accurately described the shape of the I-V cu rce rate determined by the application of the theory e in reasonable agreement with the values of source r m the ionization energy loss of fission fragments in For the pure gases (neon, argon and zenon) the magn reased with increasing atomic mass and gas pressure. Do:1) mixture the ion source rate was twice that for ions. This effect was attributed to fission fragment tes of the parent gas (neon) which produced additiona gon) by collisions of the second kind. For a 240 tor 1.2 x 1013 n sec ⁻¹ cm ⁻² the ion source rate was of or		Under these conditions, the ion density computed tive recombination loss) was -1.5×10^{11} ions cm ⁻³ . under the same conditions was estimated to be 8.3 x 1 higher than in the pure gases. This was due to the foot A+ to A_2^2 , necessary to provide A_2^2 for dissociative in the neoniargon mixture than was the equivalent completence of the number of the num

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