THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Electrical Engineering

Report on Research toward

UTILIZATION OF MONOPOLAR CROSSED-FIELD-NEUTRALIZED PLASMAS FOR POWER GENERATION BY CONTROLLED NUCLEAR FUSION

Phase I: Scale-Model Demonstration, Using an Electron-Constituted Monopolar Plasma, of Conversion from Potential Energy to High-Level Particle Kinetic Energy

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Concluded)

FIGURES

I. INTRODUCTION AND "STATE-OF-THE-PROGRAM" COMMENTS

1. Purposes and Pattern of this Report. Because the research program here dealt with is very uniquely related to myself individually, this report will be written to some extent in the first person rather than the third person. I hope the reader may have some feeling that I am talking to him across the table. "We" refers to my associate Mr. Irving W. Rozian and myself.

It is important to the Consumers Power Company, to The University of Michigan, and to myself, that there be put in writing, both in summary form and in some detail, statements of what new information has been obtained so far on the research program for which the Consumers Power Company has provided primary support, how it was obtained, what relationship it bears to the primary original objective and to possible new objectives, and what is suggested as to plans for continuance of the total program. I shall try to do this in this report.

The primary objective of the research program has been, and is, to determine the feasibility of using an ion-constituted monopolar, crossed-field-neutralized plasma (see Chapter II of this report), for producing controlled nuclear fusion to be used for bulk electric power generation. The work on the project, together with some interesting phenomena reported by another laboratory (from experiments quite remote in concept and design from our work) have added to my confidence that our efforts are along the right track, and if diligently pursued and adequately supported will eventually satisfy the primary objective.

The "State-of-the-Program" comments in this report will be followed in sequence by: a discussion of the physical principles of the proposed process and apparatus; a description of the plan and functioning of the experimental apparatus used in the research program; a description of the experimental procedure; presentations in graph form and detail discussions of many samples of experimental results, demonstrating the conversion into high-energy ordered motions and the feasibility of "confinement"; then brief summary comments and a presentation of recommendations for future phases of the total program, based on its long-term objective.

There was no point in attempting to relate the structure of this report to the order of plans and objectives stated in the original proposal, because, although the primary objective has remained the same, the program has been quite substantially modified from time to time as a result of information provided by the experimental observations, also as a result of changes in arrangements for financial support of the effort. One cannot hope to predict in any detail the nature of the results of any truly research effort, nor can one hope to schedule a firm time scale for the conduct of such work. If the results and time scale of achievement are in fact predictable, then the work is not properly describable as research. One can of course have confidence that really new information will result, and that has happened in this case.

Chapter II of this report, dealing with the physical principles underlying the research program plan, is taken in large part, with appropriate editing, from portions of a Patent Disclosure submitted to the Comsumers Power Company on December 1, 1965. I cannot hope to do better than Mr. Rozian and I did in that disclosure in describing in only partially sophisticated terms the nature of the phenomena and its relationship to the research objectives. Some other parts of this report are drawn from the text and figures of our Preliminary Memorandum Report of May 25, 1965.

2. Patent Possibilities. I consider important the fact that there now exists, in the form of the December 1, 1965, Patent Disclosure papers, the

basis for establishing a basic patent covering new and original equipment and processes. Some of the essential elements of newness of concept are as recent as March, 1965, and there are no indications that anyone else has expressed these concepts in any way whatever. There would I believe be a great deal of merit in having such a patent originate within the State of Michigan, as a result of research done under the flags of The University of Michigan and a Michigan corporation, quite apart from whatever financial benefit might accrue to the Consumers Power Company.

It is therefore my recommendation that the Consumers Power Company undertake to process such patent applications as seem appropriate on the basis of the disclosure papers. These applications should include the new electronic-device inventions described in the disclosure as well as a basic patent or patents on controlled nuclear fusion.

3. <u>Contrasts, for the Most Part Advantageous, Between the Experimental Results Obtained and Those Previously Expected</u>. The experimental results of this research effort have differed quite markedly from what I had anticipated on the basis of my interpretations of the results obtained in Dr. M. H. Miller's earlier experimentations, of a much more restricted scope than ours have been. The essential differences between what I anticipated and what has been observed, and initial expected consequences thereof, may be briefly identified as follows:

A. <u>Predominance of ordered high-kinetic-energy motions over random-in-nature thermal motions</u>. The many-directional high kinetic energies that the charged particles do in fact acquire in the crossed-field environment appear to be of an ordered-motion rather than a random-motion nature; thus the word "temperature" becomes rather meaningless. This implies that the theoretical basis for the behavior must be rather markedly different than was at first anticipated, although very likely somewhat simpler in formulation.

B. "Confinement" of the particle motions appears more easily achievable than was anticipated. It appears reasonably certain that a stream of deuterons (ionized atoms of heavy hydrogen) having ordered many-directional high-energy motions comparable in nature and energy magnitudes with the motions of the electrons in our experimental apparatus, will be very much more easily confined into a thin stream, and prevented from contact with physical boundaries, than would be the case for a deuteron stream with random energies (describable by stating a temperature) at comparable energy magnitudes. The evidence for this greater ease of confinement is clearly apparent in our experimental results.

C. Probability of high-relative-energy collisions needed for fusion is presumably greater for the observed ordered motions than for thermal motions of comparable mean energy. It seems very likely that the existence, in a stream of deuterons, of the type of many-directional motions that appear to exist in our electron stream, would have a higher probability of collisions between particles having large relative energies than the similar probability for deuterons having random energies at the same total average kinetic energy. This is discussed in Chapter II of this report.

D. The fact that the high-energy motions are ordered suggests their utilization for electronic-circuit functions. Because the particle motions are of an ordered nature, it should be possible, either for an electron-constituted or an ion-constituted stream, to extract electric-circuit energy from the stream by a process or processes generally inverse to that used in putting the energy into the stream. This suggests that, as applied using an electron stream, there exists a hitherto unknown and unused means of signal amplifications and modulation, also of radio-frequency power generation (i.e., the device should be usable as a power oscillator), and also a new means of high-energy radio-frequency signal storage and delay. These and other related new concepts have been incorporated into the Patent Disclosure papers forwarded to you last fall.

Some delay in prosecuting the present research effort has resulted from a difficulty, within my own mental processes, in accepting as hard fact, evidenced by the experimental results, the presence of high-kinetic-energy particles with a nonrandom energy distribution acquired as a result of traverse through and interaction with the d-c electric field of the crossed-field apparatus.

4. The Ion-Constituted Monopolar Plasma Should Produce Sustained Fusion at Relatively Moderate Average Particle Energies, Because of the Absence of Electrons. As discussed in our initial proposal and detailed further in Chapter II of this report, the fusion-producing monopolar ion-constituted plasma stream we propose, just because it is monopolar in containing deuterons but no electrons, would be free from the two major causes of energy loss that are present in the more usual bipolar plasmas used by other experimenters. These losses are those due respectively to "bremsstrahlung" (that is, wide-band X-ray radiation due to sharp accelerations of electrons at near misses with ions) and "cyclotron radiation" (due to acceleration of the electrons during the looping trochoidal motions they have in a crossed-field environment). Because these losses are absent, it should be possible to obtain self-sustained fusion reactions at a much lower average particle kinetic energy than the estimated 15,000 electron volts needed (but not yet attained experimentally) for self-sustained fusion in bipolar plasmas. It seems reasonable to expect

that no more than 1/3 and quite possibly as little as 1/10 of that energy may be adequate in the proposed process, that is, from 1,500 to 5,000 electron volts average particle kinetic energy.

5. The Question as to a Possible Energy-Limiting "Saturation" Effect. An obvious question arises, as to whether some kind of self-limiting or "saturation" effect may exist for our ordered motion, which will prevent its kinetic energies from reaching even the 1,500-electron volt to 5,000-electron volt average energy that I estimate will be necessary to produce self-sustained fusion by our method. Such a limiting process should exist for electrons if it is to exist for deuterons, and our experiments to date have not shown evidence of such a limiting effect. Additional experiments soon in prospect will enable us to explore this question to somewhat higher energies—we hope in these experiments to be able to approach reasonably closely to the 1,500-electron volt average kinetic energy value. There are somewhat intuitive theoretical reasons for expecting a saturation effect, but only at somewhat higher energies than this, and of such a nature such that the limit could be raised by increasing the magnetic flux density. Item D of Section 31 contains comments significantly related to "saturation."

6. The "Similitude" Question as to Whether Deuteron Behavior is in Fact Predictable by Applying Known "Scaling" Laws to Our Observed Electron Behavior. It is obviously important to raise the question as to the extent to which deuterons or tritons, with ratios of particle mass to electric charge respectively about 3600 and 5400 times larger than for electrons, will in fact behave in the same manner as our electrons. That is, will the behavior in fact follow the well-understood "scaling laws" that do predict the behavior will be similar? There is a relatively small body of experimental evidence that bears on this "similitude" question as applied to a remotely sim-

ilar environment. This evidence is not conclusive, yet it should have exposed a failure of similitude, but rather tended to confirm it. But the only real proof that deuterons will behave as our electrons do must come from building an experimental apparatus that is basically similar to the present one, but uses deuterons. The costs in building such an apparatus can reasonably be expected to be 5 to 10 times as much as for the present apparatus, and the staff cost for the experimentation from 3 to 5 times that appropriate for the present apparatus.

7. <u>We Believe that Results of Recent Experiments (Wholly Different from Ours) at Oak Ridge, Tennessee, Represent Partial Verification of Our Expectation of Fusion Capability of Our Proposed Apparatus</u>. A group at the U. S. Atomic Energy Commission's Laboratory at Oak Ridge, Tennessee, have reported some experimental results (in bipolar plasmas greatly different from our monopolar ones) which they do not understand, but which I believe I do understand. I believe their results are to be expected from a thoughtful interpretation of our results as applied to their apparatus, with use of the "similitude" scaling laws.

They establish a bipolar plasma, and send through it a high-current beam of electrons that originate from a cathode at a potential much lower than that of the bulk plasma. This whole apparatus has a strong magnetic field directed parallel to their electron beam. They report having observed some generation of neutrons in this apparatus, but do not understand it. It seems wholly probable to me that there exists in their apparatus a "positive ion sheath," between the low-potential electron beam and the bulk plasma. Such a sheath there would comprise an ion-constituted "monopolar" region in a crossed-field environment. The ions would drift circumferentially at right angles to both fields, a behavior remotely similar to that suggested in one of the re-entrant-flow "elaborations and convolutions" of our Patent Disclosure invention. It is to be expected on the basis of our results and the scaling laws that there would appear in this sheath an extremely high-energy ordered motion of the ions, which they have no means of observing, but which should be expected to produce nuclear reactions.

I do not believe these people will discover what they really have until we publish a professional paper describing our results, which will probably be a year hence. I have observed among experts skilled in this art a deep and well-entrenched prejudice against giving any serious attention, either experimental or theoretical, to monopolar behavior.

8. Preparation, by Myself, of a Publishable Analytical Interpretation of Our Results, Linked to an Adequate Theory, is a Necessary Next Step in this Total Research Program. Before one can hope to obtain, from any source whatsoever, the funding necessary to carry out the next experimental phase of the program, that of repeating the present experiments with deuterons (and quite likely obtaining low-level fusion reactions) it will be necessary to have available a complete scientifically-oriented presentation of our results, including a fairly sophisticated postulation of a theory. No theory for the observed behavior yet exists. This presentation must be in a form easily adaptable to publication in a professional journal.

I am the only person presently qualified to prepare this presentation, and the doing of this is an interesting part of my personal effort program "in retirement." Actually, many of the fundamental physical concepts are the same as those I am using in my present part-time (two days a week) employment as a Senior Research Geophysicist in the Space Physics Research Laboratory of the Department of Electrical Engineering of The University of Michigan—my new office is in the Space Research Building on the North Campus, only a few steps from the Magneto Fluid Dynamics Laboratory where Mr. Irving Rozian and I will be completing the work on this nuclear fusion project in the next few weeks.

One of my efforts in this Space Research program will be to try to determine to what extent there may be occurring in the ionosphere, 100 to 500 kilometers above the earth's surface, phenomena quite similar qualitatively to those in the apparatus Mr. Rozian and I are working with. There are free electrons up there, and they are in a crossed-field environment (there is a radial electric field outward from the earth). If one scales from millimeters to kilometers, things might really seem quite similar! I believe there will be time in my life to carry on both efforts, especially since they have a common fundamental physics background. As "digestion time" for new thoughts is required in any such effort, independently of any other; each will move ahead about as rapidly as if the other were not going on. Both are enjoyable.

9. Need, in Preparing an Adequate Theory, of Additional Experimental Data from the Modified Apparatus Now Being Made Ready for Tests. It is probable that some really very important supporting data for my planned scientifically-oriented analysis will come from experimental data Mr. Rozian and I expect to obtain between now and the end of June on our experimental apparatus as now being modified. There are three principal reasons for the importance of having this additional data, as follows:

A. We will be working at higher voltages, and therefore at higher electron kinetic energies than before, making the data more impressive as to energy magnitude.

B. The electrode configuration will be simple and regular, without the depressed segments used the last time; this will made the interpretation (by someone other than myself) much more straightforward.

C. We are putting thermocouples into some of the segments, to enable us to demonstrate quantitatively by thermal measurement the amount of heat energy produced in the probing segment by electron impact. This will remove the last shadow of a doubt in my mind, and will remove serious doubts in other people's minds, as to the means by which the electrons arrive at electrodes whose potentials are hundreds of volts below that of the cathode.

An important reason why this experimentation has been delayed longer than we anticipated has been the necessity of phasing Mr. Rozian's efforts gradually into other activities in anticipation of the termination of this present phase of the nuclear fusion work. This change-over is occurring successfully, but the price paid for the success has been a gradual diminution of his hours per week on the nuclear fusion project, with a corresponding substantial lengthening of the time for readying the apparatus for experimentation.

10. Sources of Funds for this Research; None of My Own Salary has Come from Project Funds. Roughly speaking, as to sources of financial support for this work, one may say that:

A. Funds provided by the Consumers Power Company were used for building the equipment and making, during the summer of 1964, the initial tests of it that demonstrated that the total system was capable of making the kind of measurements needed.

B. Funds provided through University of Michigan channels have been used for supporting the experimental work which, beginning in the fall of 1964, has given us the important data which convinces me of the potential value of the research.

None of my own personel salary has been charged to either the (A) or (B) items. While I was still active as a member of the instructional faculty and Department Chairman, I carried on both the project direction and the scientific study phases of this project as part of my "faculty research." Thus this was carried out under my compensation from the General Fund of the University, the same source that provides salaries for classroom teaching and for administrative duties. During that time a part of my salary was paid as compensation for research effort that I devoted to other activities, particularly in the Electron Physics Laboratory (work there used some of the same fundamental principles that apply to the nuclear fusion project), but none of my salary has at any time been charged to the Consumers Power Company project. During my 1965 year on "Retirement Furlough" my salary came from the same budget that pays Sabbatical Leave salaries. 1966 will be a satisfactory year, as between my retirement-resource income and my salary as a Senior Research Geophysicist, my income will approximate what it has in previous years. To complete the personal picture, let me say that as far as the doctors and I can judge, I am in fantastically good health for a man 70 years old.

11. <u>The Many Pessimists and the Few Optimists Among Experimenters Using Conventional Approaches to Controlled Fusion</u>. A later chapter of this report gives information, including and extended from that contained in the May 1965 Preliminary Memorandum Report, as to the attitudes of various people around the country regarding the "State of the Art" of Controlled Nuclear Fusion. A comment that has had for me considerable significance is that made informally in the fall of 1965 by a visitor here from the staff of the U. S. Atomic Energy Commission's Laboratory at Oak Ridge, Tennessee, to the general effect that he believes that in 10 years or so they will be able there to produce

controlled nuclear fusion; I think he really believes 15 years is nearer the truth. And he is in the "optimist" class; many who have worked on this problem have given up, including some of the ablest ones. Optimism for success on a similar time scale also exists in the laboratories of the Sherwood Project at the Lawrence Radiation Laboratory of the University of California in Livermore, California. I have heard the pessimists characterize Dr. Richard F. ("Dick") Post at Livermore, who heads the Sherwood work there, as an "incorrigible optimist." Actually, for reasons given above, I think the people at Oak Ridge are working along a more nearly useful track than are those in Dr. Post's group. Our own Nuclear Engineering faculty tend to hold the pessimist view, as nearly as I can judge.

12. <u>The Political Dynamite Our Success would Touch Off</u>. It is desirable for us to bear in mind that should we, using non-Federal Government money, succeed where the multimillion dollar Sherwood project (and others like it in other countries) has failed, there will be many bitter repercussions, and the Atomic Energy Commission will suffer an enormous loss of prestige. The chips in this game, politically as well as financially, are not merely blue, they are purple. That is why I like the game, and intend to play it for all it is worth. But one must hold one's cards closely, and play them carefully. The rules of the game can change overnight either way, in the political arena. The AEC has many critics, and the utilities have many friends, and the Congress calls the tune.

II. PRINCIPLES OF THE PROPOSED PROCESS AND APPARATUS

13. Prefatory Comments as to Uniqueness and Types of Use of Our Monopolar Plasma Principle. The new and useful apparatus and processing which we propose to use primarily for producing controlled nuclear fusion, makes use of physical principles from several scientific disciplines to create, sustain, and confine a unique type of electrically conducting plasma stream having extremely high kinetic energies, due to particle motions that are omnidirectionally-oriented in at least two of the three dimensional directions. By using electrons under proper conditions there may appear, as an incidental but perhaps important benefit from this project, electronic circuit applications. By using deuterons (ions of atomic heavy hydrogen) there should result production of very large amounts of energy by nuclear fusion at collisions between the particles.

The uniqueness of the type of plasma stream used lies primarily in its employment of the forces on charged particles due to crossed d-c magnetic and electric fields to neutralize the electrical space-charge forces of the stream charge-transporting particles, rather than employing for this purpose the presence of charged particles of the opposite polarity. In other respects this type of plasma generally resembles the typical low-density gaseous-conducting plasmas investigated and first named "plasmas" by Irving Langmuir and his associates. Thus the plasma types of this invention are called "monopolar" because neutralization of space-charge forces produced by the charge-transporting particles is accomplished without the presence of charged particles of the opposite polarity. There appears below an itemized comparison of the general similarities and contrasts between this invention's monopolar types and the familar low-density bipolar Langmuir-type plasmas.

Although production of power by nuclear fusion is the principle objective of the basic process here described, it may also find other applications wherein high-kinetic-energy clouds or streams of either ions of electrons are required to have a dominatingly large proportion of their particle kinetic energies in many-direction orientations rather than in the one direction of the average "drift" motion of the particles.

There appear, in later sections, descriptions of apparatus for the embodiment and realization of the aforementioned processes in monopolar, crossed-field-neutralized plasmas. Particular attention is devoted to apparatus processes employing positive ions as the charge carriers, because of their prospective utility for production of heat and power by means of controlled nuclear fusion. Several elaborations and convolutions of the elementary apparatus are described in the Patent Disclosure papers given you last fall.

In subsequent sections of this chapter there will appear: comparisons of monopolar with more conventional plasmas; a description of the physical processes that function in the plasma stream to convert potential energy into high plasma particle kinetic energy; a comparison of nuclear fusion with nuclear fission as an energy source in relation to the high kinetic energies required for large-scale controlled nuclear fusion; a discussion of the necessity for balancing fusion rate against energy loss in producing controlled fusion, with comments as to the lessened-kinetic-energy need for "break-even" in monopolar as compared with bipolar plasmas.

Discussions of the need for and means of achieving "confinement" of the plasma stream will appear after presentation of experimental data, because the data adds significance to discussion of confinement.

14. <u>Comparisons Between Conventional Bipolar Plasmas and the Monopolar Plasmas of this Method</u>. The monopolar type of plasma employed in the proposed

apparatus and processes parallels in many respects the familiar low-density type of bipolar electrically-conducting gaseous plasma investigated by Irving Langmuir and his associates. The resemblances are exhibited by the family of typical attributes itemized below.

The monopolar plasma is unique in being constituted of either positive ions or electrons (but not both), and in having essentially no neutral gas particles present, but most particularly in its employing as described under Item (B) below a crossed-field mechanism for neutralization of d-c space-charge forces, in the same general way that they are neutralized in the familiar planar Brillouin flow of electrons.

The itemization of attributes exhibiting parallelisms and contrasts between the present invention's monopolar plasmas, and typical Langmuir-type low-density plasmas, is as follows:

A. In both monopolar and bipolar plasmas the electric current is transported primarily by particles of one electrical polarity only. Typically electric current flows through a plasma by electric charge being transported almost entirely by the directed or average "drift" motion of particles of one electrical polarity only. Of course in the present monopolar plasma the charge is transported wholly in this way, either by ions in the ion-constituted plasma applicable to produce controlled nuclear fusion, or by electrons in the electron-constituted type.

B. Neutralization of d-c space-charge-produced electric forces. For a plasma of either kind to exist, there must be neutralization of the d-c electric forces on the current-transporting carriers caused by their own space charge, as otherwise these forces would cause dispersion and disintegration of the stream of carriers. The monopolar plasma we use is unique in having these space-charge-produced electric forces neutralized by the combined actions of crossed d-c magnetic and electric fields (usually externally applied). This is in contrast to having the neutralization occur due to the presence of charged particles of the opposite polarity, as is true in bipolar plasmas, as for example in the typical Langmuir-type low-density plasma, and in plasmas used in other approaches to producing controlled nuclear fusion for power generation.

To understand crossed-field neutralization, note that, as illustrated schematically in Fig. 1a for an ion-constituted monopolar plasma, the ions initially move away from the ion-source locality in what may be idealized as an approximately Brillouin-type stream, the motion being parallel to the ion-source surface and to the nonemitting plane metal surfaces that lie each way from the ion source in its same plane, and appear as continuations of it. In such a stream all the particles move along equipotentials of the d-c electric field between this surface and a parallel negative "driver" electrode spaced a short distance away. The potential distribution through and beyond this Fig. 1a idealized Brillouin-type stream is illustrated in Fig. 2. At every point within the stream the particle velocity is in the stream-flow direction, and its magnitude is the ratio E/B of the local electric field intensity E to the uniform magnetic flux density B; as its direction must be at right angles to E and to B for this idealized Brillouin-flow condition, all electrons move parallel to the electrode surfaces and along equipotentials of the d-c electric field. Thus in this idealized form, which approximates the behavior of the stream just beyond its initiation, the flow is conceived of as being of a laminar slipping-stream nature, the velocity being zero along the equipotential at the zero-value potential of the ion source, and having its greatest value along the outer edge of the stream.

Of course the space-charge-produced forces on the particles tend to diverge the stream. The combined force effect of the electric field due to the voltage applied to the electrodes is to tend to move the particles at all layers away from the sole. However, at every point in the stream the magnetic force (velocity x B) is equal and opposite to the combination of the electric field forces. The electric and magnetic forces thus cancel one another out, so that the stream neither converges nor diverges. This behavior corresponds to each particle having the velocity E/B given by the value of E at the particle's location. The space-charge density is uniform throughout the stream at a magnitude governed exclusively by the magnetic flux density. As seen in Fig. 2, the electric field strength E for each layer of the stream (negative of the potential gradient at that point) is a function of both the externally applied field and the space-charge density integrated from the sole surface to the layer in question. It is a simple exercise in the use of electromagnetic field theory and Newton's force laws to show that this idealized Brillouin flow represents a self-consistent behavior. And it is a behavior in which the action of the crossed d-c magnetic and electric fields serves to neutralize the space-charge forces.

When, as discussed later, the stream acquires growing space-charge-wave attributes as it moves along in the stream direction, and accepts energy from the d-c electrical system by moving well toward the driver electrode as illustrated in Figs. 1c and 4, it comes to have both ordered rotational and random particle motions which become enormously greater than E/B. However, the longitudinal drift velocity remains always at the value E/B, with E taking whatever value the potential structure (see Fig. 4) may call for when the stream (now truly a plasma) has moved significantly away from the ion-source potential. Thus the crossed-field neutralization of d-c space-charge forces persists even after the initially Brillouin-type stream (or a reasonable approximation thereto) has become a plasma that, however, retains the drift velocity and to a considerable extent the charge content characteristic of the earlier near-Brillouin flow. Figures 1b and 3 illustrate a situation in which the stream has been driven away from the sole as a result of reaching a point in the structure at which it is near the raised-potential sole rather than the zero-potential ion-source block, being an intermediate condition between Figs. 1a and 1c, along the stream's travel.

For an electron-constituted monopolar plasma a completely parallel situation exists, except that electrons originate from a cathode, and Figs. 2, 3, and 4 become inverted, with the driver potential above the cathode potential and the sole potential. The driver can then properly be called an anode. The velocity at right angles to E and to B has the same value E/B as in the ion-constituted monopolar plasma.

Because the crossed-field neutralization just described makes unnecessary the presence of charged particles of the opposite polarity, only particles of the polarity used to transport charge, so producing current flow, should be present; hence the term monopolar is appropriate.

It is reasonable to expect that crossed-field neutralization can have its complete effectiveness, only when the densities of particles of any kinds other than those used to transport charge are small enough so that effects due to collisions of the streaming charged particles with other kinds are negligible, as well as being small enough to make a negligible contribution to the space charge content. The presence of substantial numbers of neutral gas particles would result in collisions whose general effect would be to tend toward dispersion of the stream in response to space-charge forces. In an ion-constituted plasma of the monopolar type, the presence of a few electrons would contribute to neutralization of space-charge forces, but their presence would be severely damaging for the nuclear fusion application, as they would cause instabilities and severe radiation losses at high energies. It has not yet been determined at what relative neutral particle densities the various effects damaging to crossed-field neutralization become serious.

C. Presence of pronounced "space-charge-wave" oscillations at a high "plasma frequency." In typical low-density plasmas there exist well-ordered, high-frequency, and often large-amplitude oscillatory (in monopolar plasmas rotational) motions of the charge-transporting particles, corresponding to and being a primary cause of high-frequency "space-charge-wave" oscillating electric fields, having a "plasma frequency." These well-ordered space-charge waves (which may be of a propagational nature) are observable characteristics of typical plasmas in gases whose particle densities are from small to extremely small fractions of atmospheric molecular densities, but are not observable characteristics of high-density plasmas occurring in gases having particle densities approaching or exceeding (sometimes very greatly exceeding) atmospheric molecular densities. In typical Langmuir-type low-density plasmas the plasma radian frequency is very close to what will be called here, to avoid ambiguity, the "electron density radian frequency," dependent only on the mass and particle density of the electrons. Space-charge waves in monopolar crossed-field-neutralized plasma types constituted of either electrons or ions, presumably exhibit an alternation between kinetic energy content and electric-field energy content. At the phase of greatest kinetic energy the particle trajectories are in the nature of trochoids having large-amplitude and almost completely overlapping loops, as illustrated in a general way in Fig. 5. This makes the primary motions omnidirectional in the plane of the d-c electric field, and presumably puts the entire energy content into these motions at this phase position. For the monopolar electron-constituted plasma, theory and experiment show for the space-charge-wave oscillations a frequency of the same order as but higher by a significant factor ($\sqrt{2}$ according to the simplest theory) than the electron density frequency.

For the monopolar ion-constituted plasma as envisaged for the nuclear fusion purposes of this invention, there is a corresponding relationship of the space-charge-wave frequency to an ion density frequency that depends on the ion mass and density.

In both the electron-constituted and ion-constituted types of monopolar plasmas, the space-charge waves that carry the high particle kinetic energies are propagational in nature and can be spatially growing waves. They are essentially nonexistent at and just beyond the electron or ion source, as in Figs 1a,b, 2, and 3, but can have very large amplitudes within very short distances along the E/B drift--distances of a very few centimeters in electron-constituted monopolar plasmas. Figures 1c and 4 suggest a plasma stream location and a specific degree of potential to kinetic energy conversion after substantial growth of the space-charge wave. Illustrative possible magnitudes are given in Fig. 5. The growth rate depends on the voltage between the driver and sole electrodes, and on its variation along the structure, such as can exist in a segmented electrode system.

For net energy to be delivered to the stream from the d-c system, there must be a d-c current flow. Thus for an electron-constituted monopolar plasma there must be flow of electrons to a collector electrode at a potential substantially higher than that of the cathode. For the ion-constituted plasma there must be arrival of positive ions at and delivery of their charges to (by taking electrons from it) an electrode at a potential substantially negative relative to the ion source. This collecting electrode is in either case considerably downstream longitudially from the ion or electron source, so that these charged particles must before collection pass through the longitudinally extensive region where oscillations and associated kinetic energies are generated.

In the nuclear-fusion-producing application the ion-constituted monopolar plasma stream acquires at some point in its longitudinal travel enough collision-producing energy to cause significant numbers of energy-releasing nuclear fusion collisions. When the rate of fusion-released energy equals or exceeds the various energy losses from the plasma, as discussed later, the plasma stream has become a self-sustaining source of heat energy, and needs no further electrical energy input from the d-c electrical system. At this point the plasma stream should be in position to be passed, by means of its slow E/b drift velocity, into a reaction chamber wherein the sole function of the d-c magnetic and electric crossed fields is to provide the confinement necessary for the reaction to continue.

D. Presence of thermally random particle motions characterizable by a temperature. In any plasma of the general family of types here being discussed, including both the Langmuir-type plasmas and the monopolar plasmas of present interest, the charge-transporting carriers have substantial-energy randomly-oriented and thermalized motions describable by stating a temperature, these thermal motions being in addition to the ordered space-charge-wave motions and the directed or drift motion. The average energy of the thermal motions may be of the same order of magnitude, or of greater or less magnitude, than that of the space-charge-wave ordered motion. The thermally random motions, like the ordered space-charge-wave motions, come into being after departure of the stream from the immediate neighborhood of the electron or ion source. The temperature they represent can be modified by detail changes in electrode shapes and voltages, at locations far from the electron or ion source, and by changes in magnetic flux density. Typically, in the monopolar plasmas of present interest, the growing space-charge waves can bring the average kinetic energies of ordered motions to much higher values than the average kinetic energies corresponding to the random-motion temperature (which can itself be quite high).

E. Drift or directed velocity in stream-flow direction is very small relative to the thermal and/or space-charge-wave motions. It is a characteristic property, of any conducting region properly called a plasma (including the monopolar types), that the drift or directed velocity in the stream-flow direction, that provides the transport of charge and so the current, is very much smaller than any velocity used (as for example an rms value) to characterize the magnitude of the thermal motions. The drift velocity is also, in many if not most cases, and in all of the monopolar plasmas of present interest, much smaller than a velocity similarly characterizing the space-charge-wave motions. For cases in which the directed motion dominates, the stream is better described as a beam of charged particles rather than being called a plasma. In the present invention the drift or directed velocity E/B is very small relative to both the rotational velocities of the ordered motion and to the random thermal velocities.

F. The attribute of being confined or confinable. A plasma of any kind typically exists between regions of such nature that charge carriers of the current-carrying type that wander out of the plasma channel (as for example because of their thermal motions), experience electric or magnetic forces that return them into the channel. In the typical Langmuir plasma the return is caused by the d-c electric field in an "ion sheath" that bounds the plasma; in the crossed-field-neutralized monopolar plasmas of present interest the return is compelled by the force actions of the d-c electric and magnetic fields in the regions just outside the plasma. In plasmas of present interest this "confinability" persists adequately even when, by interaction between the d-c field, the space-charge wave fields, and the charged particles, the particles achieve substantial rotational and/or random motions.

When this occurs the plasma channel becomes wider and its edges less sharply defined; however, its position remains transversely stable, even though shifted somewhat in accordance with its having accepted potential energy from the d-c electric field for conversion into kinetic energy of rotational and random motions.

This completes the comparison between monopolar and bipolar plasmas.

15. Physical Principles of Use of the Charged-Particle Stream for Converting Potential into Kinetic Energy of a Monopolar Plasma Stream. It is best to discuss the physical principles of production and use of the monopolar plasma having high kinetic energies, in terms of the somewhat idealized model of proposed apparatus diagrammed in Fig. 6, which employs the plasma behavior properties detailed in Figs. 1 through 5, as applied using an ion-constituted stream. Figure 7 illustrates similarly a model of apparatus for producing an electron-constituted monopolar plasma stream, such as can be useful in electronic circuit applications.

The Fig. 6 apparatus model consists of a source of positive ions, presumably being stripped nuclei of deuterium (heavy hydrogen) or tritium (heavier hydrogen) and two planar electrodes, called sole and driver, between which an electric field is established by an external d-c power supply. At right angles to the electric field E is a magnetic flux B produced by coils outside the vacuum envelope. The direction of the flux B is such as to accelerate toward the sole ions having a velocity in the E/B stream-flow direction at right angles to both E and B. The region between the electrodes, containing the crossed fields, is referred to as the interaction space. At the right the plasma stream is shown as moving into another region where its charge is collected and the resources of the stream usefully employed, as for example to produce controlled nuclear fusion. Such an apparatus using more common gaseous ions than those of deuterium or tritium might be useful for producing or enhancing certain gaseous chemical reactions, or for space vehicle propulsion.

Figure 7 portrays an apparatus model for producing and using an electron-constituted monopolar crossed-field-neutralized plasma. Changes from Fig. 6 comprise the use of electrons rather than positive ions for the stream, reversal of the polarities of both the d-c magnetic and d-c electric fields, and the employment of an output structure with crossed-field attributes that provides means for electronic circuit applications and for collection of electrons of the stream. Uses can be: as a generator of modulated radio-frequency power with implied amplifier capabilities; for the storing-up of energy in the propagating stream with relatively slow propagation to an output-point delivery; as a signal delay line because of the relatively slow nature of the E/B velocity; and other electronic-circuit uses. These resources exist because the space-charge-wave motion is of an ordered nature, so that the energy it carried is in principle recoverable into an electrical circuit. Thus the output structure contains means for crossed-field wave propagation within the plasma stream, for energy storage and delay processing, and means for coupling the energy from the space-charge wave into an electrical circuit.

As a comparison and contrast with existing electron devices, if in Fig. 7 the V/B ratio were very greatly increased so as to make the E/B velocity comparable with the phase velocity of a typical slow-wave distributed microwave circuit, the driver electrode then replaced by such a circuit, launching details arranged to bring the stream initially directly away from rather than parallel to the cathode block, and microwave signal input and output arrangements made, the apparatus would become essentially a crossed-field microwave amplifier (i.e., a linear microwave magnetron amplifier). As to historical fact, the conception of the present invention's process for giving energy to and confining a plasma for controlled nuclear fusion is an outgrowth of cross-fertilization between researches respectively in microwave physical electronics and in plasma physics and engineering.

Turning again to Fig. 6, employing ions, if used without a magnetic field the device would behave like a diode. A beam of positive ions would then flow directly to the strongly negative roof electrode, the ions gaining speed and kinetic energy as they go. With an increase of the magnetic field upward from zero, the beam would curve over to the right due to the magnetic forces on moving charges. For any given voltage between source (or sole) and roof (or driver), there is a critical value of the magnetic flux density, called the "magnetic cut-off" value, at which the beam can no longer reach the more negative electrode, whether roof or driver. With a further increase of the magnetic flux density to well beyond this cut-off value, there is eventually reached a flux density at which the essentially laminar Brillouin-stream along-equipotentials current is equal to the ion emission current available at the ion source. As the magnetic field strength is still further increased, the current in the stream falls off, being governed now by the combination of values of roof voltage, magnetic flux density, and electrode spacing, rather than by the available ion emission.

Under these conditions, as has been discussed briefly in connection with Figs. 1 through 4, the stream of ions drifts quite slowly to the right through the interaction space, at right angles to both the d-c magnetic and d-c electric fields. The average motion of the ion stream (its motion is so slow that it should not be called a "beam") follows closely the pattern of equipotentials of the d-c electric field adjacent to the ion source, as illustrated in Figs. 1a and 6. As indicated in Figs. 1b and 3, the ion stream can be positioned more or less as desired between the sole and the driver electrode by raising the sole potential above the ion source potential. At initial departure from the ion source the motion, essentially in the to-the-right stream-flow direction, is of a slipping-stream laminar nature, being a close approximation to Brillouin flow. As suggested by Fig. 2, the particles just off the ion source have essentially zero velocity, and those at the outer edge of the stream have a significant but slow velocity. In all cases this velocity is in the stream-flow direction, at right angles to both the electric field E and the magnetic flux density B, and has at each plane in the stream the value E/B obtained by using the value of E at that plane.

It has been shown experimentally that for an <u>electron</u> stream originating in the corresponding way, as in the Fig. 7 apparatus, there will appear in the stream space-charge-wave oscillations of the growing-wave nature, with individual electron trajectories generally as illustrated in Fig. 5. The scaling relations, that permit predicting ion motions from a knowledge of electron motions, are well understood. Experiments have been conducted on the ion counterpart of the smoothbore diode magnetron operating at magnetic fields above the cut-off value, in which the functioning of the apparatus was governed by these scaling relations, which indicate that with the magnetic field increased by the square root of the ratio of the ion mass to the electron mass, the ion stream in an apparatus like Fig. 6 will, with proper details of design and operating conditions, similarly exhibit in a very short distance propagational and growing space-charge-wave oscillations.

This growing-wave behavior results from interactions between the charged particles of the stream, the d-c electric field, and the high-frequency space-charge-wave field itself, with influences from the d-c magnetic field. As a result of these interactions the stream traverses gradually toward the driver, while exhibiting a forward space-charge-wave phase velocity approximately synchronized with the E/B stream drift velocity toward the right. The energy accepted by the charged particles from the d-c source due to their traverse toward the driver is converted chiefly into stored energy carried by the advancing space-charge wave, being continually exchanged between storage in the Fig. 5 type of overlapping troichoidal looping motion and storage in the high-frequency electric field of the wave, much as in electromagnetic wave propagation there is a continual exchange between storage in the r-f magnetic field and in the r-f electric field. A moderate fraction of the energy converts into random thermal motion of the particles, superposed on the high-energy ordered space-charge-wave looping motions. In effect, the total behavior stores, in each wavelength of the stream, the energy accepted from the d-c system up to that point by motion of the stream transversely toward the driver electrode, the storage continually alternating between particle kinetic energy and high-frequency electric field storage, in the space-charge wave. The longitudinal motion, measurable in terms of the E/B drift and the nearly synchronous space-charge-wave phase velocity, carries this stored energy down the length of the apparatus, with a continuing increase of the energy stored per wavelength corresponding to the growth of the wave and to its transverse movement through the d-c electric field. Figure 4 illustrates graphically the relationship between the position of the plasma stream and its energy acceptance from the d-c field. Thus there comes into being the type of monopolar plasma and particle motion therein that is detailed in the preceding Section 14, contained within a stream that from the d-c standpoint still exhibits the essential characteristics of or closely derived from Brillouin flow.

For reasons of simplicity and economy in experimentation, the experimental demonstration of this behavior has been carried out for an electron-constituted monopolar crossed-field neutralized plasma. However, the scaling laws for designing apparatus to provide similar motions for ions are quite well understood, and reasonably simple. These scaling laws have been verified by experiments with apparatus which, while very different in purpose and conception from the present invention, nevertheless provided verification as to the scaling relationships.

Thus, for the Fig. 6 ion-constituted monopolar plasma stream, with an adequately optimized treatment of details of adjustment of potentials along the negative or driver electrode, and of longitudinal potential gradients in the interaction space as can be produced by steps in the electrode voltages and by variations in the geometric configuration (particularly in electrode spacing) the average kinetic energy of the ions is increased as they drift relatively slowly along the apparatus, with potentials adequate for confinement retained on sole and driver. This continues to the point where the combination of kinetic energy and charged-particle content (content does not change materially with the plasma stream's movement along the structure) becomes sufficient to initiate fusion reaction at a self-sustaining rate. Here, as suggested by Fig. 6 and the Patent Disclosure, the stream can be caused to enter a different enclosure which can serve as a reaction chamber. Once adequate self-sustaining fusion reaction has been established, generation of high kinetic energies by the crossed-field interaction may no longer be necessary; it might be feasible to make a change in operating conditions so as to draw no further d-c power once the self-sustaining fusion reaction is established, yet maintain crossed-field confinement as an aid to maintaining the ion input, to replace ions that are lost to the system within the reaction chamber.

16. *Nuclear Fission and Nuclear Fusion as Energy Sources.* Of course the primarily important aspect of the proposed system is its use of nuclear fusion (rather than nuclear fission) as a basic source of energy. The scientific

community, and also the informed laymen, are by now familiar with the idea that energy is relased when a heavy atomic nucleus splits into two or more fragments. Somewhat less familar is the idea that energy is also released when very light nuclei fuse into heavier elements. A very brief discussion of this is believed warranted here.

Fission or splitting is the principle of the first-used atomic bombs. Fusion or joining is the principle of the hydrogen bomb. The fission reaction has been brought under control for the economic production of heat and power. The fusion reaction has not yet been controlled on a sustained basis. The major difficulty in achieving controlled fusion arises from the very great amount of energy input required per particle to initiate the reaction.

The fission of a heavy nucleus takes place when a neutron enters the nucleus. Since the neutron has no electrical charge, it experiences no force of repulsion as it approaches the positively charged nucleus. Therefore a reaction can be started and sustained using particles having the very moderate kinetic energies corresponding to room temperature.

However, the fusion of heavy hydrogen requires the approach of two deuterons (double-mass protons) to one another, to within a nuclear diameter, each of them bearing a positive charge equal in magnitude to that of an electron. The electric force of repulsion between these two like charges becomes very great before the deuterons finally approach closely enough for the still stronger short-range nuclear binding force to take over and pull the protons firmly together with a net yield of energy. This happens more easily with deuterium or tritium than with hydrogen, hence the use of deuterons or tritons rather than of protons.

The protons, or deuterons, or tritons, must be flung together violently enough to overcome their mutual electrostatic repulsion. If it were actually necessary for every particle to have energy in excess of the potential energy barrier due to repulsion, it would be almost impossible to achieve fusion. However, when quantum mechanical principles are taken into account it is seen that a particle can in effect "tunnel" through the barrier without having to surmount it. The probability of tunneling is vanishingly small at low energies but becomes significant as the barrier energy is approached. The probability of a reaction is expressed as a collision "cross section," which is a function of energy.

Thus it is seen that very high particle kinetic energies are required for nuclear fusion. Gas particles in thermal equilibrium possess the Maxwellian statistical distribution of energies, with many energies well above average and many well below. There exists a considerably different distribution of energies for the high-average-energy ordered motions represented in the space-charge-wave rotational motions of a highly energetic cross-field-neutralized monopolar plasma. Corresponding to these motions there are distributions of relative velocities and of directions, and of closeness of approach of particles to one another, this latter involving the particle density; these distributions are of primary importance toward causation of nuclear fusion. Among the plasma's enormously many overlapping trochoidal-loop trajectories, as illustrated in Fig. 5, there can exist at achievable densities of fusionable particles a very significant probability that two such particles, each at a very high velocity, will approach extremely closely to one another from opposite directions, representing an extremely high relative energy of approach. Whatever the details of the distributions, if the average kinetic energy is sufficiently high and the motions sufficiently many-directional, extremely close approaches ("collisions") with relative energy of approach adequate for fusion, will it is believed represent a sufficient fraction of all the collisions to sustain a net yield of fusion power. This is possible because the energy release per fusion is very much greater than that required to bring a pair of particles close enough to cause fusion.

It is possible to demonstrate fusion, as for example by directing a beam of deuterons at a target of deuterium gas, but in this case there is a net loss rather than a net gain of energy. Even at the optimum energy for such a beam, giving maximum probability of fusion (maximum cross-section for the fusion reaction), the majority of interactions are inelastic scattering collisions rather than fusion collisions. At low energies these collisions are inelastic due to ionization of the target atoms. At higher energies the collisions are inelastic due to radiation resulting from the acceleration of charges. These inelastic collisions downgrade the energy of the majority of the incident particles to the point where they are no longer effective for fusion.

It appears, therefore, that the promising environment for fusion reactions is a plasma in which the level of kinetic energies due to the many-direction motions of the particles is high enough to give a probability of many potential fusion collisions before the average particle escapes to a region of less average energy. It is not important whether, initially, the high level of kinetic energies exists in the form of many-direction ordered motions of the space-charge wave, or in the form of completely thermalized motions describable by a temperature, or some combination of the two, as long as the total kinetic energy behavior is adequate. The only theoretical studies as yet available deal with the condition of completely thermalized motions. These studies indicate that, to the extent that the theory of gases can be applied to fully ionized plasmas, a body of particles whose high-energy motions lead to many collisions before encountering a boundary, will in general assume a thermalized velocity distribution properly describable by assigning a temperature, hence frequent use of the term "thermonuclear." For any temperature there is a definite and well-defined average particle kinetic energy. Thus one can speak of a 300,000,000-degree Kelvin temperature, meaning thereby a specific mean energy in a thermal-equilibrium distribution of kinetic energies (the Maxwell-Boltzmann or Maxwellian distribution). This particular 300,000,000-degree Kelvin temperature corresponds to an average-particle kinetic energy of not quite 39,000 electron volts, that is, the average particle lacks a little of having the kinetic energy required by an electron in "falling freely" through a potential difference of 39,000 volts, a quite reasonably attainable voltage in engineering terms. This is the temperature at which the deuterium-deuterium reaction has a maximum cross section. A mixture of deuterium and tritium requires only perhaps 1/3 of this energy. However, the lowest kinetic energy a which there can be a net yield of fusion power may be much lower than these figures suggest, because of considerations dealt with in the next section.

17. The "Break-Even" Energy, at which Fusion Rates and Energy Loss Rates are Balanced, will be Relatively Low in a Monopolar Plasma. There exists a "break-even" average kinetic energy, for any plasma intended to produce sustained nuclear fusion, at which fusion rates and loss rates are balanced. For in any such plasma there are mechanisms that cause loss of energy to the environment. At the "break-even" average energy (and correspondingly at a break-even temperature for a thermal distribution) there is a balance between the rate of production of energy by fusion collisions and the rate of energy loss by the various loss mechanisms.

Thus it is seen that one of the major engineering problems of obtaining fusion power is the achievement, at an adequately high particle density, of a level of kinetic energy high enough to make the fusion reaction power generation greater than the power losses, giving a net power yield.

It is convenient to discuss loss mechanisms under the presumption that the plasma is successfully confined to a reasonably well-defined region, usually by employing a magnetic field as discussed later. Under conditions of adequate confinement there are two principal energy loss mechanisms for the kinds of plasmas that have been so far employed in other laboratories in attempts to produce controlled nuclear fusion. The first of these is what is known as bremsstrahlung radiation which will now be described. The plasmas referred to—those used in other laboraties—all have electrons present in concentrations approximately equal to that of the ions, the presence of the electrons being the means of neutralizing the space-charge forces of the ions. These electrons, at the very high mean plasma energies used, move much more rapidly than the ions, and therefore electron-ion close approaches are much more common than ion-ion close approaches. At any "near miss" in an electron-ion close approach the electron will of course experience an extremely sharp deflection of its course, in some cases almost a complete reversal. This represents extreme acceleration of the electron, and according to classical electromagnetic theory electromagnetic radiation occurs whenever a charged particle undergoes acceleration. Therefore the many close electron-ion approaches result in very substantial electromagnetic radiation, which occurs in the ultraviolet or X-ray portions of the spectrum. This is called bremsstrahlung radiation. As the plasmas referred to operate at low gas densities, they are transparent to this radiation, which proceeds outward and is lost, being absorbed in the environment.

The second major loss is also due to the presence of electrons. It is the so-called "cyclotron" or "synchrotron" radiation. In the magnetic field used for producing confinement, the electrons at their high energies pursue circular or helical trajectories around paths of magnetic flux. In this motion the electrons are again subject to acceleration, and correspondingly generate electromagnetic radiation, which is typically in the microwave or infrared region, and perhaps somewhat more easily subject to reabsorption in the gas than is bremsstrahlung radiation. However, again, most of it is transmitted to the environment and so is lost from the plasma. The ions, being much heavier, execute very much larger circles and helices, with correspondingly less rapid acceleration and very small radiation losses.

It is apparent from the above discussion that a very great engineering gain can come from not having electrons in the reacting plasma. They do not participate in the fusion reaction, and they are responsible for the major losses that must be counteracted by achieving higher mean energies and therefore higher reaction rates. For this reason it seems essentially certain that the "break-even" value of mean plasma particle kinetic energy, at which energy release from the fusion reactions equals and begins to exceed the loss rate, will in a monopolar crossed-field-neutralized ion-constituted plasma be a very much lower value than in the electron-bearing plasmas used by all other laboratories in their approach to controlled nuclear fusion. This is the reason why our present "bogey" is to obtain in our electrons average energies corresponding to 10,000,000° or 15,000,000°K, rather than the sometimes mentioned 100,000,000°K bogey for the bipolar plasma break-even condition. The bipolar plasma is subject to both bremsstrahlung and cyclotron radiation losses, whereas our ion-constituted monopolar plasma has neither.

As to energy input, to our advantage, in any small regions in the high-energy plasma stream there exist ions having oppositely-directed looping motions almost wholly in the two plane-of-the-loops dimensions, giving very high relative energies of approach. Statistically these approach energies must be higher than for the usual three-dimensional thermal motions. Therefore the probability of fusion-producing collisions must be higher for the same average ion energy, than for thermal motions. Thus for given average deuteron energy, our ordered-motion fusion energy release rate should be higher, as well as our loss rate being lower, than in the conventional bipolar plasmas.

III. PLAN AND TEST UTILIZATION OF THE EXPERIMENTAL APPARATUS

18. Purpose of the Present "Scale Model" Experimental Program Employing an Electron-Constituted Monopolar Plasma Stream. It would have required very expensive equipment and a very considerable operational staff to test experimentally with an ion-constituted monopolar plasma the possibility of converting potential energy to a high level of kinetic energy in the plasma, whereas only moderately expensive equipment and a very small operational staff has been required to carry out experimental research on this possibility with an electron-constituted monopolar plasma. The two most important items of cost contrast are, first, the necessity of employing a much greater magnetic flux density to cause this conversion with protons or deuterons as compared with the flux density required with electrons, and second, the much greater cost and operational complexity of an ion source for the stream as compared with that of an electron source. This cost and complexity contrast, in combination with confidence in the validity of the similitude relations between the electron-constituted and the ion-constituted plasma stream behaviors, were the reasons for having confidence in the utility of carrying out the 1964-65 and 1965-66 experiments using an electron-constituted plasma.

The experimental program, using the electron-constituted plasma, that has been carried out under the present projects, has shown that the desired conversion from potential to particle kinetic energy does in fact take place, but in rather different and more advantageous ways than were anticipated. With the knowledge we have obtained using apparatus similar to the Fig. 7 model using electrons, we can proceed toward a design plan of apparatus patterned after the Fig. 6 model using positive ions (deuterons it will be), with very much better design criteria, a less expensive design, and much better understanding of what to expect during operations, than would have been possible without the "scale model" study using the electron-constituted plasma. Also, use of the electron-constituted plasma has given us directly information applying to the use of the conversion principles for electronic circuit purposes.

For example, the entire discussion of physical principles in Chapter II above has been developed out of a study of the scale model experimentation, and differs quite markedly from the kind of discussion I had expected to be preparing at this stage of the program.

Thus the experimentation on apparatus patterned after Fig. 7 has been very fruitful, and has accomplished its primary purpose.

19. __Comments on the Operational Pattern of the Experimental Program.__ It has been found characteristic of this program for experimenting with apparatus patterned after the Fig. 7 model, that many weeks or months are required to get the experimental equipment into operable condition, whether for an initial or any subsequent electrode configuration, but that when the apparatus is operable enormous amounts of experimental data can be accumulated in a relatively few days. It then again takes several weeks to put this data into graphical form and adequately interpret its meaning.

The Fig. 7 type of electrode structure was of course enclosed in a vacuum envelope; the vacuum envelope was mounted on the flat table-like top of a portable vacuum system, for convenience in insertion into and withdrawing from the air gap of the bulky and heavy electromagnet used to provide the magnetic field. The vacuum system acquired for the project served its purpose well, with of course the usual frustratingly necessary attention to eliminating leaks and reconditioning. This experimentation required only a moderately good vacuum, of the order of 1 to 10 microtorr (one "microtorr" is 10^{-6} millimeters of mercury pressure).

As with any demountable (i.e., not "sealed off") vacuum apparatus, leaks occasionally appeared in the system, especially in relation to the water-cooling pipes passing through the electrodes. Very substantial delay and expense has been incurred in the more recent phase of the program from the necessity for totally reconditioning the leak detector used, which was a piece of equipment available within the University. However, it was very much less expensive to recondition the leak detector than it would have been to purchase another one of comparable quality. This problem accounted for about a 3-month delay during the summer and fall of 1965.

Considering the complexity of the electrode structure, the necessity for circulating water through distinct sets of electrodes at radically different voltages, the multiplicity of leads into the vacuum envelope (to 36 sole segments, 6 driver segments, the cathode, roof, and collector), the need for permitting later introduction of microwave circuitry to measure the r-f frequency generated during operation, provision for introducing thermocouple leads, the high heat dissipation rates appearing, and various other items, the apparatus has functioned satisfactorily, and with a minimum of the kinds of trouble one expects to have with such a system.

Figure 8 is a chart of the calibration of the electromagnet assembly, a rather heavy and bulky piece of apparatus which was made available by the Plasma Engineering Laboratory of the Department of Electrical Engineering. The coils used are far from new, and during the course of the experimentation one of them developed a short circuit, requiring a complete rewinding of that coil. This was not expensive as to cost of materials, but resulted in significant delay of the work.

When operated at the higher currents that are required to produce across the 7-inch air gap the 3000-gauss and 4000-gauss fields needed for the higher-energy operation, the coils heat up fairly rapidly. To avoid continuing serious trouble from coil overheating, a thermocouple was buried in the coil that was rewound, making it possible to stop operation before the heating proceeds to a point hazardous to the coil insulation. Because data can be taken with great rapidity during an operational run, the necessity for permitting the coil to cool off between runs has not been a significant cause of delay.

The electrode structure and a few aspects of the external circuitry provisions will be dealt with in separate sections.

20. <u>The Electrode Structure</u>. Figure 9 illustrates schematically the electrode structure used in the experimentation with an electron-constituted monopolar plasma stream. This whole structure was placed in an evacuated container, the vacuum envelope being of Pyrex glass, thus permitting visual observation of the condition of the hot electron-emitting thermionic cathode. An external electromagnet (not shown in the figure) permitted establishing a d-c magnetic field at magnetic flux densities ranging as desired from 1000 gauss to 3600 gauss, directed away from the viewer of this figure.

The function of this electrode structure is to cause the origin, at a thermonically emitting cathode, of a ribbon-like electron stream, and then as in the Fig. 7 model to cause this stream to pass longitudinally down the structure. The stream flow direction is at right angles both to the magnetic flux of density B webers per square meter (directed away from the viewed) and to the transverse (i.e., perpendicular to the electrodes) electric field of E volts per meter that the d-c voltages applied to the electrodes cause to exist in the interaction region between the sole and driver electrodes. As discussed earlier in Section 15 of this report the longitudinal or "drift" velocity of the electron stream (which quickly becomes a monopolar plasma stream) occurs at the quite slow crossed-field velocity E/B meters per second.

It is necessary for this velocity to be slow, as for example corresponding in our apparatus to drift-velocity kinetic energies between perhaps one-tenth and one electron volt, in order for the observed large-scale conversion of potential to kinetic energy to occur in the apparatus. The many-directional generally rotational velocities that result from the conversion have kinetic energies of hundreds of electron volts, these being superposed on the slow drift velocity.

The various electrodes used serve purposes as follows:

A. Cathode. The cathode consists of a hot ribbon filament of tungsten, 0.0035 inch thick, 0.10 inch wide, and with an active length of 1.5 inches. It provides, when directly heated by passage of 60-cycle a-c current typically of 55 amperes at 13 volts, the electron emission required for the electron beam; this cathode has the capability of producing up to about 300 milliamperes of electron emission; the current actually drawn is controlled by the magnetic flux density and the "roof" electrode voltage, and is typically between 10 and 50 milliamperes.

B. Cathode block. The cathode block is slotted widthwise to receive the cathode filament, so that the surface of the filament is in fact approximately flush with the surface of the cathode block. Note from Fig. 1a that the ribbon-like electron stream in leaving the cathode passes over a portion of the block, moving essentially parallel to the block's surface, this being the nature of the "Brillouin flow" at the point of stream origin. The ribbon stream typically extends about 1-1/2 inches in the width direction, and is a few thousandths of an inch in thickness. The cathode block is cooled by circulating water thorugh it.

C. Roof Electrode. The roof electrode, or "roof," faces and is spaced 3/4 inch from the cathode block. By varying the voltage applied to this roof electrode the Brillouin-flow current can be varied from a very small value up to the "temperature-limited" electron emission capability of the cathode filament. At weak magnetic field strengths the electrons would move directly out toward the roof electrode, but in the presently reported research the magnetic flux density was maintained at a value high enough to cause the electron stream to move longitudinally parallel to the cathode block, as suggested by Fig. 1a.

D. Driver electrode assembly. The driver electrode assembly, sometimes called the anode assembly, comprises several segments, A, B, C, etc., that are flush with the roof electrode, and extend widthwise about 2-1/2 inches. The driver segment voltages can be varied individually. For the most effective interaction for producing very high electron kinetic energies, one or more of the driver segments are operated at voltages very substantially below that of the roof electrode. The effectiveness of such operation is related to its producing a relatively weak transverse electric field E in the interaction region, and so a slow E/B drift velocity. The driver electrode assembly is also water-cooled, because under some conditions of operation, one or another of the driver electrode segments collect a substantial current of electrons having rather high kinetic energies on arrival.

Experience with the apparatus during the February and March, 1965, experimentation period demonstrated the necessity for operating the several driver electrode segments at very substantially differing voltages, up to 2000 or more volts between segments. This requirement had not been foreseen in the original apparatus design. However, fortunately the insulation between these driver segments did prove in most cases to be able to withstand such voltages. In the rebuilding of the electrode structure now in process, stronger insulation is being provided between driver segments and from driver segments to the water-cooling pipes that pass through them, as a means of permitting operation at higher voltages and correspondingly greater particle kinetic energies.

E. Sole electrode assembly. The sole electrode assembly is made up of many sole segments electrically insulated from one another, each extending about 3 inches widthwise, and 1/4 inch in the longitudinal direction of stream flow. The sole electrode assembly must as a whole be held at a potential of from one hundred to several hundred volts below that of the cathode in order to prevent excessively many electrons from reaching it due to the high kinetic energies they gain from the crossed-field interaction. Also, the last five sole segments have during the tests to date been connected together and held at a potential well above that of the cathode, to collect the electrons at the end of their travel along the interaction region.

In order to measure the kinetic energies of the electrons, the current to one or another sole segment is measured while this segment's voltage is varied upward from that of the rest of the sole, this being carried on to the point where this probing sole segment's voltage is high enough so that it collects a major fraction of the cathode current. Typical behavior, for a probing segment located at a point along the structure where the kinetic energies are high, is observed to be that the segment current is very close to being half the cathode current when the segment is at cathode potential. This typical behavior will serve as a very useful "check point" on the theory, when an adequate theory has been developed. When collecting such a current magnitude as this the probing segment is accepting substantial heat input from the impact of the high-energy electrons; the sole is water-cooled to provide removal of this heat.

For reasons discussed elsewhere in this report, four different geometric configurations of sole segments have been or will have been used during different periods in the experimentation. These configurations are illustrated by Figs. 10a,b,c,d,e. Making the changes in segment configurations has been a very time-consuming and expensive part of the research. Each change was felt to be necessary, and very significant information as to the behavior of the electron stream has been obtained from each configuration. For example, it has been by studying the behavior for each configuration in turn that it has been possible to distinguish the generation of high electron temperature due to random motions from the generation of ordered-motion high kinetic energies.

In sole electrode Configurations Nos. 3 and 4 there were introduced depressed sole segments. Basic to the reason for doing this was the realization that in Dr. M. H. Miller's earlier similar experiments, and in ours, the electron stream just after leaving the cathode in fact followed the electric equipotentials down into the depression between the cathode block and Sole Segment No. 1 (in this depression the electric field is very weak) and that having descended into this depression and followed the equipotentials out again, it arrived at Sole Segment No. 1 having an electron temperature of from one hundred thousand to several hundred thousand degrees Kelvin. It was important to the understanding of the total behavior to determine whether the electron temperature could be still further increased by having the electron stream follow equipotentials down into and back out from depressions at farther points along the sole. As discussed elsewhere, it was found that the temperature could in fact be increased (it approximately doubled) by such treatment, but this behavior ultimately proved to be of very limited value toward the project's primary objective.

The provision for depressed sole segments was incorporated into the original design by shaping the segments so that by merely inverting any one of them, a depressed area appeared. However, this exposed the layer of insulating material along the vertical surfaces of the two adjacent segments. Because these surfaces would accept and retain electrons, thus establishing a charged surface materially altering the potential, it was necessary to remove, carefully and by hand, this insulating layer on the exposed surface. This was a laborious and time-consuming operation, but a successful one.

In the sole electrode Configuration No. 5, now being made ready for experimentation, thermocouples will be incorporated in certain of the sole segments, to permit measuring to at least a fair approximation the heat delivered by the electrons on their collection at a sole segment. This will give important evidence relative to our concepts as to what is happening to the electrons of the stream.

Along with the necessity, mentioned in relation to the driver electrode assembly, of operating at higher driver electrode voltages in forthcoming experiments, goes also a necessity for maintaining between cathode and the sole electrode as a whole a higher voltage than heretofore. To permit this the insulation between cathode and sole is being strengthened in the reassembly now in process. The necessity for doing this is in fact borne of success in the program, for it is because of the high particle kinetic energies we find it possible to achieve that it is necessary to operate with a more strongly negative sole voltage.

F. <u>Proximity control electrode assembly</u>. For the experiments referred to above for determining the effectiveness of depressed electrodes in raising the electron temperature, it was found, partly by calculation and partly by experiment, that in order to make the electrons actually move into a geometrically depressed region, it is necessary to keep the electron stream in close proximity to the sole electrode structure. With the sole assembly as a whole at 150 or 250 volts below the cathode potential, this proximity is not maintained. On the other hand, if the whole sole assembly is operated up to within 50 volts or less of cathode potential, adequate proximity is maintained, but then at any substantial electron temperature the various sole segments collect so many electrons that the stream current is excessively rapidly attenuated as it progresses along the structure. To combat this situation, a "proximity control bus," operated at perhaps 50 to 100 volts below cathode potential, has been provided in the external circuitry. A depressed segment together with the two adjacent segments can be connected to this proximity control bus, thus holding the stream close to the electrode structure in the region at and near the depression, thereby compelling it to follow equipotentials down into and up out of the depression. With this arrangement only the segments connected to the proximity control bus draw significant current from the electron stream. This arrangement served its intended purpose, and permitted a study of the effect of depressions in raising the electron temperature.

The "proximity control electrode assembly" consists of the segment groups connected to the external proximity control bus, whenever such a bus is used.

G. Collector electrode. For reasons having to do with magnitudes in the electron behavior, the collector electrode has up to the present time been used to collect only a portion of the electrons; it has been advantageous up to now to employ as the primary collecting electrode the last 5 segments of the sole, by connecting them together and operating them at a few hundred volts above the cathode potential. The collector electrode is water-cooled, and this will be important in the forthcoming final phase of the current experimental program, in which the collector electrode will be the terminal point of the electron stream.

IV. SEQUENTIAL STAGES IN THE EXPERIMENTAL PROGRAM

21. General Relationship of Stages of Experimentation to Sole Segments Configuration and Driver Segment Voltages. The various several stages in the experimental program with the electron-constituted monopolar plasma stream can be distinguished from one another partly in terms of the sequential use of the several (Figures 10a,b,c,d,e) sole segment Configurations, partly in terms of the use of different voltages for different driver electrode segments. The various stages will be discussed individually, and in a following chapter experimental data for the latest stage will be presented, as being the data of greatest significance relative to the primary objective of the project.

22. Stage 1, Confirmation of Parallelism with the Behavior Observed Earlier by Dr. M. H. Miller. The whole concept of this program grew out of experimental behavior observed several years earlier by Dr. M. H. Miller in the course of his Ph.D. thesis research. It was therefore important first of all to demonstrate whether the apparatus built for use on this present program did behave, as to its major aspects, in the ways that Dr. Miller had observed in his apparatus, except for changes due to our apparatus being larger in every dimension and operable at higher values of magnetic flux density, electron stream current, voltage, and power level. This parallelism was in fact demonstrated during Stage 1 of the experimental work, carried on during June and the early part of July, 1964, using sole segment Configuration No. 1, illustrated in Fig. 10a, in which there were no depressed sole segments. Electron temperatures observed were much higher than those observed in Dr. Miller's experiments, and it became evident that the higher electron temperatures were associated with higher magnetic flux densities.

23. Stage 2, Proof of Electron Temperature Enhancement Due to Passage Down into and up out of a Short Depression in the Level of the Sole. During these early weeks of the experimental effort, attention was being directed primarily toward finding means of increasing the temperature of the electrons in the stream, because at that time the concept was that of proposing a truly thermal approach to nuclear fusion, by discovering a crossed-field monopolar plasma means of raising deuterons and/or tritons to extreme temperatures. Passage of the electrons through the depression just beyond the cathode block had been observed in Dr. Miller's apparatus and in Stage 1 of our program to produce electron temperatures ranging from one hundred thousand to several hundred thousand degrees Kelvin. However, much higher temperatures than these would be necessary to serve the purpose of initiating self-sustained nuclear fusion. A reasonably obvious initial approach was that of sending the stream down into and out a similar depression farther along the structure, created by inverting an individual sole segment at some distance along the sole.

Therefore, at the beginning of Stage 2 of the experimentation, for a time extending from late July into early August, 1964, experiments using sole segment Configuration No. 2, illustrated in Fig. 10b, were carried out to investigate this possibility. In this Configuration No. 2 the depressed Sole Segments were Nos. 3, 7, 12 and 13, 17, 19, 21. The plan was to use segments Nos. 3 and 7 to determine any temperature change resulting from sending the stream down into and back out from a depression one segment in extent, and Nos. 12, 13 to make a similar determination for a depression two segments in extent.

The results of these experiments were not conclusive, and an examination of the data in the light of the details of the configuration showed there to be two needs for change, one in external circuit provisions for the test procedure, and one in the electrodes.

As to the first of these, the Stage 1 tests had shown that because of the high electron kinetic energies obtained, it was necessary to operate the sole electrode as a whole at least 150 volts below the cathode potential to prevent excessive drain of electrons to all the sole segments. Careful analysis of behavior in the light of the physics of the situation led to the realization that with the sole at this low potential, the electron stream must of necessity take a position so far from the plane of the sole segments that the equipotential it must follow would not really dip very far into the depressed segment region. It was clear that this difficulty could be overcome by arranging to connect any depressed segments, together with those just before and after it, to a "proximity control bus," operated only some 20 to 50 volts below cathode potential. This would locally move the equipotential followed by the stream close to the sole, and compel it to descend deeply into the depressed region. These few segments, because they would be only a few, would not bleed electrons excessively from the stream; furthermore, the electron drain to the depressed segment would be reduced by the fact of its being depressed. In accordance with these concepts, a proximity control bus and means of connecting segments thereto were provided, comprising new circuitry arrangements.

With this new arrangement, an assembly of five segments became the test array for evaluation of the effect of the single depression, and an array of six segments an array for evaluation of a two-segment-extent depression, for example:

For Sole Segment No. 7 as the depressed segment, Nos. 6 and 8 served as "guard" or proximity control segments, being connected along with No. 7 to the proximity control bus; No. 5 was used as a probing segment to measure the electron temperature in the stream before it reached the depression; and No. 9 was used as a probing segment to measure the electron temperature in the stream after its emergence from the depression. Thus the five Sole Segments Nos. 5, 6, 7, 8, and 9 comprised the measurement array.

For Sole Segments Nos. 12 and 13 as depressed segments: Nos. 11 and 14 served as guard or proximity control segments, so that Nos. 11, 12, 13, and 14 were all connected to the proximity bus; No. 10 was the probing segment to measure the electron temperature in the approaching stream, with No. 15 measuring it in the departing stream. Thus the six Sole Segments Nos. 10, 11, 12, 13, 14, and 15 comprised the measurement array for a two-segment depression. There were other similar farther-along test arrays.

As to the second need for change, one should recall that each sole segment is insulated from its two neighbors, this being accomplished by a thin layer of glass, glazed onto the segment's two side surfaces prior to assembly. This means that, as an example, when early in Stage 2, Sole Segment No. 3 being depressed (accomplished by merely inverting it) this exposed the layers of glass insulation on the vertical faces of adjacent faces of Sole Segments Nos. 2 and 4. Similarly making No. 7 a depressed segment exposed the glazing on the vertical faces of adjacent Nos. 6 and 8. There was evidence in the data taken in late July and early August, 1964, suggesting that at the initiation of a test run electrons accumulated on these glazed surfaces, establishing there a negative charge layer, and that this to a very considerable degree prevented the nearby equipotentials (the ones the stream followed) from dipping down into the depression.

Glazing was also present on the side face of Sole Segment No. 1 that was exposed to the depression between the cathode block and the No. 1 Sole Segment. It seems probable that this glazing had some effect on details of the volt-ampere characteristics of Sole Segment No. 1 when used as a probing segment. However, by this time it was becoming apparent that the combination of the cathode block, the roof electrode, and Sole Segments Nos. 1 and 2 should be thought of as a stream launching and measurement subsystem. This made the use of Sole Segment No. 1 as a probing segment not straightforwardly informative, because in the process of varying its voltage as a probe one certainly modified very markedly the launching process. Thus Sole Segment No. 2 became in reality the useful probing segment for measuring launching behavior. The glazing on the side face of Sole Segment No. 1 certainly had some influence on the stream launching. As the launching had been distinctly successful in many test runs, both for Stage 1 and for the late July and early August runs of Stage 2, it was evident that the glazing on Sole Segment No. 1 was not significantly harmful to the launching of the stream.

However, the glazing on the side faces adjacent to depressed segments 7, 12, and 13, and others beyond them, would clearly represent a serious prejudice to validity of measurements made on the test array planned as Sole Segment Nos. 5, 6, 7, 8, and 9, and on the test array planned as No. 10, 11, 12, 13, 14, and 15, and farther-along test arrays. The obvious corrective effort was to remove the glazing from these exposed side surfaces, and this change was incorporated into the design plan for a revised configuration.

However, it seemed best to leave the glazing on the exposed face of Sole Segment No. 1. The decision to do so was in accord with an important general principle in experimental research, that only one kind of change should be made at a time, in order to be sure that any changes in measured results are due to that one kind of change. It also seemed desirable to leave Sole Segment No. 3 depressed, with the adjacent side surfaces still glazed, as a means of minimizing changes adjacent to Sole Segment No. 2 which was used as a probing segment to measure the stream launching effectiveness and characteristics.

During the middle and latter part of August, 1964, the above-outlined changes in circuitry were made, and the configuration changed. The new sole segment arrangement, identified as sole segment Configuration No. 3, illustrated in Fig. 10c, was specifically as follows:

A. Glazing was retained on the exposed face of sole segment No. 1, to make sure that all details of stream launching remained unchanged from previous test runs.

B. Sole Segment No. 3 was retained in its depressed state, and the glazing retained on adjacent exposed faces of Sole Segments Nos. 2 and 4, as a means of insuring no change in the measurement of the launching to be accomplished by using Sole Segment No. 2 as a probing segment.

C. Sole Segment No. 7 was retained in its depressed-by-inversion condition, and the glazing removed from the adjacent exposed vertical surfaces of Sole Segments Nos. 6 and 8, the examination of the effect of No. 7 as a depressed segment to be accomplished by using Sole Segments Nos. 5, 6, 7, 8, 9, as a measurement array with Sole Segments Nos. 6, 7, 8 connected to the proximity control bus, and Sole Segments Nos. 5 and 9 used as probing segments.

D. Sole Segment No. 10 was depressed (by inverting it) and the glazing removed from the adjacent exposed surfaces of Sole Segments Nos. 9 and 11, examination of the effect of Sole Segment No. 10 as a depressed segment to be made by using Sole Segments Nos. 8, 9, 10, 11, 12, as a measurement array with Sole Segments Nos. 9, 10, 11, connected to the proximity control bus, and Sole Segments Nos. 8 and 12 used as probing segments. This measurement would not be made during the same run as that in which Sole Segments Nos. 5, 6, 7, 8, 9, were used as a measurement array.

E. Sole Segments Nos. 13 and 14 were depressed (by inverting them) and the glazing removed from the adjacent exposed surfaces of Sole Segments Nos. 12 and 15, examination of the effect of a two-segment depression to be made by using Sole Segments 11, 12, 13, 14, 15, 16, as a measurement array with Sole Segments Nos. 12, 13, 14, 15, connected to the proximity bus, and Sole Segments Nos. 11 and 16 used as probing segments.

F. Sole Segment No. 18 was depressed (by inverting it) and the glazing removed from the adjacent exposed vertical surfaces of Sole Segments Nos. 17 and 19, examination to be made by using Sole Segments Nos. 16, 17, 18, 19, 20, as a measurement array.

G. Sole Segment No. 22 was depressed (by inverting it) and the glazing removed from the adjacent exposed vertical surfaces of Sole Segments Nos. 21 and 23, examinations to be jointly with depressed Sole Segments Nos. 24 and 25, the array to include Sole Segments Nos. 20 through 27.

H. Sole Segments Nos. 24 and 25 were depressed (by inverting them) and the glazing removed from the adjacent exposed surfaces of Sole Segments 23 and 26; the purpose of this was to permit study of the effect of a two-segment depression immediately following a one-segment depression.

During September, 1964, various series of experiments were carried out using this sole segment Configuration No. 3 and the proximity control bus resource.

These experiments showed definitely that a substantial electron temperature increase (by a factor between 1.5 and 2) did in fact result from passage into and out of a single-segment depression, if the proximity control bus was used to compel the stream actually to move down into the depression and out of it, and with unglazed vertical surfaces on the sides of the depression.

They also showed that similar enhancement of the electron temperature did not result from passage into and out of a depression of two-segment extent. This was in reasonable accord with the concept I have had as to the mechanisms, in that I have always felt that this temperature increase is caused by a slowing-down of the E/B drift velocity due to lowering of the electric field E. The electric field at the bottom of a one-segment depression is much weaker than at the bottom of a two-segment depression.

24. Stage 3, Efforts toward Cascading Temperature Amplifications. The results from Stage 2 were encouraging, but the temperatures reached still fell far short of any conceivable minimum value for causing fusion among deuterons or tritons. It seemed at this point that a reasonable next step would be to have temperature enhancement occur successively in several depressions, thus causing a cascading of the temperature increase. Toward this end the electrode structure was modified into sole segment Configuration No. 4, illustrated in Fig. 10d in which Sole Segments Nos. 4, 8, 12, 16, 20, 24, and 28 were depressed, giving a sequence of single-segment depressions. The proximity control bus resource was also available, as for example by operating Sole Segments Nos. 7, 8, and 9 connected to the proximity bus, held at a potential only moderately below that of the cathode, to assuredly cause the stream to move into the depressions where a weak electric field exists.

The effort at cascading was not successful; this became clear in the Stage 3 experiments, carried out in November, 1964. Examination of the data suggests as a primary reason for its failure that beyond a certain point the selective loss of high-energy electrons to the segments connected to the proximity bus led to a decline of temperature to about the same extent that enhancement of temperature occurred in the successive depressions.

The Stage 3 experiments were terminated, before really exhaustive test results were obtained, by failure of the insulation of one of the magnet coils. As mentioned earlier in this report, this necessitated rewinding of the coil. This was accomplished during my 5-week post-retirement vacation trip during the Christmas holidays of 1964 and through January, 1965.

On my return I made a careful study of the results obtained in Stage 3. It became evident to me, on both theoretical and experimental grounds, that the necessity for proximity to the segments at a depression in order to cause temperature enhancement, is in direct conflict with the requirement for confinement of a high-temperature stream. Thus the Stage 3 experimental result was that use of cascading depressions was the wrong way to meet the requirements of the primary objective of the project.

25. *Stage 4, Production of a Slow Drift Velocity by Lowering the Voltages on Driver Segments*. An underlying need was by this time clear—to make the drift velocity of the stream slow down without having the stream come into proximity with an electrode. Study of the electric field configuration made it evident that this could be accomplished by lowering the voltage of Driver Segment A, just beyond the roof electrode, while keeping the roof voltage as before in order to maintain the same launching behavior from the cathode. Such experiments were carried out during February and March, 1965, using, unchanged, sole segment Configuration No. 4.

The results of these experiments were extremely striking, in fact spectacular, in that they resulted in a *very substantial enhancement of the average kinetic energy* of the electrons of the stream, but *without an increase in electron temperature* as measured by the behavior of the electrons in the tail of the curve of probability density distribution in energy.

As a result of a critical study of this new development, it became clear during April, 1965, that we had found a hitherto unthought-of way to meet the basic requirement of obtaining very high many-directional energies, this being by producing them in an ordered motion rather than in random motions. The Memorandum Progress Report of May 25, 1965, described this aspect of the matter in fair detail, and the November 29, 1965, Patent Disclosure papers, to a considerable extent re-presented with editorial changes in this report, carried the conceptual description much farther.

26. Stage 5, Apparatus Changes Nearing Readiness for Test, being an Optimization of Provisions for Producing and Measuring the High-Energy Many-Directional Over-Lapping-Loop Trochoidal Motions. Having made a complete change-over in concept from the requirement of a high particle temperature to that of the more-easily-confined high-kinetic-energy ordered motion, it is obviously essential to carry out experiments using an electrode structure and electrode voltages designed to make such motions reach as high an energy as possible with resources available, and with measurement means chosen both to determine as completely as possible just what are the properties of this new kind of ordered motion, and to demonstrate what we have learned to our (most certainly skeptical) scientific peers. Those are the objectives in the design and assembly modification of the electrode structure as being put together in the first half of 1966, with expectation of making observations on it within a very few weeks. This will employ sole Configuration No. 5, being in most respects a return essentially to sole Configuration No. 1, but with a wholly different treatment of driver and collector electrode voltages, much more flexible power supply resources for providing the differing roof, driver, and collector voltages, thermocouples to measure heating of the probing segments, and a microwave probe to measure the frequency of the r-f

wave within the apparatus.

The next chapter of this report will present and discuss in some detail samples of experimental data taken in the Stage 4 experimentation, as being of very much greater interest to the project's primary objective than any other data we have taken.

V. SAMPLE EXPERIMENTAL RESULTS, SHOWING CONVERSION INTO HIGH-ENERGY ORDERED MOTIONS

27. From Experimentation on February 17, 1965, Evidence for and Significance of Conversion into High-Energy Ordered Rather than Random Thermal Motions. Figures 11 and 12 present graphically an illustrative sample of the experimental data from which the significant conclusions up to the present time have been drawn, this sample being from observations made on February 17, 1965. In making these observations, sole segment Configuration No. 4 was used. Driver electrode Group A was operated at a voltage much below that of the other driver electrode groups and the roof electrode, for reasons discussed farther on in Section 28 of this report. The sole electrode was as a whole held at 250 volts below the potential of the cathode, with, however, the voltage applied to various selected probing sole segments being varied upward in sequential steps from this -250 volts during the observations. The significant measurements were those of currents to particular probing segments versus the voltages on them, in each case all segments other than the one used as a probe being at sole potential.

Figure 11 charts several such probing-segment volt-ampere relationships for the particular sole segment Configuration No. 4, electrode voltages as indicated in the figure. Observations of this type are charted in the figure for Sole Segments Nos. 1, 2, 5, 7, 10, and 13. For example Sole Segment No. 13 drew 6 milliamperes of electron current (about 1/4 of the 25 milliamperes of cathode current) when at 110 volts below the potential of the cathode.

Figure 12 charts the currents drawn to successive probing sole segments, with the probing segment voltages as the parameter, from the same kinds of observations as in Fig. 11, but sectioned differently. This presentation indicates clearly the nature of the effects of using a lowered voltage on a segment of the driver electrode.

In the absence of energy exchanges within the electron stream, no electrons can reach an electrode that is held at a potential lower than that of the cathode of origin of the electrons. The presence of very substantial currents to probing sole segments at far below cathode potential is adequate evidence that energy exchanges have occurred in the stream, giving electrons the kinetic energy necessary to penetrate through a substantial retarding potential. This retarding potential is the difference between the potential at the stream location and that of the probing segment; the retarding potential will in general be substantially greater than that between the cathode and the probing segment. This is because, as illustrated schematically in Fig. 4 for the ion-constituted stream, in order to exchange energy with the d-c electric field, the stream must move toward the driver electrode, which places it at a potential between that of the cathode and of the driver. Table I, stating the operating conditions for Figs. 11 and 12 is on page 110 of this report.

Note the following specific aspects of Fig. 11:

A. *The "temperature" of the tail of the electron energy distribution curves remains the same for all segments as it is at injection at Sole Segment No. 1.* Several kinetic energy distribution curves that, for various kinds of particle assemblies, can be predicted by theory and/or observed experimentally have the following property:

$$\left.\begin{array}{l}\text{In the higher-energy "tail" the dis-}\\ \text{tribution decreases toward zero ac-}\\ \text{cording to the expression}\end{array}\right] : \quad \exp\frac{-v_k}{V_T} \qquad (1)$$

In this expression, and in later ones:

v_k = particle kinetic energy in electron volts;

V_T = the kinetic temperature in electron volts, defined by the following relationship:

$$V_T\, q_e = k_B T = \frac{1}{2} m_e U_T^2 \; ; \tag{2}$$

T = temperature in degrees Kelvin;

k_B = Boltzmann's gas constant, being 1.38×10^{-23} joule per particle per degree Kelvin;

q_e = the absolute value of the charge carried by an electron, being 1.6×10^{-19} coulomb;

m = the mass per particle of the particles of which the stream is constituted;

m_e = the mass of an electron, being 9.11×10^{-31} kilogram, thus

m/m_e = the "mass ratio," of the mass of a particle of the stream to that of an electron; for the present experiments $m/m_e = 1$; for a stream of deuterons $m/m_e \cong 3600$;

U_T = the particle velocity, in meters per second, characteristic of the temperature T, being <u>defined</u> by Eq. (2).

From these relations and numerical values it is found that

$$T = 11{,}600\, V_T \; ; \tag{3}$$

$$U_T = \frac{5.93 \times 10^5 \sqrt{V_T}}{\sqrt{m/m_e}} \tag{4}$$

If the high-energy tail of the energy distribution curve for an electron or ion stream has the Eq. (1) attribute, the current that reaches a probing electrode in spite of a retarding potential will exhibit the following behavior at the lower currents, that have become smaller because of the lowered probe potential:

$$\frac{i_a}{i_b} = \frac{\exp \dfrac{v_a}{V_T}}{\exp \dfrac{v_b}{V_T}} = \exp \frac{v_a - v_b}{V_T} \tag{5}$$

In this expression, as illustrated in the triangle extending from 0.01 to 0.1 milliampere and from -140 to -89 volts in Fig. 11,

i_a, v_a = the Sole Segment current i_{ss} and voltage v_{ss} at some selected point along the volt-ampere curve of some particular segment used as a probe.

i_b, v_b = those at a lower-current point along the same curve.

Taking natural logarithms of Eq. (5) gives

$$\ln \frac{i_a}{i_b} = \frac{v_a - v_b}{V_T} , \qquad (6a)$$

which is also expressible as

$$\frac{v_a - v_b}{\ln(i_a/i_b)} = V_T . \qquad (6b)$$

For the illustrative triangle in Fig. 11 this becomes

$$V_T = \frac{-89 -(-140)}{\ln(0.10/0.01)} = \frac{51}{\ln 10} = \frac{51}{2.3} = 22.2 \text{ electron volts} \qquad (7)$$

This 22.2 electron-volt kinetic temperature corresponds, from Eq. (3), to 237,000° Kelvin. Note the indication here that a gentle slope corresponds to a high temperature.

Important in Fig. 11 is the fact that the volt-ampere curves for the segments all exhibit approximately the same "temperature" property in the high-energy tail of the distribution curves, in spite of the fact that the average kinetic energies are very much greater at Sole Segments Nos. 10 and 13 than at Sole Segment No. 1. The temperature indicated by the slope of the low-current part of the volt-ampere curves for Sole Segments Nos. 1 or 2 (they usually exhibit the same slope) will in this treatment be called the "injection" temperature. There appears to be a slight decline in the tail-temperature attribute (below the injection value) along the sole, as the lines for Sole Segments Nos. 10 and 13 have a very slightly steeper slope than do those for Sole Segments Nos. 1 and 2. Dr. Miller observed a similar behavior in his earlier experiments; presumably it is due to some of the higher-energy electrons escaping into the sole, which represents of course a "cooling" process.

B. *A major fraction of the stream electrons exhibit nonthermal energy distributions for which the average energies are comparable with the averages for very-high-temperature thermal distributions.* It is possible, from any one of the curves in Fig. 11, to determine quantitatively the probability density distribution in kinetic energy for the electrons. In the Preliminary Memorandum Report of May 25, 1965, this was done for one of the March 19, 1965, high-energy operations, and is done for part of the Fig. 11 data later in this report. However, it is possible at this point by a less rigorous process to make an approximate study of energy magnitudes in Fig. 11, and to draw therefrom interesting conclusions as to certain gross aspects of the behavior. This will now be done.

In Fig. 11, from the point at 10 milliamperes and -30 volts on the Sole Segment No. 13 curve, there has been drawn a straight-line tangent that represents a continuation of an approximately straight-line high-current portion of this curve. On this tangent a triangle has been constructed between the two points: 10 milliamperes, -30 volts; 4 milliamperes, -177 volts. If the volt-ampere curve had in fact followed this tangent down to very small currents, such behavior would have been evidence of a nearly thermal distribution over a wide range of energy values, such that, for the electrons,

$$\left[\begin{array}{c}\text{Kinetic}\\ \text{temperature}\end{array}\right] = V_T = \frac{-30 -(-177)}{\ln(10/4)} = 160 \text{ electron volts;} \tag{8a}$$

$$\left[\begin{array}{c}\text{Degree-Kelvin}\\ \text{temperature}\end{array}\right] = T = 160 \times 11{,}600 = 1{,}860{,}000^\circ\text{K} . \tag{8b}$$

For a truly thermal (Maxwell-Boltzmann) distribution, the average electron energy is $(3/2)V_T$, which would in this illustrative case be 240 electron volts. There is presented later in this report a more careful study of the distribution of energies for Sole Segment No. 11; the later more careful study indicates an average electron energy of at least 260 electron volts per electron. The average d-c energy input was about 600 electron volts per electron, this being the combined watts per ampere from d-c currents at the respective voltages to: Sole Segments Nos. 32 to 36 used as collecting segments; roof and collector electrodes; and driver electrode Group A.

In combination, the two simple facts: that the average energy is roughly that corresponding to a kinetic temperature of 160 electron volts, and that the high-energy "tail" of the distribution curve corresponds to a kinetic temperature of about 22 electron volts, is adequate evidence that in this Table I operation the electrons of the stream possessed an energy distribution differing very markedly from a thermal distribution by the time they reached Sole Segment No. 13.

C. This type of nonthermal energy distribution can be expected to be as effective as a thermal distribution having the same average energy, possibly more so, for producing nuclear fusion. In a conversation in his laboratory, during April, 1965, with Dr. Richard Post, Director of the Sherwood Project Laboratory of the Lawrence Radiation Laboratory of the University of California, at Livermore, California, I discussed with him the question as to the relative importance of the high-energy "tail" of a thermalized (i.e., Maxwell-Boltzmann) distribution in causing collisions with the frequency and energy needed for initiating nuclear fusion. His comment was that the primary importance attaches to the average energy in the distribution, and that if one has adequate average energy and density, fusion-producing collisions will occur as desired. Of course this question can be answered specifically by a theoretical study, which will be a matter for our later attention; see page 34.

Figure 13 shows the volt-ampere curve for the highest-energy sole segment from a set of observation taken March 19, 1965, with a magnetic flux density of 2800 gauss and with driver electrode voltages in the 1000 to 2700-volt range. It will be seen that the higher-current straight slant line corresponds to a kinetic temperature of 397 electron volts, that is, a degree-Kelvin temperature of 4,600,000°K, with a "tail" temperature attribute of about 270,000°K. The average electron kinetic energy for a truly thermal distribution at a kinetic temperature of 397 electron volts, would be 595 electron volts. The energy distribution of this Fig. 13 curve was analyzed and discussed in some detail in the Memorandum Progress Report of May 25, 1965, as largely repeated farther on in this report. That study resulted in an estimate, from the Fig. 13 data, of an average kinetic energy of slightly more than 500 electron volts. The average d-c energy input was about 960 electron volts per electron, this being the combined watts per ampere from d-c currents at the respective voltages to: Sole Segments Nos. 32 to 36 used as collecting segments; roof and collector electrodes, and driver electrode Group A.

Thus it seems reasonably clear Fig. 13 results from the behavior of electrons having an average kinetic energy between 500 and 600 electron volts, and in the neighborhood of the average energy of a thermal distribution at a temperature at approximately or somewhat exceeding 4,000,000°K. This is within a factor of 2.5 of the 10,000,000°K energy-measure (not really temperature) at which deuteron behavior would become extremely interesting in relation to the nuclear-fusion objective of this program.

Modifications presently nearly completed in the apparatus will permit operation at substantially higher values of the driver voltage, which should give substantially higher average-energy values than have yet been observed.

The present effort is, of course, toward increasing the average kinetic energy in the stream, with little concern over the relatively unimportant injection-controlled temperature attribute of the high-energy tail of the distribution.

D. Electronic-circuit utility that appears probable, because of the ordered (rather than thermally random) nature of the kinetic energies. The kinetic energies have a nonthermal distribution, as just discussed above in Item (B); that is, they obey an ordered or quasi-ordered and by no means random distribution function.

Once a kinetic energy distribution among particles has become thermally random, the kinetic energy contained is present as heat energy, and can only be reconverted to an ordered form of energy by some sort of "heat engine." No heat engine with an electrical output appears to exist in this system. However, as long as the kinetic energy is largely in an ordered motion established by electrical interaction, it is presumably possible to devise an inverse process which will take the energy out again electrically. As discussed farther on, there is in our experimental results some evidence to support this point of view.

The concept just stated has led me to the belief that the electron-constituted monopolar plasma can be usefully employed in electronic circuitry to provide power oscillation, power amplification, high-power-level energy storage and output delay, and other useful electronic circuit functions. This aspect of the results of the work is dealt with in considerable detail in the Patent Disclosure papers of December 1, 1965.

28. Lowered-Voltage Operation of Selected Driver Electrode Segments as the Means of Producing High-Kinetic-Energy Primarily Ordered Motion. It had become apparent in the fall of 1964, from the results of experiments with depressed sole segments, that:

(1) It is in fact possible to enhance the mean kinetic energy of the electrons by passing the electron stream through a region of weak electric field (in those earlier observations it was the weak field at the bottom of the depression in the sole), but that

(2) This could not be a useful method of reaching extremely high average kinetic energies, because the equipotential followed by the charged-particle stream could be made to dip sharply into the weak-field region only by having it pass close to the electrode structure (sole segments that are connected to the proximity control bus), and this closeness led directly to collection on this structure of the higher-energy electrons. This introduced a tendency toward lowering of the average energy, thus offsetting the weak-field energy enhancement.

A reasonable next step toward finding a successful means of meeting the project's primary objective appeared to be to expose the stream, after "injection" past the first few sole segments, to a weak-electric-field region produced by operating one or more of the driver electrode segments at a voltage substantially lower than that of the roof electrode.

The need for operating in this new way exposed a possible experimental difficulty. The insulation between driver electrode Groups A, B, C, etc., and between each of these and the water-cooling tubes that provided their physical support as well as cooling them, had been designed primarily to permit measurement of current collected on the respective groups, and not with the expectation of need to apply substantial d-c voltages from one group to the next. A test of the actual insulation strength showed, however, that with the exception of driver electrode Group C, it should prove feasible to apply voltage differences of betwen 1000 and 1200 volts between individual groups and the support structure, and between each group and its two adjacent neighbors. It was therefore possible to plan and carry out an experimental program using lower potentials on selected driver segment Groups than on the roof electrode.

The results were very striking, and did indeed show such operation to be a means of substantial crossed-field conversion from potential to kinetic energy by introducing a region of weak electric field. However, various aspects of the results were not as anticipated. These unexpected aspects will have important effects on the design of similar apparatus employing an ion-constituted plasma stream for producing controlled fusion. Itemized appropriate comments follow, being drawn largely from a study of Fig. 12 and other similar data presentations:

A. Details of the arrangements for the reduced-voltage operation of driver electrode segment groups in the Fig. 11, Fig. 12 observations. A right-margin insert in Fig. 11 shows the relationship of groups of driver electrode segments to the individual sole segments facing them. For the data in Figs. 11 and 12, with the roof electrode and all other driver electrode groups at 1750 volts, driver Group A was held at about half this, actually at 850 volts. Note that Group A begins opposite the middle of Sole Segment No. 5, and ends opposite the middle of Sole Segment No. 10; also note that the sole as a whole was 250 volts below cathode potential, except for the probing sole segments being used.

B. The weakening, diverging, and converging space-charge-free equipotential pattern. The voltage pattern of driver electrode groups just described produced two interrelated but distinct effects on the electric field pattern as thought of in the absence of space charge; first, the space-charge-free electric field at Sole Segments Nos. 6, 7, 8, 9, was about 55% of that at all the other segments; second, the space-charge-free equipotentials had a diverging pattern (bending the higher-voltage equipotentials away from the sole) at Sole Segments Nos. 4, 5, 6, and a converging pattern (bending the higher-voltage equipotentials toward the sole) at Sole Segments Nos. 9, 10, 11. In considering the effects of this field pattern on the stream, it must be realized that the "electron lens" effects on this high-density, slow-drift type of stream are totally different from those familiar for low-density, high-directed-energy electron beams. The reason for this difference is the extremely pronounced effect of space charge on the actual field pattern.

C. Marked increase of collection of electrons against opposing potentials, as between points of entry into and emergence from the weak-field region under the lowered-voltage Group A. We observed a very much greater collection of electrons, against strong retarding probing sole segment potentials, at locations just beyond emergence from the weak-electric-field region under Group A, than occurred just prior to entry into this region. To illustrate this, note from Fig. 12 that when at 130 volts below cathode potential, 1.0 milliampere was collected at Sole Segment No. 3, located well ahead of driver Group A; in marked contrast to this, at the same voltage 5 milliamperes went to Sole Segment No. 11 just beyond Group A. At -210 volts the corresponding numbers were 0.024 milliampere and 1.4 milliamperes. This illustrates the central fact of enhancement of kinetic energy, and therefore of ability to penetrate against an opposing sole segment potential, gained during passage through the weak-field region.

D. No significant changes occurred at driver groups held at the higher voltages. Note that collections varied only slightly over the whole extent from Sole Segment No. 11 to Sole Segment No. 26, that face driver Groups

B, C, D, E, all of which were at the higher voltage. That is, the stream properties acquired in passing by the reduced-voltage Group A did not change during passage through a farther-on stronger-field region.

E. *The question as to whether the changes in electron kinetic energy may result primarily from passage through a region of changing transverse-to-the-stream electric field rather than from passage through a lessened-magnitude electric field.* A careful study of Fig. 12 shows that the most rapid enchancement of electron kinetic energy, as evidenced by increase of current collection against retarding potentials, occurred just before completion of travel past Group A. This is a region in which there is locally a convergence of the equipotentials. If in such a region the electron stream's path remains centered along some given equipotential, it must as it advances experience an increasing transverse electric field strength. It may be that this exposure to a changing transverse-to-the stream electric field strength is the cause of the enhancement of the amplitude of the space-charge wave that causes the conversion from potential to kinetic energy. Of course, as this conversion takes place the stream becomes centered along progressively higher and higher equipotential. This means that as it advances through the region of converging equipotentials, the stream's path does not bend toward the sole to follow the convergence, but instead moves more directly longitudinally, thus crossing consecutively to higher and higher equipotentials, without necessarily moving physically toward the driver electrode. One is tempted to think that the stream behaves as though it had a forward inertia, deterring it from bending its path to follow the convergence of the equipotentials. This "forward inertia" concept is not a valid one, at least in any such simple terms, because the stream's slow forward drift is in fact being somewhat accelerated along any equipotential it may tend to follow, this acceleration being due to the increase of the transverse electric field and so of its E/B velocity.

There is some rather unclear evidence suggesting that the electron kinetic energy declines during the approach to Group A, this occurring in a region of diverging equipotentials. This is a region where the transverse-to-the-stream electric field is decreasing along the stream's path, and this raises the question as to whether exposure to a declining transverse electric field may cause an attenuation of the space-charge wave. The evidence just described obviously indicates a need for further experimentation, and in due course a theoretical study, to determine whether in fact the enhancement of electron kinetic energy results from passage through a weak transverse electric field region, or in contrast originates from passing through a transition from a weak to a strong transverse-to-the-stream electric field. This need governed much of the subsequent experimentation, and this "transition-region" concept will be found to dominate much of the discussion of results obtained subsequent to February 17, 1965. See also especially Section 30 and Figs. 22a,b.

F. *The Group A segments draw significant current when, as a result of the reducing of Group A voltage, large conversion to kinetic energies occurs; this is undoubtedly extremely significant as to the nature of the stream behavior*. Typical behavior during operation such as that leading to Figs. 11 and 12 was for the electrode consisting of the driver Group A segments to collect significant electron current, ranging from 1 to several milliamperes, out of cathode currents of from 22 to 35 or so milliamperes. In fact, this proved to be a limiting feature in the operation, in that if the Group A voltage was *lowered* sufficiently, the current to it became larger than could be tolerated by the potential divider system used to control this voltage. The situation would become catastrophically unstable, in that the increased current to Group A tended to react in the external circuit reduce the Group A voltage, so causing it to draw still more current, so to drop still lower and so on. It was necessary to stop lowering the Group A voltage before this catastrophic unstability could appear. Of course this current from Group A provides part of the d-c power input to the stream. Emphasis is needed on the experimental fact that *lowering* the Group A voltage caused an *increase* in its current.

G. *Stream-behavior significance of the existence of current to the lowered Group A electrode.* It is a familiar fact of theory and experiment with crossed-field apparatus, that electrons are able to move across magnetic flux lines toward a positive electrode (the driver in this case) *only* as a result of their having experienced an interaction *in which they transfer to some third energy form* (i.e., *a form other than potential energy of their own forward energy*) *the energy accepted from the d-c electric field by moving through it.* All microwave magnetron oscillators and crossed-field power amplifiers depend on this principle for their functioning; in such devices the power converted is delivered as useful r-f power output. In the present apparatus, it is being converted to kinetic energy of rotational motion of the electrons. Thus the appearance of these substantial currents to the reduced-voltage driver electrodes is completely consistent with the appearance of high kinetic energies of the electrons of the stream.

However, there exists here a marked contrast with the usual radar microwave magnetron type of operation, in that in a microwave magnetron oscillator the electrons are rotating at a very high velocity, and in synchronism with an r-f electric field that is part of a resonant circuit system, whereas in our apparatus the electrons have only a very slow drift, and there is no resonant output circuit.

29. *Experimental Study of the Relations Between Kinetic Energy Enhancement and Transitions from Weak to Strong Electric Fields.* Figure 12 contains

strong indications that during approach to a transition from a region of weak transverse electric field to a strong-transverse-field region there are important influences toward enhancement of the electron kinetic energy. In order to explore this further, experiments were conducted with various choices for reduced voltages on driver groups. The results will be presented in order of conduct of the experiments.

A. Figure 14; results with Group A alone at a reduced voltage. The data for this figure are from observations very similar to those in Fig. 12, but taken two days later, on February 19, 1965. This February 19 data is used because its operating conditions provide an excellent comparison with subsequent observations. The ordinate used is the ratio of the probing segment current to the cathode current. Curves for only a few sole segment voltages are shown. The indications here are much the same as those described earlier relative to Fig. 12.

B. Figure 15; results with a double group, Groups A and B together, at a reduced voltage. Comparisons with the Fig. 14 one-group-reduced condition are as follows:

(1) The maximum sole-segment currents, being those that appear at segments just beyond the end point of the Fig. 15 pair of reduced-voltage Groups A, B, are approximately the same as those reached just beyond the end of the one reduced-voltage Group A in Fig. 14. Thus the mere extension of the reduced-voltage portion of the driver electrode did not markedly enhance the total effect.

(2) The steep growth of the curves at the electric field transition just at the end point of the Fig. 15 Groups A, B,

reduced-voltage pair shows a very close parallel to the steep growth at the corresponding transition under the end point of the Fig. 14 lone Group A reduced-voltage portion.

(3) Figure 15 shows a gradual exponential growth in energy, steeper for the more negative probe voltages, between the early decline and the abrupt rise. In Fig. 14 any such gradual growth is masked by the abrupt rise.

(4) There appears at the beginning point of the Fig. 15 double-group reduced voltage portion a greater tendency for an initial decline of sole segment currents along the structure, than appears under the single-group voltage reduction.

C. Figure 16, a triple group, Groups, A, B, and C together, at a reduced voltage. Comparisons are as follows, for these results of observation on March 8, 1965:

(1) The maximum probing sole-segment currents, that appear in Fig. 16 just beyond the end point of the triplet of reduced-voltage Groups A, B, C, appear to be somewhat less than for either the Fig. 15 reduced-voltage pair or the Fig. 14 single group; this reduction is probably not very significant, primarily because various experimental conditions were not quite the same for Fig. 16 as for Figs. 14 and 15, particularly proximity control.

(2) There appears in Fig. 16 a steep growth at the electric field transition just under the end point of the triplet, very much as in Figs. 14 and 15.

(3) The Fig. 16 growth rate in the middle portion of the Groups A, B, C, triplet cannot be fairly compared with that under the middle of the Groups A, B, pair in Fig. 15, for reasons related to changed operating conditions and deserving separate comment, which will now be given.

(4) The tendency for a decline in probing segment current just beyond the beginning-point of the reduced-voltage driver portion, that is evident in Fig. 15 for the Groups A, B, pair reduction, was felt to be objectionable. Also, it seemed likely that this was to some degree dependent on the "injection" conditions. Therefore the injection arrangment was modified by connecting Sole Segments Nos. 1, 2, 3, 4, to a proximity control bus, held only about 100 volts below cathode potential, while operating the remainder of the sole (except for the probing segments) at about 450 volts below cathode potential. Because the kinetic energy is not yet high at Sole Segments Nos. 1, 2, 3, 4, they can be operated at only 100 volts below cathode potential without excessive current drain to them. The reduced-voltage triplet condition was tried both with and without this proximity control. Comparison of Fig. 16, taken with it, with Fig. 15, shows that early-segment proximity control reduces not only early-segment probing currents, but also probe collection all along the structure. This and confirming evidence at higher energies on March 20 indicate that early-segment prox-

imity control is harmful.

D. *Figure 17, use of a stepped-voltage driver pair, with the Group B voltage intermediate between that of Groups A and C, and with injection employing proximity control.* Since the results presented in Figs. 14, 15, and 16 all indicated sharp growth at a transition, it was clearly desirable to try using two transitions in sequence. This was done with results as charted in Fig. 17. Proximity control was again used, as its undesirable features had not yet become apparent. Comments are as follows:

(1) This arrangement provided more total energy enhancement than any of the other arrangements tried, with a significant but not major increase over Fig. 15, as to maximum sole segment current collection versus retarding voltage (probably in spite of proximity control).

(2) There was a very striking new aspect of the behavior, in that increases of sole segment collection current occurred about equally at the two transition regions under the two voltage steps, respectively at the Group A, B junction and the Group B, C junction.

(3) The beginning-point decline was almost wholly eliminated, this being presumably due partly to the use of proximity control at injection, and partly to the almost immediate growth that appeared because of the nearness (to the beginning point) of the transition step from Group A to Group B. It is worth noting here that by far the greatest part of the driver-electrode current collection went to Group A, with none to Group B and a very little to Group C, although the growth of

energy at the Group B, C, junction about equalled that at the Group A, B, junction.

E. Figure 18, suggesting reversibility of the energy conversion phenomenon. Some aspects of Fig. 15 indicated that a downward voltage step might have an effect opposite to that of an upward voltage step, and such behavior would not be inconsistent with the concept that the motion of the electrons is of an ordered or quasi-ordered nature. To investigate this possibility, the data charted in Fig. 18 were taken, being essentially the same as Fig. 17 except for the lowering of the driver potential on Group D.

The obvious first-thought and probably correct interpretation of the Fig. 18 results is that under the Group C,D, junction there is a "deconversion" from electron kinetic energy to d-c potential energy, with reconversion back to kinetic energy under the Group D, E, junction. If this is the true interpretation, the motion must indeed be very largely of an ordered rather than random nature. Very critical further experimental examination of this apparent reversibility of the conversion is essential, as there may conceivably be other causes for it, as for example having to do with the transverse-direction location of the stream. That particular alternative explanation would be a little difficult to accept, because of the fact that in their energy exchanges the electrons tend to be affected by transverse changes in potential, quite regardless of the transverse distance over which these potential changes take place. Another alternative might relate to the basic nature of the measurement process being used.

The very great importance of this question of interpretation lies in the point of view that if this "deconversion" can in fact deliver energy against a d-c voltage as here indicated, presumably it could also deliver energy into a properly designed r-f circuit structure, which would represent generation of r-f power. It is with this strong probability in view that the Patent Disclosure of December 1, 1965, under this project has claimed a new high-frequency kind of electronic circuit behavior.

F. Figure 19, suggesting that effects on the electric field due to sole voltage spatial variations have close parallels to the effects of similar driver voltage variations on the electric field. In the experiments leading to Fig. 19, the "proximity control bus" was connected, in the case of Curve X to Sole Segments Nos. 4, 5, 6, 7, 8; for Curve Y to Sole Segments Nos. 5, 6, 7, 8, 9, and for Curve Z to Sole Segments 6, 7, 8, 9, 10. The results show that in this test the effect was not so much that of "proximity control," as it was that of establishing transition-points in the electric field.

It is desirable to bear in mind in examining this figure that for all other experiments the currents to depressed Sole Segments Nos. 4, 8, 12, 16, when used as probes were routinely insignificantly small relative to those to their adjacent neighbors each way, so small as to be meaningless and usually not recorded. But for this test they had meaning, as will be seen. Detail comments will be itemized.

(1) The gross-aspect evidence from Fig. 19 clearly is that the dominating effect of raising the voltage of the 5-segment set to 350 volts above the potential of the remainder of the sole was that of decreasing the electric field between sole and driver, thus establishing transverse field transitions at both ends of the set. At the left, low-numbered end, where the stream entered a weak field, this resulted in a decrease of the probe current at strongly negative voltages; at the right, high-numbered end, where the stream moved into a stronger

field again, the result was an extremely rapid rise (a factor of 100 in a two-segment space) in the current collection against a probe 200 volts below cathode potential.

(2) Raising the voltage of the 5-segment set had negligible effect on the overall behavior of current collection at Sole Segments Nos. 18, 19, beyond Driver Group B, the maximum energy location, as this remained about the same as in Fig. 17.

(3) Physically depressed segments located wholly outside the 5-segment sets behaved in the familiar ways, that is, when used as probes they drew negligible current relative to their neighbors. This is illustrated by Sole Segment No. 4 in Curve Z, for which this segment was wholly outside the Sole Segment set Nos. 6, 7, 8, 9, 10. It is also illustrated by Sole Segment No. 12 for the X and Y curves.

(4) A physically depressed segment just ahead of or beyond the 5-segment "proximity control bus" set behaved as though it were a member of the set, the point being that it, too, produced a weak field, because of the greater spacing it caused. Thus along Curve Y, using the 5-segment Sole Segment set Nos. 5, 6, 7, 8, 9, Sole Segment No. 4 behaved exactly as did its immediate neighbor Sole Segment No. 5; in Curve X, Sole Segment No. 5 was experiencing the influence of the transition, where Sole Segment No. 4 was not. Somewhat similarly, in Curve Z, Sole Segment No. 12, because it

was depressed, did not experience the sharp rise in current as a probe that Sole Segment No. 10 exhibited in Curve X, and that Sole Segment No. 11 exhibited in Curve Y.

(5) Both the sharp drop in current as a probe at the entering transition, and the sharp rise at the exit transition, occur for the 5-segment set at about the second segment beyond the junction. Thus along Curve Y the entering junction is between Sole Segments Nos. 4, 5, but the sharp current drop occurs to Sole Segment No. 6. Similarly for Curve Y the exit junction is between Sole Segments Nos. 9, 10, but the sharp rise is at Sole Segment No. 11. Curves X and Z behave similarly. Thus there is in Fig. 19 some delaying effect related to the direction of motion of the stream through the transition, the transition being due to change in <u>sole</u> voltage. No such delay appears in Figs. 14, 15, 16, or 17; in fact, in these cases the enhancement of current against a retarding potential appeared if anything to <u>precede</u> the junctions at which the voltage step occurs; in all those cases the transitions were due to voltage steps between Groups of the driver electrode. These observations should prove useful as "check point" for an adequate theory of the behavior when one is developed.

30. <u>Distribution of Kinetic Energies of the Electrons as Determined from the February 17, 1965, Experimental Data</u>. The central questions at issue in regard to the presently reported experiments are these: what kinds of distribu-

tions of kinetic energies, and at what average values, have been observed to exist among the electrons; by what means can the average energy due to many-directional motions be made as high as possible, and how high is this likely to become?

This section will present and discuss the evidence pertinent to these questions that can be drawn from the Fig. 11 and Fig. 12 data taken on February 17, 1965. This set of data is chosen partly because it is one of the most complete sets we have, and partly because it typifies very well the nature of the energy distributions we obtained whenever we used reduced voltages on selected driver electrode Groups. The average kinetic energies obtained on February 17, 1965, were not as high as those obtained from the less complete set of data obtained on March 19, 1965, presented later. At the higher-energy conditions we were limited to shorter "run times" in the experimentation, so that to take thoroughly complete data it was necessary to operate below the maximum-energy conditions, as was done for the February 17 data.

For each segment's curve in Fig. 11, a curve that represents the integrated distribution of electron kinetic energy is obtainable by plotting the ratio i_{ss}/I_k as ordinate against v_{ss} as abscissa; here and later:

I_k = current from the cathode, being controlled by cathode length, cathode-to-roof spacing, roof voltage, and magnetic flux density;

i_{ss} = current drawn by a probing sole segment, due to electrons from the electron stream arriving at the segment;

v_{ss} = voltage of the probing sole segment, controlled by the operator of the experiment, and measured relative to the cathode;

B = d-c magnetic flux density, webers per square meter (10,000 gauss = 1 weber per square meter);

Integrated distribution curves so obtained have been plotted in Fig. 20 for Sole Segments Nos. 2, 3, 5, 7, 9, and 11, from the Fig. 11 data taken on February 17, 1965. Figure 21 presents the corresponding curves of probability density distribution in kinetic energy, being the respective negative slopes of the curves in Fig. 20. Because variations in the voltage of Sole Segment No. 1 presumably produce significant variation in the condition of the beam at injection, it seems better at least initially to think of it as an element in the stream injection control system rather than as a segment useful as a measuring probe, hence its omission from Fig. 20 and Fig. 21; however, see also the later presentation and discussion of the behavior as measured by means of Sole Segment No. 1.

Comments as follows are pertinent relative to the reasons for selecting, for plotting, data from the particular segments represented in Figs. 20 and 21:

A. Sole Segment No. 2 is chosen as being the first of the segments that can properly be considered as a measurement-making probe, in that it does in fact lie beyond Sole Segment No. 1. However, careful comparison in Fig. 12 of the behavior for Sole Segments Nos, 2, 3, and 5, suggests that the current collection by Sole Segment No. 2 is still strongly influenced by the transition from a weak electric field to a strong electric field that results from the narrowing of the electrode spacing that occurs at Sole Segment No. 1. In this connection, note from a comparison of the sharp rises in curves for the X, Y, and Z conditions in Fig. 19 that, for a transition from a weak to a strong field due to a voltage change at the sole face of the channel, the sharpest current-collection changes occur just beyond the step change. A similar behavior can be expected if the change in field results from a step in sole geometry. This is consistent with Sole Segment No. 2 being in a region where the effect of the weak-to-strong step transition in electric field at Sole Segment No. 1 has not yet fully affected the measurement.

B. Sole Segment No. 5 is included because a study of Fig. 12 suggests that this is about in the middle of the transition that is in process due to the driver-face voltage step between the roof electrode and Group A.

C. Sole Segment No. 7 is included because a study of Fig. 12 suggests that here the effect of the driver-face voltage step between Group A and Group C has begun to be observed for the higher-energy electrons (from -130 to -230 volts below cathode), but not for the lower-energy electrons.

D. Sole Segment No. 9 is included as being clearly about in the middle of the transition due to the driver-face voltage steps between Group A and Group B.

E. Sole Segment No. 13 is included because Fig. 12 shows that at this point the sequential effects of the two driver-face voltage steps have taken full effect, thus Sole Segment No. 13 represents behavior at the "output" from the conversion system due to these two voltage steps.

This completes the itemization of the reasons for the selections of the various specific segments for plotting in Figs. 20 and 21.

Figures 20 and 21 suggest the presence of two separate stages in the effects of the transitions. First, the basic <u>nature</u> of the distribution shows a change by the time Sole Segment No. 7 is reached, and the change is complete at Sole Segment No. 9. Here there has appeared an almost straight-line kind of integrated distribution (Fig. 20), in complete contrast with the curvature for any near-Maxwellian distribution as at Sole Segment No. 2. Although at Sole Segment No. 9 not many electrons penetrate to the probe, the weakness of the electric field under driver electrode Group A has completely altered the distribution. One can only conclude that a new "ordered-motion" distribution has come into being by the time Sole Segment No. 9 has been reached.

Second, the curves for Sole Segments Nos. 9 and 13 show that the transition in the field due to the step rise in driver voltage at the Group A, B, junction increases greatly the collection of electrons against retarding fields, but without causing a change in the basic nature of the distribution. The average energy in the distribution rises almost abruptly at this junction, but the "nearly-square-box" Fig. 21 form achieved earlier does not change here, nor does the width of the "box" change significantly.

Figure 22b, derived from Fig. 22a, shows the probability density distribution in kinetic energy, respectively at the input (Sole Segment No. 3) and output (Sole Segment No. 11) of the conversion system comprising two sequential driver-face voltage steps, the first step being a voltage reduction at the junction between the roof electrode and driver-electrode Group A, the second a voltage increase at the junction between Group A and Group B.

From the Sole Segment No. 3 output-condition curve in Fig. 22b, describing in relative terms the probability density distribution in kinetic energy of the electrons, it is possible to deduce a least value of the average electron kinetic energy, that is, a value that one can be sure is equal to or less than the average kinetic energy.

In order to make this determination it is first necessary to recognize that nearly all of the kinetic energy of the electrons is due to circular or elliptical motions lying primarily in transverse planes, that is, in planes at right angles to the direction of the magnetic flux. Thus nearly all of the kinetic energy results from motions in the two dimensions of such planes, very little being in the third dimension. It also implies that as the stream passes near the sole segment used as a probe, all electrons having adequate energy to do so will reach this segment promptly, regardless of their directions of motion at first approach. The reason for this is that the cyclic period of the looping motion (this period is very nearly the inverse of the cyclotron frequency) is extremely short compared with the time required for any electron to traverse the longitudinal extent of the probing segment. If the electron is moving away from the segment at its first longitudinally-advancing approach, it will very quickly return via its looping path and be collected, if its energy is adequate relative to the potential structure.

To comment in detail, Fig. 22a presents two integrated distribution curves, one for the input-location Sole Segment No. 3, the other for the output-location Sole Segment No. 11, derived from data similar to that of Fig. 11, for the February 17, 1965, observations. For example, in Fig. 22a the curve for Sole Segment No. 11 describes the fraction of all the electrons having given amounts of kinetic energy above and below what would be necessary to bring them to this segment if it were at cathode potential. Figure 21b describes probability density distributions in electron kinetic energy, again relative to the kinetic energy necessary to bring an electron to Sole Segments Nos. 3 or 11 if it were at cathode potential. Thus the ordinates of the Sole Segment No. 11 curve in Fig. 22b are the negative slopes of the Fig. 22a curve for this segment. Note that Fig. 22a contains plots of observed data points for Sole Segment No. 11 from strongly negative voltages on this segment when used as a probing segment up to about 70 volts above cathode potential. The extrapolation of this curve for its remaining higher-voltage portion is based on the presumption that the curve is symmetrical about its half-value point, which occurs very slightly above cathode potential. At this half-value reference point the collected current on this segment is half the cathode current. This presumption is rather strongly supported by the observed fact that in this and many other similar sets of our data the probing segment at the maximum-energy location draws very close to half the cathode current when at cathode potential.

It is crystal clear from Figs. 22a and 22b that at the Sole Segment No. 11 output point the electrons do not exhibit an energy distribution of the Maxwell Boltzmann type. It is equally clear from semilogarithmic plots of the data that the high-energy tail of this distribution does have locally the shape corresponding to a kinetic temperature, for this particular segment, of about 22 electron volts, that is, about 250,000 degrees Kelvin.

The most important aspect of the Sole Segment No. 11 curves in Figs. 22a and 22b is their indication that the electrons at this output stage have excesses and deficiencies of kinetic energy, relative to that required to return an electron to cathode potential in spite of a retarding electric field, ranging up to about between 280 and 320 electron volts. Now it is reasonably apparent that if electrons exhibit in a smoothly-varying way (as they do in Figs. 22a and 22b) deficiencies from this half-value reference point ranging to about 300 electron volts, the kinetic energies at the half-value point must have at least this same value. Because interest attaches to the quasi-ordered motion that gives the "flat top" to the curve for Sole Segment No. 11 curve in Fig. 22b and the corresponding straight-line in Fig. 22a, the least-value average energy has been identified for Sole Segment No. 11 as half of the difference between the intercepts at 0 and 1.0 of the Fig. 22a straight line giving half of 285 -(-235), or half of 520 electron volts. Thus the evidence from these figures is that at the Sole Segment No. 11 output point the average kinetic energy of the electrons of the stream is at least 260 electron volts per electron. As discussed in Item (B) of Section 27 above, this is in general consistent with the gross-aspect shape of the Sole Segment No. 13 curve in Fig. 11, taken under the same conditions.

It is probably reasonable to presume that the average kinetic energy in the stream at Sole Segment No. 11 was during these observations reasonably close to 260 electron volts per electron. This means that at this location the electron stream must be located transversely away from the sole at least as far as the transverse location of the d-c space-charge-free equipotential that is 260 volts above cathode potential. This is necessary in order that the electrons can have accepted from the d-c circuit the potential energy necessary to give the electrons their observed kinetic energy.

The advancing space-charge wave presumably possesses stored energy in its r-f electrostatic field that may equal the kinetic energy stored in the electron's motions, but at different points in the wave. Thus the measured kinetic energy must be the total transportable stored energy per electron. As illustrated (for the ion-constituted stream) in Fig. 4, the actual potential difference, in the operational state, between sole and stream location, also that between the cathode and the stream location, may be considerably less than the corresponding space-charge-free potential differences. It is the operational-condition retarding potential that the electrons must overcome to be collected on a sole segment used as a probe.

Certainly a great deal of sophisticated theoretical analysis will be required before we will clearly understand what factors govern the achievement of these energy distributions.

Finally one must note that the Fig.22b probability density distribution curve for Sole Segment No. 3, describing the input condition, has a shape much more nearly resembling a Maxwell-Boltzmann distribution than at "output" at Sole Segment No. 11, and that the average kinetic energy at "input" is much less than at "output."

Because it exhibits a several-decade essentially straight-line semilogarithmic behavior characteristic of a thermal kinetic energy distribution, Fig. 23 is presented showing the behavior for Sole Segment No. 1 in Figs. 11 and 12. For the higher electron energies, in fact for all of those arriving at voltages at and below cathode potential, this curve provides an excellent means of determining the temperature of the largely thermalized energy distribution at stream injection into the channel between the sole and driver electrodes. However, at the higher-current portion of the curve, above $I_{ss}/I_k \cong 1/3$, the Fig. 23 curve should not be interpreted as an integrated distribution curve of electron kinetic energy, because when at and significantly above cathode potential, variations in the voltage on Sole Segment No. 1 must cause variations in the injection conditions of the stream—for these higher voltages. Thus this Sole Segment No. 1 is part of the injection control system. Therefore in the Fig. 24 nonlogarithmic plot of the Fig. 23 data, the portion of the curve above about a 1/3 current fraction should be thought of primarily as a graph of the response of the current ratio to the control-electrode function of this segment.

However, the regularity of the Fig. 23 plot for current fractions below about 1/3 suggests that, when the voltage on Sole Segment No. 1 drops to and below cathode potential, the electrode geometry, the roof voltage, and the magnetic flux density exercise the primary control over the injection conditions. This makes it appear reasonable to use the portion of the Fig. 23 curve that lies below the 1/3 current ratio to determine the electron temperature at injection. Because the curve as a whole is not in fact an integrated energy distribution curve (the significance of the 1.0 value is much in doubt) it cannot be used to obtain a complete curve of probability density distribution in energy.

31. <u>High-Energy Conditions Observed on March 19 and 20, 1965</u>. Between the beginning on February 17, 1965, of the Winter-Spring 1965 series of experimental observations and the middle of March, the choices of experimental parameters were made primarily with a view to determining the effects of various kinds of driver electrode voltage steps on the enhancement of electron kinetic

energies. These experiments were carried out with a magnetic flux density of about 2000 gauss, requiring about 200 amperes to the magnet coils. The duration of any experimental data-taking run of the apparatus was limited by the rise in temperature of the magnet coils. A thermocouple had been buried in one of the coils, and a determination made as to a limit-point on the thermocouple meter at which the observational program should be interrupted to permit cooling of the coils. Typically it was possible to obtain a fairly extensive set of data in the course of 1 to 1-1/2 hours in the morning, and again the same afternoon.

By mid-March it had become fairly clear what the best choices of electrode voltages were for obtaining the maximum electron kinetic energies obtainable with the existing apparatus using a flux density of 2000 gauss, and with a maximum of about 2500 volts from the sole to any driver electrode group. Use of a voltage much higher than that would introduce a risk of voltage breakdown between groups or between a group and its water-cooled support rods, but it would be necessary to operate at these higher voltages if higher magnetic flux densities were to be used in ways to maximize value from their use. Operating at these higher magnetic flux densities would require shortening the observation time for each run, because of the more rapid heating of the coils. However, largely off-setting the requirement of shorter observation periods was the fact that we had learned what particular observations were essential to obtaining the greatest amount of useful information in the shortest possible time.

It had also become apparent by mid-March, 1965 what modifications would be necessary in the equipment to enable us to obtain still higher energies than would ever be possible with the equipment in its existing state, and to obtain certain new kinds of information—for example, the frequency of the r-f oscillations certain to be present within the device, and the rate of heat input to a sole segment when drawing substantial current against significant retarding potentials.

At this point the decision was made to operate for a few days with the apparatus at its upper limits of usable parameters as it then existed, to see what maximum average electron kinetic energies could be obtained. The requirement of shortened observation time per run for such experiments appeared to offer no serious difficulty, and we felt it worthwhile to take the risk of voltage breakdown at the higher voltages, especially since the next phase of the effort would in any case involve dismantling and reinsulating for higher-voltage operations.

The first such experiments were conducted on March 19, 1965, using a magnetic flux density of about 2800 gauss, with 3000 volts on the roof electrode and on driver electrode Groups C and D. No insulation failures occurred, and on March 20, 1965, a few observations were made at 3600 gauss. Figures 25 through 29 show the results of these observations in their most interesting aspects. Comments on these high-energy observations will be itemized:

A. Figure 25 presents a "raw-data" plot, from the 2800-gauss operation on March 19, 1965, of the behavior at the "input" at Sole Segment No. 3 and at the "output" at Sole Segment No. 18, with the roof electrode (facing the cathode), and driver electrode Groups C, D, E, and F at 2500 volts above the cathode, but with driver electrode Groups A and B respectively at about 750 volts and 1500 volts above the cathode. This provided a Group A, B, C, increasing-level voltage sequence of about 750, 1500, and 2500 volts above the cathode potential, with Groups D and E also at 2500 volts, all patterned after the similar but lower-magnetic-flux-density Fig. 17 sequence of 500, 1125, and 1850 volts, on Groups A, B, and C, with Groups D and E also at 1850 volts.

B. Figure 26 shows the integrated distribution in energy for Sole Segment No. 18, corresponding to the Fig. 25 curve for this segment.

C. Figure 27 shows the probability density distribution in kinetic energy for this same Sole Segment No. 18. Ordinates in this curve are the negative slopes of the Fig. 26 curves, taken on March 19, using 2800 gauss and the 750, 1500, and 2500-volt rising Groups A, B, C, sequence, with the roof electrode and Groups D and E also at 2500 volts above the cathode. Figures 26 and 27 are related to their basic data exactly as Figs. 22a and 22b are related to the basic February 17 observations. By pursuing logic and calculations quite closely paralleling those on page 83 of the Section 30 discussion, it is found that the average kinetic energy at Sole Segment No. 18 on March 19, 1965, was approximately 500 electron volts per electron. Correspondingly it must be presumed that the stream has at Sole Segment No. 18 moved out transversely at least as far as the d-c space-charge-free equipotential that is 500 volts above the cathode potential, and possibly considerably farther than that.

D. On March 20 (this was a Saturday), the 2800-gauss experimentation was resumed; the data taken is presented in Fig. 28. For these experiments an effort was made to operate Group D at about 3500 volts above the cathode, to enable establishing a Groups A, B, C, D, increasing-level voltage sequence of about 750, 1500, 2500, and 3500 volts respectively, holding Groups E and F at 2500 volts; the roof electrode was operated at 2500 volts relative to the cathode. Because of uncertainties as to the ability of the external d-c voltage-divider circuitry to hold this 3500 volts on Group D in the face of rather undependable insulation between this Group and its neighboring Groups and the cooling tubes that provide its physical support, we cannot be completely sure whether on March 20 Group D operated at 3500 volts or at 2500 volts above cathode potential.

Figure 28 shows, for this March 20 experimentation at 2800 gauss, the segment-to-segment variation of currents to sole segments used as probes, respectively at -300 volts and -200 volts relative to the cathode.

These sole-segment and current-collection data show, as expected, marked energy enhancements at the Groups A, B, junction and at the Groups B, C, junction, but there was no marked further kinetic energy enhancement at the Groups C, D, junction; such enhancement was to be expected, and its absence needs explanation. In the data in Fig. 28 taken with probing segments at -200 volts relative to the cathode, there is evidence, as for example at Sole Segment No. 26, of a significant energy enhancement while passing by Group D. Both in the data at -300 volts and those at -200 volts there appears a significant decline of energy in passing the Groups D, F, junction. This decline could be the result of a step decrease in voltage from 3500 volts on Group D to 2500 volts on Group E, or it could relate to the close approach to the Sole Segments Nos. 32 to 36, which were operated at +250 volts relative to the cathode to permit them to serve as a collector electrode. An approach to them represents transition to a region of weaker electric field, which would tend toward a kinetic energy decrease. There exist at least two possible explanations of the absence of a marked enhancement of kinetic energy at approach to the Groups C, D, junction, as follows:

(1) It may be that Group D was operating at 2500 volts because of insulation failure between it and its neighbors, or,

(2) It may be that Group D was operating at 3500 volts, but that no substantial enhancement of kinetic energy was possible at the Group C, D, junction because the electrons had already accepted it in the many-directional kinetic energy form a very major fraction of the d-c electron-volt-per-electron energy (i.e., watts per ampere) being delivered to the stream. Thus Fig. 27 indicates that in

> the preceding day's tests the stream had acquired at Sole Segment No. 18 something between 500 and 600 electron volts per electron of many-directional kinetic energy, out of an available 960 electron volts per electron from the d-c system. It is reasonable to expect it to become increasingly difficult for further enhancement to occur as the energy content approaches more and more closely to the energy available.

If the latter is the true explanation, it carries the implication that considerably more energy enhancement should be achievable by increasing the d-c voltages on the electrodes on which the major portions of the stream are collected. Because of changes now being made in the apparatus, it should be in prospective experiments be a relatively simple matter to test out this aspect of the behavior of the stream.

E. The March 20 observations included these from a short-duration test with a magnetic flux density of 3600 gauss, and with the d-c power supply circuitry arranged to provide a Groups A, B, C, D, increasing-level voltage sequence of about 1000, 2000, 3000, and 4000 volts relative to the cathode, with Groups E and F and the roof electrode at 2500 volts, these latter representing no change from the 2800-gauss experiments. Figure 29 shows for these 3600-gauss observations the segment-to-segment variation of currents to sole segments used as probes, taken at -300 volts relative to the cathode. There appears here a significantly greater energy enhancement, by the time Sole Segment No. 18 is reached, than appears in Fig. 28 for the corresponding 2800-gauss operation. There was also a significant increase in available watts per ampere, appearing as a more-than-proportionately-greater increase of current collection at the collector electrode, which was operated at 2500 volts above cathode potential. We do not yet know the reason why in this 3600-gauss test the cathode current was greater than at 2800 gauss for the same roof voltage—one expects some decrease—but we feel it is probably related to the use of an increased voltage on driver electrode Group A, which is not really remote from the stream launching region.

This concludes the itemization of the behavior of the apparatus during the high-energy March 19 and 20, 1965, experimentation.

However, it is well to mention here that the Fig. 29 data represent the extreme in electron energies obtainable with the equipment as of the spring months of 1965. By comparing Fig. 29 with Fig. 28, it is possible to make what is believed to be a reasonably dependable estimate as to the average electron kinetic energy existing at its greatest point in Fig. 29 as being about 750 electron volts per electron. This is about the same as the average electron energy in a thermalized electron swarm at a temperature of 6,000,000 degrees Kelvin. This is near enough to our present "bogey" of being able to reach the 10,000,000-degree energy equivalent with the present apparatus, to suggest that with appropriate modifications toward permitting operation at higher driving voltages and watts per ampere d-c input, it should be possible to reach and quite probably surpass the bogey.

With this point of view in mind, experiments were discontinued after the March 20, 1965, observations, and work begun toward the rather complex redesign and reassembly process needed to permit obtaining higher average electron kinetic energies, and at the same time obtaining more definitive information as to just what goes on in the electron stream during the process of conversion from potential to many-directional kinetic energy.

32. "Confinement" of the High-Energy Electron Stream. Providing plasma "confinement" is the second major problem (essentially on a par with that of

producing a balance between fusion and loss rates) in obtaining controlled fusion reaction on a sustained time scale. Up to the present time no real solution to the confinement problem has been achieved with bipolar plasmas (containing electrons and ions in approximately equal densities), used in other laboratories conducting research toward controlled fusion.

It will be recalled that the present program is pointed toward using a monopolar plasma containing only positive ions (deuterons or tritons). The present work with electrons is to be thought of as a scale model experiment on a monopolar plasma consisting of electrons.

It is clear that in order for either a monopolar or bipolar plasma to survive and maintain an adequate particle density, the ions that are to participate in the fusion reaction must be "confined" or "contained" in some reasonably well-defined region. It is characteristic of the usual conducting gas of an electron-and-ion-bearing plasma that it will not penetrate far into a strong magnetic field. (The basic principle is much the same as in the failure of an r-f magnetic field in induction heating to penetrate beyond the "skin depth" into a good electrical conductor.) Therefore one can "confine" such a conducting gas by subjecting it to a magnetic field environment, into which it will not penetrate. This action has to do with conductivity due to motions of the electrons primarily, the movements of the ions being subsequently governed by the fact that space-charge forces tend to compel ions to follow where the electron swarms lead—this has to do with transient rather than d-c space-charge forces.

However, fast-moving electron streams comprise electric currents that set up magnetic fields which can become comparable with those used for confinement. These magnetic fields set up by the streaming electrons of a bipolar plasma tend to cause "instabilities," that is, runaway transient-pulse or oscillatory behaviors, including the appearance of "pinch" and "kink" instabilities. As a result of the various instabilities the plasma channel can and often does become totally distorted or even discontinuous, thus destroying confinement. This unstable behavior becomes especially evident and seriously deleterious to confinement when, in order to raise the plasma temperature and increase its density by magnetic compression, the externally applied magnetic field is given a fast transient impulse.

These various instabilities that appear in bipolar plasmas are not easily subject to prediction by calculation, and have been important causes of the failure up to the present time of approaches used in other laboratories toward nuclear fusion control.

There are no electrons in the ion-constituted monopolar plasmas that the present invention proposes for producing sustained and controlled large-scale nuclear fusion. This makes the prediction by calculation of the confinement response enormously simpler than for a bipolar plasma, both for the electrically-driven growing-energy period and after self-sustaining reaction is obtained, as for example in a reaction chamber. Also, any instabilities of ion behavior that may appear in the crossed-field environment will have very much slower rates of appearance and of distortion of the plasma channel than result from electron action in electron-bearing bipolar plasmas. In experiments so far carried on (all in our apparatus) with electron-constituted monopolar crossed-field neutralized plasmas there have appeared no evidences of instabilities tending toward distortion or severance of the plasma stream. There do appear growing-wave oscillations, which behave in an orderly way and provide the essential function in the conversion of potential energy into particle kinetic energy. The means of confinement of these plasmas at energies so far obtained have been easily predictable and achievable.

It is especially important to note that, for a given average particle kinetic energy, it is found considerably easier to confine electrons that are subject to the high-average-energy ordered motion of space-charge-waves than would be true for an equally high average energy in a thermalized distribution.

33. "Confinement" in Relationship to Our Experimental Data. It has been pointed out above that in Fig. 11 and other similar figures the steepness of slopes of the curves in their lower-current regions is a negative measure of the electron temperature of the electrons in the tail of the curve of probability density distribution in kinetic energy. The hotter the electrons, the more gentle the slope of the curve. Note the following items regarding these straight-line portions of the semilogarithmic plots of current, in our data:

A. The "temperatures" of the electrons in the tails of the curves of probability distribution in energy range between 200,000°K and 400,000°K, being generally higher for the higher magnetic flux densities.

B. Because of the gentleness of the higher-temperature slopes, the higher the electron temperature, the greater is the fraction of cathode current that reaches a sole segment used as a probe, at some strongly negative potential—for example, 500 volts below cathode potential. This is illustrated in Fig. 30 which presents the volt-ampere curve from Sole Segment No. 13 in Fig. 11, also a fictitious curve for a thermal distribution having about the same average kinetic energy in the electron swarm; the "tails" of two distributions have greatly contrasting temperatures.

C. Successful "confinement" requires that the current to any neighboring electrode must be an extremely small fraction (as for example 0.001%) of the total current in the stream.

D. In Fig. 30, to keep the fractional collection at a 0.01% figure requires only a very moderate -342 volts for the measured Sole Segment No. 13

volt-ampere curve with its 205,000°K tail, whereas to maintain this same percentage for the 1,860,000°K tail requires much more, -1370 volts. It will be a less toublesome engineering problem to produce the moderate voltages our low tail temperatures call for than to confine high-temperature tails.

E. Therefore, for a given average stream energy, corresponding to some specific temperature equivalent (for example 10,000,000°K) the negative voltage required on the sole electrode to keep its current as a whole below 0.001% of stream current might be troublesome to maintain for a stream having a thermal-equilibrium "tail" temperature of 10,000,000°K, but not at all difficult to maintain with a "tail" temperature of some 500,000°K.

F. Thus the requirements for confinement appear relatively easy to meet for our proposed system for the simple reason that the particles in the tail of the distribution curve have a "temperature" for which the average energy is only a very small fraction of that actually existing in the stream as a whole, because the distribution is nonthermal. The evidence for this is experimental, and is clearly evident in Fig. 11 and similar figures.

The theoretical basis for this behavior has not yet been established; to establish it is an item of unfinished business in the present program. However, there is every reason to expect that whatever the theory may be, the behaviour will be the same, except for well-understood scaling factors, for deuterons as for electrons.

Thus there is clear experimental evidence for my belief that provisions for confinement of the monopolar crossed-field-neutralized type of plasma envisioned in the proposed system does not appear to offer insurmountable difficulties. Even when the high-energy rotational particle motions, together with with some degree of thermalized motions, appear in this plasma, the basic approximately Brillouin-flow nature of the d-c aspects of the stream persists with resulting prevention of escape of the particles to the sole or driver surfaces, provided an adequate voltage structure is maintained.

Contrasting comments, relative to the problem of achieving magnetic confinement without the crossed-field resource, are significant. A charged particle cannot move through a magnetic field in a direction crossing magnetic-flux paths without experiencing a force which turns its motion into a circular or near-circular path, the path being truly circular if the magnetic flux density is uniform and no electric field is present. However, a charged particle can in principle move to another region of the magnetic field that is at or near the same electric potential, by means of the circuitous motions that are permitted, and especially in the presence of minor perturbations of the fields or particle motions. So to speak, the charged particle cannot in the absence of an electric field distinguish one part of the magnetic field from another. Therefore, from the standpoint of energy considerations, it may just as well be found in one portion of the magnetic field as in another. This makes purely magnetic confinement, as often used in bipolar plasmas, a somewhat uncertain matter.

The mechanistic concepts of crossed-field confinement employed in the presently proposed system can be fairly easily described in an approximate conceptual way in a few phrases, under two items, as follows:

A. When a strong electric field is present, crossed with the magnetic field, a positively charged particle cannot move toward the positive (sole) boundary of its confinement or interaction space without giving up kinetic energy in exchange for potential energy. As the kinetic energy declines, the magnetic force (velocity x magnetic flux density) decreases, permitting the electric field to force the particle back in the direction away from the more positive electrode.

B. Conversely, a positively charged particle cannot approach the negative or driver electrode surface of its confinement or interaction space without gaining kinetic energy in exchange for potential energy. As its kinetic energy increases, the magnetic force (velocity x magnetic flux density) increases, tending to force the particle back toward its equilibrium position. For a particle that has not moved far enough in the longitudinal stream-flow direction, from its point of entry, to have participated significantly in the growing-wave interaction, this equilibrium position is near to the equipotential corresponding to the potential of the ion source. For quite far downstream positions, such that substantial conversion from potential to kinetic energy has occurred, the equilibrium position has of course moved toward the driver electrode.

However, the interactions with the space-charge-wave high-frequency electric field, and various scattering processes, result respectively in orderly reversible exchanges, and in random exchanges, among the particles, permitting for example one of them to gain kinetic energy while another loses it, and thereby become able to move toward a boundary of the interaction or confinement space. These actions represent in effect exchanges of the particles between one part and another of the curve of density distribution in energy. Those in one part of this distribution can approach toward the more positive or sole electrode, and those in the other part toward the more negative or driver electrode, these being the two boundaries of the interaction or confinement space in the interaction region. In principle the two must occur with some reasonable degree of symmetry about the mean, as is suggested by Figs. 22b and 27.

The requirement for confinement in this situation is in general that the energy difference between the extremes of the distribution must remain moderate relative to the total d-c potential difference between these bounding electrodes, with the additional presumption that the plasma stream is in the middle region between the boundaries rather than being close to either one. As long as the situation so described exists, losses of particles to the bounding electrodes will occur only for those few particles that are scattered into the extreme high or low tails of the energy distribution, relative to its mean. Experimentally, it has been found that in these tails the "temperature" is far below that corresponding to the stream average kinetic energy.

As any given group of the particles advances as part of the plasma stream, its average kinetic energy rises very substantially, as a result of the continuing interaction which involves acceptance of energy from the d-c potential structure, with a corresponding delivery of energy into rotational kinetic energy of the particles and into the electric field energy of the space-charge wave. Because of the overlapping nature of the rotational motions, and the exchanges between the kinetic energies of the particles and the electric field energy of the space-charge wave (this is reversible and has a systematic time dependence on a high-frequency time scale) the spread of energies in the energy distribution will increase, roughly in proportion to the growth of the mean kinetic energy. Therefore confinement of the particles in the higher-energy conditions that appear downstream will require in all likelihood somewhat larger spacings between the electrodes, and a correspondingly higher d-c voltage between them, than is called for near the ion source. The geometric placement of the downstream portions of the electrodes may well also be affected, as to the plane of centers between them, by the transverse shift of the stream toward the driver electrode at the downstream end.

The amplitude of the high-frequency electric field of the space-charge wave may also have a bearing on the confinement requirements, in that it may be easier for the particles to escape to the bounding electrodes from the minimum and maximum positions of the advancing space-charge wave than if the fields of the wave were not there. This wave is of a slow-wave nature, in that its electric field pattern is to a first approximation derivable from an advancing scalar potential (this is true both for the electron-constituted and ion-constituted monopolar plasma streams). The self-concealment attribute of the space-charge wave may not be quite adequate to prevent the lateral boundaries of the wave structure from reaching out nearly to the bounding electrodes, which are of course at their respective d-c potential values. In that case some of the high-energy particles may be able to "slide out" from a potential maximum or minimum of the wave to the adjacent electrode of potential nearest to it. However, an adequate d-c potential structure can prevent this.

In summary, as discussed above, experiments indicate that for a given average kinetic energy, there are far fewer particles in the extreme tails of the distribution curve for the energy of the ordered space-charge wave than for a fully thermalized situation. Therefore confinement is far easier to achieve for a high-energy ordered space-charge wave than for a thermalized distribution at the same average energy.

The ion-to-ion collision rate of course increases as the average kinetic energy increases with advance of the stream along the structure. As the collision rate increases, whether for elastic or inelastic collisions or any relative proportioning between them, the distribution in kinetic energy becomes increasingly like a thermal distribution. This behavior must be considered in the design of electrode spacings and choice of voltages to maintain confinement. The stronger the d-c magnetic field, the more easily confinement will be achieved, particularly when fusion reactions are occurring, and in any fusion reaction chamber that the plasma stream may be introduced into to permit the stream to serve its useful power-generating function.

VI. SUMMARY, RECOMMENDATIONS FOR FUTURE PHASES

34. Major Conclusions Reached from the Research. A review of the material in earlier sections should indicate why I have reached the following four major conclusions, chiefly as a result of our experimental results:

A. Feasibility of conversion to high particle kinetic energies. Conversion from potential energy to very high many-directional particle kinetic energies is achievable by means of a relatively slowly advancing stream of charged particles (electrons in our experiments) comprising a monopolar crossed-field-neutralized plasma; by using an appropriate ion-constituted plasma of this type, production of many-directional ion kinetic energies adequate to initiate self-sustained nuclear fusion should be achievable.

B. The particle motions are of a largely ordered rather than random thermal-equilibrium nature. We have unexpected but convincing evidence that the high-energy particle motions (presumably wave motions of almost wholly overlapping trochoids) are primarily ordered, rather than thermally random.

C. The ordered nature of the motions aids confinement. Our ordered motion may have a high average kinetic energy, but in its distribution's high-energy "tail" the energies are very much smaller than for thermal motions of the same average energy. Confinement behavior becomes relatively easily predictable; confinement of the stream appears relatively straightforward for the energy-growth region, and feasible for the sustained-reaction region.

D. The ordered nature of the motions makes it appear probable that an electron-constituted monopolar stream may have important electronic-circuit applications. This is discussed in some detail in the Patent Disclosure papers of November, 1965.

These conclusions led to the Chapter I "State-of-the-Program" Comments.

35. My Belief in the Importance of Prompt Attention to Processing Patent Applications. The most immediately urgent matter in the "forward look" is that of processing patent applications of whatever detail nature your patent attorneys may think desirable, based on the Patent Disclosure papers over the signatures of Mr. Irving Rozian and myself that were given to you on December 1, 1965.

The careful study that I have given to last year's experimental data in the process of preparing this present report has convinced me more fully than ever of the promise that our approach holds. I would like very much indeed to see your proprietary interests and the need-for-recognition interests of The University of Michigan and of the State of Michigan protected by your proceeding to preparation and filing of the patent applications necessary toward that end.

36. The Complete Sharing of the Responsibilities for this Program Represented in Mr. Irving Rozian's Immeasurably Valuable Contributions. Very important to the "forward look" in a program that must of necessity be largely carried by men much younger than myself, is the urgency that I convey to you now the fact that Mr. Rozian's contributions to our experimental program have been of immeasurable value. Early in the program he accepted the professional responsibility of bringing into physical being the very complex experimental apparatus that I envisioned and established design criteria for—with his ever-present counsel.

Because of the heavy responsibilities I was then carrying as Department Chairman (including overview and line responsibility for an annual expenditure of about $4,000,000 a year in research) it was absolutely necessary that

I delegate quite completely to someone this complex matter of the detail designing, building, and bringing into operational state the project's experimental apparatus. He has carried out this responsibility extremely well. It required him to master experimental techniques previously not in his repertoire (this would have been true of almost anyone, because of the variety of skills needed), and he has become sufficiently well versed in these new-to-him areas to be able to be informally very helpful indeed to many other members of the University research staff.

During the observational stages of our work, Mr. Rozian and I have worked together as a well-coördinated team. He has always been able to provide means of operation to meet our demands for flexibility in making observations that appeared as our data began to take shape. I have been the one to choose the plan of experimentation; he has been the one to provide in the apparatus the resources to carry out the plan, and he and I together have actually operated the equipment and made the experimental observations here reported on.

Mr. Rozian has at all times been completely loyal to the purposes of the program, and has contributed in very imaginative ways toward guiding the program toward optimization among the more than one kinds of value its purposes have included. Thus he has enthusiastically shared in the "scientific venturesomeness" of the program. I might comment that in a university, as elsewhere, it is not always easy to find men willing to embark on a venturesome career course when other choices of effort exist that have greater firm assurance of early positive results. Mr. Rozian shares well with me an enthusiasm for moving into new frontiers where there are many unknowns, and where risks of failure are substantial but where the stakes are high and the potential achievements very great.

Thus it was in my view a most thoroughly mutually satisfactory arrangement for Mr. Rozian and I to sign the Patent Disclosure papers last November as co-inventors. Part of the virtue of this is that, being a much younger man than I, he will be able to represent for a much longer time than I, the pattern of original conception and of diligent pursuit toward proving them out, that the work of the past three years on this program have involved.

Where I have said "we" in this report, I am referring to Mr. Rozian and myself, and am referring to his sharing with me in both the immediate and long-term professional thoughts and judgments in regard to this program.

37. Potential Values to be Achieved from the Use of Controlled Nuclear Fusions for Electric Power Generation. This matter of "potential value" was dealt with in some detail in our original proposal papers to you, and I will make only brief comments here. The realization, appearing from our experimental results, that the fruition is expected to come from quasi-ordered rather than random thermal motions of the ions, represents an advantageous change in the potential value, as compared with my thoughts expressed in the proposal papers.

Underlying the questions of patents, of recognition of originality of our concepts and acceptance of the venture risks, and underlying discussions of the nature of continuance of the total program, is the necessity of giving attention to values to be achieved, that is, what would be the virtues in generation of bulk power by controlled nuclear fusion, once we do know how to accomplish it?

The heavy hydrogen that would be used as "fuel" for nuclear fusion power generation is in plentiful supply at very low cost—and only very little is needed. It is not at all radioactive—the oceans contain enormous quantities of it. The fusion products include as the heaviest items ordinary helium and lithium. The fusion reactions do not in themselves produce any radioactively harmful substances. Thermal neutrons (that is, moderate-energy neutrons) do result from the fusion in the reaction chamber, and attention must be given to using envelope materials that do not become radioactively harmful from the internal bombardment by neutrons. Dr. Richard Post, Director of the Sherwood Project Laboratory at Livermore, California, has I believe good reason for his belief that once a feasible method of controlling nuclear fusions has been devised, the engineering aspects of building and operating the apparatus should be considerably simpler and less costly than is true for nuclear fission power generation. In any initial phases controlled nuclear fusion power will appear as a heat source, the heat being used to drive conventional electric power generators. Since all fusion processes involve the use of electrically charged particles, it may well come about that a means will be found for generating the power directly in electrical form, but there is no early promise of this.

Thus for nuclear fusion the "fuel" would be of trivial cost and completely safe to handle, the construction relatively straightforward, and the operation relatively simple and free from radioactive-material hazards if well designed. Probably the largest item of cost will be that for providing the necessary very high magnetic flux densities—cryogenic apparatus will be required for this part of the equipment.

But on the whole, the economics of any conceivable process appear very advantageous, providing we once learn how to "light the match" of controlled fusion. Certainly the economic prospects are attractive enough to warrant further research and development toward a promising method of lighting the match.

38. <u>The Obvious Next Phase in the Total Program will be to Conduct Experiments Using Deuterons, Generally Paralleling What We have Done</u>. The obvious next major Phase II in a total program for using our proposed method for nuclear fusion power generation, is to build and carry out experiments

very similar to those here reported on, but capable of using deuterons rather than electrons. Actually, much of the needed information could be obtained by using protons (nuclei of ordinary atomic hydrogen) rather than deuterons.

Such experimental equipment using deuterons could well employ stream current no larger and possibly smaller than the 20 to 50 milliamperes we have used, and the electrode voltages might need to be twice or three times what we have used, thus ranging up to 15,000 to 20,000 volts.

The most important change would be in the requirement for magnetic flux densities ranging from 120,000 gauss to 200,000 gauss. For experimentation purposes it would probably be satisfactory to have these flux densities produced for short periods only, as for example, a few seconds (perhaps as short as a few tens of milliseconds) for each of successive measurement operations. Production of such flux densities is at present "within the state of the art" by more than one method.

The next most important difference from the present apparatus would be in the provisions for an ion source and for terminal disposal or recirculation of the deuterons. Our electrons recirculate through the metallic electrical circuit; deuterons cannot do so. Apparatus for producing such an ion stream as would be needed is also within the present "state of the art," but is relatively bulky and expensive, especially when provided with the flexibilities of control and recirculation or disposal we will need.

The primary purpose of this next Phase II whould be to gain experience with giving protons and deuterons high kinetic energies by the same means we have given them to electrons. However, because fusion reaction may conceivably set in at a lower energy than the expectations, provisions should be made for identifying its presence and measuring its magnitude. Also, a fusion reaction chamber should be provided, partly to gain experience with its design, partly to gain experience with confinement of the reacting monopolar plasma if fusion reactions should appear, as may well happen. The reaction chamber should incorporate means for measuring carefully and disposing of any heat that may result from fusion reactions within it. In this next phase it is not likely that the reaction chamber walls will be heated to a high temperature.

Thus the primary purpose of the next experimental Phase II should be to obtain mastery of the science and art of producing and maintaining a high-energy ion-constituted cross-field-neutralized monopolar plasma stream, but we should plan Phase II to permit rapid moving into the next phase if experimental evidence warrants.

Thus the emphasis on fusion reaction should come in a Phase III of the experimentations, which might however use the same apparatus and professional staff as those involved in Phase II.

The cost of building the apparatus for Phase II, of study of the science and technology of the monopolar <u>ion</u>-constituted stream, will probably not be less than $250,000 nor more than $500,000. The budget for experimental operation should be at least $100,000, possibly $150,000, annually, with the expectation of moving into the Phase III of research on fusion reaction whenever research result indications warrant it. The budget should be set up to provide for a minimum of three years of operational research on Phase II, and into Phase III, with the equipment, <u>after</u> it has been completed and proved to be in operable condition.

39. <u>Steps Needed to Initiate the Phase II Experimentation on an Ion-Constituted Monopolar Plasma</u>. The most immediate needs for the total program, after the urgency for patent processing has been looked after, have to do with planning how to obtain and administer budgetary support of the extent and nature suggested above for undertaking Phase II. The following itemized action

and planning concepts and functions seem to me to require attention in order to provide for moving ahead:

A. Adequate budgetary support can only be obtained by exposing to properly-chosen and scientifically well-informed people adequate evidence of the promise of the method.

There will be needed for this purpose:

(1) Copies of parts or all of this report.

(2) Copies of the Patent Disclosure papers.

(3) A report on or publication of a reasonably adequate theory for the observed electron behavior. If I do this myself, it will in my present pattern of living take me at least a year. If I could have a capable person work under my direction on it, we might achieve an adequate theory in 6 to 8 months.

(4) A report on the application of the scaling laws, toward design of the deuteron apparatus, needs preparation. I have this about half done.

(5) Experimental evidence from the modified apparatus; especially we need thermocouple evidence of electrode heating by electron impact, microwave measurements of the frequency of the disturbance, evidence as to whether any "saturation" appears, and operation at maximum energy; some of this Mr. Rozian and I will be able to obtain this summer, according to present plans. Reporting of results adequately will take until sometime in the fall of this year.

(6) A publication in the open literature of our experimental results as presented in this report. If you authorize me to use the information in this way, I could probably have a manuscript ready by April 1, 1966.

B. An investigative inquiry should be carried out, by visiting the properly informed people, as to the best methods now feasible for producing the needed high magnetic flux density and the ion stream.

C. A tentative gross-aspect design of the second-phase apparatus needs to be prepared, for inclusion in a proposal to secure funds.

D. A proposal requesting budgetary support—a quite complete one—needs preparation, as for example, for submission to the Edison Electric Institute.

E. Thought needs to be given as to whether the next phase of the experimentation should be carried out in your laboratories, or ours, or elsewhere, and as to who should be in immediate charge. Let me say that Mr. Rozian has shown great competence and resourcefulness as an experimenter in the present program.

F. Negotiations for support need to be diligently and enthusiastically pursued, by personal representations in promising quarters.

40. Closure. Let me say in closing that it has been very enjoyable to find myself functioning jointly in the interests of Consumer's Power Company, The University of Michigan, and my own enthusiasm, on this project. Mr. Rozian and I have found it extremely pleasant to work with Mr. Robert Kettner and Mr. Gilbert Keeley from time to time.

Also, a great human satisfaction exists in my recollection of the continuing encouragement toward this effort that was always evident in the attitude toward it of the late Dean S. S. Attwood of the College of Engineering. He and I have been lifelong friends and colleagues, but I was clearly aware that his encouragement toward this effort on my part was based not at all on personal friendship, but rather on his belief in the worth of my resources of free-wheeling scientific imagination, and my record of professional achievement. I always enjoyed and had a profound respect for his remarkable gifts of long-term vision. He could always see well beyond the top of the hill that lay ahead of the hill now facing us. His encouragement in this effort helped to give me confidence in the wisdom of my own enthusiasm.

And my own enthusiasm for this present total program has not waned. I believe we are on the right track, and that our approach will if pursued, by all concerned, with diligence, imagination, flexibility of mind, and enthusiasm in making outside representations, lead to extremely important achievements.

It is my most sincere hope that in one way or another many of us in Michigan may have the satisfaction of playing leading parts in creating the new values the approach we are using promises. Do not forfeit the leadership.

This is nothing eternal but change. An important part of the responsibility of every member of the engineering profession is always to listen for the changing of the winds, and to do what he can toward creating new winds of change.

TABLE I

OPERATING CONDITIONS FOR FIGURES 11 AND 12

Date and Time: February 17, 1965, about 3:15 to 4:00 p.m.

Magnetic Field:

Direct current: 200 amperes, falling off to 175
Flux density (Fig. 8): 2000 gauss, falling off to 1750

Electron Stream and Conditions Governing It:

Sole potential relative to cathode: -250 volts
Roof electrode, facing Sole Segments Nos. 1 to 5, and facing cathode block, potential relative to cathode: +1750 volts
Spacing cathode to roof electrode: 3/4 inch = 19.05 mm
Active length of filament: 1-1/2 inches = 38.1 mm
Cathode current: 25.5 milliamperes falling off to 22

Driver Electrode Conditions:

Group A, facing Sole Segments Nos. 5 to 10, potential relative to cathode: +850 volts
Groups B, C, D, E, facing Sole Segments Nos. 10 to 36, potential relative to cathode: +1750 volts

Stream Collection:

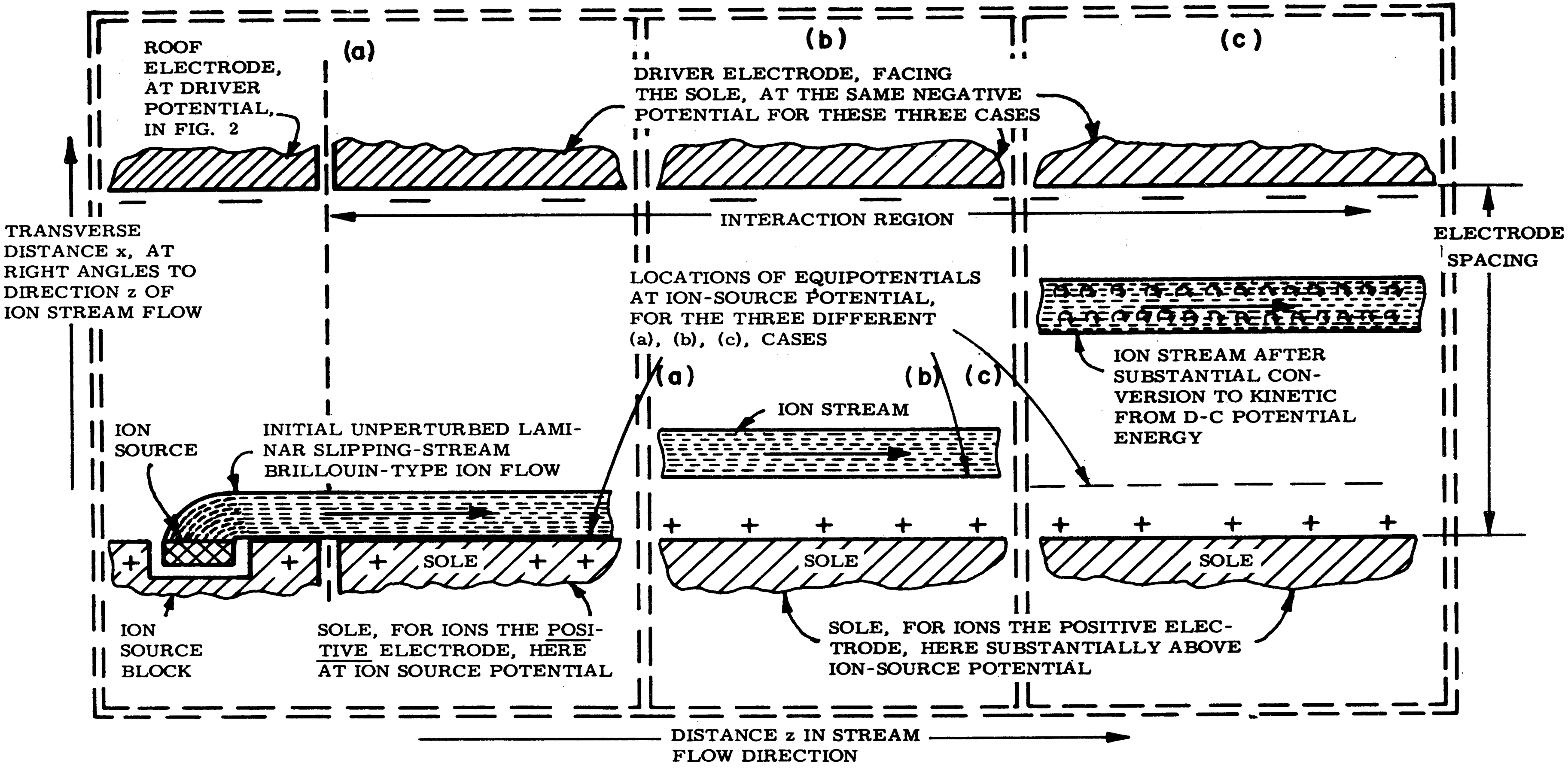
Sole Segments Nos. 32 to 36: + 250 volts; ~18 milliamperes
Collector electrode: +1750 volts; ~ 5 milliamperes
Driver electrode Group A: + 850 volts; ~ 2 milliamperes

Probing Segments:

During these observational runs nearly all segments were used in turn as probes; to avoid confusion, in the Fig. 11 presentation only selected ones are shown. It was found that the physically depressed segments, Sole Segments Nos. 4, 8, 12, 16, 20, 24, 28, drew so little current as to make data from them uninteresting. Reasons for selections of segments for charting are discussed in connection with Fig. 12.

Sole Electrode Conditions:

Configuration No. 4, depressed Sole Segments Nos. 4, 8, 12, 16, 20, 24, 28.



(a) BRILLOUIN-TYPE ION STREAM ORIGINATING FROM EMBEDDED ION SOURCE: SEE FIG. 2

(b) BRILLOUIN-DERIVED ION STREAM FLOW WHERE SOLE IS ABOVE ION SOURCE POTENTIAL, THUS PUSHING THE STREAM SOMEWHAT AWAY FROM THE SOLE; SEE FIG. 3

(c) BRILLOUIN-DERIVED ION STREAM WITH HIGH ROTATIONAL ENERGY CONTENT, WHOSE KINETIC ENERGY EXISTS BY CONVERSION FROM D-C POTENTIAL ENERGY CORRESPONDING TO THE STREAM'S TRANSVERSE SHIFT; SEE FIG. 4

Figure 1. Ion stream position shift with associated conversion to kinetic from D-C potential energy, in interaction region.

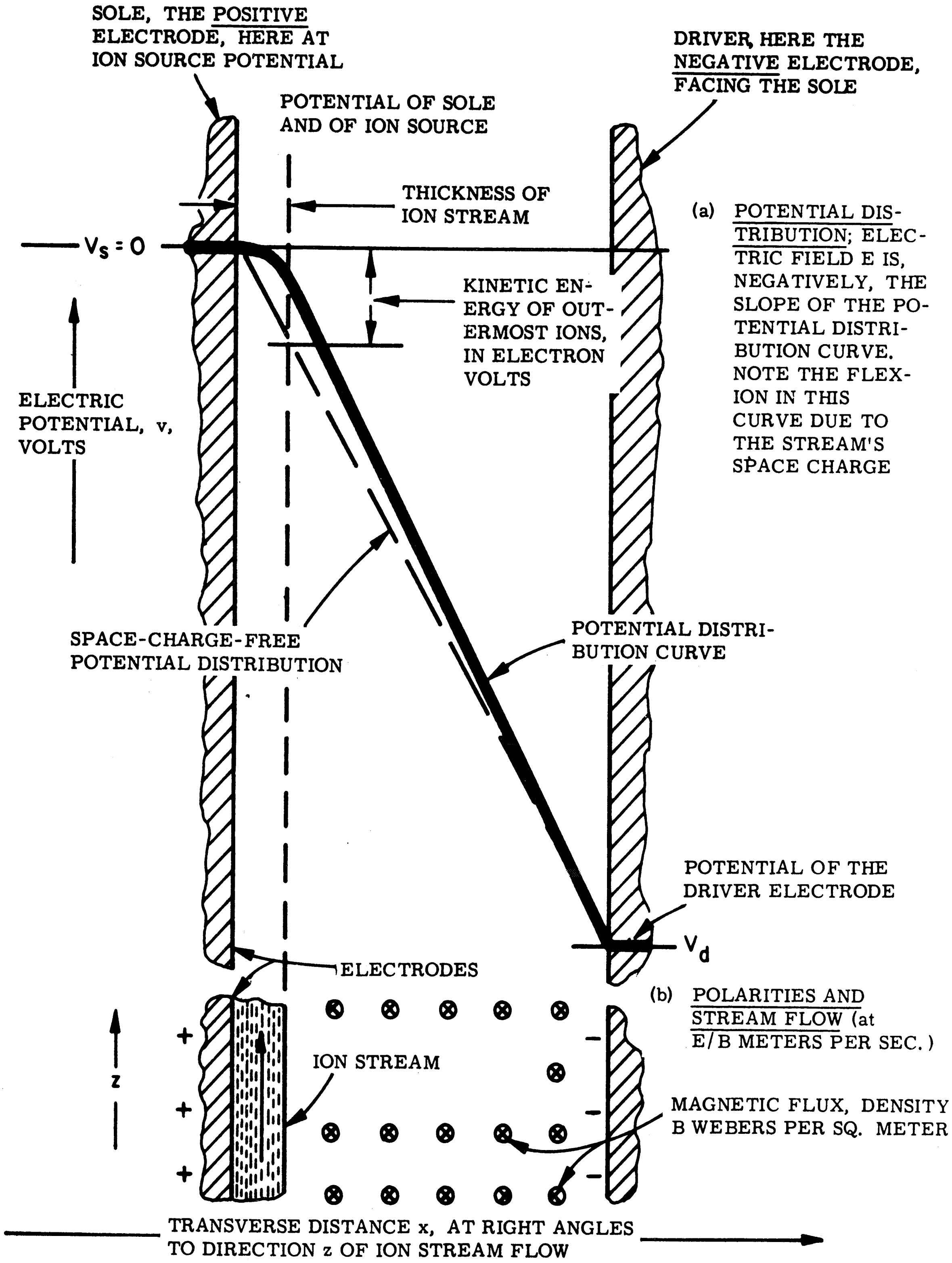


Figure 2. Initial unperturbed slipping-stream laminar Brillouin-type ion flow in crossed D-C electric and magnetic fields, with sole at ion-source potential.

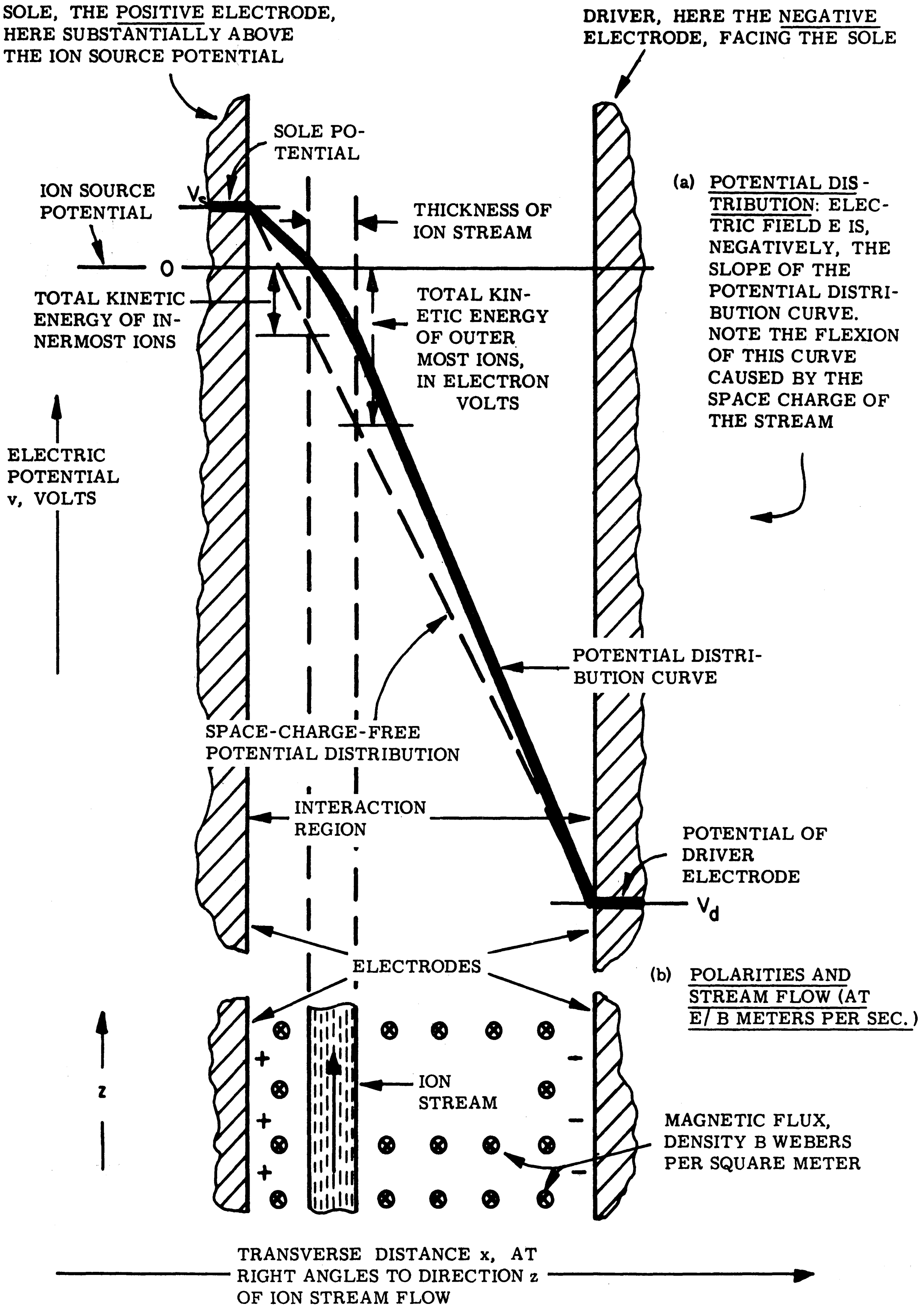


Figure 3. Brillouin-derived ion stream flow in crossed fields, with sole substantially above ion source potential, but innermost ions at ion source potential.

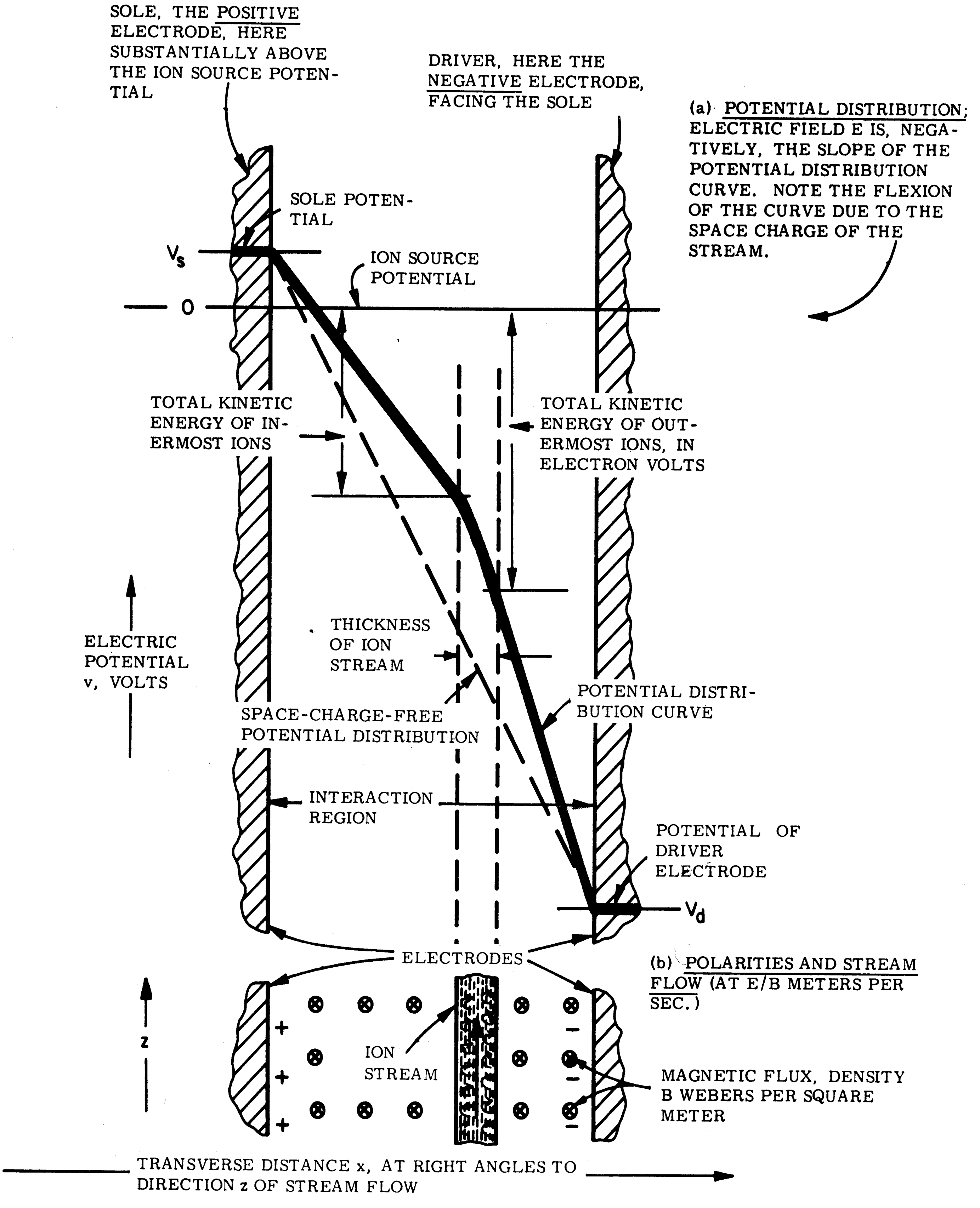
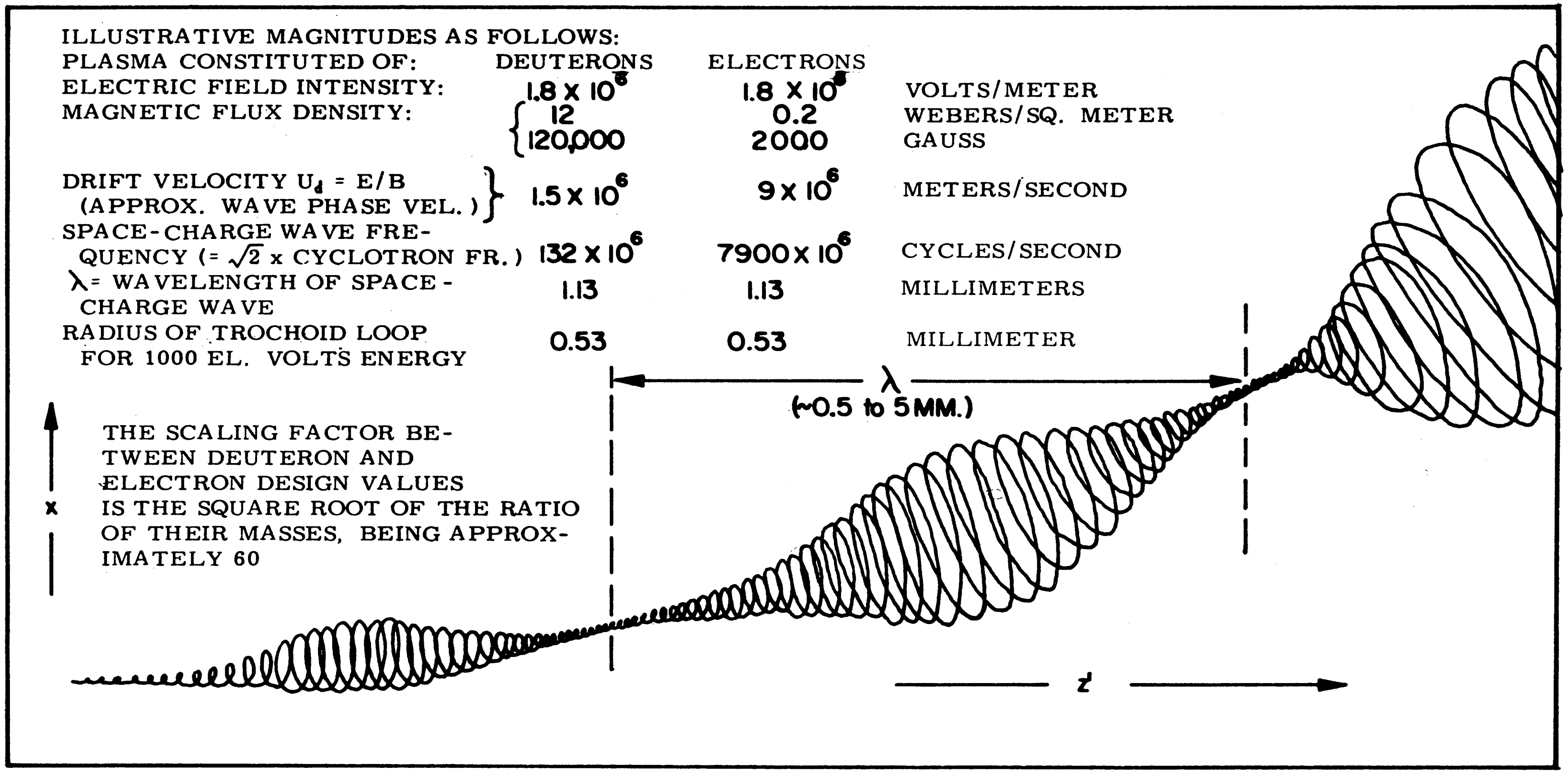


Figure 4. Brillouin-derived ion stream flow in crossed fields, with sole substantially above ion source potential, and with substantial conversion to kinetic from D-C potential energy, corresponding to stream's transverse shift.



ILLUSTRATIVE MAGNITUDES AS FOLLOWS:

PLASMA CONSTITUTED OF:	DEUTERONS	ELECTRONS	
ELECTRIC FIELD INTENSITY:	1.8×10^{8}	$1.8 \times 10^{[illegible]}$	VOLTS/METER
MAGNETIC FLUX DENSITY:	12 120,000	0.2 2000	WEBERS/SQ. METER GAUSS
DRIFT VELOCITY $U_d = E/B$ (APPROX. WAVE PHASE VEL.)	1.5×10^{6}	9×10^{6}	METERS/SECOND
SPACE-CHARGE WAVE FREQUENCY (= $\sqrt{2}$ x CYCLOTRON FR.)	132×10^{6}	7900×10^{6}	CYCLES/SECOND
λ= WAVELENGTH OF SPACE-CHARGE WAVE	1.13	1.13	MILLIMETERS
RADIUS OF TROCHOID LOOP FOR 1000 EL. VOLTS ENERGY	0.53	0.53	MILLIMETER

THE SCALING FACTOR BETWEEN DEUTERON AND ELECTRON DESIGN VALUES IS THE SQUARE ROOT OF THE RATIO OF THEIR MASSES, BEING APPROXIMATELY 60

Figure 5. Diagram of one conceptual model of the trajectory of an individual electron or ion of the growing space-charge wave in a monopolar crossed-field-neutralized plasma, in the advancing z' frame of reference moving with the phase velocity of the propagating space-charge wave. In the wave there are enormously many particles with such trajectories, overlapping almost completely in both the x and z' coordinates; drawn to a greatly enlarged scale.

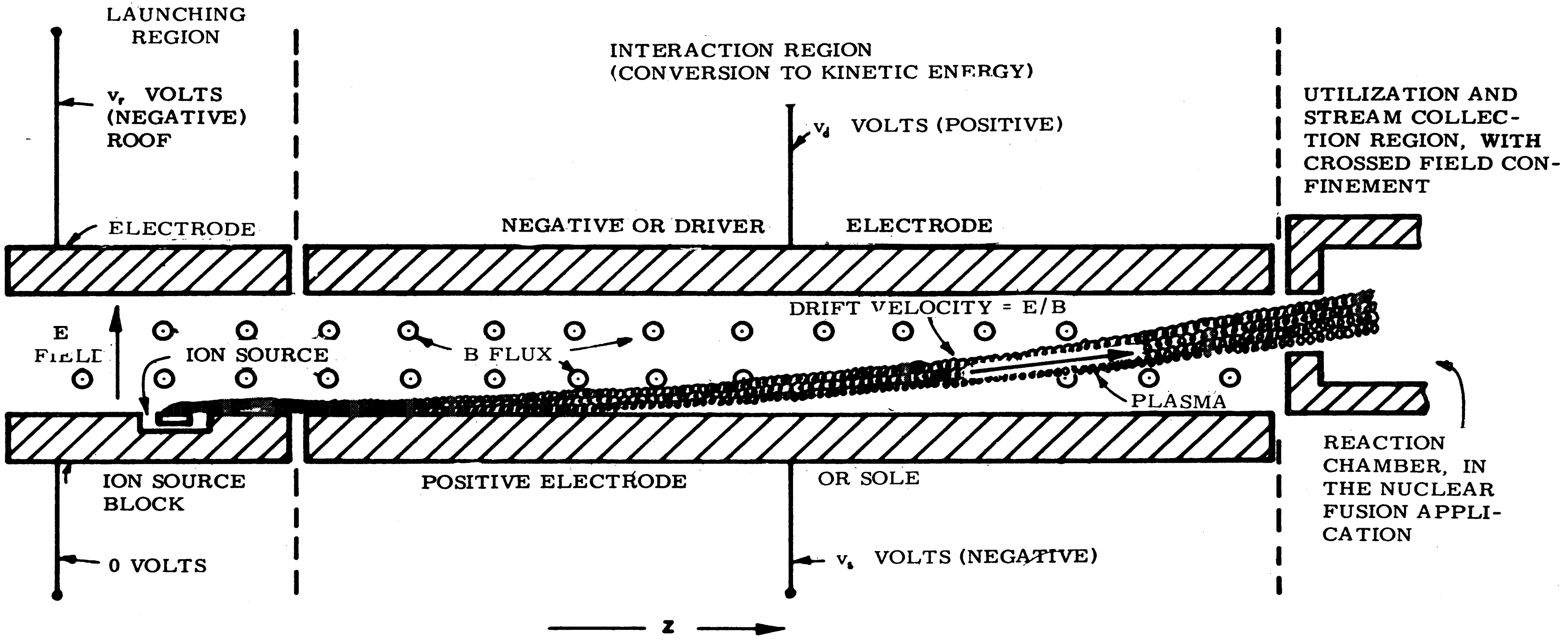


Figure 6. Elementary linear crossed-field device for producing an ion-constituted monopolar crossed-field-neutralized plasma; see Figs. 1, 2, 3, 4.

Flow regime is for a V/B ratio (voltage to magnetic flux density) very much less than that for magnetic cut-off of direct ion flow to the roof electrode.

Depending on design objectives, the vertical spacing and geometry of electrodes in the launching region may differ from those in the interaction region.

Either or both the magnetic and electric fields may be varied along the device, the latter for example by segmenting driver electrode and/or sole, and having differing spacings and voltages on successive segments.

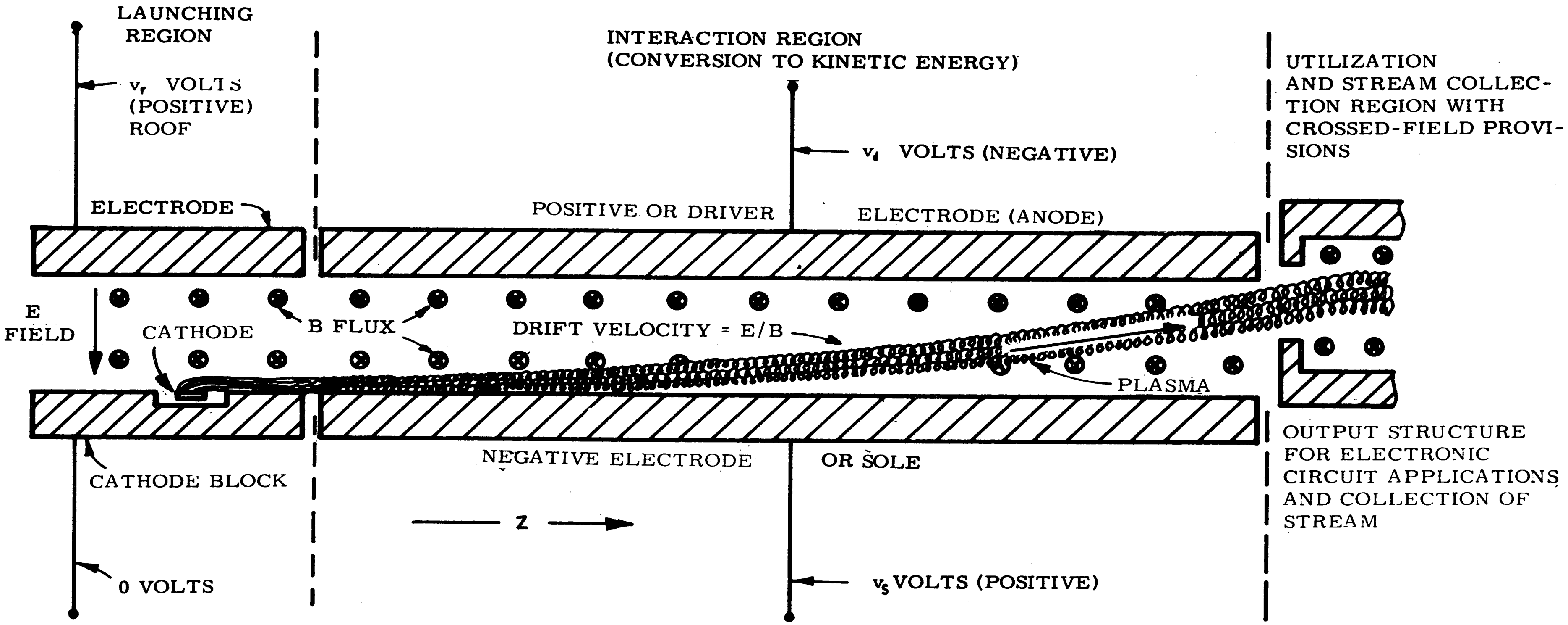


Figure 7. Elementary linear crossed-field device for producing an electron-constituted monopolar crossed-field-neutralized plasma.

Flow regime is for a V/B ratio (voltage to magnetic flux density) very much less than that for magnetic cut-off of direct electron flow from cathode to roof electrode.

Depending on design objectives, the vertical spacing and geometry of launching-region electrodes may differ from those in the interaction region.

Either or both the magnetic and electric fields may be varied along the device, the latter for example by segmenting the driver electrode and/or sole, and having the differing spacings and voltages on successive segments.

The output structure may be an extended crossed-field region including wave-to-circuit coupling, and collection.

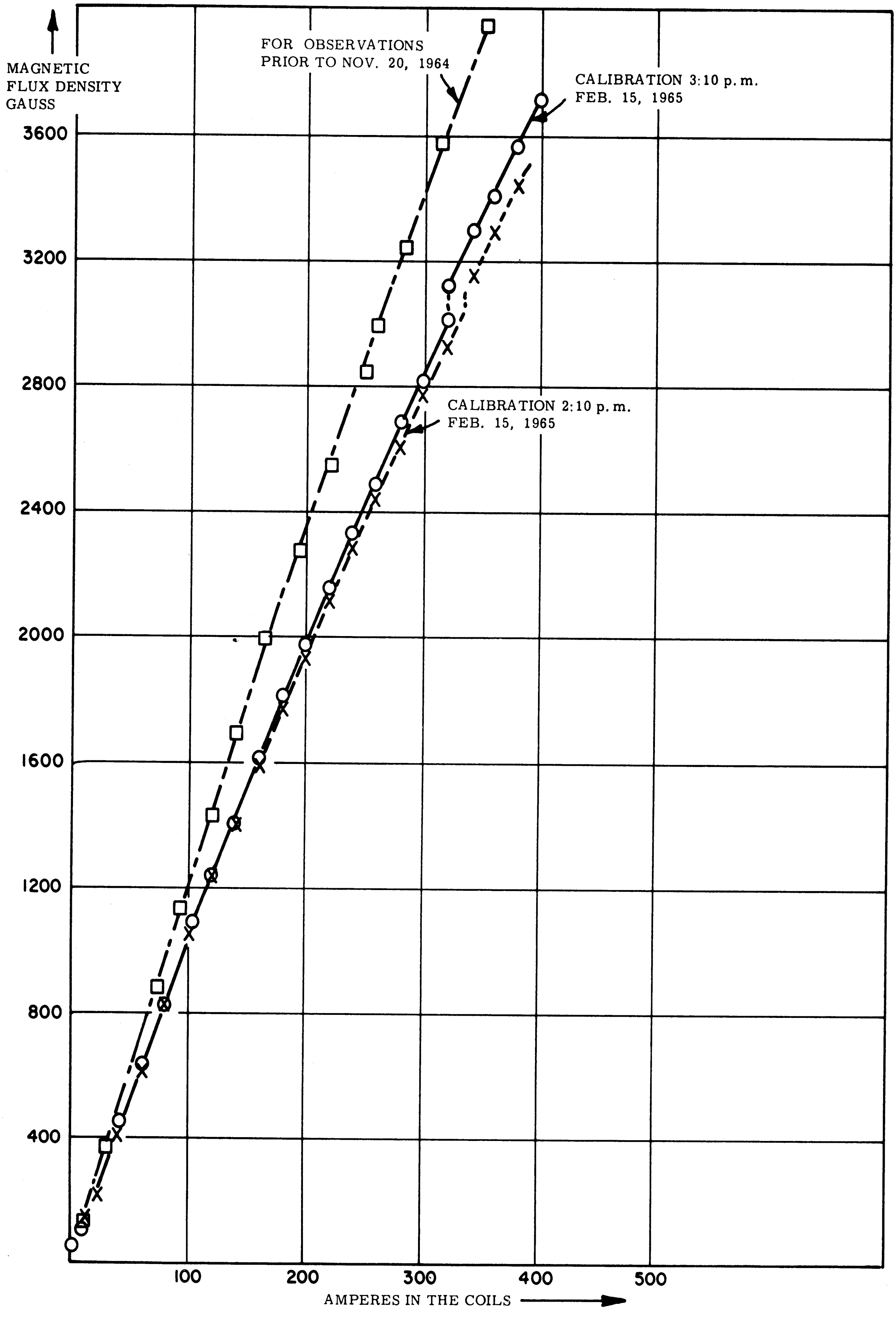
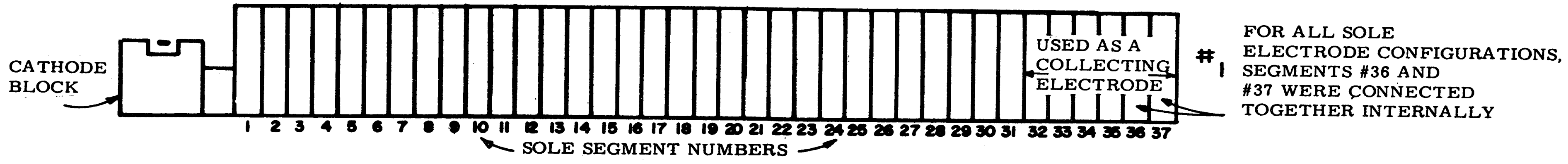
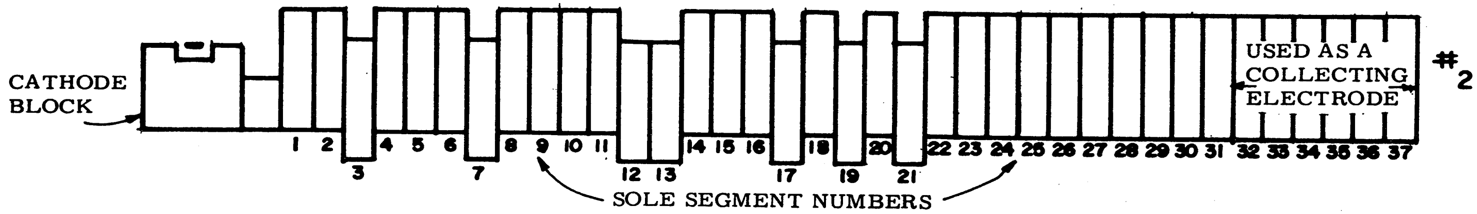


Figure 8. Magnetic field calibration.
Magnetic flux density vs. current through the two magnet coils in parallel

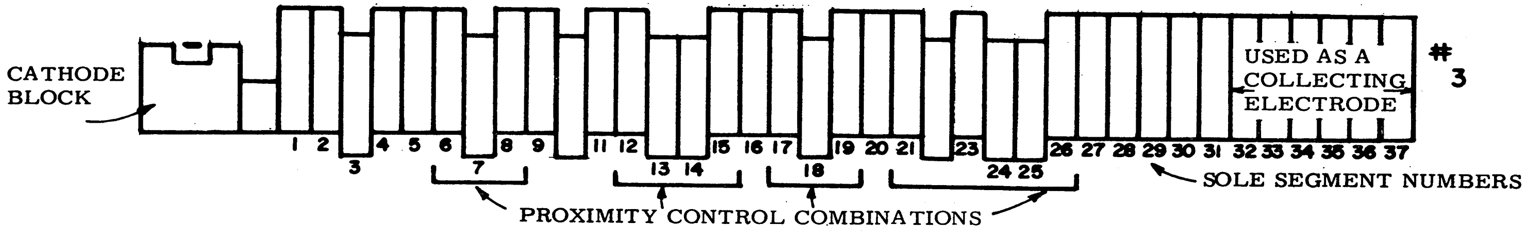
W.G. Dow and I. Rozian



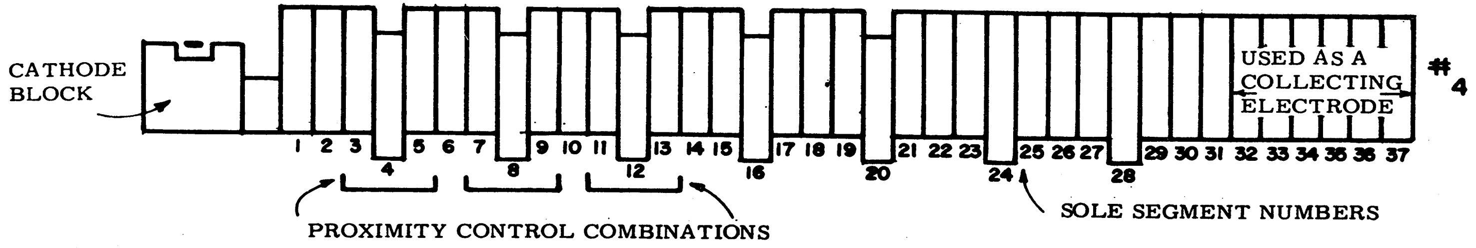
(a) Sole electrode configuration #1, no depressed segments, June and early July, 1964.



(b) Sole electrode configuration #2, late July and early August, 1964.



(c) Sole electrode configuration #3, late August through October, 1964.



(d) Sole electrode configuration #4, November, 1964, and February and March 1965.

(e) Sole electrode configuration #5, May and June, 1966, no depressed segments, no collection on sole.

Figure 10. Sole electrode configurations, showing segments depressed by inversion.

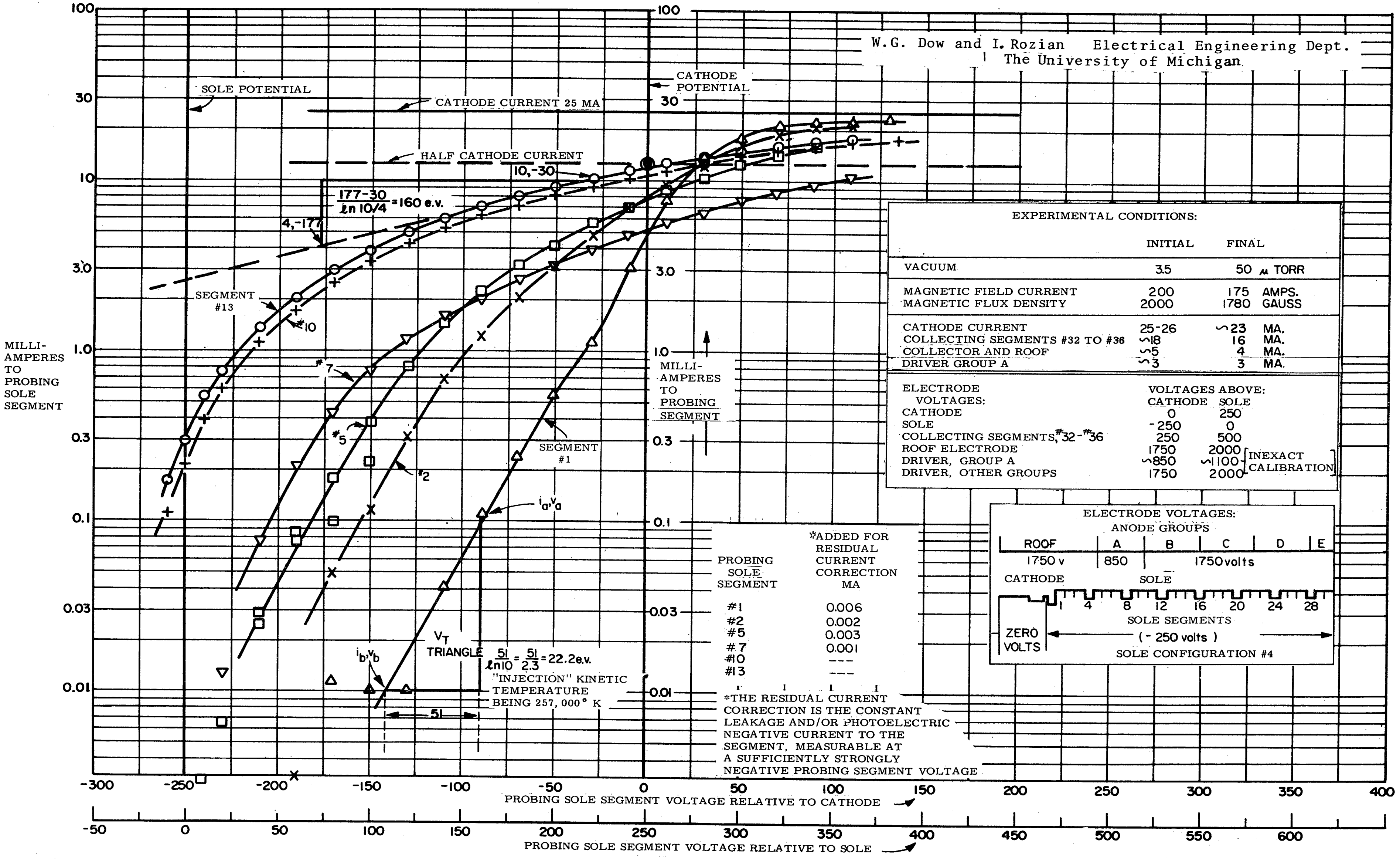


Figure 11. Volt-ampere curves for sole segments used as probes of a monopolar electron constituted crossed-field-neutralized plasma. Feb. 17, 1965, Run No. 1 3:15 to about 4:00 PM.

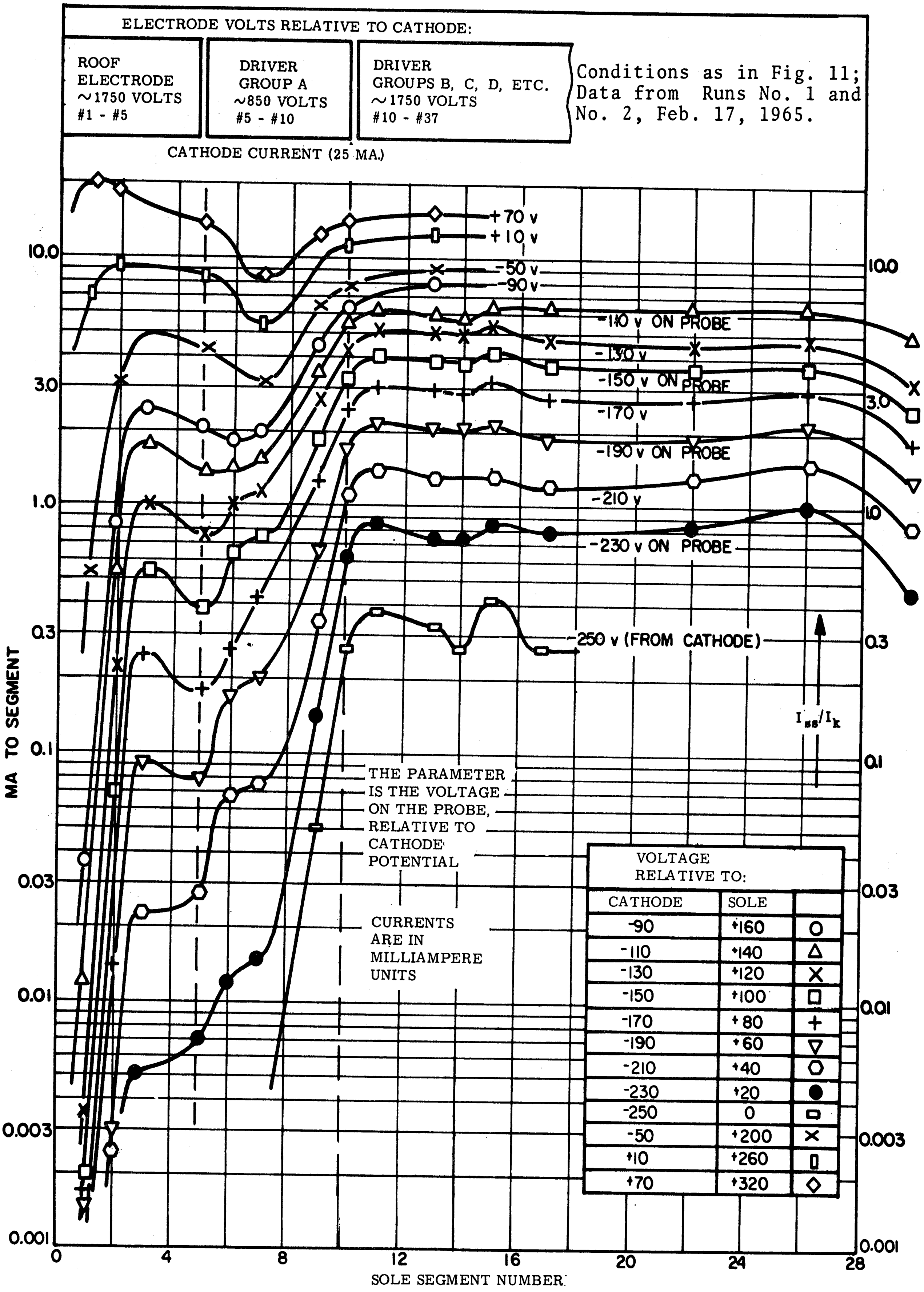
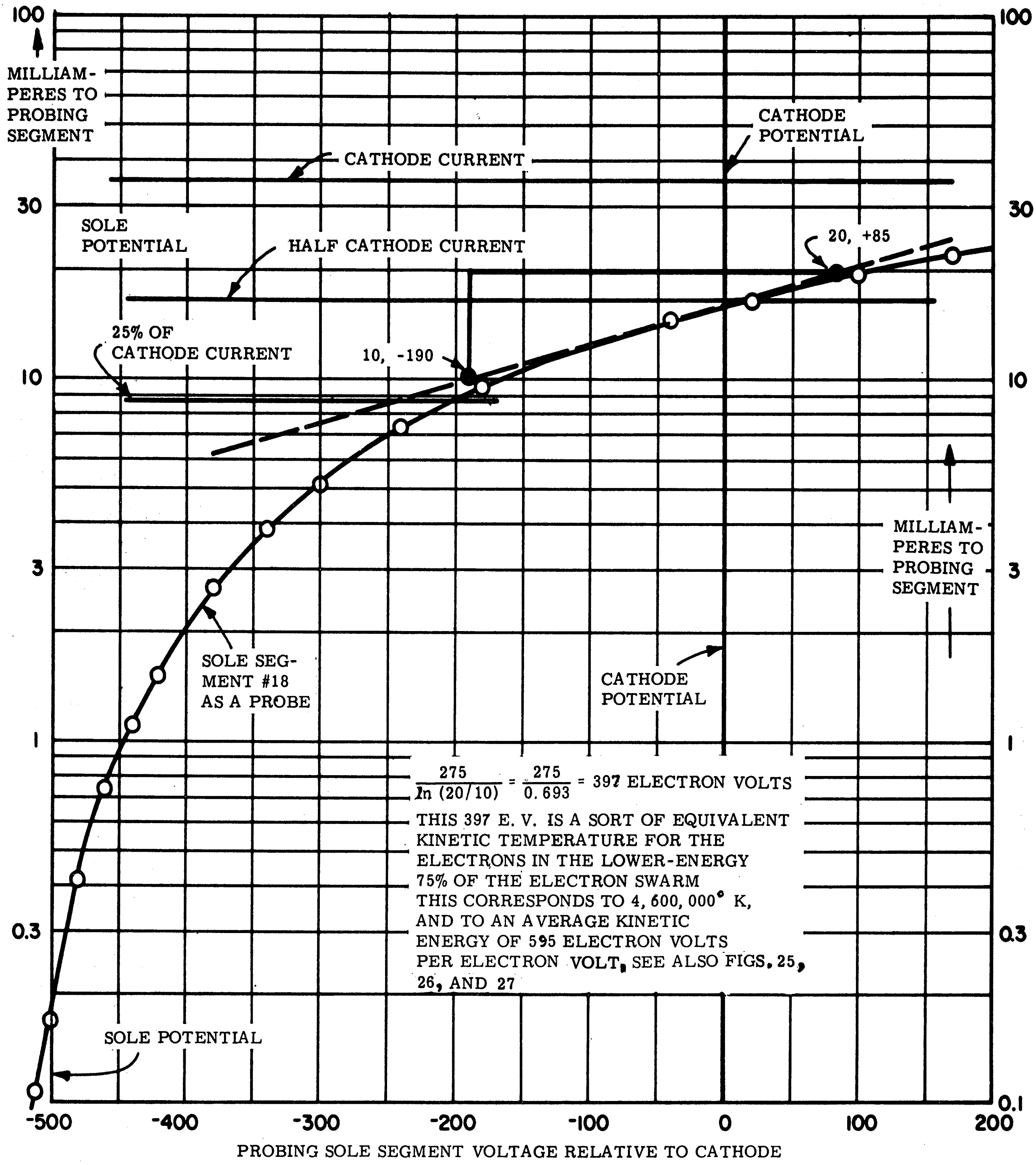


Figure 12. Probing sole segment current profiles, probe voltage the parameter, showing conversion from potential to particle kinetic energy.

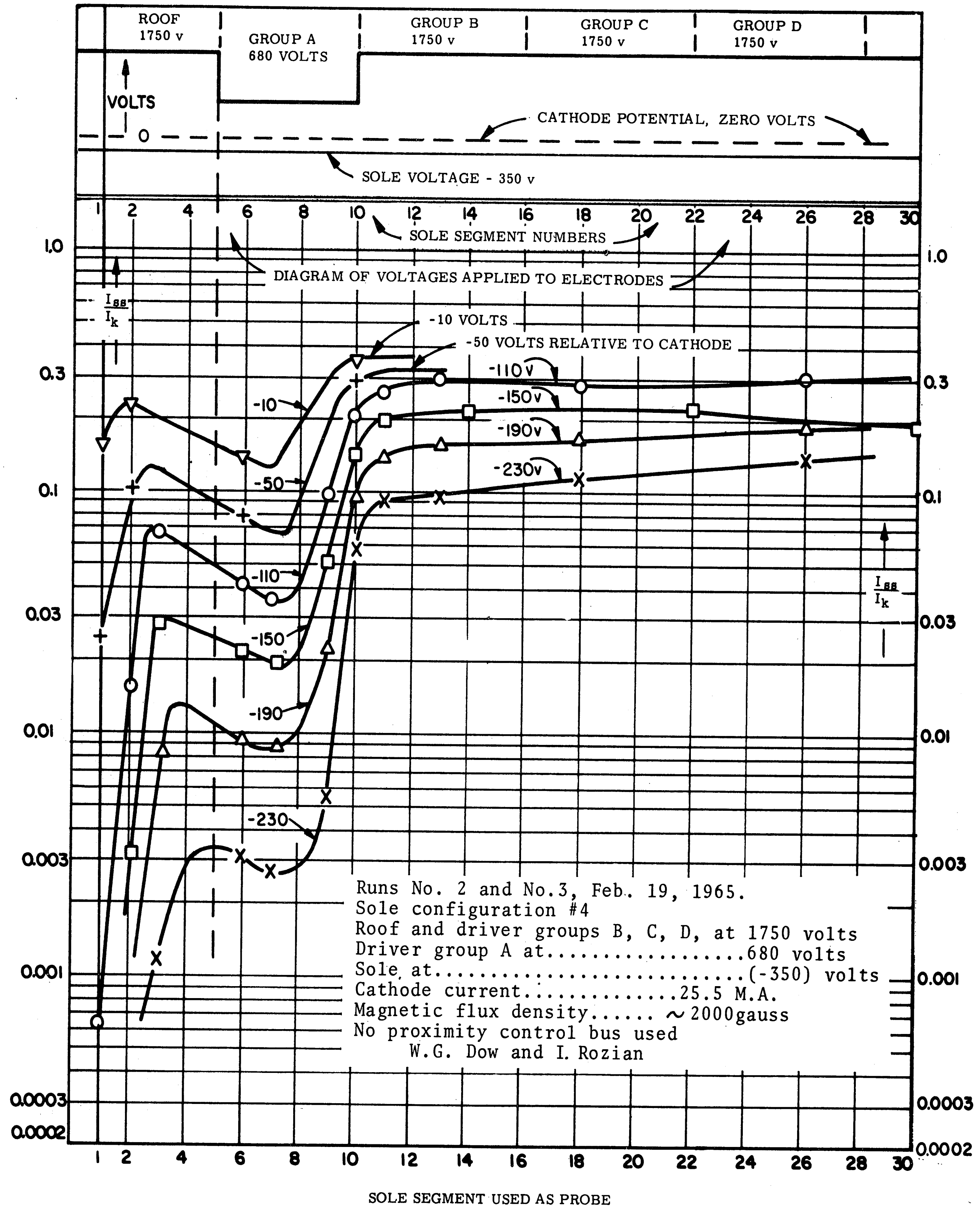


$\frac{275}{\ln(20/10)} = \frac{275}{0.693} = 397$ ELECTRON VOLTS

THIS 397 E. V. IS A SORT OF EQUIVALENT KINETIC TEMPERATURE FOR THE ELECTRONS IN THE LOWER-ENERGY 75% OF THE ELECTRON SWARM THIS CORRESPONDS TO 4,600,000° K, AND TO AN AVERAGE KINETIC ENERGY OF 595 ELECTRON VOLTS PER ELECTRON VOLT, SEE ALSO FIGS. 25, 26, AND 27

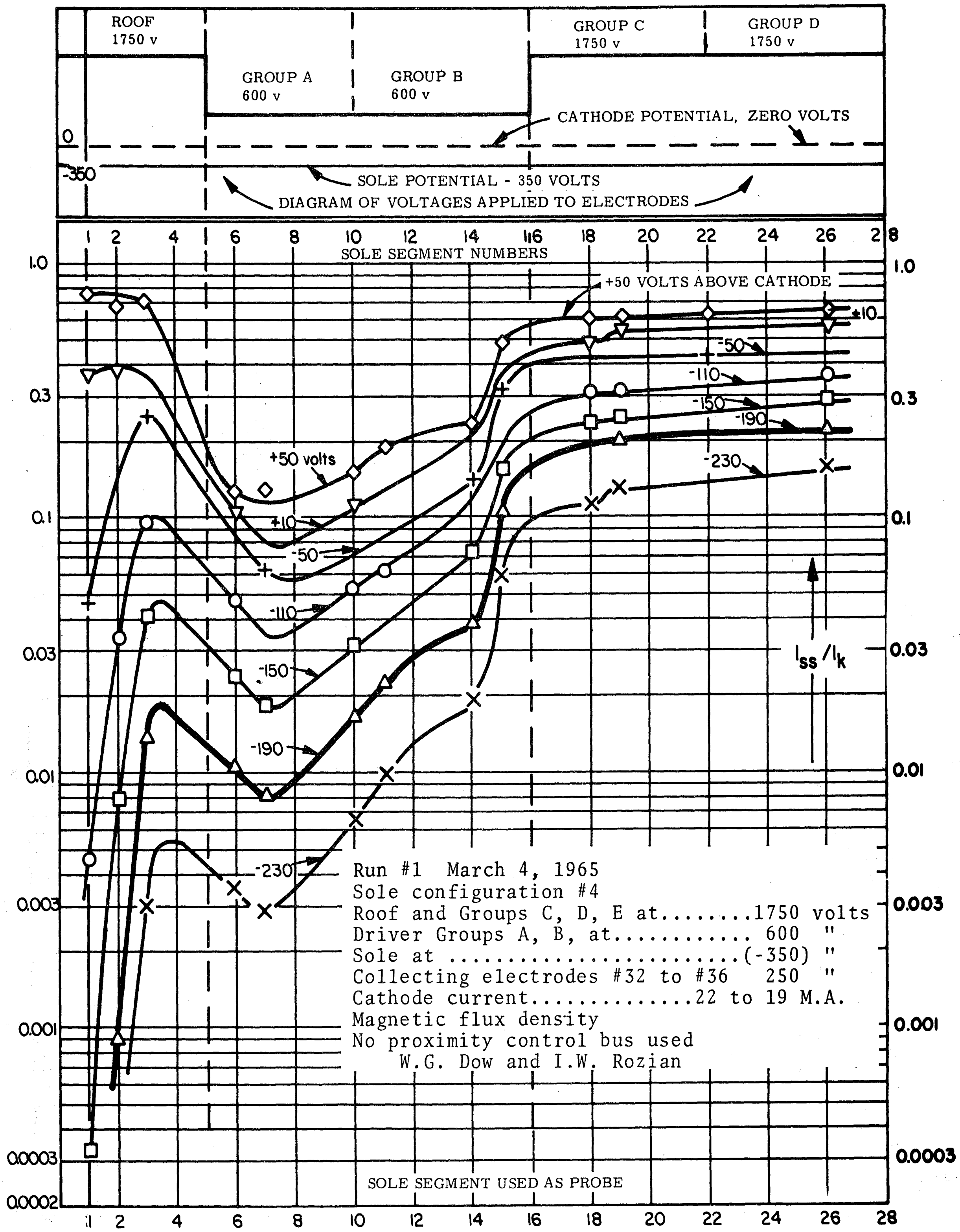
Figure 13. Volt-ampere curve for sole segment #18, being that at the highest-kinetic energy location, for the highest energy 2800-gauss operation with sole configuration on No. 4, being for Run No. 1 on March 19, 1965. Conditions as follows, voltages relative to cathode:

Driver group A at ~ 700 volts
Driver group B at ~1450 volts
Roof and other
Driver groups at ~2500 volts
Sole at -500 volts
Cathode current 35 M.A.



Runs No. 2 and No.3, Feb. 19, 1965.
Sole configuration #4
Roof and driver groups B, C, D, at 1750 volts
Driver group A at.................680 volts
Sole at..........................(-350) volts
Cathode current..............25.5 M.A.
Magnetic flux density...... ~ 2000gauss
No proximity control bus used
W.G. Dow and I. Rozian

Figure 14. Profiles of ratio Iss/Ik of probing segment current to cathode current, with driver electrode group A at a depressed voltage. These were conditions generally similar to those for Fig. 12.



Run #1 March 4, 1965
Sole configuration #4
Roof and Groups C, D, E at........1750 volts
Driver Groups A, B, at............ 600 "
Sole at ....(-350) "
Collecting electrodes #32 to #36 250 "
Cathode current..............22 to 19 M.A.
Magnetic flux density
No proximity control bus used
W.G. Dow and I.W. Rozian

Figure 15. Profiles of ratio I_{ss}/I_k of probing sole segment current to cathode current, with two driver electrode groups at a depressed voltage. Contrast this with Fig. 14. Probing segment voltage, relative to cathode, is the parameter.

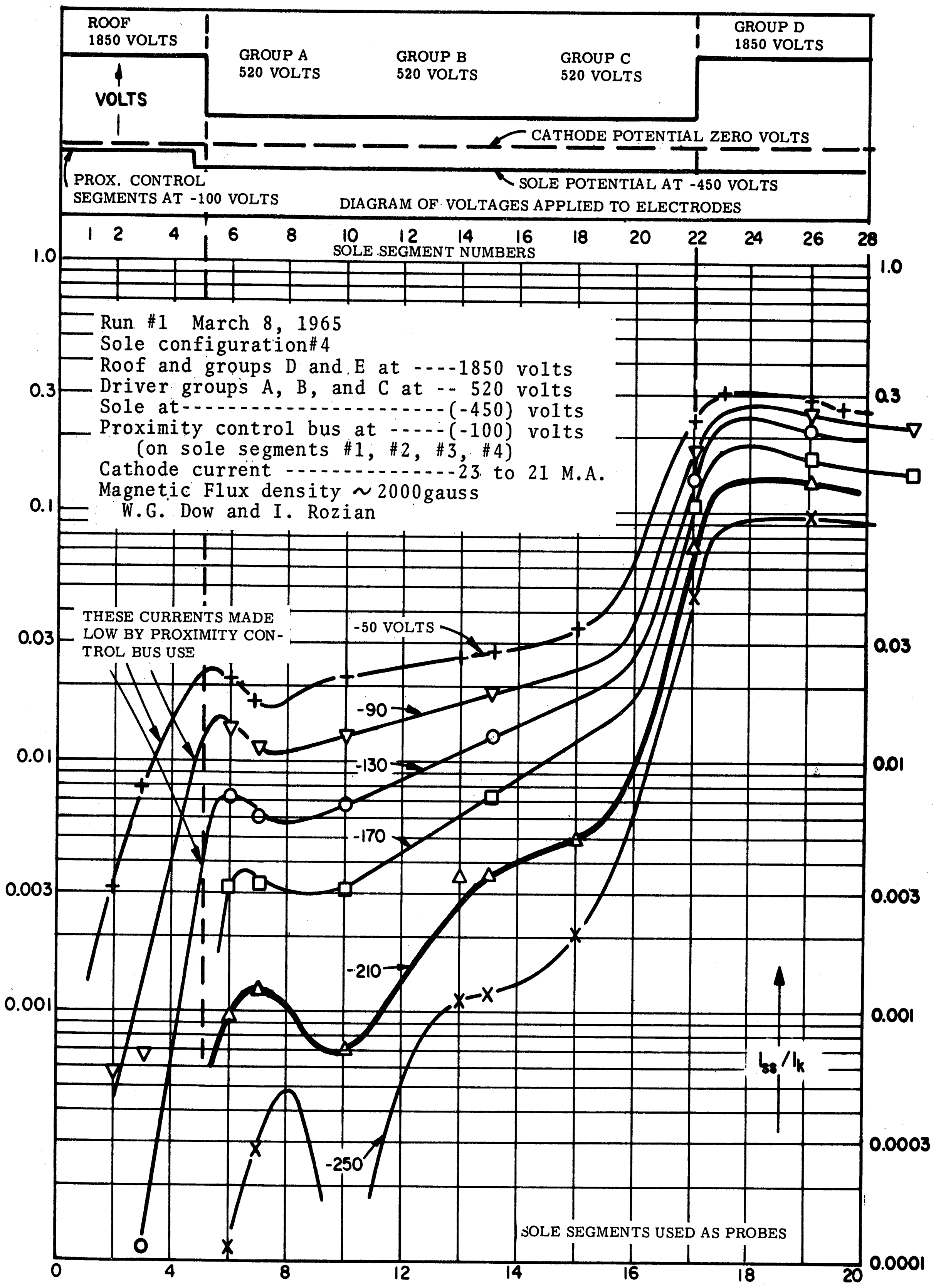
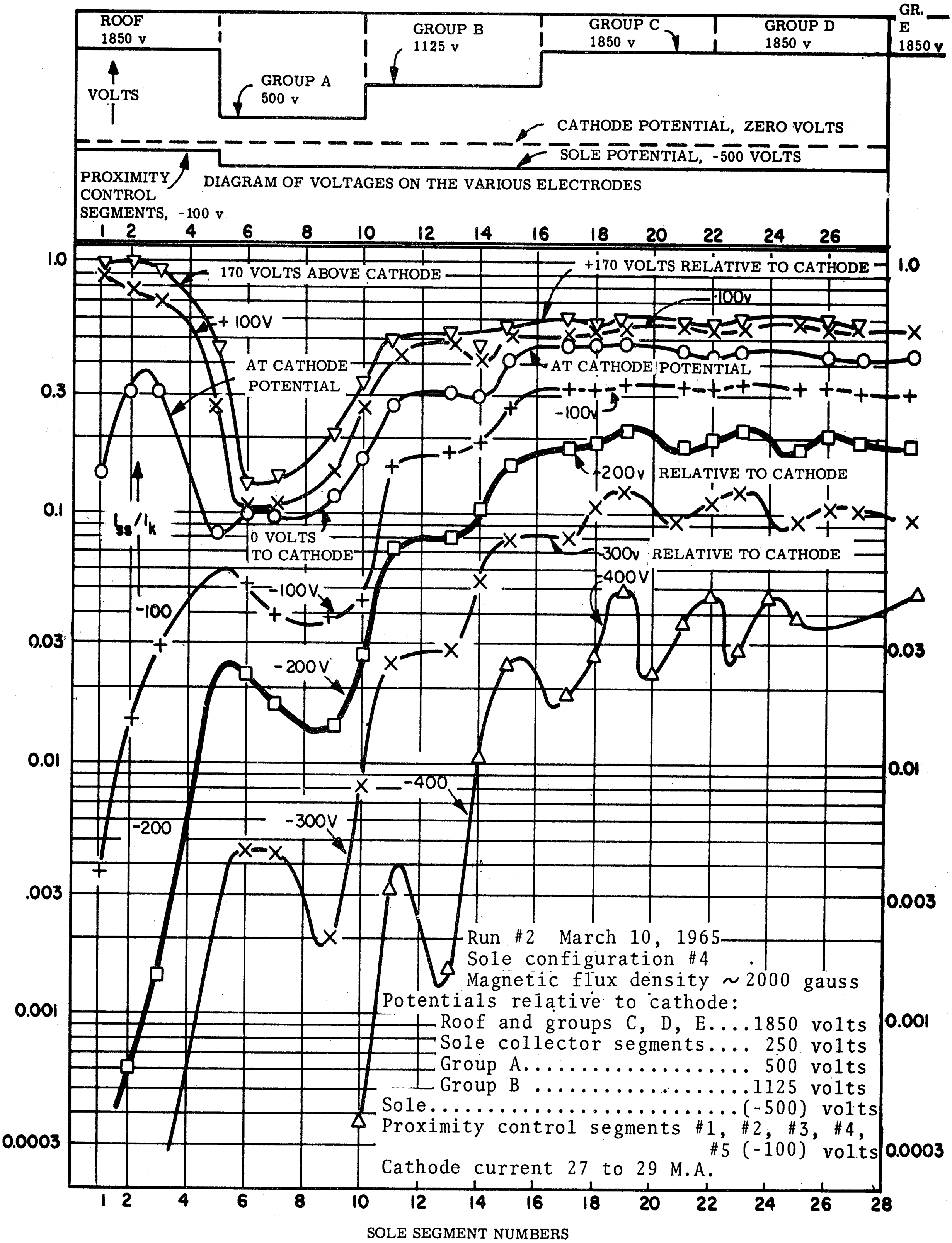
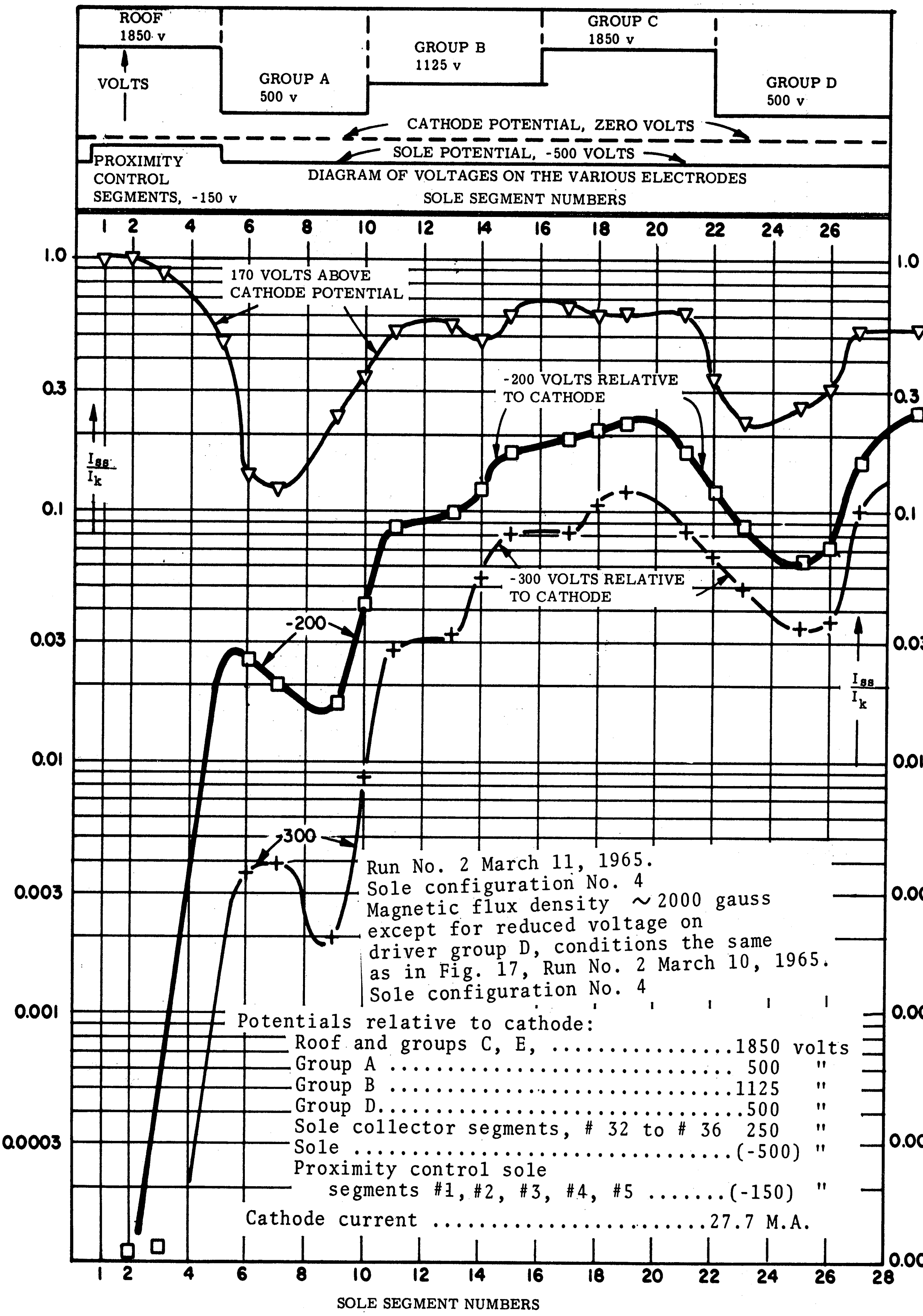


Figure 16. Profiles of ratio Iss/Ik of probing sole segment current to cathode current with three driver electrode groups at a depressed voltage. Contrast with Figs. 14, 15. Probing segment voltage relative to cathode is the parameter.



Run #2 March 10, 1965
Sole configuration #4
Magnetic flux density ~ 2000 gauss
Potentials relative to cathode:
Roof and groups C, D, E....1850 volts
Sole collector segments.... 250 volts
Group A.................. 500 volts
Group B ....1125 volts
Sole......................(-500) volts
Proximity control segments #1, #2, #3, #4, #5 (-100) volts
Cathode current 27 to 29 M.A.

Figure 17. Profiles of the ratio I_{ss}/I_k of current in sole segment used as a probe to cathode current, with driver electrode groups depressed in steps; proximity control bus connected to early segments. Parameter is voltage of probing segment relative to cathode. Note spatial periodicity relative to depressed segments #4, #8, #12, #16, #20 #24.



Run No. 2 March 11, 1965.
Sole configuration No. 4
Magnetic flux density ~ 2000 gauss
except for reduced voltage on
driver group D, conditions the same
as in Fig. 17, Run No. 2 March 10, 1965.
Sole configuration No. 4

Potentials relative to cathode:

Roof and groups C, E,	1850 volts
Group A	500 "
Group B	1125 "
Group D	500 "
Sole collector segments, # 32 to # 36	250 "
Sole	(-500) "
Proximity control sole segments #1, #2, #3, #4, #5	(-150) "
Cathode current	27.7 M.A.

Figure 18. Profiles of the ratio I_{ss}/I_k of current in sole segment used as a probe to cathode current. Group D voltage depressed following a stepwise increase in groups A, B, C, showing at group D return toward the previous condition at group A; this demonstrates reversibility in the behavior. Parameter is the voltage applied to probing segment.

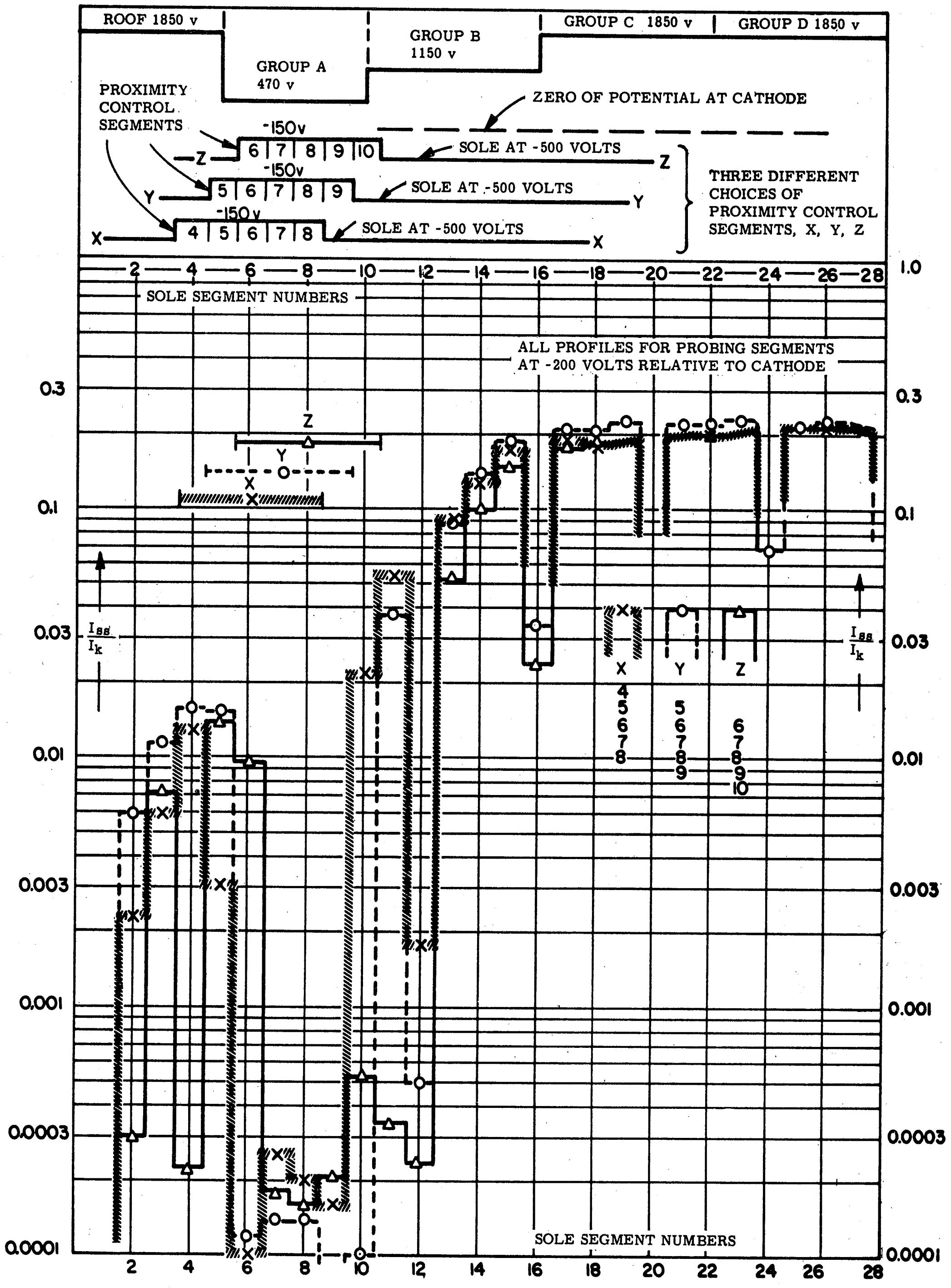


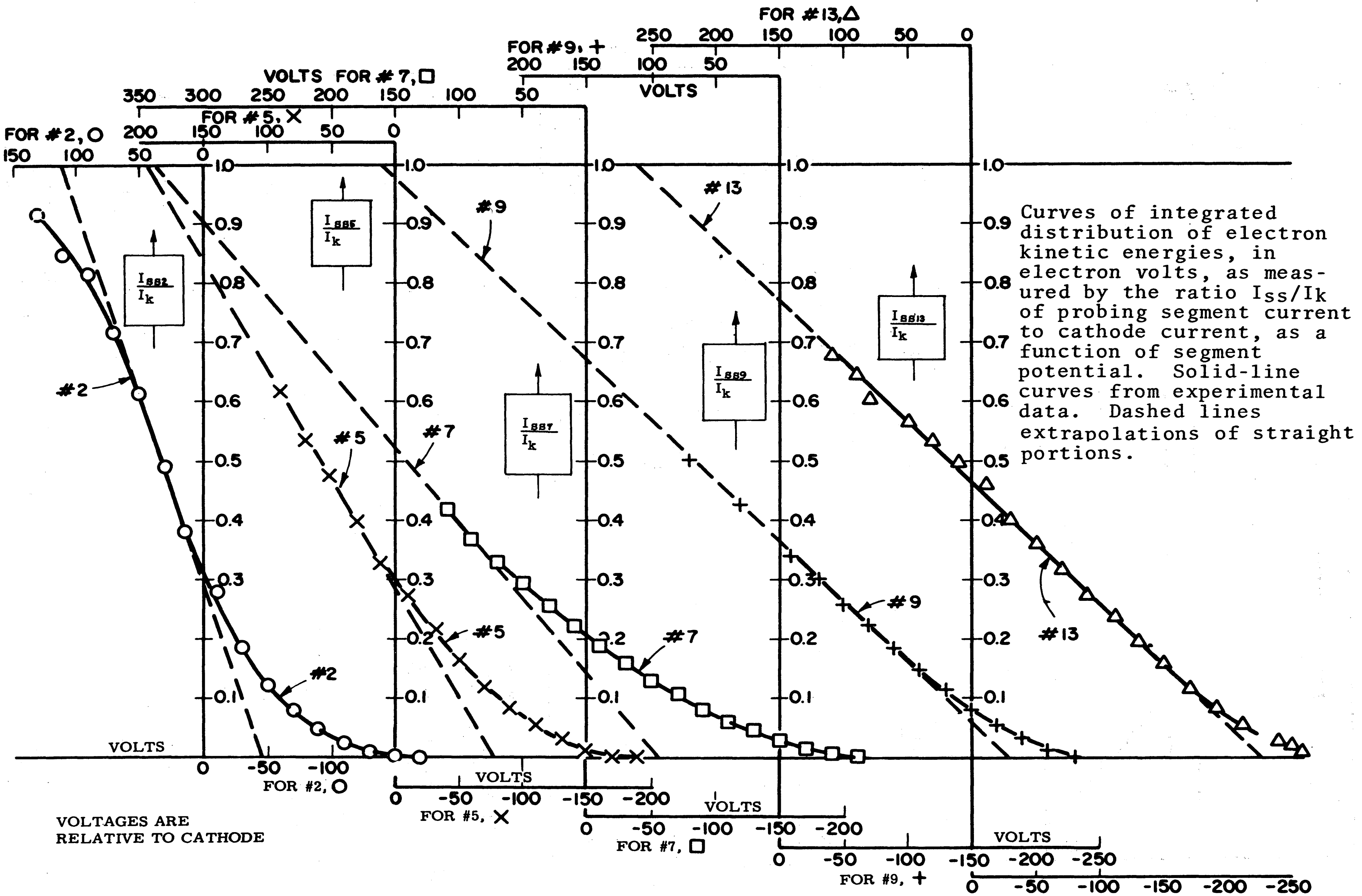
Figure 19. Run #2, March 18, 1965. Three profiles of the ratio I_{ss}/I_k of current to sole segment used as probe to cathode current, for three different sets of proximity control segments, identified as

X, using 4, 5, 6, 7, 8 ⎤
Y, using 5, 6, 7, 8, 9 ⎥ at -150 v
Z, using 7, 8, 9, 10, 11 ⎦

Sole configuration #4
Magnetic flux density ~ 2000 gauss
Cathode current.......25 M.A.
Potentials relative to cathode:

Roof and Driver Groups C, D, E...1850 volts
Group A .... 470 "
Group B ....1150 "
Sole ....(-500) "
Proximity control segments ......(-150) "

W. G. Dow and I. Rozian



Curves of integrated distribution of electron kinetic energies, in electron volts, as measured by the ratio Iss/Ik of probing segment current to cathode current, as a function of segment potential. Solid-line curves from experimental data. Dashed lines extrapolations of straight portions.

Figure 20. Data from Feb. 17, 1965, same conditions as for Fig. 11.

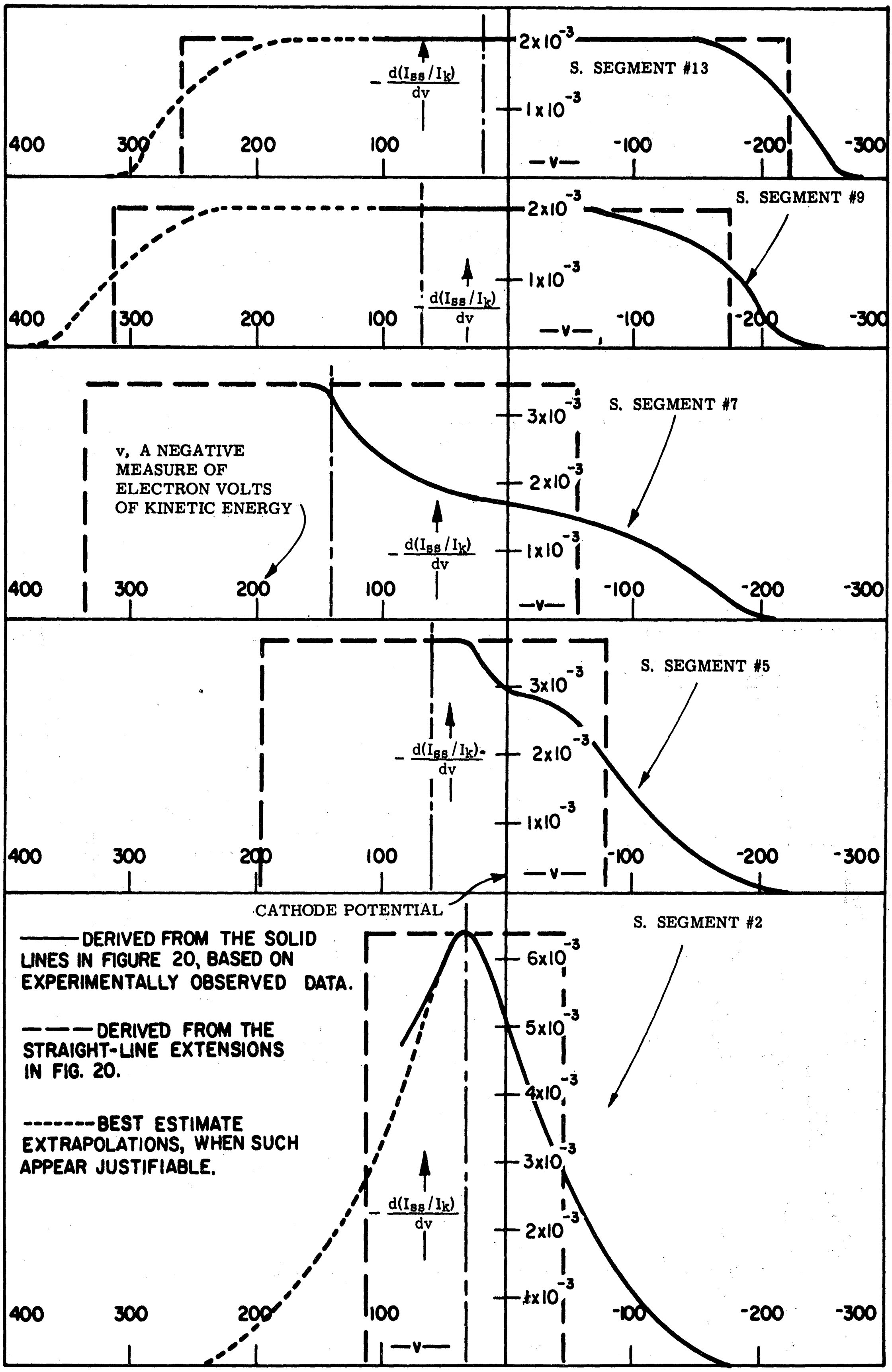
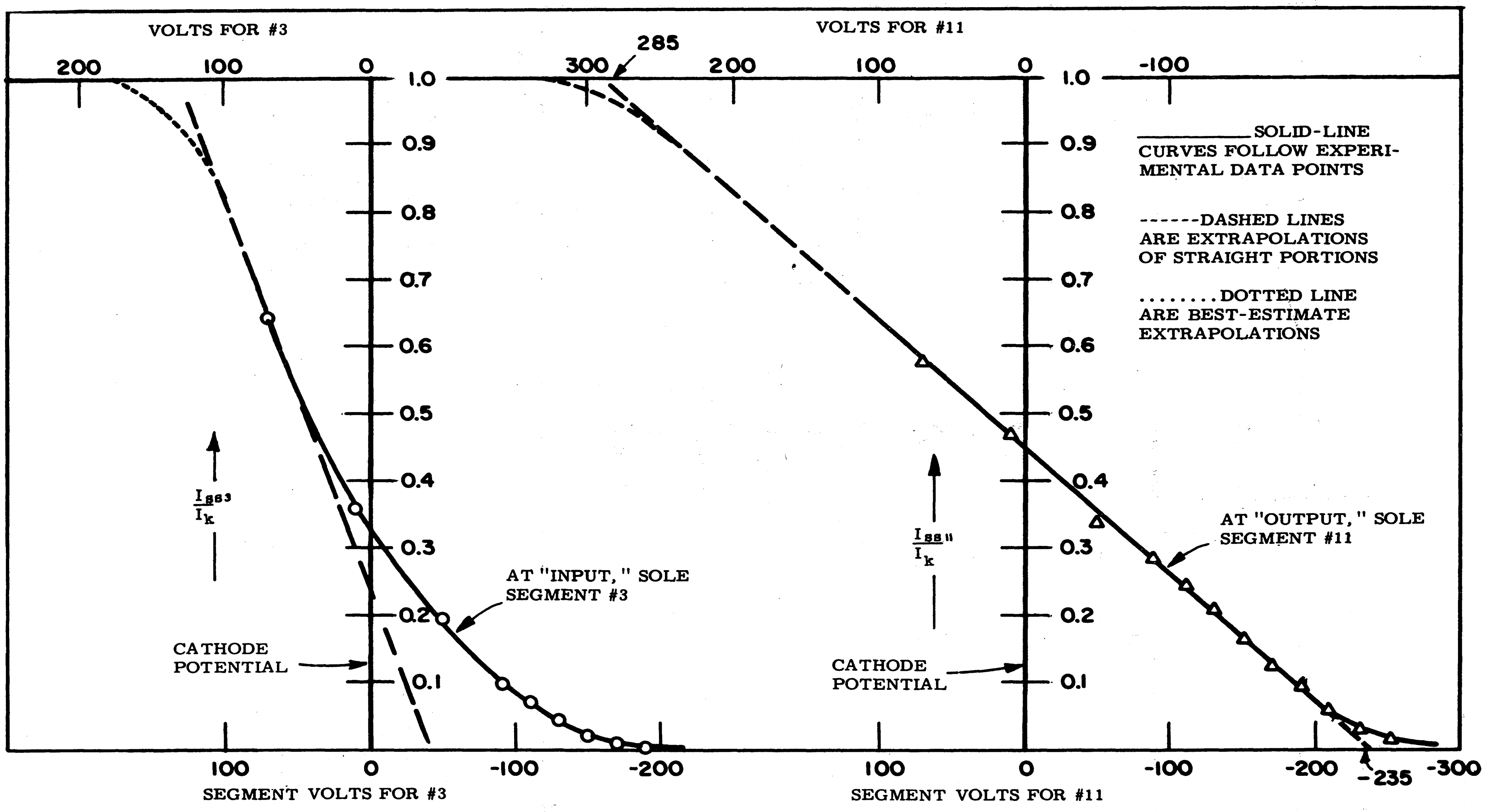


Figure 21. Probability density distributions in energy corresponding to the 5 integrated distributions in Fig. 20, being negative slopes of the Fig. 20 curves of I_{ss}/I_k vs. v. Operating conditions the same as for Fig. 11.



Curves of integrated distribution of kinetic energies in electron volts, as measured by the ratio I_{ss}/I_k of probing sole segment current to cathode current, as a function of segment potential.

Figure 22a. Data from Feb. 17, 1965 conditions the same as for Figs. 11 and 20, but from a different data run.

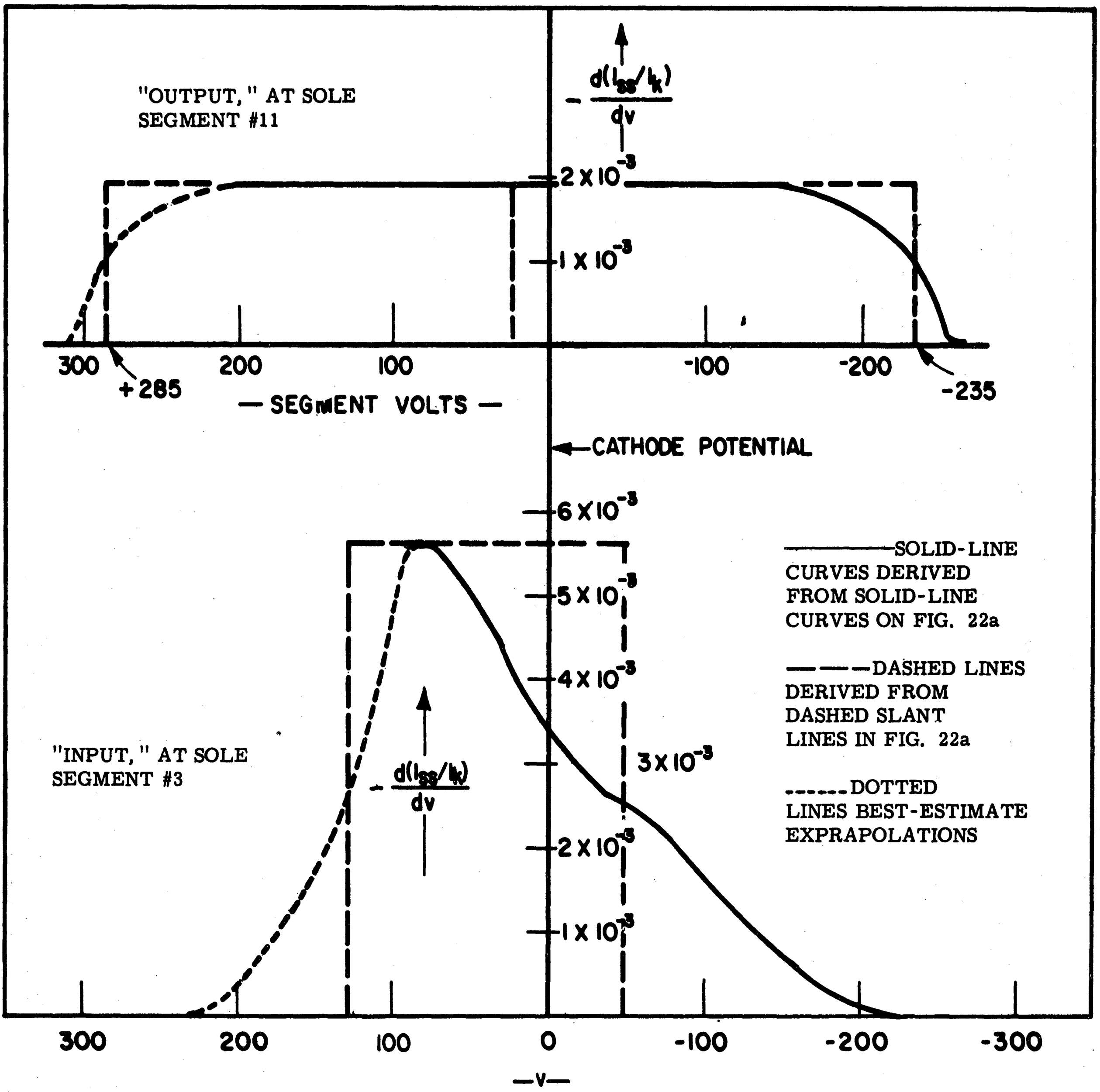


Figure 22b. Probability density distributions in kinetic energy corresponding to the two integrated distribution curves in Fig. 22, being the negative slopes of the Fig. 22 curves of I_{ss}/I_k vs. segment voltage v.

The lower curve is at "input", sole segment #3

The upper curve is at "output", sole segment #11

Derived from data taken Feb. 17, 1965, with conditions as in Fig. 11, but from a different data-run.

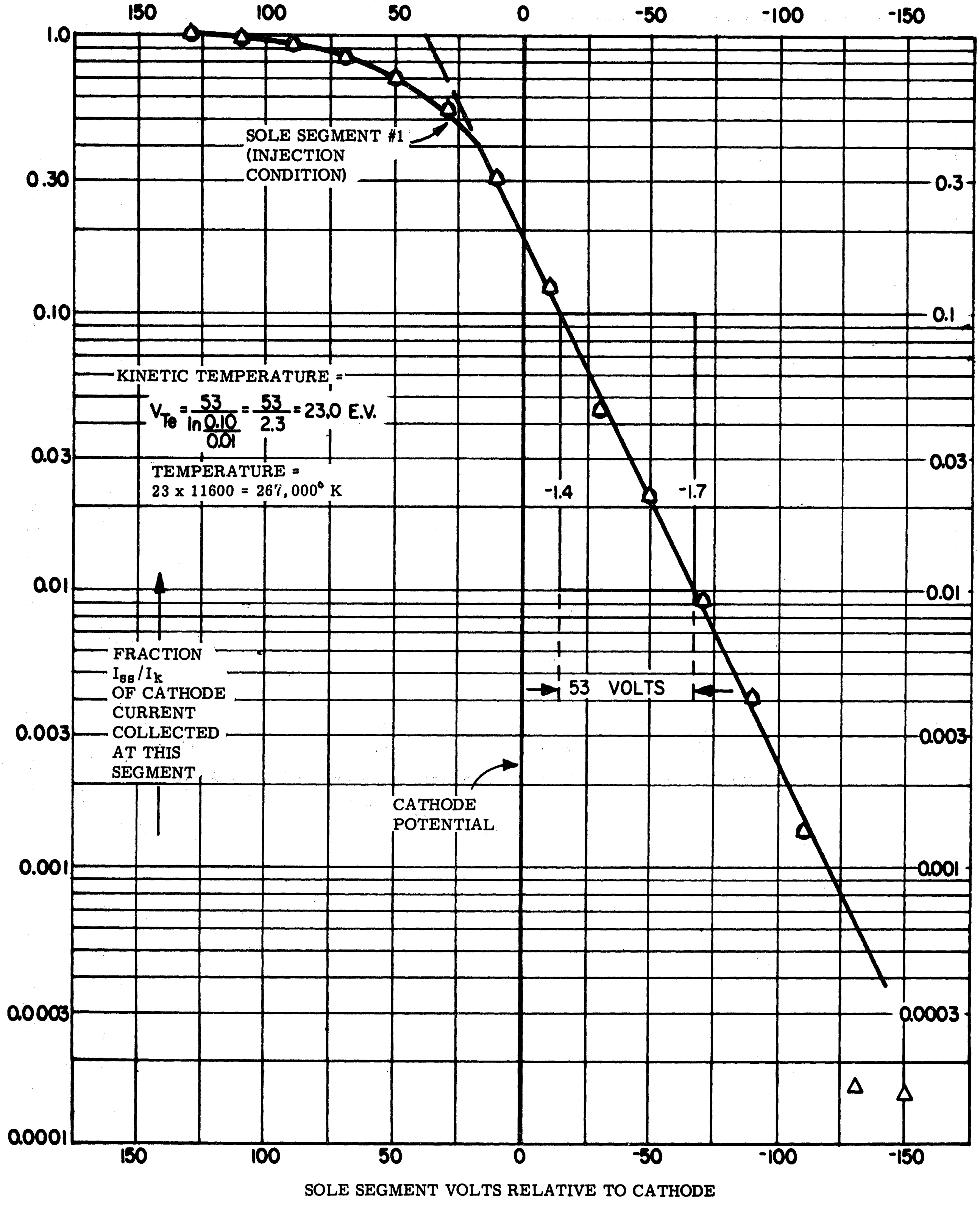


Figure 23. Determination of "injection" electron temperature from sole segment #1 used as a probing segment. From data taken Feb 17, 1965, conditions the same as in Fig. 11.

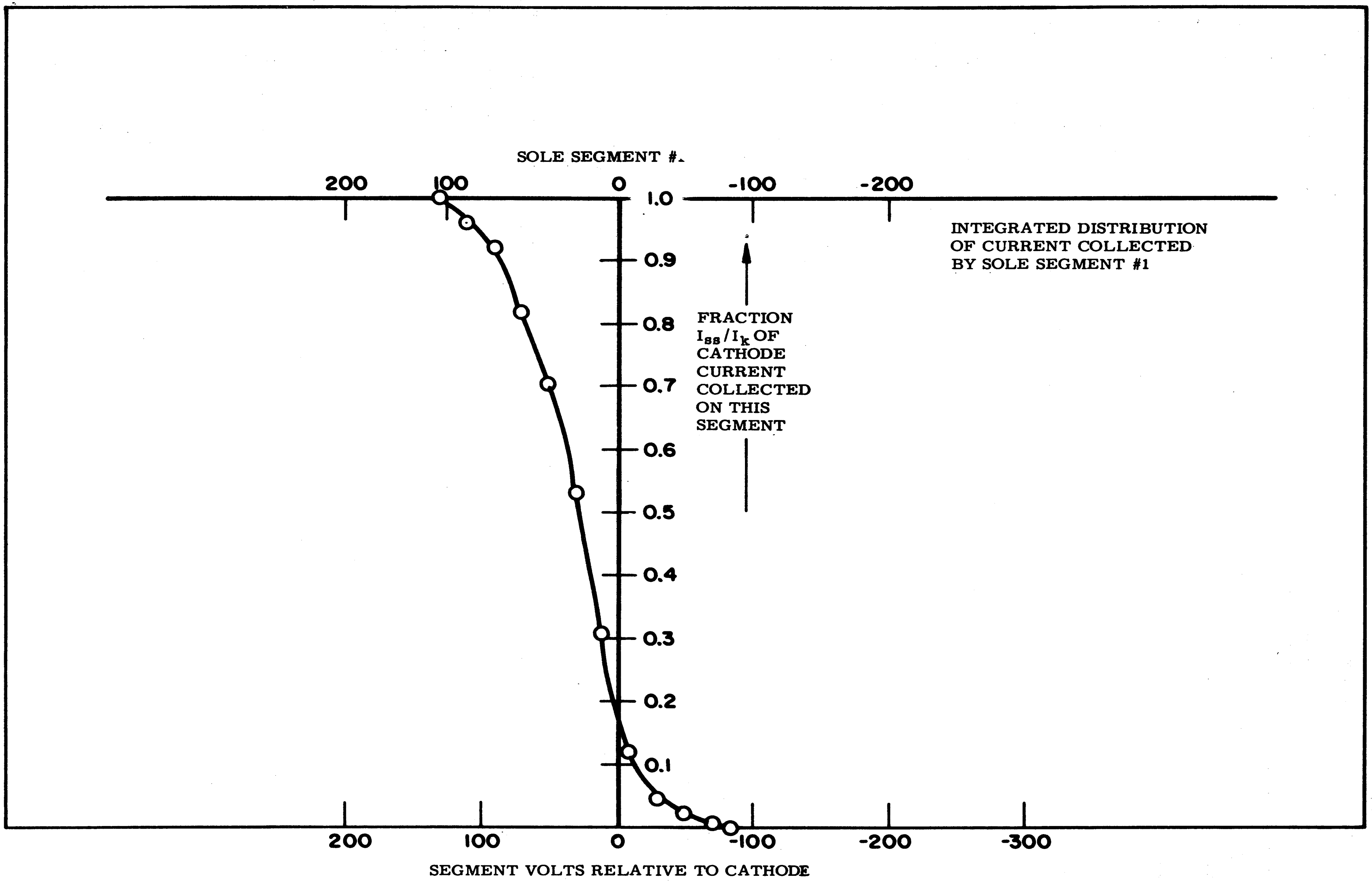
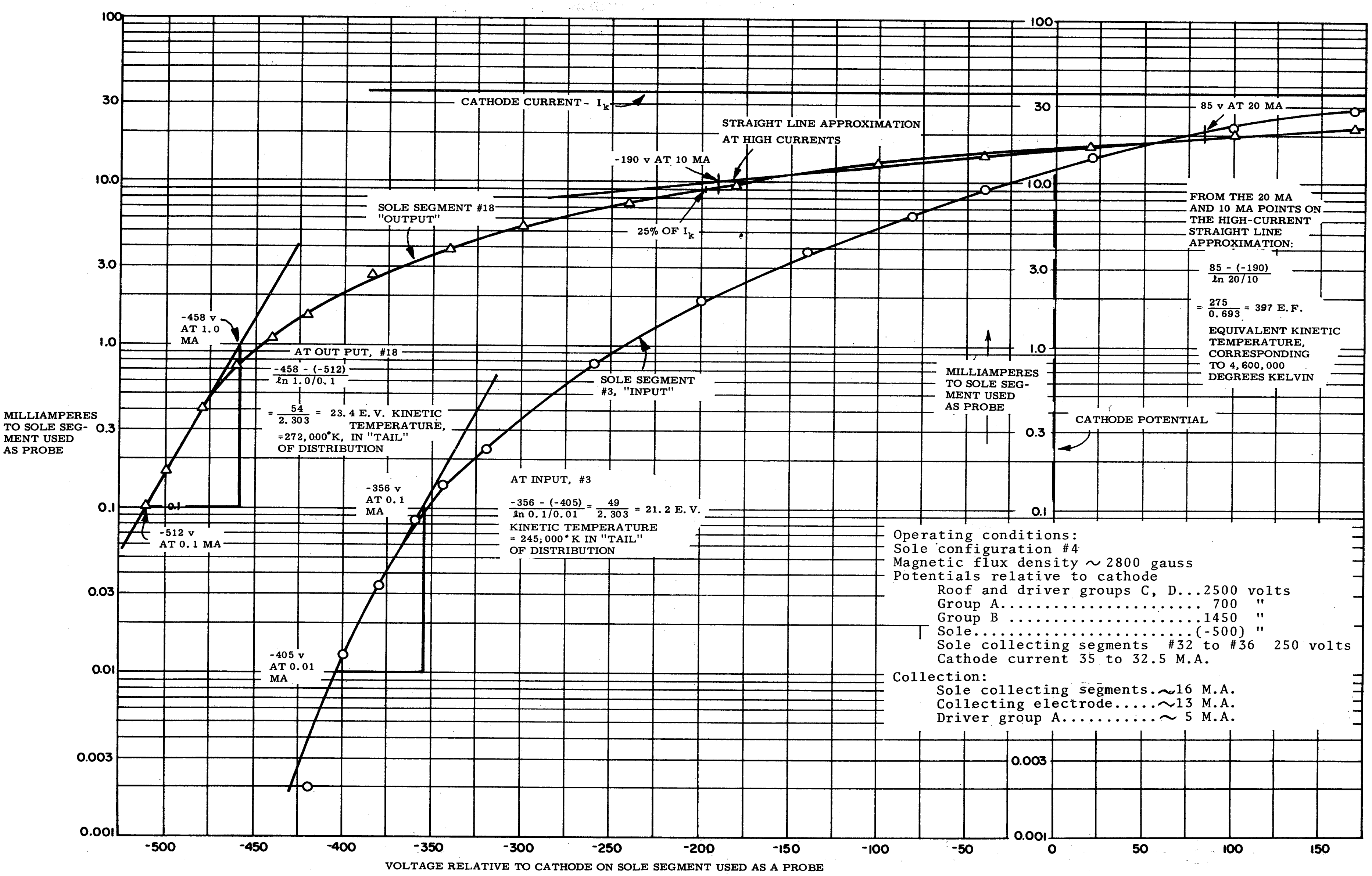


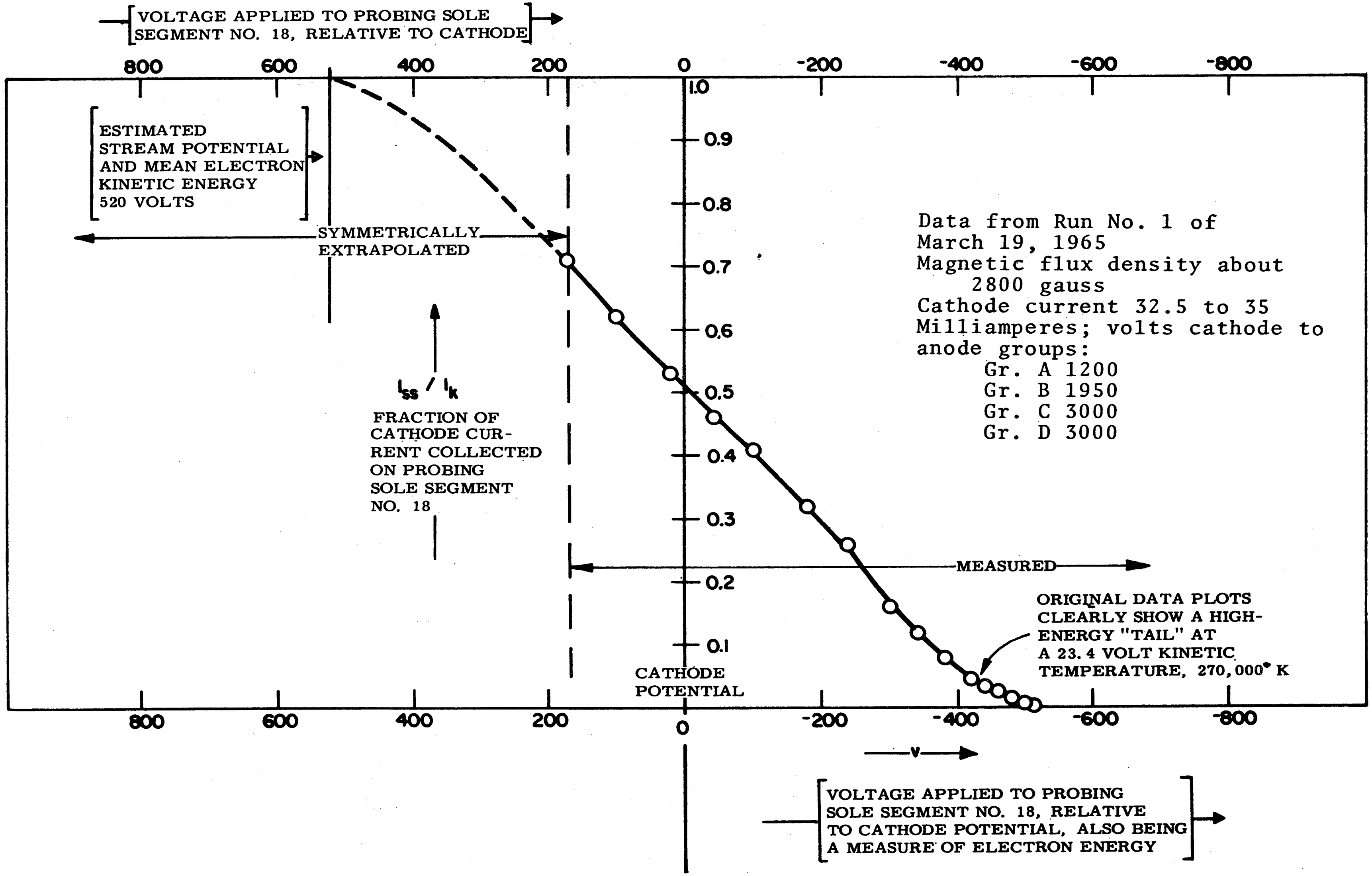
Figure 24. Nonlogrithmic plot of the data of Fig. 23, Runs Nos. 1 and 2, Feb. 17, 1965.



Operating conditions:
Sole configuration #4
Magnetic flux density ~ 2800 gauss
Potentials relative to cathode
Roof and driver groups C, D...2500 volts
Group A..................... 700 "
Group B ....1450 "
Sole.......................(-500) "
Sole collecting segments #32 to #36 250 volts
Cathode current 35 to 32.5 M.A.

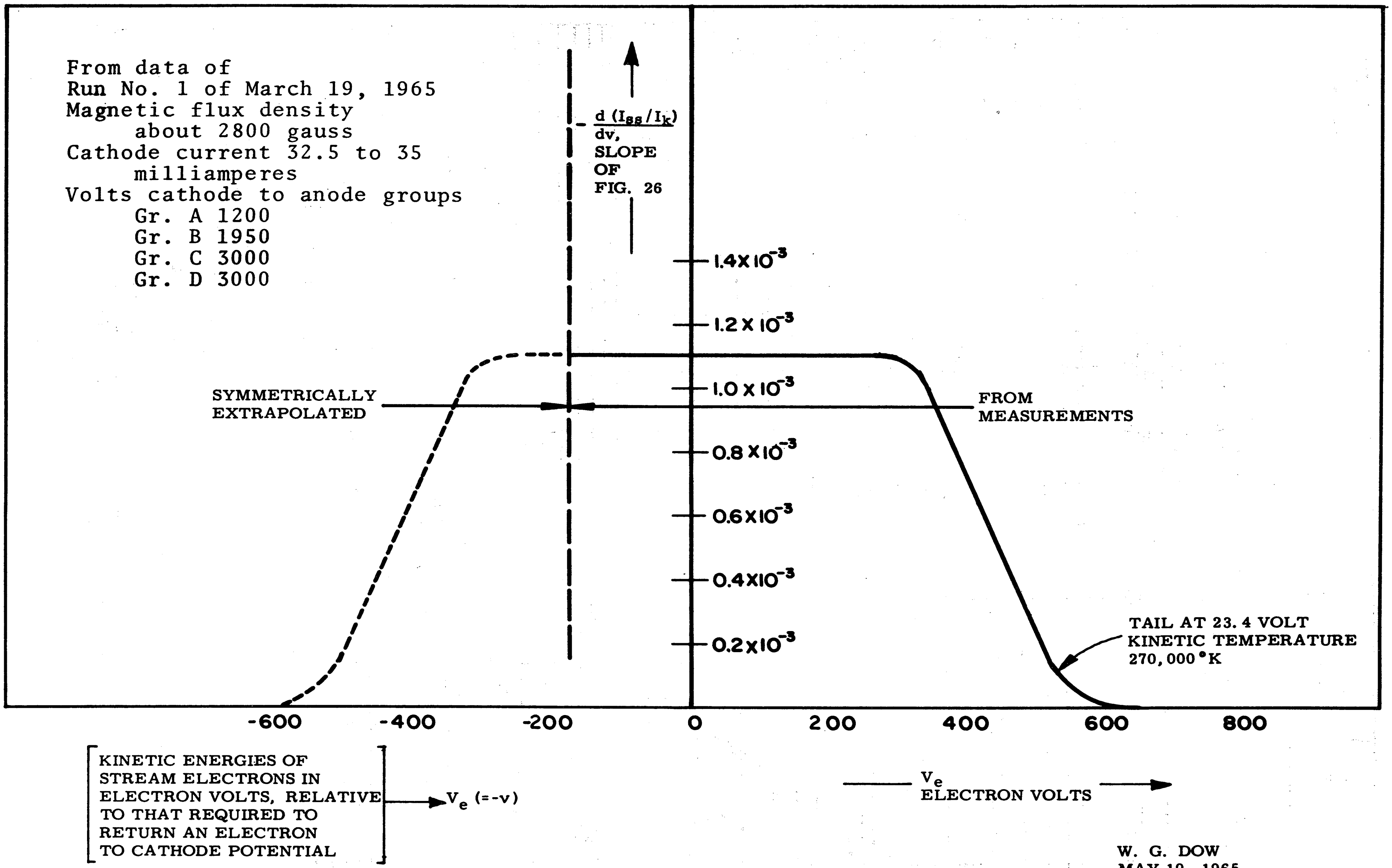
Collection:
Sole collecting segments.~16 M.A.
Collecting electrode.....~13 M.A.
Driver group A..........~ 5 M.A.

Figure 25. Currents to sole segments used as probes, for the #3 "input" and #18 "output" segments, Run #1 March 19, 1965.



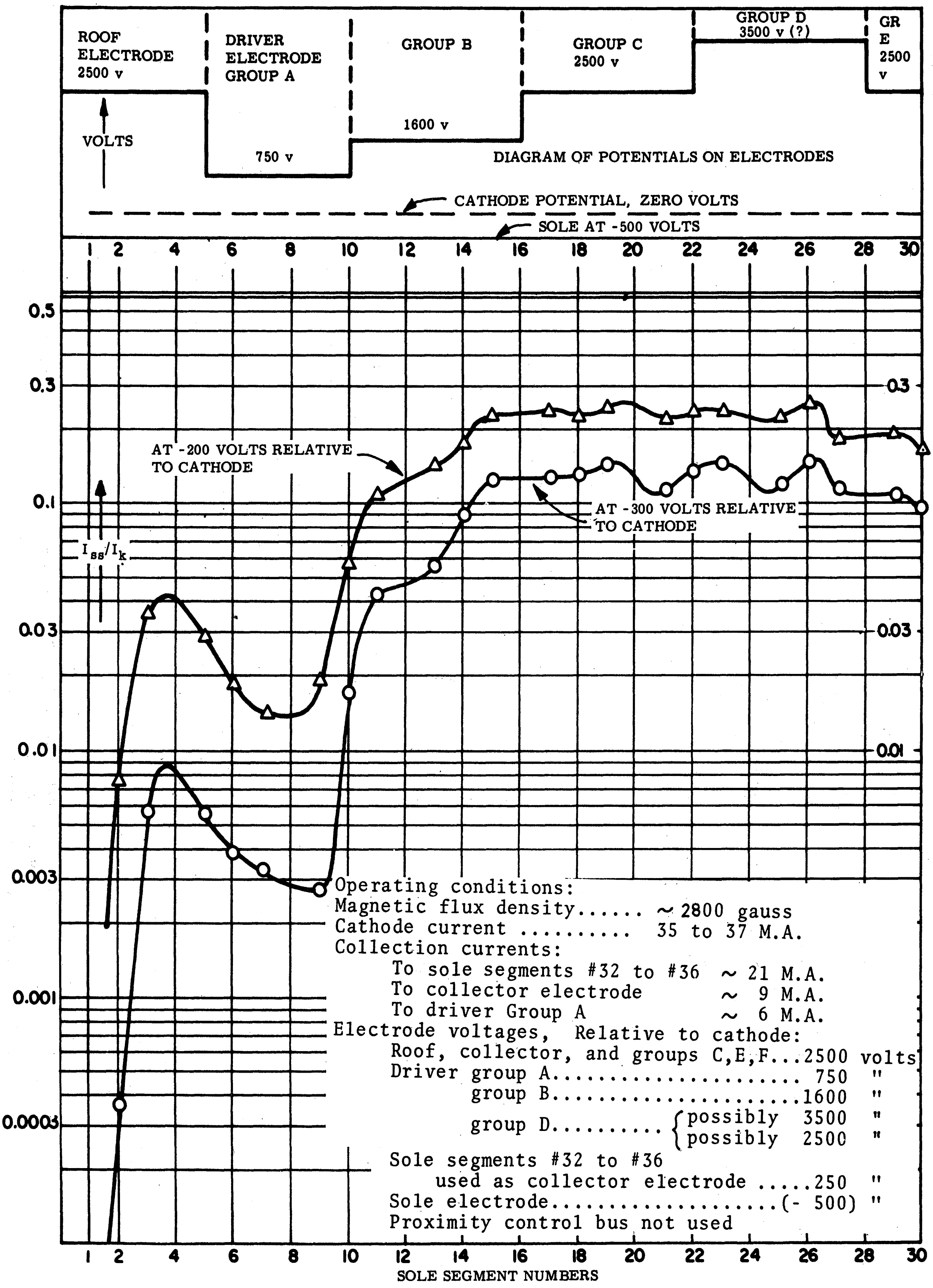
Data from Run No. 1 of
March 19, 1965
Magnetic flux density about
2800 gauss
Cathode current 32.5 to 35
Milliamperes; volts cathode to
anode groups:
Gr. A 1200
Gr. B 1950
Gr. C 3000
Gr. D 3000

Figure 26. Integrated distribution of electrons, relative to their kinetic energies in electron volts. To be collected on the probing segment at, for example, -200 volts. Relative to the cathode, an electron's kinetic energy must be 200 electron volts more than that necessary to return it to cathode potential. Segment No. 18 of Fig. 25



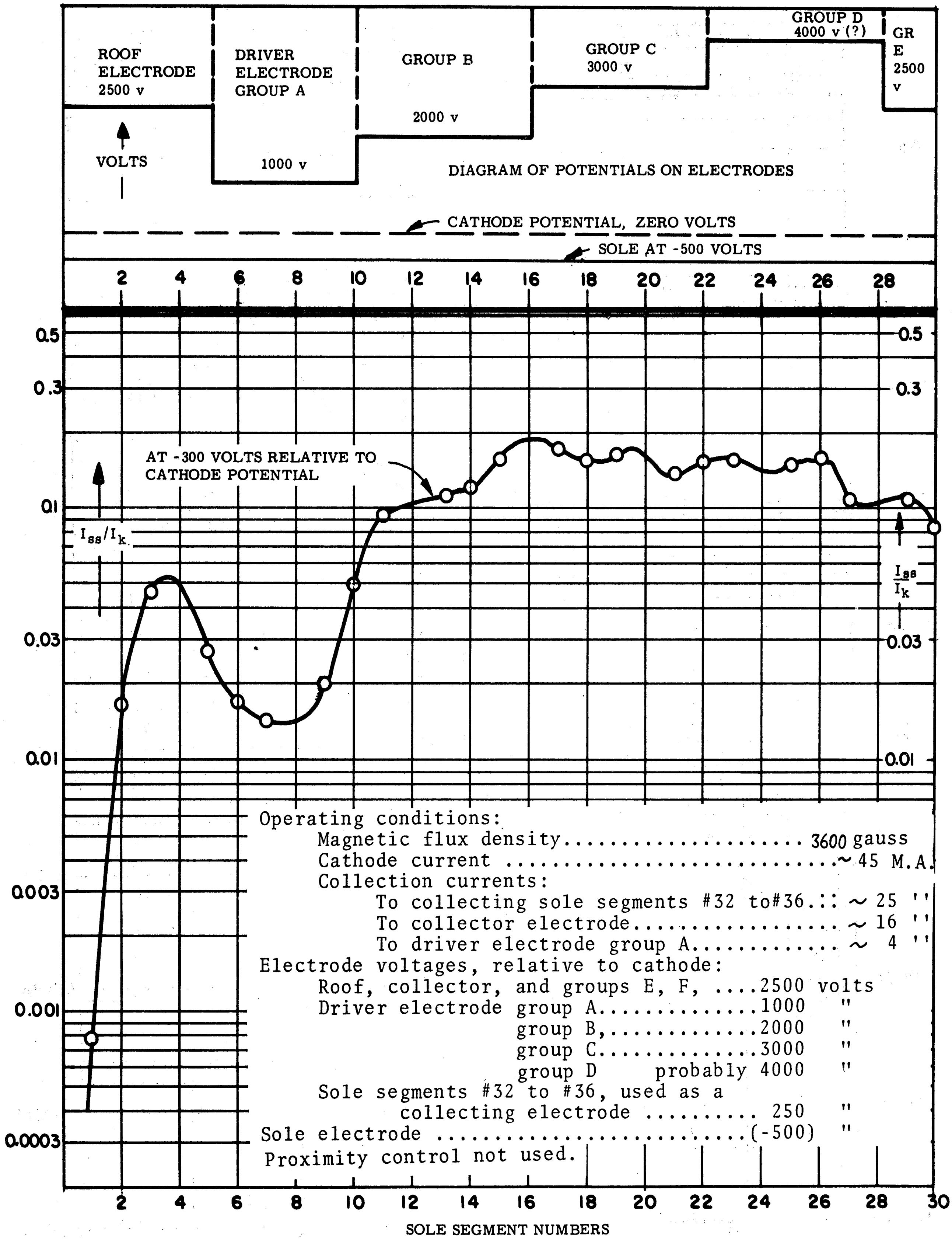
W. G. DOW
MAY 19, 1965

Figure 27. Probability density distribution of electron kinetic energies, shown as symmetrically above and below the energy necessary to return an electron to cathode potential. Negative slope of the Fig. 26 curve.



Operating conditions:
Magnetic flux density...... ~ 2800 gauss
Cathode current .... 35 to 37 M.A.
Collection currents:
To sole segments #32 to #36 ~ 21 M.A.
To collector electrode ~ 9 M.A.
To driver Group A ~ 6 M.A.
Electrode voltages, Relative to cathode:
Roof, collector, and groups C,E,F...2500 volts
Driver group A...................... 750 "
group B......................1600 "
group D.......... {possibly 3500 "
{possibly 2500 "
Sole segments #32 to #36
used as collector electrode .....250 "
Sole electrode...................(- 500) "
Proximity control bus not used

Figure 28. Data from Run No.2, March 20, 1965
Profiles along sole segments, at -200 volts and at -300 volts, of the ratio I_{ss}/I_k of current I_{ss} of sole segment used as a probe to cathode current I_k, using sole configuration #4.



Operating conditions:
Magnetic flux density.................... 3600 gauss
Cathode current ....~ 45 M.A.
Collection currents:
To collecting sole segments #32 to #36.:: ~ 25 ''
To collector electrode.................. ~ 16 ''
To driver electrode group A............. ~ 4 ''
Electrode voltages, relative to cathode:
Roof, collector, and groups E, F, ...2500 volts
Driver electrode group A..............1000 "
group B,.............2000 "
group C..............3000 "
group D probably 4000 "
Sole segments #32 to #36, used as a collecting electrode .... 250 "
Sole electrode ....(-500) "
Proximity control not used.

Figure 29. Data from high-magnetic-field portion of Run No. 2, March 20, 1965, showing the highest-kinetic-energy condition observed in this program during 1965.
Profile along sole segments, at 300 volts below cathode potential, of the ratio I_{ss}/I_k of current I_{ss} of sole segment used as a probe to cathode current I_k, using sole configuration #4.

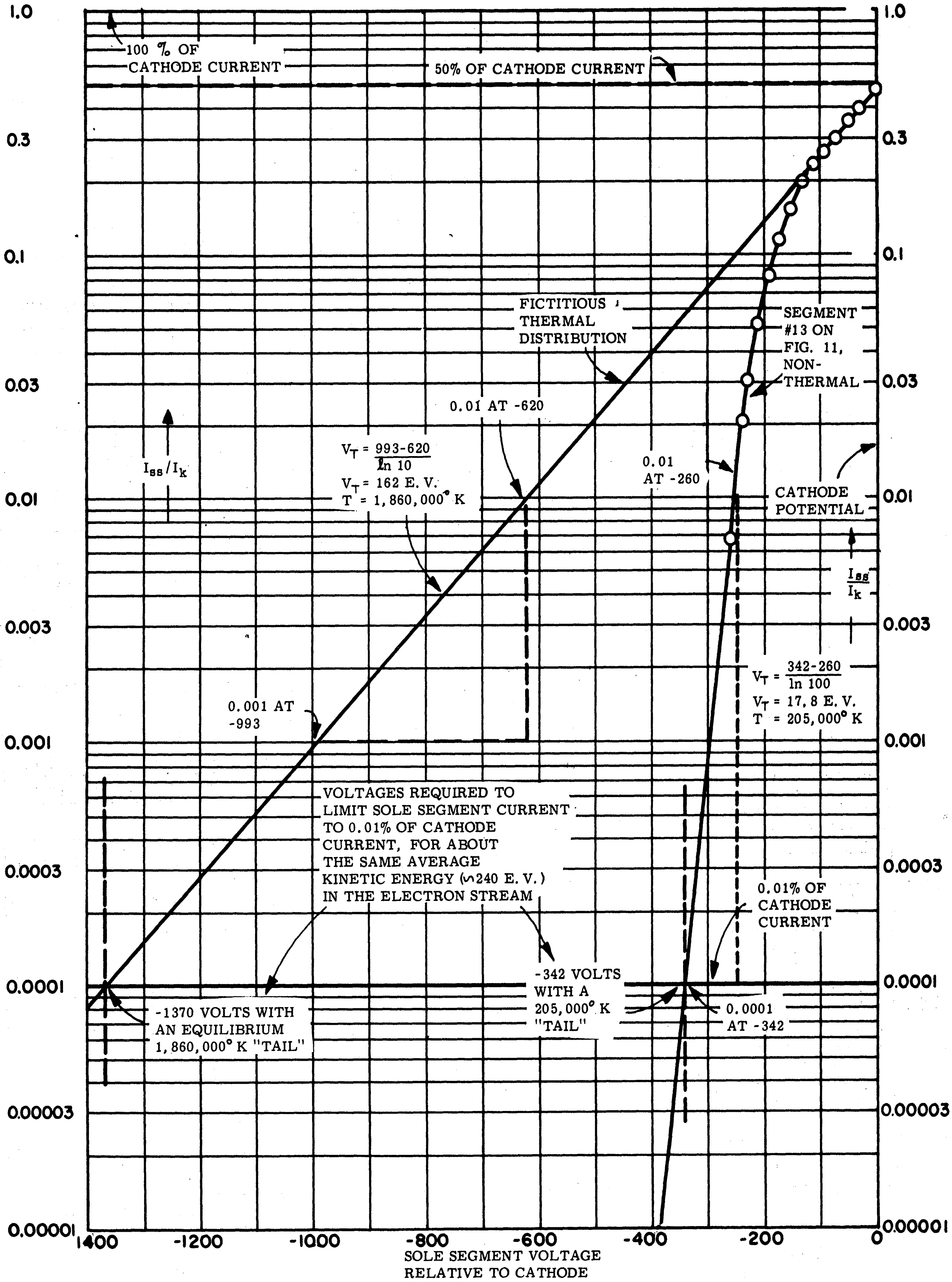


Figure 30. Illustration of the relative ease of "confinement" of the particles in this program's non-thermal stream as compared with a stream having a thermalized distribution. The non-thermal curve is from segment #13 of Fig. 11. Curves of ratio Iss/Ik of sole segment current to cathode current