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STATUS OF POROUS IONIZERS FOR CONTACT IONIZATION OF CESIUM

by Larry C. Headley

Lewis Research Center

Cleveland, Ohio

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SUMMARY

Much of the recent information obtained from tests of materials under consideration for use as porous ionizers in cesium-ion sources and cesium-ion thrustors is summarized herein. The information presented for the various materials includes sintering characteristics, pore densities and diameters, work functions, emittances, methods of manufacture, and ionization performance. The ionization performance is described by including graphs of ion-current density against critical temperature, neutral fraction against critical temperature, and ion-current density against neutral fraction.

INTRODUCTION

One of the most critical components of a cesium contact-ionization thrustor with respect to reliability and lifetime is the ionizer. Ionizers in most present-day thrustors are made basically of porous tungsten. The cesium is fed to the upstream surface of the heated porous tungsten ionizer from where it flows through the material. The cesium is then ionized on the downstream surface. The ions are drawn off by applied electric fields and are accelerated out of the thrustor, thereby producing thrust. All the cesium that flows through the ionizer is not ionized. A small percentage emerges as neutral atoms. Once the neutral atoms are in the exhaust, charge-exchange interactions may occur. These interactions create nearly stationary ions in a region from which they can be accelerated into the electrodes where they cause harmful erosion. This erosion forms one of the principal limitations on the lifetime of the thrustor.

In order to be an efficient ionizer, the porous tungsten must operate at rather high temperatures, around 900° to 1300° C. At these temperatures, many porous ionizers show some tendency to sinter and become less porous, thus restricting cesium flow. This can be another serious limitation on the overall lifetime of the thrustor.

A third limitation, not on lifetime but on efficiency, concerns the operating temperature of the ionizer. A part of the ionizer must, of course, face the outside of the thrustor, since the ions must be expelled from the spacecraft. This portion of the ionizer radiates heat to space at a rate defined by the Stefan-Boltzmann law. Therefore, heat must be supplied to the ionizer at no less than this rate in order to keep the ionizer at a constant temperature. The rate of heat loss is directly proportional to the emittance and to the effective area of the ionizer. In order to keep the emitting area small for a given thrust level, ionizers that produce large ion-current densities must be fabricated. Obviously, ionizers that have low emittances are also advantageous.

For a given mission, a thrustor will have certain requirements of lifetime and efficiency. To fulfill these requirements, it will be necessary to obtain an ionizer that has known properties, such as the variation of current density with critical temperature, neutral fraction, sintering characteristics, and emittance. A considerable proliferation of data on a great many materials that have been and are being made and tested as ionizers is presently available; however, to date, no comprehensive presentation of these data has been made. As a result, a considerable amount of time must be spent in determining which ionizer is probably best for a given purpose. In addition, evaluation of data on a new ionizer for determination of its comparative worth or promise requires familiarization with a great amount of technical literature.

This report summarizes various developments to date in the field of porous-ionizer materials to make comparisons of existing and future materials more convenient. In such a summary, of course, complete detailed information cannot be given on each material, nor is finding a means of comparison that is common to each investigator's data always possible. Cross-plotting and interpolation have been done liberally in an effort to accommodate as much of the reported data as possible. Consultation of the references will be necessary, however, for more complete information about a material of specific interest. Note that table I, a list of materials, is coded numerically so as to form the basic means of identifying materials in all subsequent tables and plots. References 1 to 15 constitute the primary ones used in preparing this report. Duplicate or additional general information on the subject is given in the Bibliography.

TEST CONDITIONS

Comparisons of the data of various investigators can sometimes lead to contradictory conclusions unless all the conditions involved in the test are carefully considered. For example, ionizers tested in thrustors frequently produce lower neutral-fraction measurements than ionizers from the same materials tested in geometries where there are no electrodes near the path of the ion beam. This difference may be related to the impingement of neutral atoms on the electrodes in the thrustor. The atmosphere in which the test is made can also be very important. For example, small amounts of oxygen or carbon can drastically affect the performance of the ionizer, both in critical temperature and neutral fraction (e.g., see ref. 1). Because of this effect, information regarding tests in which a coating of some kind was applied to the ionizer has been included only when the coating was intentionally applied and did not exist only under out-of-the-ordinary vacuum conditions. Some complications regarding test conditions are, of course, unavoidable, since neither ionizer test geometries nor vacuum test facilities have been standardized. The test conditions are standardized in that most of the materials tested by a given group have been tested under essentially the same conditions.

An additional complication that arises when ionizers are used is the choice of surface treatment. There are many ways of treating the emitting surface of an ionizer, including grinding, polishing, etching, and sputtering. Some of these treatments may be more effective than others in improving performance (lowering neutral fraction, critical temperature, etc.). Obviously, some of these treatments may affect the emittances of the materials. No single treatment seems to be best in all cases. Additional details on test conditions and surface treatments are given in references 1 to 14.

DATA PRESENTATION

Materials and Suppliers

Establishing a simple method of coordinating the large variety and large volume of data presented is difficult. However, a straightforward method was chosen in which each material tested has been given a "description number" that is used throughout the report. These numbers are listed in table I. To aid in identifying chronological trends among the various data, the ordering of the numerical description numbers has been roughly from the earliest to the most recent data. This order of listing is, in general, suitable, although it may not be exact in all cases since material tested at a given time may not be reported until some time later. Also, examination of the list shows that because a given material may be tested by different groups at different times, it appears more than once in the list (e.g., numbers 9 and 32). Reference numbers, source numbers designating material suppliers (see table II), and a brief description of each material are also shown in table I. When single powder diameters are given in the description, they are average values.

Pore Densities and Diameters, Work Functions, and Emittances

Pore densities and diameters, work functions, and emittances were compiled from the literature for the various materials. Pore densities are expressed in number of pores per square centimeter of ionizer surface area (table III); different counting methods were used by the various investigators. Pore diameters (also shown in table III) are averages of many measurements. In table IV, work functions are given. Values are usually determined from measurements of electron emission and temperature or from the well-known Saha-Langmuir equation by means of the measurement of the variation of neutral fraction with temperature for a given current density. Emittances have been reported in the literature for only a few porous materials. They are listed in table V along with the temperatures at which they were measured.

Sintering

Sintering characteristics are plotted in figure 1. Curves are drawn of the variation of the percentage of maximum theoretical density of the material with time at a given temperature. As the material becomes more dense, cesium-feed-pressure requirements increase, and at high densities, the materials become useless as ionizers. A leveling off of density with time indicates stability. Most of these tests were accelerated in that they were conducted at temperatures higher than usual to establish comparative trends in a short period of time. Figure 1 shows that all the materials exhibit some degree of sintering with time; many of them exceeding 85 percent of theoretical density in less than 1 hour. The trend toward improved sintering characteristics with calendar time is evident in proceeding through figure 1. (The description numbers are chronological.)

Performance

Performance information is given in figures 2 to 4. These graphs show, for each material for which the information is available, the variation of ion-current density with critical temperature (fig. 2), neutral fraction with critical temperature (fig. 3), and ion-current density with neutral fraction (fig. 4). Included on figure 2 for reference is a zero-field Taylor-Langmuir curve for solid tungsten (ref. 25). Also, Saha-Langmuir curves for three work functions covering the range of table IV are shown for reference on figure 3. Since data were not always reported in the form presented herein, they were cross-plotted and interpolated to prepare figures 2 to 4.

The critical temperature shown on the figures is the ionizer temperature required to produce a minimum neutral fraction for a given ion-current density. An idea of the rate of progress in the field can be obtained by simply noting the changes in the curves as the description numbers increase in value. Undue reliance should not be placed on this method, however, since older materials were sometimes retested, for example, to check out vacuum systems. In general, though, the materials with the best performance tend to have high numbers

MATERIALS AND FABRICATION TECHNIQUES

Porous tungsten ionizers in recent years have been compacted from closely sized spherical powders. The average diameter of the spherical particles comprising this powder is usually a few microns. Some other fabrication procedures that have also been investigated are described in the following paragraphs.

Porous tungsten substrates have been coated with iridium, rhenium, tantalum, carbon, silicon, and several other materials. One of the more promising of these materials is iridium, a refractory metal with a high work function. The high-work-function surface enhances the propellant utilization factor (or lowers the neutral fraction) and, as a result, should permit thrustor operation at higher current densities. A thin coating (less than 1 μm thick) tested in a thrustor appeared to improve performance but disappeared quickly from the surface (ref. 2). This disappearance was thought to be caused by the sputtering of particles emitted from the accelerator electrode. On the other hand, thick layers of coating materials tend to clog pores and decrease performance. A compromise may be possible.

Compacts have been made of tungsten with other materials in various proportions. Ionization performance is not greatly enhanced over that of compacts made from the pure tungsten powder, but sometimes sintering stability is greatly improved. One interesting material of this type is 85 percent tungsten, 5 percent tantalum, and 10 percent rhenium (ref. 3). The lifetime of this material with respect to sintering appears to be on the order of ten times that of the pure porous tungsten. Ionization performance does not seem to be greatly different from that of the best pure porous tungsten material.

A porous material containing 62.5 percent tungsten and 37.5 percent rhenium was made by hydrogen reduction of a two-phase structure (ref. 4). The material has a very high pore density, which is thought to be indicative of good ionization performance. The ionization performance of the material has not yet been reported.

More recently a material was made from a mixture of tungsten powder, copper powder, and boron nitride (ref. 3). The mixture is compacted and heated in vacuum to remove the copper, which results in a very low-density material that also has low pore density and large pores. A compact of 2 percent boron nitride, 90 percent tungsten, and 8 percent copper powder exhibits the lowest critical temperature and neutral fractions. The shape of pores has been proposed as one possible reason for improved ionization performance. This particular compact has not been tested for sintering stability. However, a material made of 4 percent boron nitride, 88 percent tungsten, and 8 percent copper was found to have very small changes in density during sintering (ref. 3).

CONCLUDING REMARKS

Examination of the information presented in this report shows that a large number of pure materials, mixtures, alloys, and coated materials has been fabricated and evaluated. The large number itself suggests that a real understanding of the basic principles governing the fabrication of a suitable material is lacking. The stringent requirements imposed by the desired application in ion thrustors undoubtedly contribute to the problem.

The recently developed porous materials made from mixtures of tungsten, copper flake, and boron nitride appear to give the lowest neutral fractions. Their performance in long-duration tests in ion thrustors, however, has not been evaluated.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 10, 1967,
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TABLE I. - MATERIALS

Description number	Material description (a)	Date		Source	Reference (b)
		Tested	Reported		
1	Porous tungsten of various pore densities	-----	11-63	--	5
2	Porous rhenium	-----	11-63	--	5
3	Porous molybdenum	-----	11-63	--	5
4	Porous tantalum	-----	11-63	--	5
5	Porous tungsten compacted from spherical powder (E-6)	2-64	7-65	1	6
6	Porous tungsten compacted from spherical powder 4 to 8 μm in diam (E7A); same as description 8	5-64	7-65	1	6
7	Porous tungsten compacted from spherical powder 1 to 4 μm in diam (E-3); same as description 11; also reported in refs. 8 to 10	-----	5-64	1	7
8	Porous tungsten; same as description 6	-----	5-64	1	7
9	Porous tungsten compacted from spherical powder 2 to 5 μm in diam (E-4); same as description 32; also reported in ref. 11	6-64	7-65	1	6
10	Porous tungsten compacted from spherical powder (Mod. E); same as description 47; also reported in ref. 11	6-64	7-65	2	6
11	Porous tungsten; same as description 7	6-64	7-65	1	6
12	Porous tungsten compacted from spherical powder (12-1)	7-64	7-65	3	6
13	Porous tungsten compacted from spherical powder 1 to 10 μm in diam (G-1); same as description 54	8-64	7-65	1	6
14	Porous tungsten compacted from spherical powder 4 to 8 μm in diam (G2A); also reported in ref. 11	9-64	7-65	4	6
15	Porous material compacted from spherical tungsten powder 2 to 5 μm in diam and 10-percent-tantalum powder (E-4); also reported in ref. 11; same as description 33	9-64	7-65	1	6
16	Porous tungsten compacted from sperical powder 1 to 10 μm in diam (G-3); same as description 56; also reported in ref. 11	10-64	7-65	1	6
17	Porous material compacted from spherical tungsten powder 1.7 to 5 μm in diam and 10-percent-tantalum powder 1 to 3 μm in diam (LB-10); same as description 40; also reported in ref. 11	11-64	7-65	1	6
18	Porous material compacted from spherical tungsten powder 1.7 to 5 μm in diam and 2-percent-tantalum powder 1 to 3 μm in diam (LB-2); same as description 36; also reported in ref. 11	11-64	3-66	1	6
19	Porous material compacted from spherical tungsten powder 1.7 to 5 μm in diam and 5-percent-tantalum powder 1 to 3 μm in diam (LB-5); same as description 38; also reported in ref. 11	11-64	7-65	1	6
20	Porous tungsten compacted from spherical powder (G-4); same as description 57	1-65	7-65	1	6
21	Porous material made by carbiding surface of material in description 14	1-65	7-65	1	6
22	Porous tungsten compacted from spherical powder (10-1)	3-65	7-65	3	6
23	Porous tungsten compacted from spherical powder 10 μm in diam (G2B); same as description 55	3-65	7-65	4	6
24	Porous tungsten compacted from spherical powder 10 μm in diam (G5B); same as description 58	4-65	7-65	5	6
25	Porous tungsten compacted from spherical powder 1.7 to 5 μm in diam (Lot L); also reported in ref. 9	-----	4-65	6	8

[a]Numbers and letters in parentheses are designations used in the references.
[b]See table II.

TABLE I. - Continued. MATERIALS

Description number	Material description (a)	Date		Source	Reference (b)
		Tested	Reported		
26	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) coated with 100-Å-thick tantalum coating; also reported in ref. 9	----	4-65	1	8
27	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) coated with 835-Å-thick tantalum coating; also reported in ref. 9	----	4-65	1	8
28	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) coated with 150-Å-thick rhenium coating; also reported in ref. 9	----	4-65	1	8
29	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) coated with 45-Å-thick rhenium coating; also reported in ref. 9	----	4-65	1	8
30	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) coated with 17-Å-thick osmium coating; also reported in ref. 9	----	4-65	1	8
31	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) coated with 133-Å-thick osmium coating; also reported in ref. 9	----	4-65	1	8
32	Porous tungsten; same as description 9; also reported in ref. 9	----	4-65	1	8
33	Porous material; same as description 15	----	4-65	1	8
34	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) and 1/2 percent of 1- to 3-μm-diam-tantalum powder (Lot 8F); also reported in ref. 9	----	4-65	1	8
35	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) and 1/2 percent of 1- to 5-μm-diam-tantalum powder (Lot CF); also reported in ref. 9	----	4-65	1	8
36	Porous material; same as description 18	----	4-65	1	8
37	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) and 2 percent of 1- to 5-μm-diam-tantalum powder (Lot CF)	----	4-65	1	8
38	Porous material; same as description 19	----	4-65	1	8
39	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) and 5 percent of 1- to 5-μm-diam-tantalum powder (Lot CF); also reported in ref. 9	----	4-65	1	8
40	Porous material; same as description 17; also reported in ref. 9	----	4-65	1	8
41	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) and 10-percent of 1- to 5-μm-diam-tantalum powder (Lot CF); also reported in ref. 9	----	4-65	1	8
42	Porous material compacted from 4- to 8-μm-diam-spherical tungsten powder (Lot E7A) to which 1/10 percent of rhenium has been added	----	4-65	1	8
43	Porous material compacted from 4- to 8-μm-diam-spherical tungsten powder (Lot E7A) to which 5-percent tantalum has been added	----	4-65	1	8
44	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) to which 4.94-percent rhenium has been added	----	4-65	1	8
45	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) to which 5-percent rhenium has been added	----	4-65	1	8

[a]Numbers and letters in parentheses are designations used in the references.
[b]See table II.

TABLE I. - Continued. MATERIALS

Description number	Material description (a)	Date		Source	Reference (b)
		Tested	Reported		
46	Porous material compacted from 1.7- to 5-μm-diam-spherical tungsten powder (Lot L) to which 7-percent tantalum has been added	-----	4-65	1	8
47	Porous tungsten; same as description 10; also reported in ref. 9	-----	4-65	1	8
48	Porous material made by coating porous tungsten (Mod. B) with 0.005-inch-thick layer of 2.4-μm-diam-spherical tungsten powder and then coating result with thin layer of iridium	7-65	6-66	2	12
49	Porous material compacted from 75-percent-tungsten and 25-percent-rhenium spherical powder	8-65	6-66	4	12
50	Porous iridium (No. 280)	8-65	6-66	4	13
51	Porous material compacted from 3.9-μm-diam-spherical tungsten powder and coated with a 1/2- to 1-μm-thick iridium layer (Sample B); same as description 71	8-65	6-66	4	13
52	Porous material made by chemically coating porous tungsten (Mod. B) with thin layer of rhenium	9-65	6-66	4	12
53	Porous material made by compacting 3.9-μm-diam-spherical tungsten powder then coating result with 1- to 2-μm-thick iridium layer (Sample A); same as description 72	9-65	6-66	4	13
54	Porous tungsten (G-1); same as description 13	-----	9-65	1	14
55	Porous tungsten (G-2b); same as description 23	-----	9-65	4	14
56	Porous tungsten (G-3); same as description 15	-----	9-65	1	14
57	Porous tungsten (G-4); same as description 20	-----	9-65	1	14
58	Porous tungsten (G-5); same as description 24	-----	9-65	5	14
59	Porous tungsten compacted from 5-μm-diam-spherical powder (F-8)	-----	9-65	7	14
60	Porous tungsten compacted from 3.9-μm-diam-spherical powder (Sample F); same as description 67 and 70	12-65	6-66	4	13
61	Porous material compacted from prealloyed 2- to 5-μm-diam-spherical powder, 95 percent tungsten, 5 percent rhenium (No. 2); same as description 73	12-65	6-66	5	13
62	Porous material compacted from 2- to 5-μm-diam-particles made of 50 percent tungsten and 50 percent iridium (No. 276)	1-66	6-66	4	13
63	Porous material compacted from 3- to 6-μm-diam-tungsten powder and 50-percent iridium powder 2 to 6 μm in diam (No. 225)	1-66	6-66	4	13
64	Porous material compacted from 1- to 40-μm-diam-spherical tungsten powder and coated with 3-μm-thick iridium layer	-----	3-66	1	2
65	Porous material made by coating porous tungsten (Mod. E) with 1.5-μm-thick layer of rhenium deposited by sputtering	-----	3-66	2	2
66	Porous tungsten compacted from 1- to 40-μm-diam-spherical powder	-----	3-66	1	2
67	Porous tungsten; same as description 60 and 70	-----	3-66	4	2
68	Porous material compacted from 1- to 40-μm-diam-spherical tungsten powder and coated with 1.5-μm-thick iridium layer (Unit 7)	-----	3-66	1	2
69	Porous material compacted from 1- to 40-μm-diam-spherical tungsten powder and coated with 0.3-μm-thick chemical deposite of iridium (Unit 13)	-----	3-66	1	2

[a]Numbers and letters in parentheses are designations used in the references.
[b]See table II.

TABLE I. - Concluded. MATERIALS

Description number	Material description (a)	Date		Source	Reference (b)
		Tested	Reported		
70	Porous tungsten; same as description 60 and 67	----	3-66	4	11
71	Porous material; same as description 51	----	3-66	4	11
72	Porous material; same as description 53	----	3-66	4	11
73	Porous material; same as description 61	----	3-66	5	11
74	Porous tungsten compacted from spherical powder 3.6 to 8 μm in diam (4848-B2-1)	----	3-66	6	11
75	Porous tungsten compacted from spherical powder 3.6 μm in diam (Lot A)	----	3-66	6	4
76	Porous tungsten compacted from spherical powder 3.6 μm in diam (Lot B)	----	3-66	6	4
77	Porous tungsten compacted from spherical powder 5.1 μm in diam (Lot D)	----	3-66	6	4
78	Porous tungsten compacted from spherical powder 6.9 μm in diam (Lot F)	----	3-66	6	4
79	Porous material made by removal of one phase of two-phase alloy of tungsten and 37.5-percent rhenium	----	3-66	5	4
80	Porous tungsten compacted from spherical powder, 3.9 μm in diam (ST 1-9)	4-66	6-66	5	13
81	Porous tungsten (No. 788)	5-66	6-66	1	13
82	Porous material made of iridium coated with carbon (No. 280)	----	6-66	4	13
83	Porous material compacted from 3.9-μm-diam-spherical tungsten powder coated with tantalum (No. 324-S Sample G)	----	6-66	4	13
84	Porous material compacted from 3.9-μm-diam-spherical tungsten powder coated with niobium (No. 324-S Sample D)	----	6-66	4	13
85	Porous material compacted from 3.9-μm-diam-spherical tungsten powder coated with platinum (No. 324-S Sample G)	----	6-66	4	13
86	Porous material compacted from 3.9-μm-diam-spherical tungsten powder coated with silicon (No. 324-S Sample H)	----	6-66	4	13
87	Porous material compacted from 2- to 5-μm-diam-prealloyed tungsten - 5 percent rhenium, spherical powder sputter-coated with 1.3-μm-thick layer of rhenium (No. 2)	----	6-66	5	13
88	Porous material compacted from mixture of 0.25- to 2.5-μm-diam-spherical tungsten powder, 5-percent-tantalum powder, and 10-percent-rhenium powder	----	6-66	1	3
89	Porous material compacted from mixture of 0.8-μm-diam hydrogen reduced, tungsten powder and 8-percent-copper flake	----	6-66	1	3
90	Porous material compacted from mixture of 0.8-μm-diam hydrogen reduced, tungsten powder, 8-percent-copper flake, and 4 percent boron nitride	----	6-66	1	3
91	Porous material compacted from a mixture of 0.8-μm-diam hydrogen reduced, tungsten powder, 8-percent-copper flake, and 2 percent boron nitride	----	6-66	1	3

[a]Numbers and letters in parenthese are designations used in the references.
[b]See table II.

TABLE II. - SUPPLIERS OF

MATERIALS OF TABLE I

Source	Supplier
1	Electro-Optical Systems, Inc.
2	Philips-Metalonics
3	Astromet Associates Corp.
4	Hughes Research Laboratories
5	TRW Systems, Inc.
[a]6	Union Carbide Corp.
7	Spectra Mat Corp.

[a]Source of powder only.

TABLE III. - PORE DENSITIES AND AVERAGE PORE DIAMETERS

Description number (a)	Pore density, pores/cm^2	Pore diameter, μm	Description number (a)	Pore density, pores/cm^2	Pore diameter, μm
3	2.0×10^6	1.4	56	4.6×10^6	1.5
4	1.69	3.6	57	4.4	1.4
7	4.01	1.5	58	5.5	1.6
8	1.64	3.83	60	7.6	2.0
16	4.6	1.5	61	7.2	2.0
25	4.06	2.48	63	3.5	3.5
26	6.07	2.01	64	3.08	2.85
27	3.22	2.49	65	2.3	3.5
28	0.66	5.28	66	3.08	2.85
29	4.01	2.45	67	4.33	2.1
30	2.75	3.10	68	3.08	2.85
31	.59	6.28	69	3.08	2.85
32	4.03	2.37	70	7.6	2.0
33	3.51	2.34	71	7.6	2.0
34	5.73	2.0	72	7.6	2.0
35	5.67	2.06	73	7.2	2.0
36	5.09	2.09	74	4.9	2.3
37	5.22	2.05	75	6.6	1.9
38	4.47	2.20	76	5.9	----
39	4.33	2.24	77	4.4	2.4
40	3.4	2.37	78	3.1	2.0
41	3.15	2.62	79	>10	2.0
45	2.9	2.7	80	5.9	2.0
46	2.66	2.86	88	12	1.58
48	1.2	----	89	1.71	3.86
49	1.7	2.8			
52	2.27	----			
53	7.6	2.0			
54	5.1	1.5			
55	10.7	1.2			

[a]See table I.

TABLE IV. - WORK FUNCTIONS

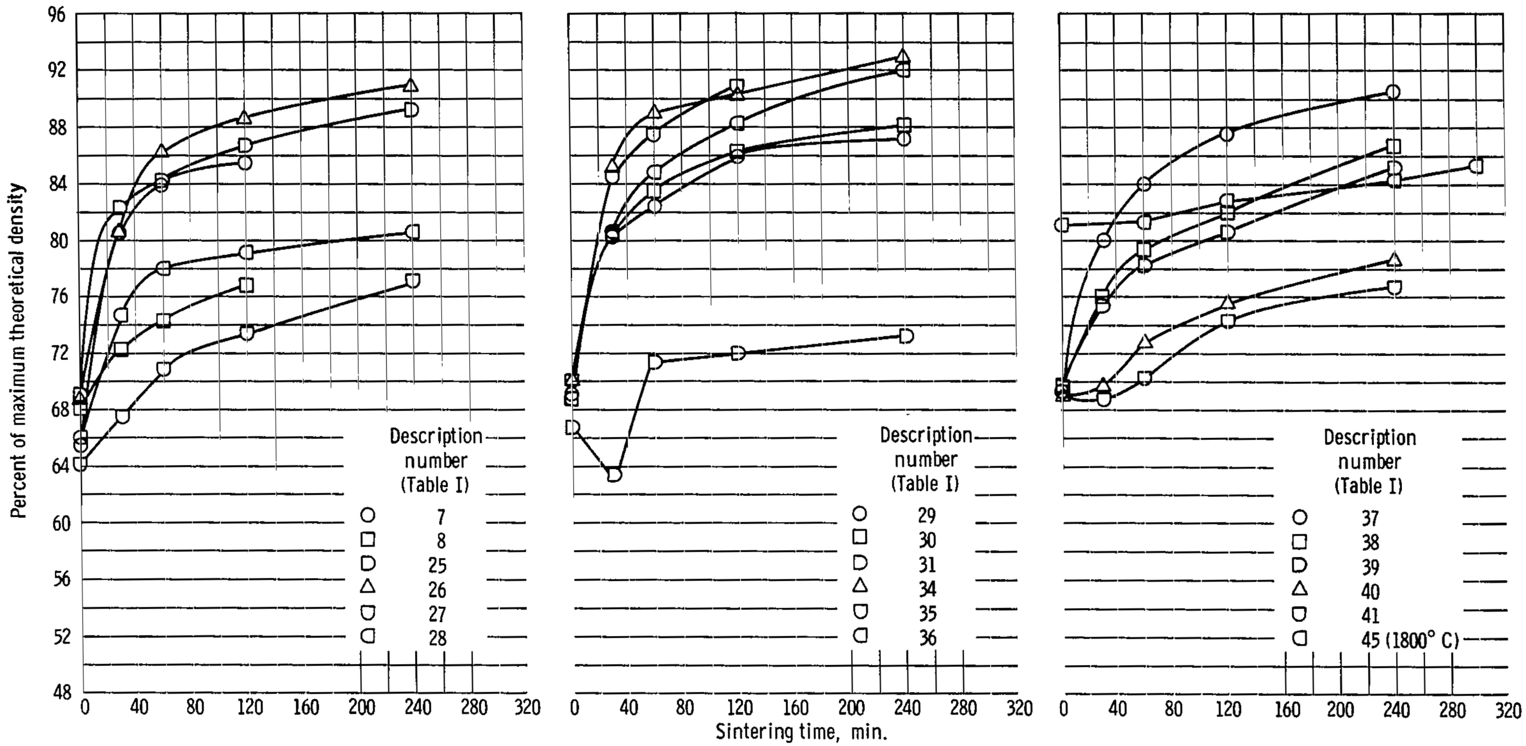
Description number (a)	Work function, eV	Description number (a)	Work function, eV
1	4.7	51	4.9
2	4.9	52	4.69
3	3.8	53	4.8
4	4.3	56	4.6
5	4.81	57	4.75
6	4.8	60	4.8
9	4.76	61	4.75
10	4.72	62	4.8
11	4.72	63	5.0
12	4.69	64	5.05
13	4.83	65	5.2
14	4.9	66	4.58
15	4.83	68	5.1
16	4.81	69	4.92
17	4.95	70	4.8
18	4.9	71	4.9
19	4.8	72	4.8
20	4.87	73	4.75
21	4.8	74	4.75
22	4.8	76	4.75
23	4.8	80	4.77
24	4.8	81	4.7
26	4.95	88	5.0
29	4.7	89	5.1
33	4.65	90	4.65
		91	4.85
40	4.75		
41	4.75		
48	5.0		
49	4.64		
50	5.15		

[a]See table I.

TABLE V. - EMITTANCES

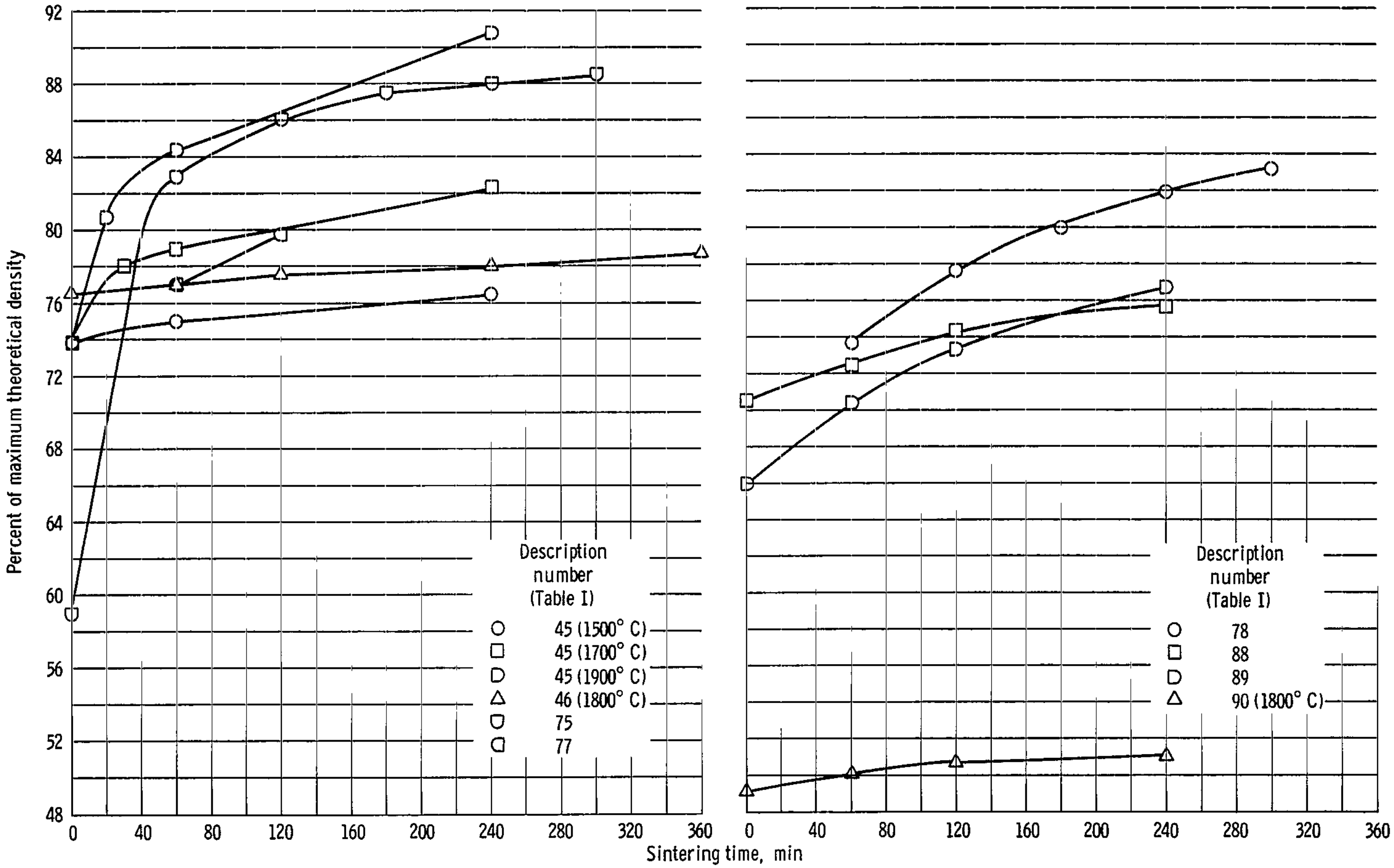
Description number (a)	Emittance	Temperature, ^{o}K
1	~0.62	1423
2	.47	1423
3	.5	1423
4	.5	1423
54	~.33	-----
56	.30	1565
58	~.31	~1379
59	.29	1432

[a]See table I.



(a) Description numbers 7 to 45.

Figure 1. - Variation of percent of maximum theoretical density with sintering time. Temperature, 2000° C unless otherwise noted; pressure, 10^{-5} torr.



(b) Description numbers 45 to 90.

Figure 1. - Concluded.

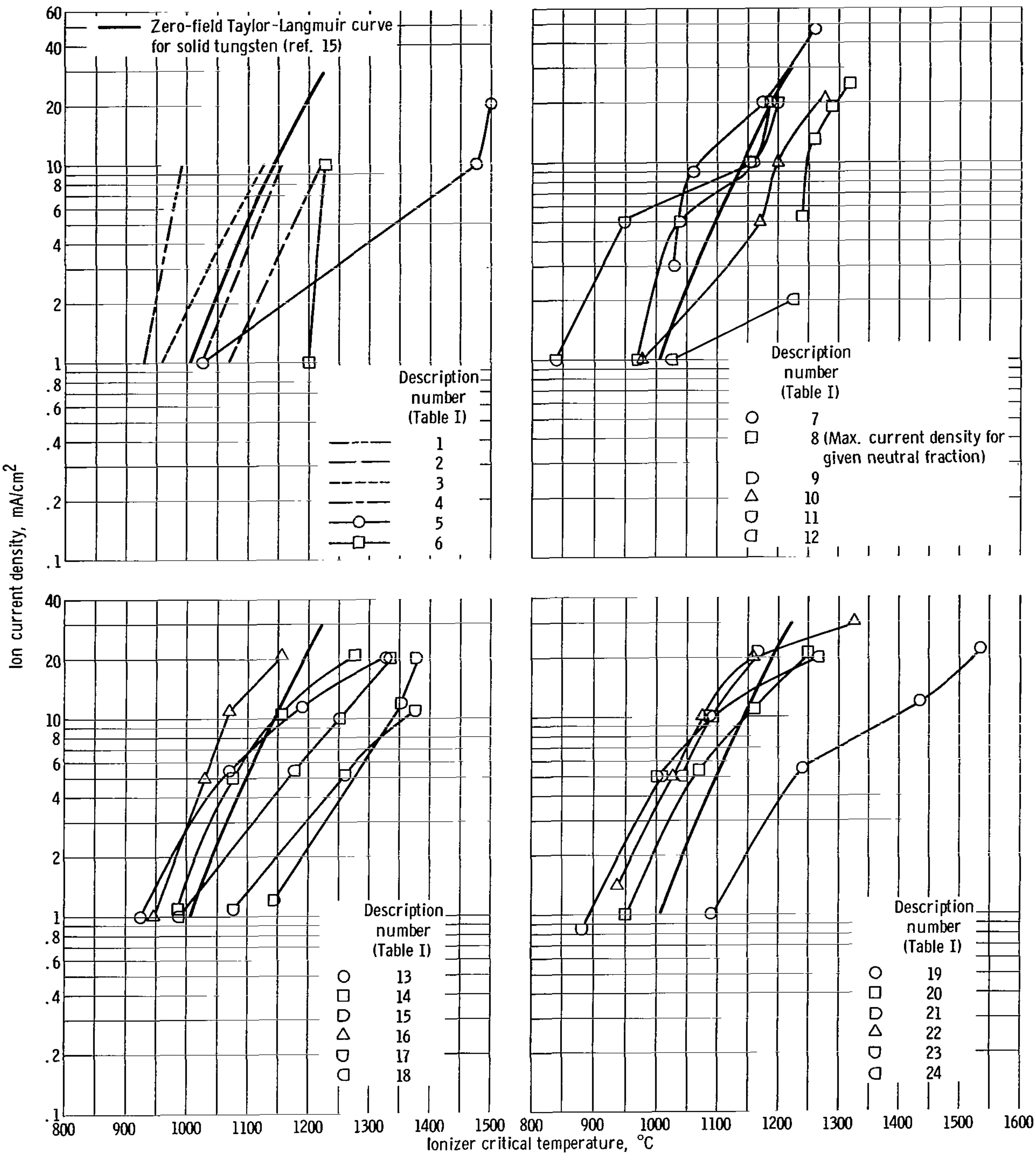


Figure 2. - Variation of ion current density with ionizer critical temperature.

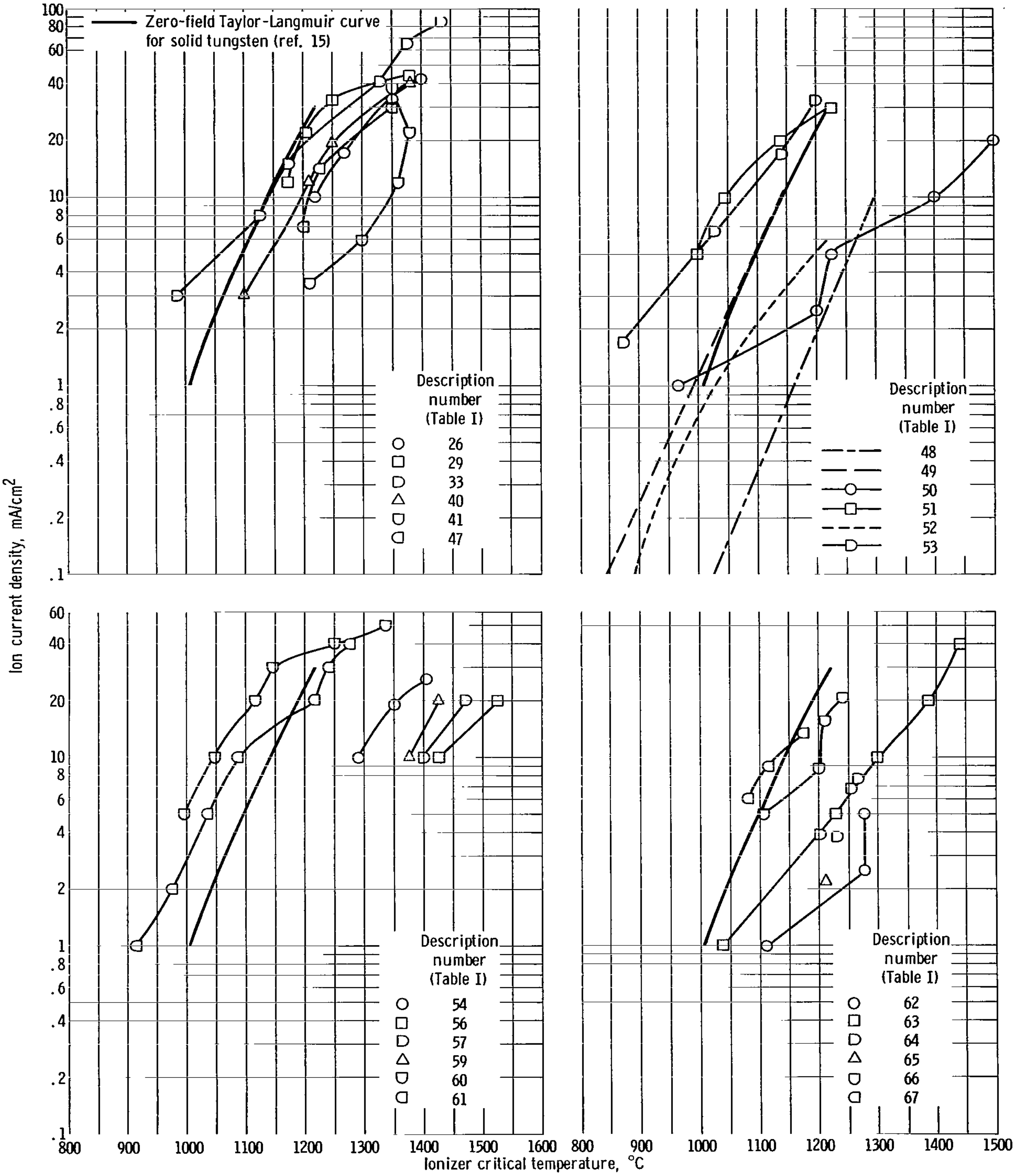


Figure 2. - Continued.

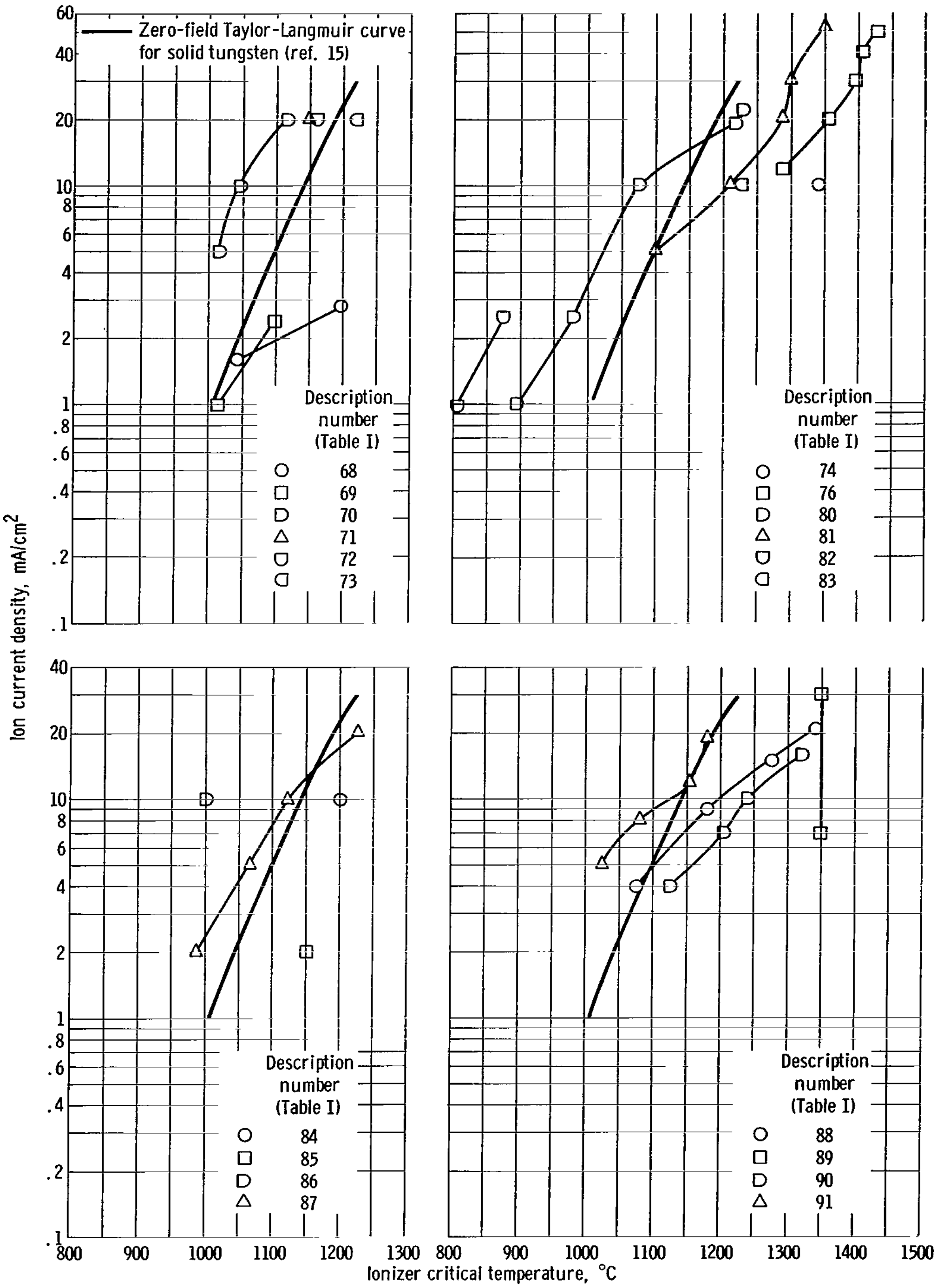


Figure 2. - Concluded.

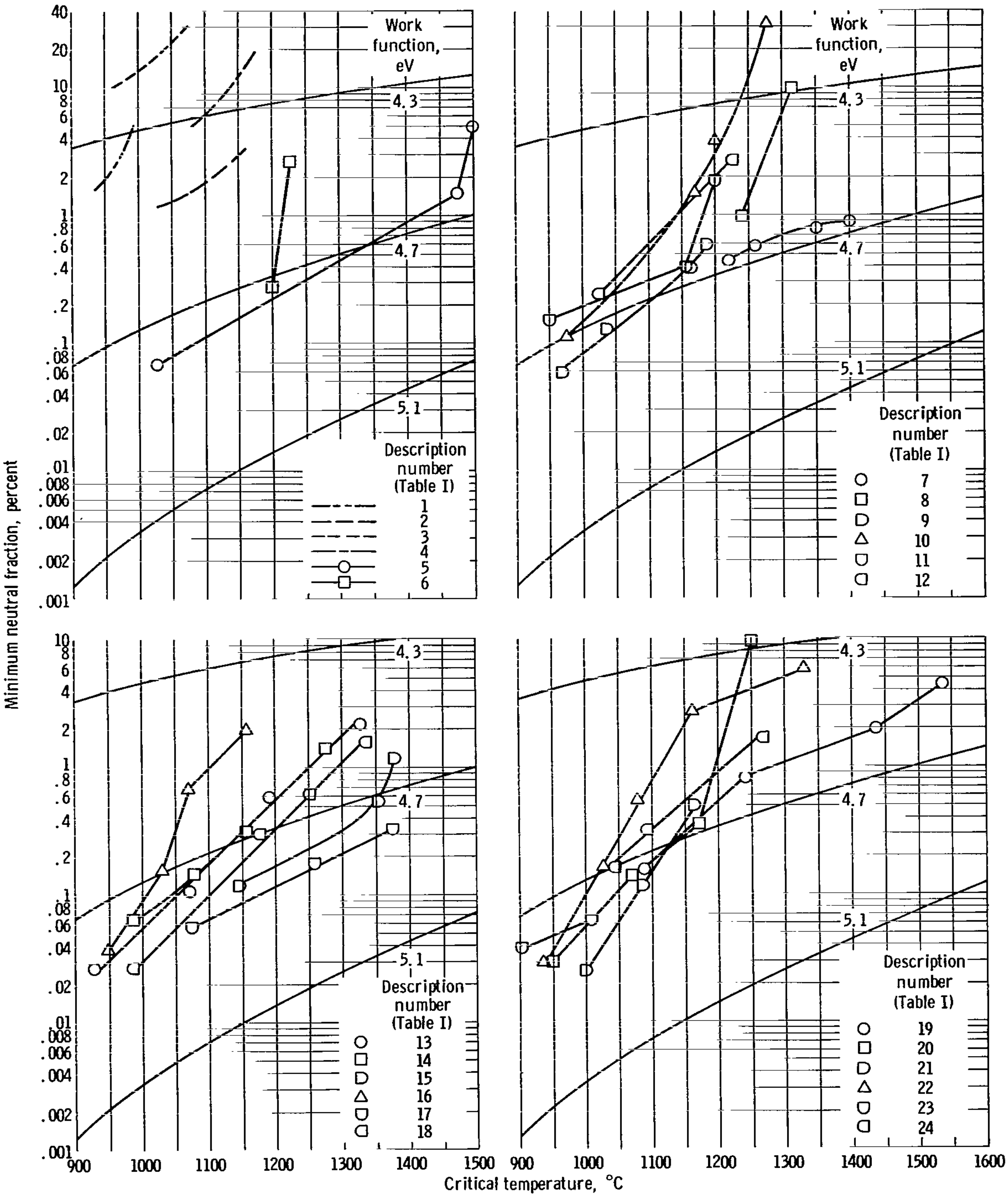


Figure 3. - Variation of minimum neutral fraction with critical temperature. Curves for three work functions plotted from the Saha-Langmuir equation are shown for reference.

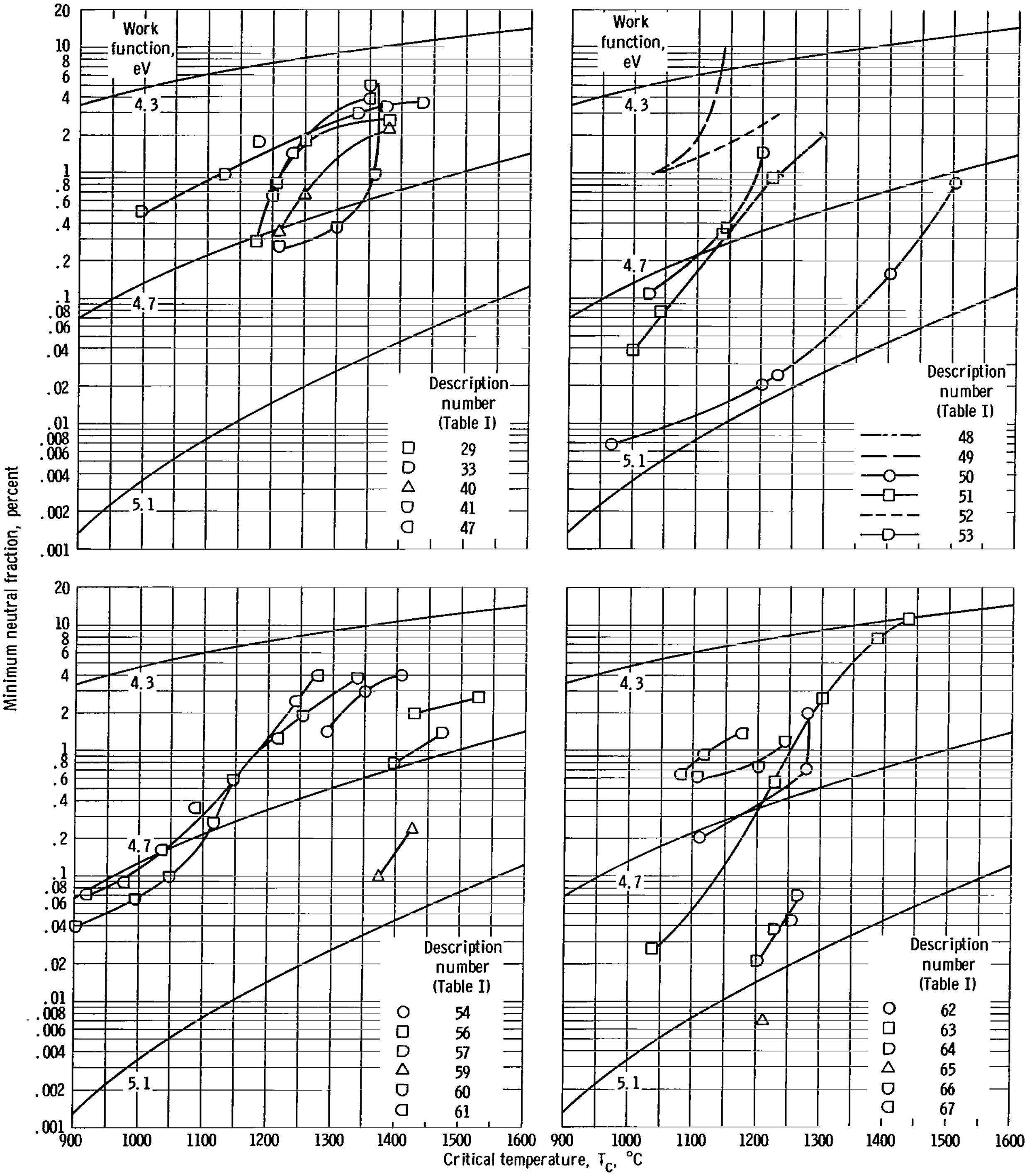


Figure 3. - Continued.

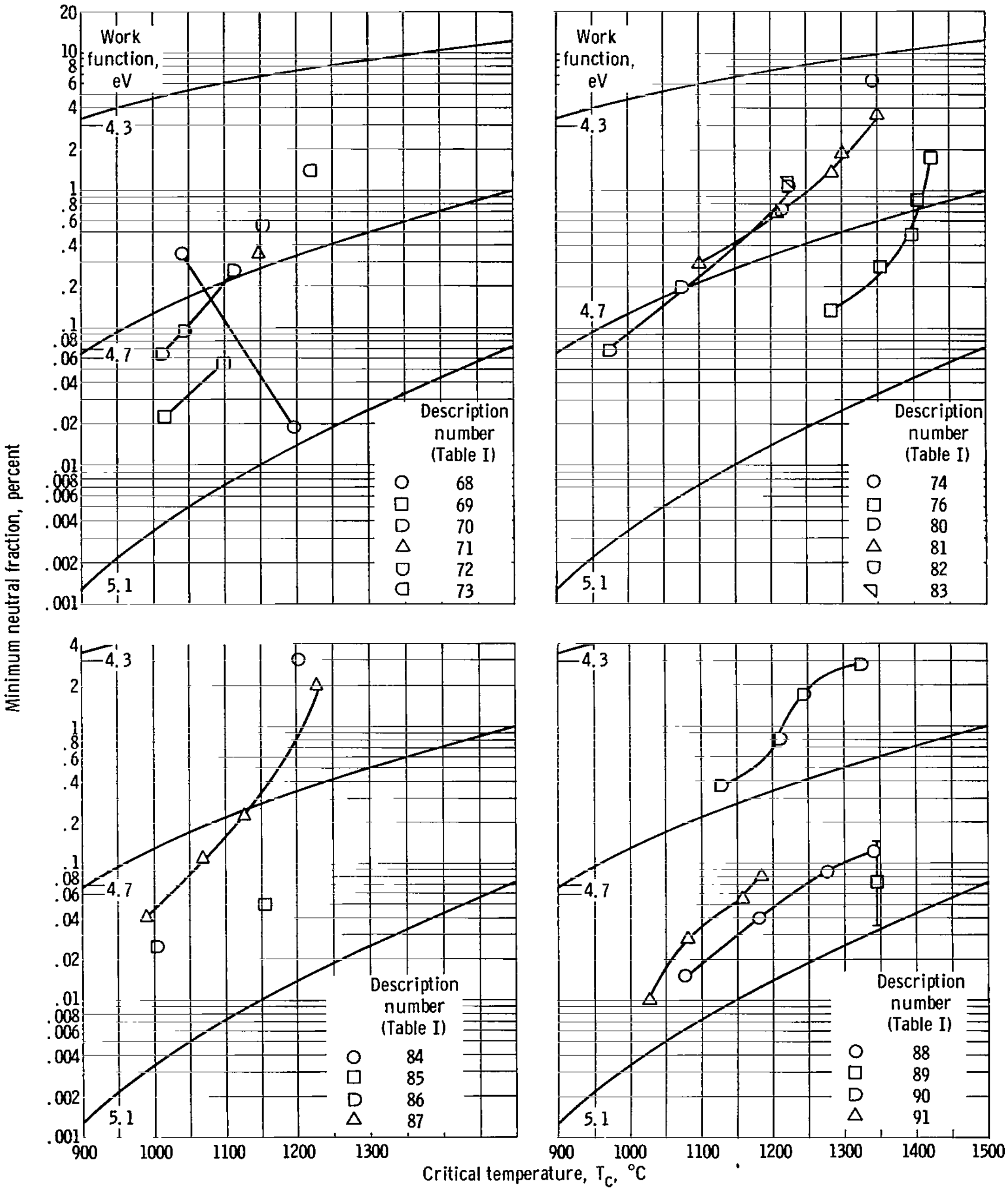
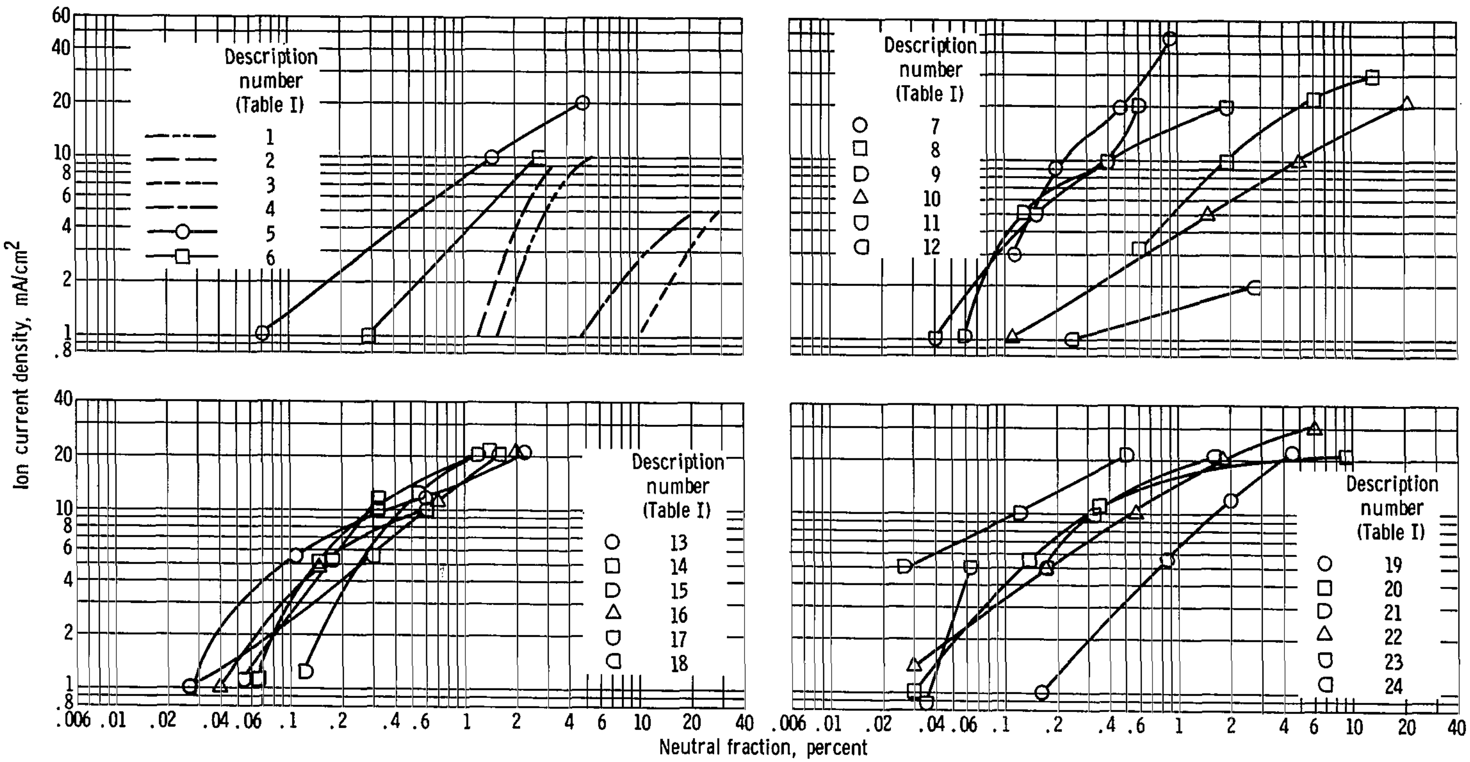
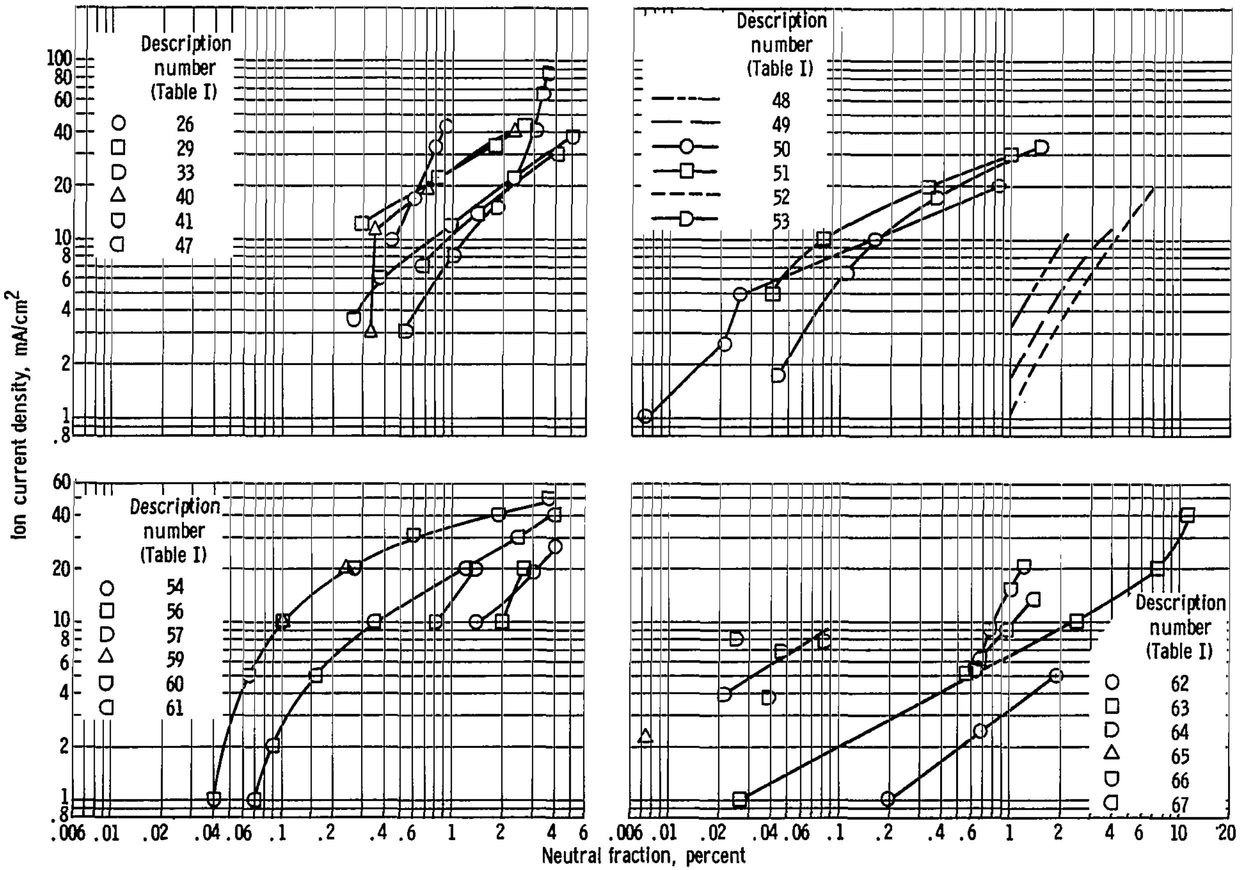


Figure 3. - Concluded.



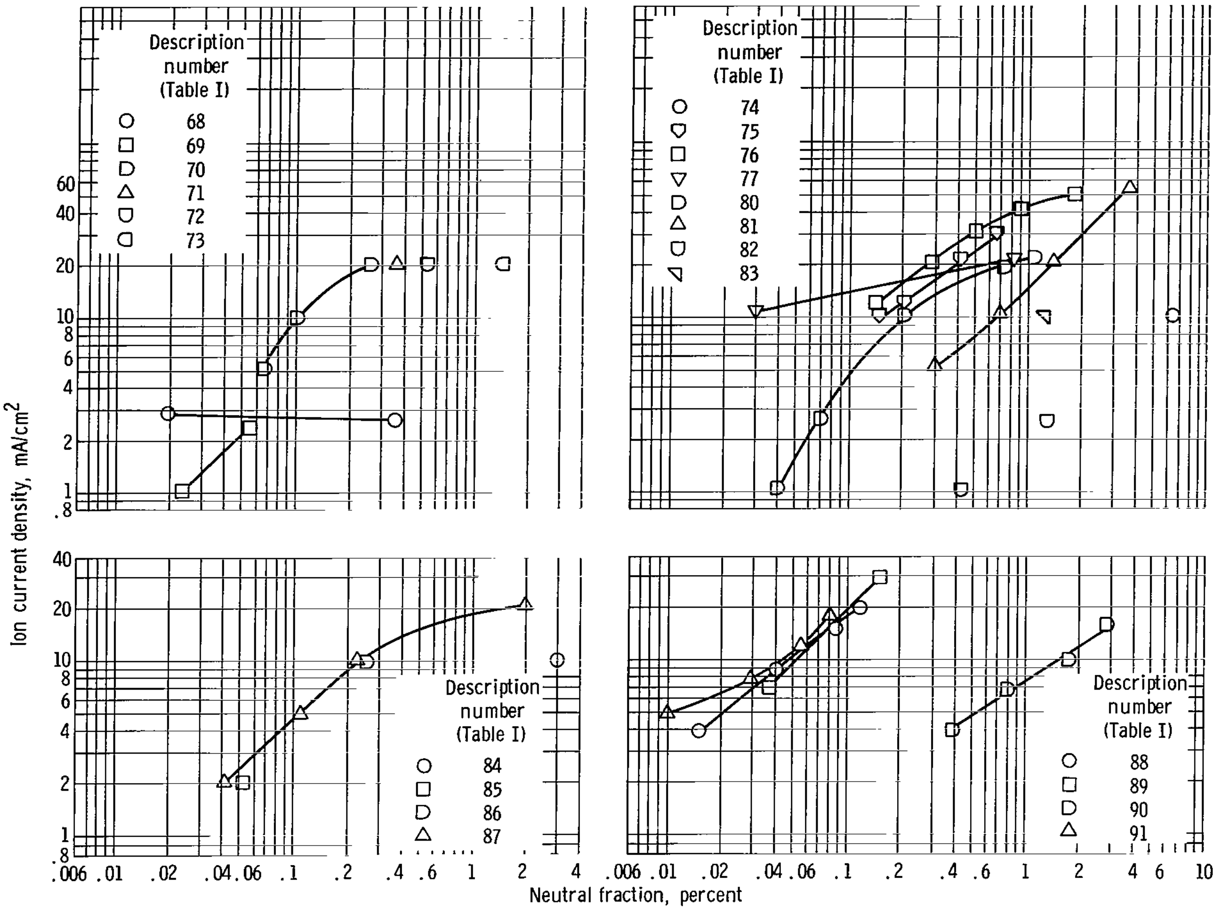
(a) Description numbers 1 to 24.

Figure 4. - Variation of ion current density with neutral fraction.



(b) Description numbers 26 to 67.

Figure 4. - Continued.



(c) Description numbers 68 to 91.

Figure 4. - Concluded.

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