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Ion-Beam Characteristics of the Controlatron / Zetatron Family of the Gas-Filled Neutron Tubes

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ION-BEAM CHARACTERISTICS OF THE CONTROLATRON/ZETATRON FAMILY
OF THE GAS-FILLED NEUTRON TUBES

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ABSTRACT

A gas filled tube used to produce a neutron flux with the $D(T, He^4)n$ reaction is described. Deuterium and tritium ions generated in a reflex discharge are extracted and accelerated to 100 keV by means of an accelerator electrode onto a deuterio-tritide target electrode. The electrodes are designed to focus the ion beam onto the target. Total tube currents consisting of extracted ions, unsuppressed secondary electrons, and ions generated by interactions with the background gas are typically 100 mA. The characteristics of the extracted ion beam are discussed. Accelerating voltages greater than 50 kV are required to focus the beam through the accelerator aperture for configurations that give beams with the proper energy density onto the target. The perveance of the beam is discussed. Maximum perveance values are 2 to 20 nanopervs. Tube focusing and neutron production characteristics are described.

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I. INTRODUCTION

The use of neutrons for experiments has become widespread, involving numerous fields, including activation analysis,¹ medical applications,^{2,3,4} medical tracer production,⁵ uranium borehole logging,⁶ security portal monitoring,⁷ reactor coolant flow metering,⁸ and reactor physics studies.⁵ In several of these experiments a need has developed for a small, reliable, high-output pulsed neutron source. This study is part of a program to develop a 10^9 n/sec pulsed tube using the $D(T,He^4)n$ nuclear reaction.

Neutron tubes usually consist of a reflex discharge ion source⁹ fed by a resistively heated deuterio-tritide occluder gas reservoir, an accelerator, and a deuterio-tritide occluder target. Some of the properties of very intense ion beams have been reviewed by Green,¹⁰ in which the characteristics of space charge limited currents between planar electrodes are analyzed and compared to theory. This paper discusses the characteristics of the beam extracted from the ion source by a circular, cylindrical accelerator in a small, confined space. Some of the ways the beam interacts with a loaded occluder target are considered. The current density and divergence of the beam at the target are of particular importance for the proper operation of the tube.

The beam properties were studied using the experimental tube shown in Figure 1.

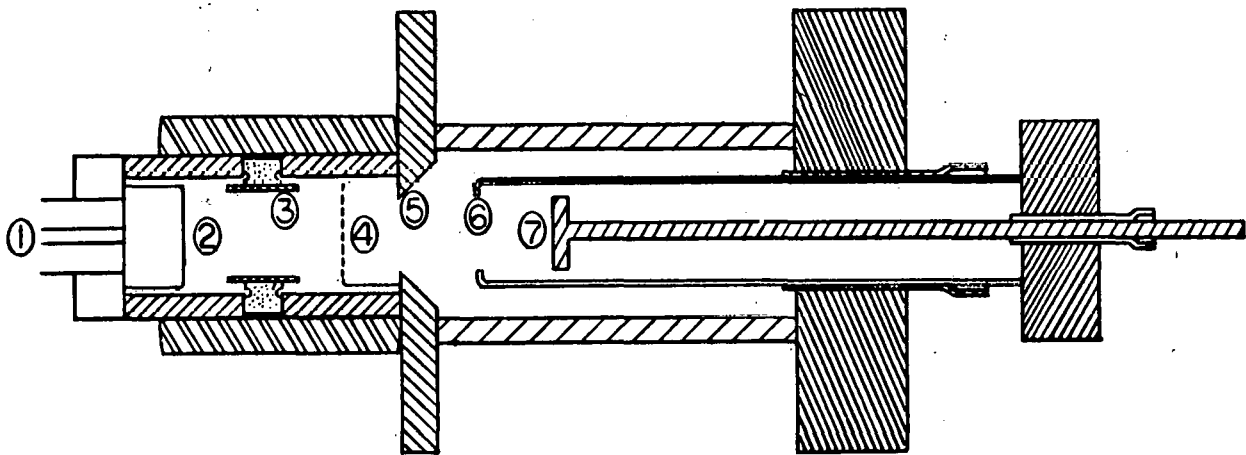


FIGURE 1. Schematic of the accelerator tube used in the experiments. The diameter is about 10 cm. Labeled components are: 1) gas feed, 2) primary cathode, 3) anode, 4) secondary cathode, 5) extractor aperture, 6) accelerator, and 7) target. The Zetatron is about 2.5 cm by 10 cm.

Tests were performed using only deuterium. The reflex discharge ion source uses a permanent magnet to produce a 0.06 Tesla axial field and, when operated at a pressure of 1 to 3 Pa, a 0.8 A, 10 μ sec source arc current pulse produces a 40 mA, 10 μ sec pulsed ion beam. Characteristics of similar ion sources are described elsewhere.¹¹ Ions are extracted from the secondary cathode (see Figure 1) by an electric field to sufficient energies (generally 100 to 130 keV) to produce the desired nuclear reaction. The spacial distribution of the ions and their focusing characteristics depend on the plasma boundary, which is in turn determined by the electrode configuration, injection current densities, and the field strengths. The target and accelerator electrodes are movable over a wide range to permit study of the beam properties. Extraction characteristics will be discussed, together with the implications of the resulting beam profiles. Some results on sealed versions of the tube will also be given.

II. THEORY AND BASIS OF THE EXPERIMENT

The principle focusing properties of an accelerator of the type discussed here are measured with the aid of a focusing curve. "Focus" is defined as the condition in which essentially all of the beam is delivered to the target. Conditions leading to larger beam sizes result in "underfocus", in which the beam intercepts the accelerator electrode. "Overfocus" is a condition which describes a beam with power densities high enough to cause outgassing of the target. Figure 2 shows a typical focus curve, which has the following characteristics:

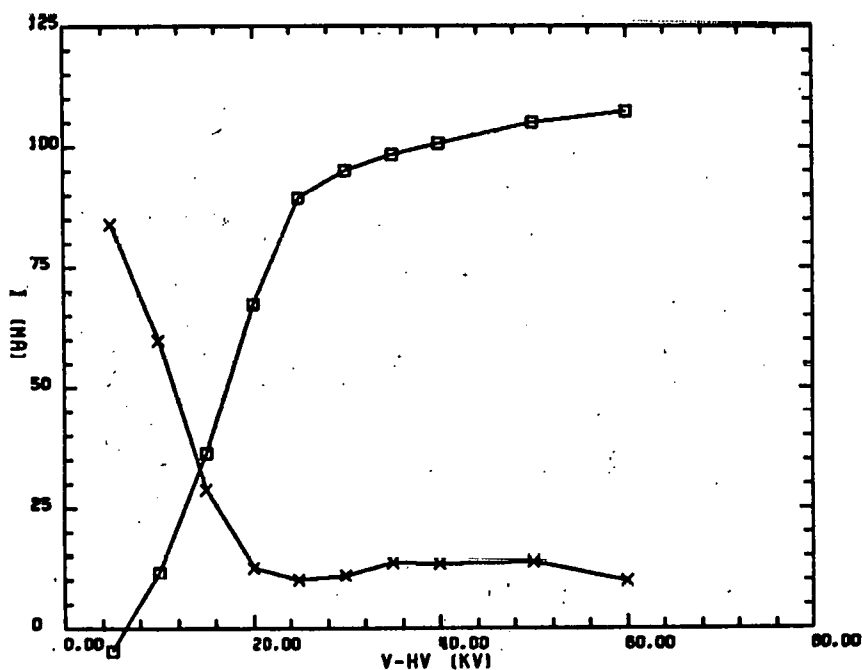


FIGURE 2. Focus curve for a 0.8 A source arc current pulse with tube P10244. Squares are the target and X's are the accelerator currents.

1. For focus conditions the target current consists of beam ions, secondary electrons generated by beam ions colliding with the target, and any ions generated by collisions with the background gas which are drawn to the target.
2. For focus voltages the accelerator current is independent of voltage and consists of ions generated by collisions with the background gas. Under certain circumstances some secondary electrons originating at the target may also be collected by the accelerator.
3. For underfocus voltages the accelerator current increases rapidly with decreasing voltage due to beam ions which intercept the accelerator and their secondary electrons.

For a given electrode configuration, the ion beam envelope is a function of the beam perveance,¹² defined by

$$P_g = I/V^{3/2} \quad (1)$$

where

$$P_g = f(V) \quad (2)$$

I is the target ion current and V is the accelerating voltage (the usual perveance unit for ion beams is nanopervs or $10^{-9}AV^{-3/2}$). The subscript g is used to indicate that the perveance is an implied function of the geometric configuration. Since we are only interested in current transported to the target, we need only to define perveance for focus conditions. Therefore, for a given configuration, accelerating voltage, and injection current, the perveance is maximum for conditions that produce the largest beam diameter without intercepting the accelerator and it falls off approximately with $V^{-3/2}$. In a well designed tube, the normal operating perveance is as close as possible to the maximum perveance. This limits the energy density on the target and minimizes the chance of overfocus.

For a given accelerator configuration, the maximum perveance does not appear to be a function of voltage. Therefore, in order to maintain constant perveance the current and voltage scale as $I/V^{3/2}$. The perveance is calculated from the ion beam current incident on the target, so that secondary electron current must be determined. In order to calculate the secondary contribution to the total target current, the incoming beam is assumed to be principally diatomic ions which dissociate upon impact. Each dissociated ion interacts with the surface with an energy inversely proportional to its mass. Using data based on Barnett, et al,¹³ an idealized curve was generated which reasonably approximates the secondary yields, γ , for D^+ and D_2^+ ions as seen in

Figure 3. The ion current is then given by

$$I_{\text{ion}} = \frac{I_{\text{tgt}}}{1 + \gamma} \quad (3)$$

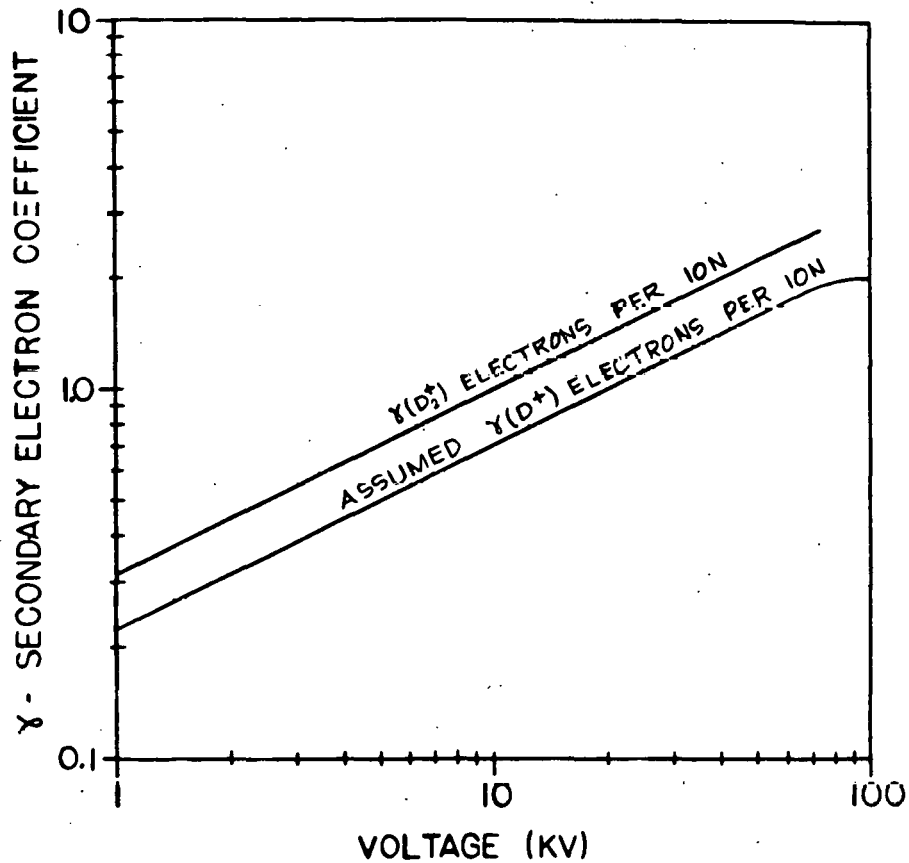


FIGURE 3. Calculated secondary yield curve for D_2^+ and the assumed starting curve for D^+ after Barnett, et al.¹³

For the case of a plane parallel gap with space charge limited current, the maximum perveance given by Morgan, et al,¹⁴ is

$$\hat{p}_g = \frac{C}{A \sqrt{Z^2}} \quad (4)$$

where C is a constant, A is the average mass of the beam species in a.m.u., and $Z = d/r$ is the electrode spacing, d , normalized to the accelerator aperture radius, r . For minor deviations from the plane gap Morgan introduced an empirical correction to d , making it $d + r$. For significant deviations, the correction must be more

general, so we have used the correction $d + \epsilon$. It can be seen from Equation 4 that \hat{P}_g can be adjusted by varying d or r to eliminate overfocus for a specified current and voltage.

Neutron production curves have been reported by Shope¹⁵ for the neutron producing, nuclear reactions using deuterium and tritium. For an assumed beam composition consisting primarily of diatomic and smaller amounts of monatomic and triatomic ions the neutron yield can be estimated. Calculated outputs are compared with measurements on Zetatrons and similar tubes.

III. RESULTS AND DISCUSSION

Figure 4 shows the ion beam current (Eq. 3) and perveance (Eq. 1) versus voltage for the deuterium filled experimental tube and Zetatron (P10244). The extracted beam currents corrected for secondary yields are in agreement with measurements by Bickes and O'Hagan.¹¹ Calculated perveance values are also in excellent agreement with computer calculations developed by Boers,¹⁶ as discussed below.

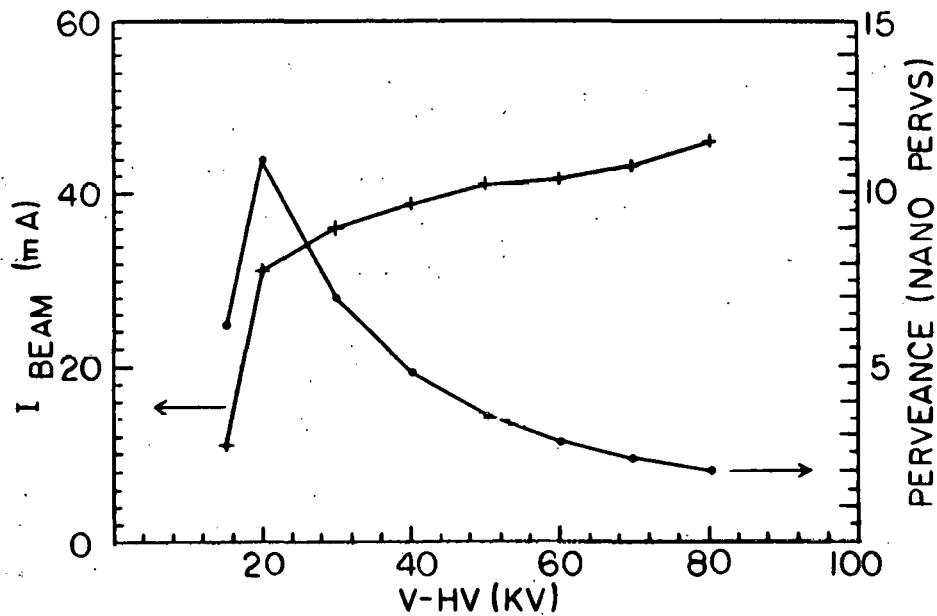


FIGURE 4a. Calculated beam currents and perveance values for the experimental demountable tube.

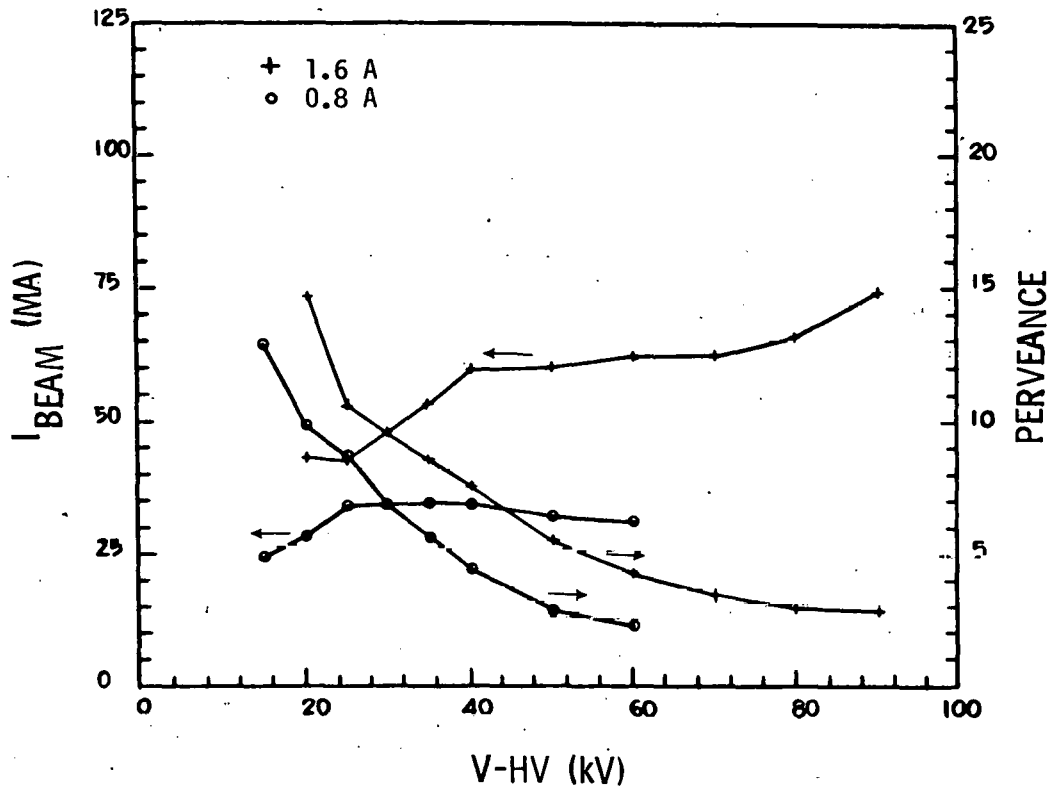


FIGURE 4b. Calculated beam currents and perveance values for Zetatron tube No. P10244.

Figure 5 shows the measured maximum perveance as a function of the spacing of the accelerator electrode from the source extraction aperture, for the deuterium gas filled experimental tube with 0.8 A source current, or about 40 mA of beam current. Combining Equations 1 and 4 gives

$$V^{3/2} = \frac{A^{1/2} I}{C} \left(\frac{d + \epsilon}{2} \right)^2 \quad (5)$$

The square root of Equation 5 can be graphically analyzed. Figure 6 shows a plot of $V^{3/4}$ versus d for voltages V and spacings d corresponding to maximum perveance conditions. The resulting empirical relationship is

$$p_g = \frac{1.30 \times 10^{-6}}{(d - 2.3)^2} \quad (6)$$

The degree to which the empirically determined numbers in Equation 6 are meaningful depends on the amount of change in the position and shape of the plasma boundary and field penetration of the accelerator for different voltages at maximum perveance, i.e., how constant ϵ remains.

MAXIMUM PERVEANCE vs ACCELERATOR SEPARATION

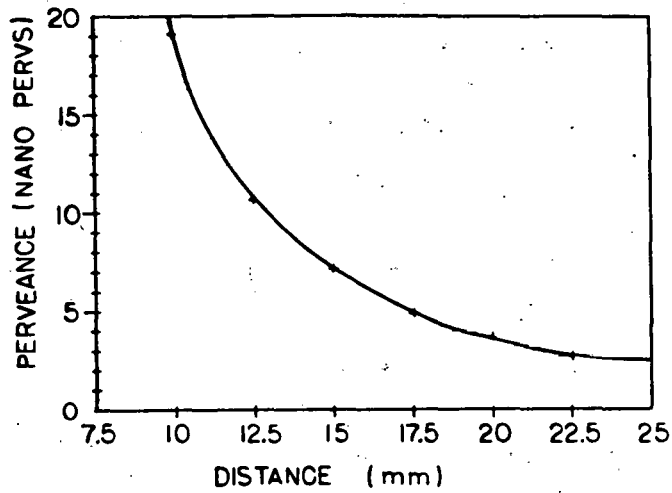


FIGURE 5. Maximum perveance for the experimental tube versus the separation of the accelerator from the extraction aperture.

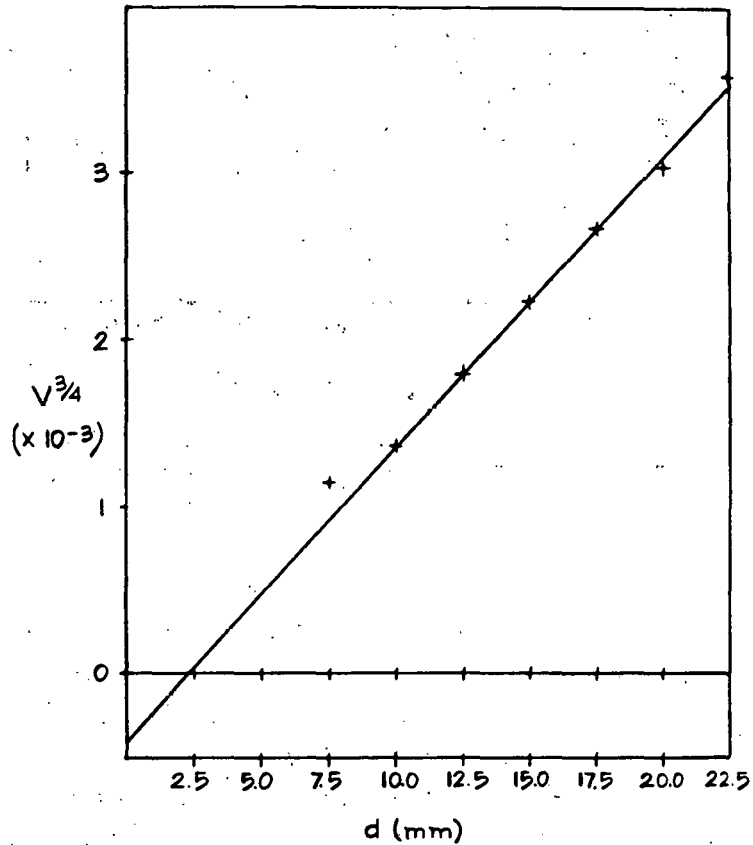


FIGURE 6. $V^{3/4}$ versus d , for maximum perveance conditions, for determining the empirical perveance relationship (after Equation 5).

Perveance data can be combined with the I - V characteristic by making use of the curvilinear $I^{2/3}$ versus V, or perveance graph paper. Figure 7 shows the data of both the experimental tube and the Zetatron P10244 plotted on perveance paper. The family of constant perveance lines are straight lines radiating out from the origin. A part of the family of curves for different source drives is shown. Maximum perveance is found to be the low voltage asymptote.

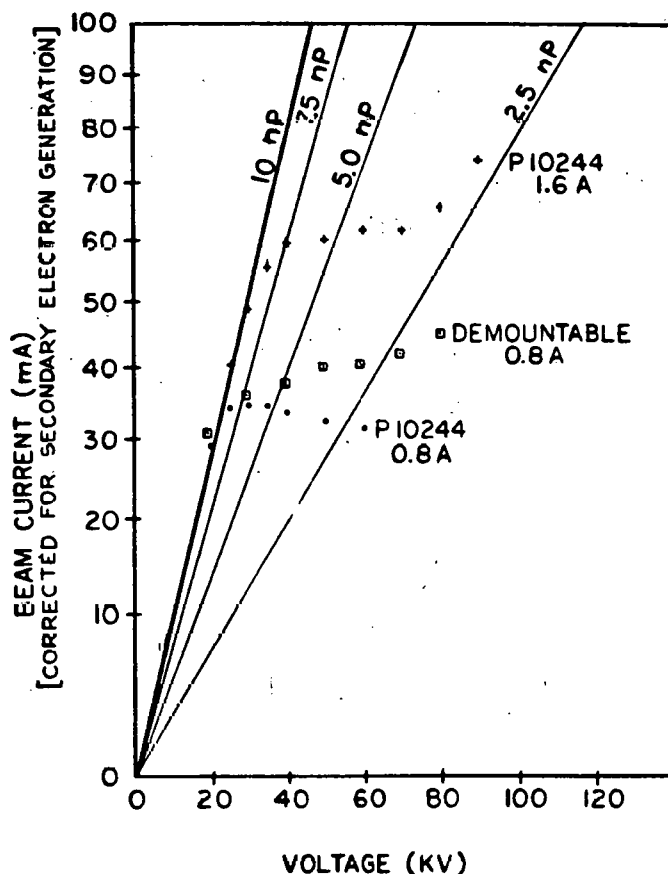


FIGURE 7. Tube electrical data plotted on perveance paper.

The beam characteristic has been simulated on the computer for inputs of the accelerating voltage, an assumed ion current density at the ion source secondary cathode, and electrode configuration. The plasma boundary, potential distribution, and beam particle paths are then computed. Figure 8 shows pairs of field and beam plots for maximum perveance conditions and for conditions corresponding to normal operation. The field penetration of the accelerator, overfocus, and other features discussed above can be seen. The calculated perveance of 10.2 nanopervs for 12.5 mm separation was in excellent agreement with measured values of about 11 nanopervs. The two beam profiles shown in Figure 9 are for spacings of 12.5 mm and 22.5 mm. The corresponding perveances are 16% and 80%, respectively, of their maximum values.

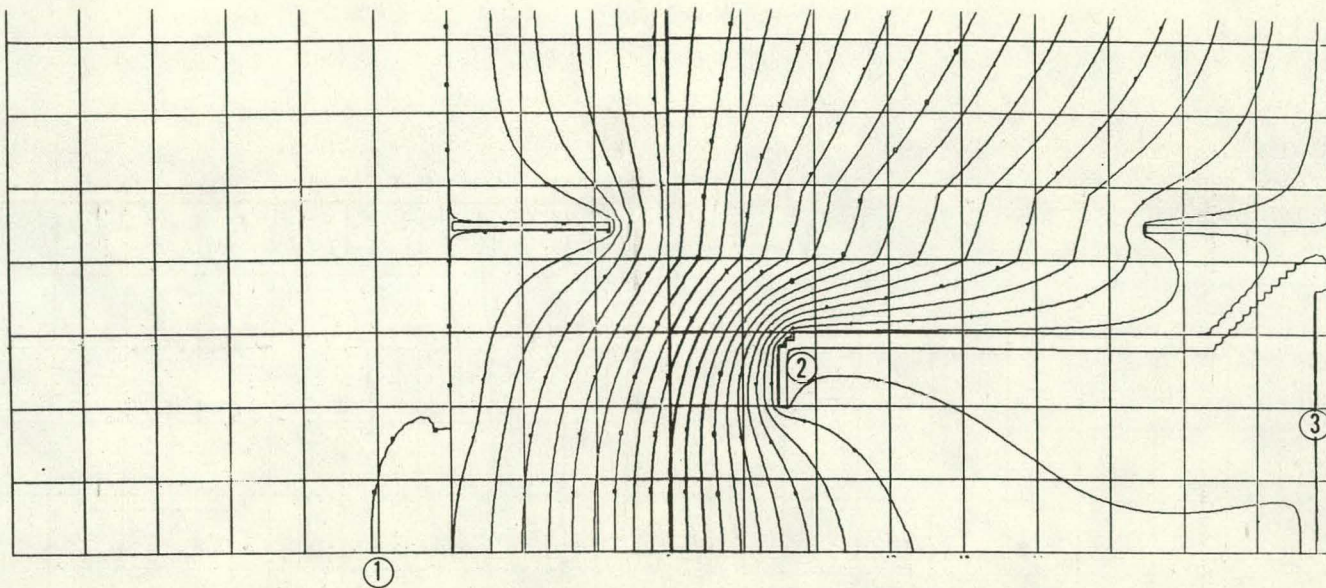


FIGURE 8a.

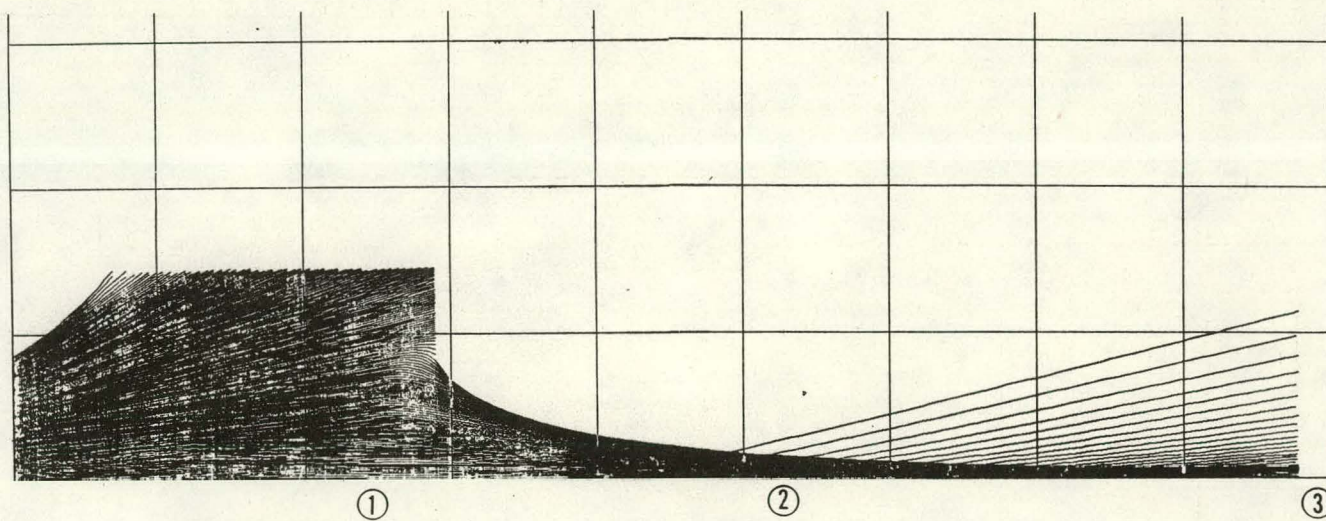


FIGURE 8b.

FIGURE 8. Potential and beam plots from the computer model: a) potential for 12.5 mm spacing, b) beam for 12.5 mm spacing, c) potential for 22.5 mm spacing, and d) beam for 22.5 mm spacing. The spacing refers to the separation of the accelerator electrode, labeled 2, from the extraction aperture, labeled 1 in the field plots. Extraction takes place at the plasma boundary or the first potential line on the potential plots. The target is labeled 3.

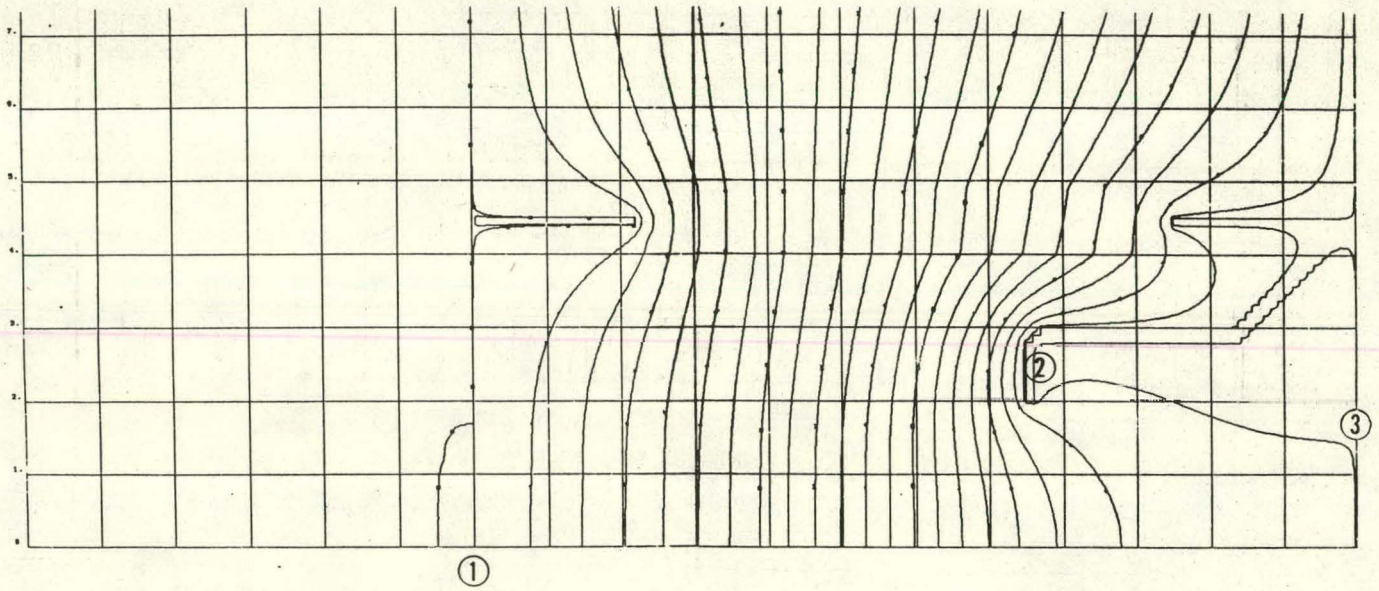


FIGURE 8c.

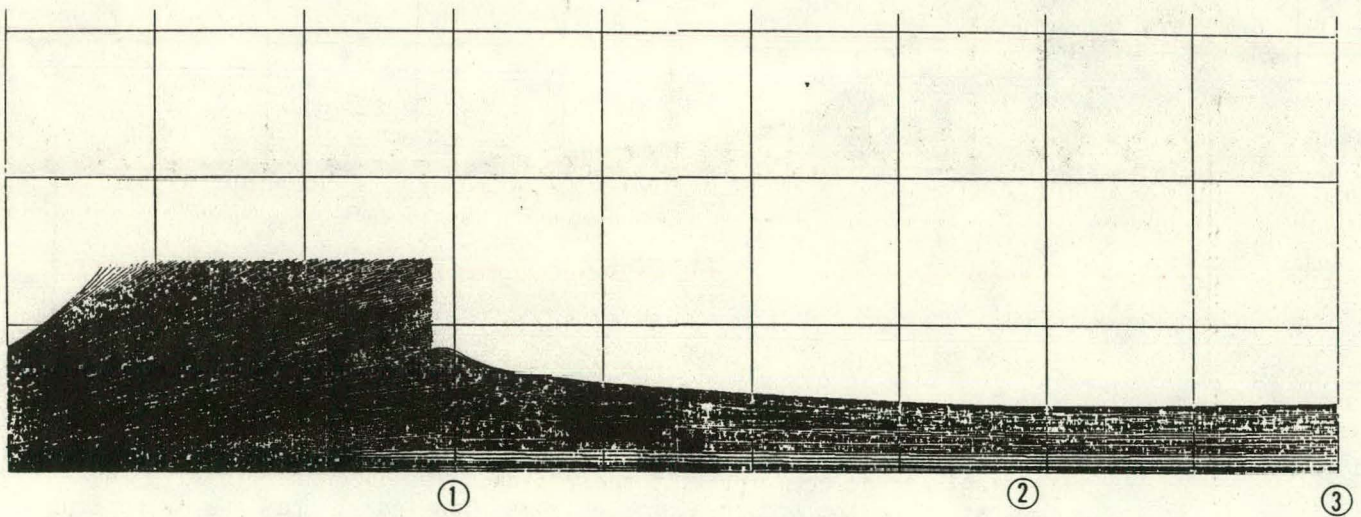


FIGURE 8d.

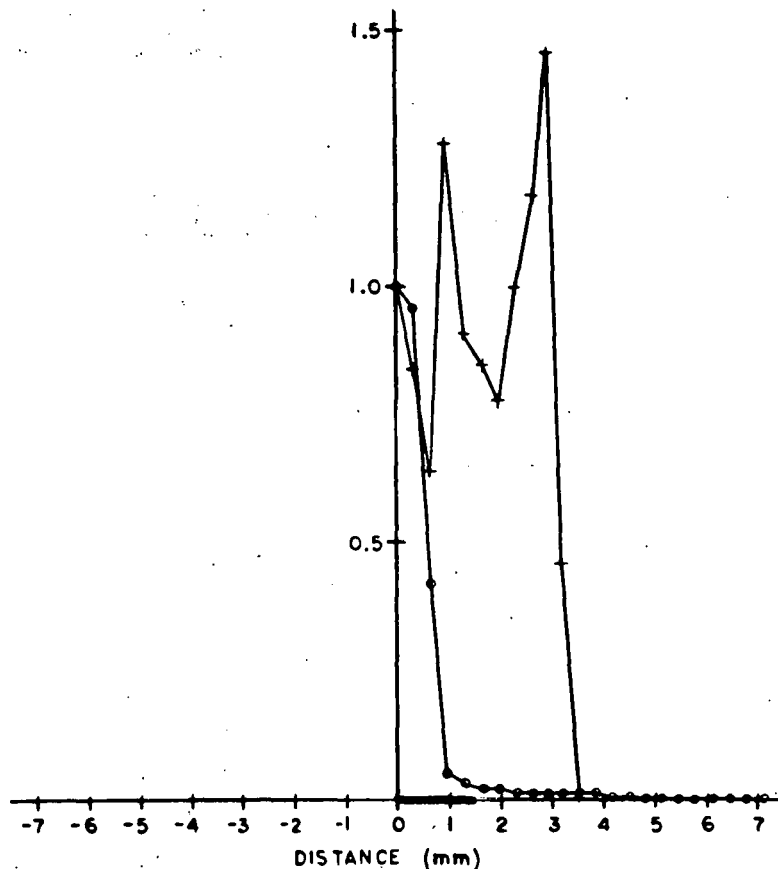


FIGURE 9. Beam current density profiles, normalized to the value at the center of the target, from the computer model for 12.5 mm (●) and 22.5 mm (+) spacings. The radius of the depleted region of an analyzed Zetatron target is indicated by a darkened region on the axis (see text).

The 12.5 mm separation corresponds to the configuration of a sealed neutron generator tube developed at Sandia National Laboratories called a Zetatron.¹⁷ The Zetatron utilizes a deuterium-tritium gas mixture, which has a somewhat broader and higher range of ion masses in its beam and, therefore, would be expected to broaden the beam diameter at the target. The neutron output has been calculated using the computer program UY2¹⁸ for calculating neutron yields based on the data of Shope.¹⁵ The calculations use beam fractions measured by Bacon and O'Hagan¹⁹ of $5 \pm 3\%$ monatomic, $80 \pm 8\%$ diatomic, and $15 \pm 7\%$ triatomic species for a deuterium filled tube, modified for use with a D-T gas mixture. Table I shows nominal output for the tolerance range given by Bacon and O'Hagen with a 50-50 target mixture. Table II shows the output at 100 and 130 keV for the extremes of the tolerance range and a

10% target ratio range. The entire range of outputs is only about $\pm 15\%$ of nominal which is much less than the difference between Shope's calculations and measured neutron outputs. The measured outputs correspond to approximately 7×10^6 n/A - μ sec at 130 kV. One can infer from this that either there is less beam current at the target or less target gas available for neutron production.

TABLE I. Neutron yields from Shope's thick target yields¹⁵ calculated using Newman's computer program UY2.¹⁸

TITANIUM OR SCANDIUM TARGET OCCLUDER BEAM:

$$D^+ = .03, D_2^+ = .20, D_3^+ = .02$$

$$T^+ = .03, T_2^+ = .20, T_3^+ = .02$$

$$D^+ = .40, D_2^+ = .06, DT_3^+ = .06$$

TARGET:

$$T = .50, D = .50, AR = 1.80$$

TARGET VOLTAGE	YIELD/ AMPERE - μ sec
20 kV	8.36 E + 3
30 kV	5.46 E + 4
40 kV	1.51 E + 5
50 kV	3.91 E + 5
60 kV	8.16 E + 5
70 kV	1.56 E + 6
80 kV	2.52 E + 6
90 kV	4.04 E + 6
100 kV	5.69 E + 6
110 kV	8.20 E + 6
120 kV	1.08 E + 7
130 kV	1.43 E + 7
140 kV	1.80 E + 7
150 kV	2.23 E + 7

CONTRIBUTION FROM EACH BEAM COMPONENT

TARGET VOLTAGE	D^+	D_2^+	D_3^+	T^+	T_2^+	T_3^+	DT^+	D_2T^+	DT_2^+
20 kV	.26	.18	.02	.05	.06	.01	.36	.04	.03
30 kV	.26	.33	.00	.05	.07	.00	.26	.01	.01
40 kV	.31	.23	.01	.08	.05	.00	.29	.02	.01
50 kV	.28	.33	.01	.08	.07	.00	.20	.02	.01
60 kV	.26	.28	.01	.08	.06	.00	.30	.01	.01
70 kV	.22	.31	.01	.08	.08	.00	.28	.01	.01
80 kV	.21	.29	.01	.08	.08	.00	.31	.02	.01
90 kV	.18	.31	.01	.08	.09	.00	.32	.02	.01
100 kV	.16	.31	.01	.08	.09	.00	.34	.02	.01
110 kV	.14	.31	.01	.07	.10	.00	.34	.02	.01
120 kV	.13	.31	.01	.07	.10	.00	.35	.02	.01
130 kV	.11	.31	.01	.07	.11	.00	.36	.02	.01
140 kV	.10	.31	.01	.07	.11	.00	.37	.02	.01
150 kV	.09	.31	.01	.06	.12	.00	.37	.02	.01

TABLE II. Outputs at $\begin{pmatrix} 100 \text{ kV} \\ 130 \text{ kV} \end{pmatrix}$ for beam fractions of $5 \pm 3\%$ monatomic, $80 \pm 8\%$ diatomic, and $15 \pm 7\%$ triatomic with target fractions of $50 \pm 10\%$ for D and T, with a 1 A-usec beam pulse. The entries correspond to low, normal, and high output conditions.

		TARGET FRACTIONS INCREASING OUTPUT →		
		Low	Normal	High
↑ BEAM FRACTIONS INCREASING OUTPUT	6.27×10^6	6.61×10^6	6.95×10^6	
	1.54×10^7	1.60×10^7	1.66×10^7	
	5.41×10^6	5.69×10^6	5.96×10^6	
	1.38×10^7	1.43×10^7	1.48×10^7	
	4.55×10^6	4.76×10^6	4.98×10^6	
	1.21×10^7	1.25×10^7	1.29×10^7	

Figure 10 shows a typical average output over an extended operating time. The output in neutrons per second (100 pulses per second) is in the mid- 10^8 range, and drops slowly with operation. One Zetatron tube was operated

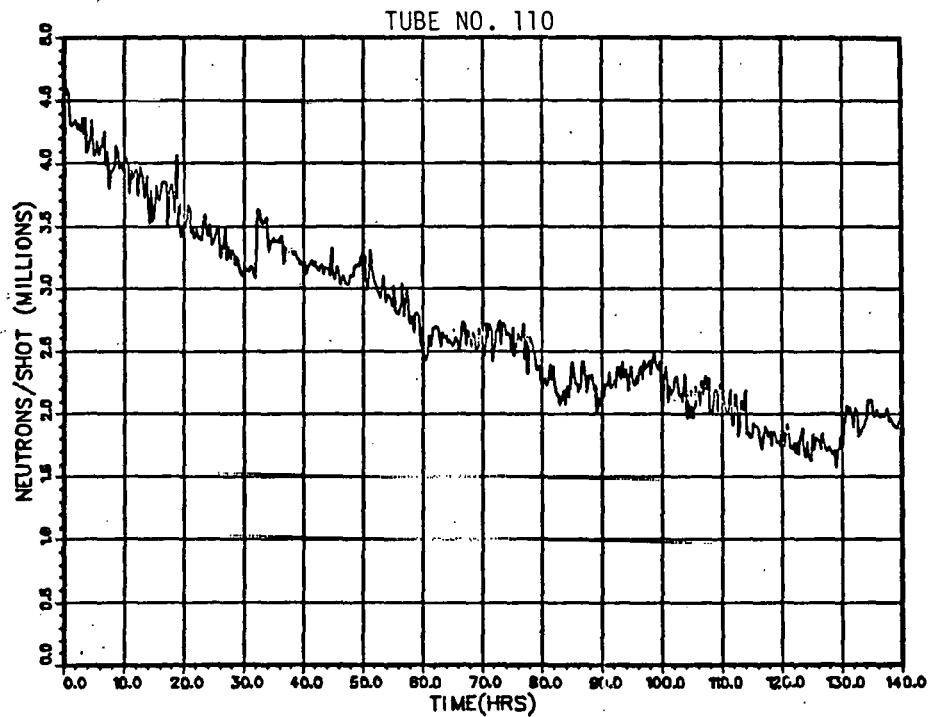


FIGURE 10. Output versus operations (in terms of operating time at 100 pulses per second) for a Zetatron.

for 350 hours at 100 pulses per second, and was then analyzed for indications of target degradation.²⁰ Figure 11 shows the normalized target loading, with about a 3 mm depleted region in the center corresponding to the region receiving the bulk of the beam. For comparison the size of the depleted region is shown shaded on the axis of Figure 9. While the neutron production rates are much higher, the observed neutron production efficiencies are somewhat low when compared to the efficiencies of other similar devices.²¹

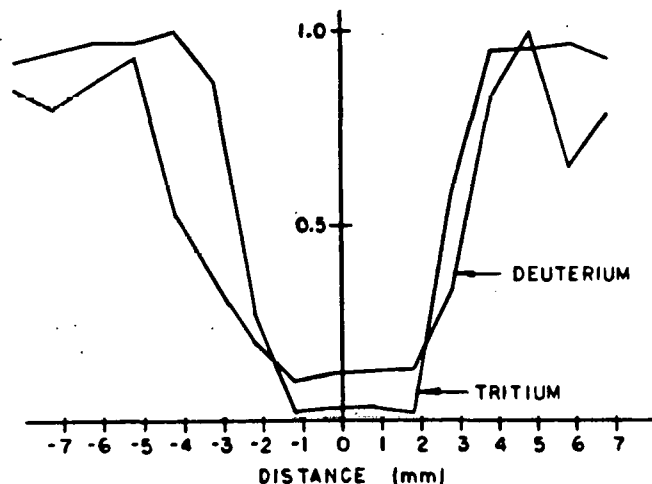


FIGURE 11. Normalized target loading of a life-tested tube showing the depleted region in the center.

IV. SUMMARY AND CONCLUSIONS

The beam characteristics of a small ion accelerator have been studied. Beam focusing characteristics can be controlled over a wide range, with a corresponding range of beam profiles. Perveance values are in the range of 1 to 10 nanopervs and ion beam currents of 30 to 40 mA for source currents of 1 A are found. The perveance has its maximum at the edge of focus, and falls off approximately with $v^{-3/2}$. Identical perveance values have been calculated with a computer model. Simulated beam profiles show a highly overfocused condition, well below maximum perveance which likely damages the target--a condition which is also observed experimentally in target analyses. Operation at perveance near maximum allows the beam to spread as much as possible, minimizing energy densities at the target. Neutron output measurements must still be made for much of the range of operation. Neutron rates of greater than 10^8 n/sec have been measured for Zetatrons.

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2350 J. T. Grissom
2352 F. M. Bacon
2352 J. E. Boers
2352 J. B. O'Hagan
2352 R. J. Walko
2353 J. T. Cutchen
2354 B. E. Barnaby
2354 B. E. Barnaby (5 copies for further distribution to AWRE/UK)
2354 R. S. Berg
2354 L. A. Shope
2354 M. L. O'Neal
2354 J. H. Borrego
2355 H. M. Bivens
2355 D. R. Humphreys
2355 W. A. Stephenson
2515 R. W. Bickes, Jr.
8214 M. A. Pound
3141 L. J. Erickson (5)
3151 W. L. Garner (3)
3151-4 J. Hernandez (25) for DOE/TIC Index

