MC 241
BOX 1 FOLDER 3

Biographical

file copy

WAYNE B. NOTTINGHAM
Professor of Physics
M.I.T.

Date of Birth:	April 17, 1899
Place of Birth:	Tipton, Indiana

A. Education

1920, 1929	Purdue, B.S. and E.E.
1926, 1929	Princeton, A.M. and Ph.D.
1920-1921	Benjamin Franklin fellow, American-Scandinavian Foundation, Upsala University, Sweden
1926-1931	Bartol research fellow of Franklin Institute

B. Industrial Experience

1921-25	Engineer Western Electric and Bell Telephone
1954-1955	Vice President - Research Electronics Corporation of America

C. Teaching

1931-1936	Assistant Professor of Physics, M.I.T.
1936-1942	Associate Professor of Physics, M.I.T.
1942-	Professor of Physics,M.I.T.

D. Award

1932	Louis E. Levy medal of Franklin Institute

E. M.I.T. Projects

1944	Served as special representative M.I.T. radiation lab. to O.S.R.D.
1942-50	Cons. chemical warfare development lab.

Editors: National Research Corporation Appoints Dr. Wayne B. Nottingham Special Consultant in Ultra-High Vacuum Field.

As part of an expanding program to make available high vacuum equipment and techniques for advanced electronics and space technology, ~~NRC~~ National Research Corporation has retained Dr. Wayne B. Nottingham as special consultant in the ultra-high vacuum field.

Dr. Nottingham is Professor of Physics at Massachusetts Institute of Technology and is well known for his research on extremely low pressure equipment. He devised the Nottingham gauge, an electronic pressure measuring device which operates successfully in vacuum of about 10^{-10} millimeters of mercury or about one ten-trillionth of atmospheric pressure.

Dr. Nottingham received a Bachelor of Science degree in Physics at Purdue University in 1920, and his Doctorate at Princeton in 1929. He was a Franklin Fellow of the American-Scandinavian Foundation, Upsala, 1920-21, and a Bartol Research Foundation Fellow, Franklin Institute, 1926-31.

He was formerly Vice President in charge of research for Electronics Corporation of America, Cambridge. He is also noted for important scientific contributions in the fields of electron physics, thermionic emission, gas discharges, photoelectric effects and field emission.

Dr. Nottingham and his wife live in Cambridge, Massachusetts and Stowe Tok Inn, Stowe, Vermont.

2 C THE BOSTON HERALD, FRIDAY, MARCH 27, 1964

Electronics Expert to Retire

DR. NOTTINGHAM OF MIT FETED BY COLLEAGUES

One of MIT's more distinguished professors, Dr. Wayne F. Nottingham, was bidden goodbye by some of the country's leading electronic specialists here last night at a surprise dinner in honor of his forthcoming retirement.

Professor Nottingham's parting with MIT will come in June after 33 years in the physics department, where he specialized in electronics. The group that feted him was composed of 250 colleagues and former students now attending the 24th annual Physical Electronics seminar, a conclave he originated more than 25 years ago.

The invitation-only seminar was originally proposed as a round-table meeting at which scientists and engineers could hold forth on pet projects and "way-out" research and be applauded—or heckled—by a jury of their peers.

Without realizing that a part of the program would be taken over by his admirers, Prof. Nottingham planned his own testimonial. The speakers of the evening talked about "Fifty Years Of Physical Electronics" (the physics of free electrons in gases, solids, vacuums and at the surfaces of materials) and in doing so they reviewed a good many of their mentor's own contributions to the electronic age.

The professor and his wife are avid skiers and operate a lodge at Stowe, Vt. They make their year-round home in Cambridge.

(Herald Science Dept.)

From

FEB 27 1963

TIMES-HERALD
DALLAS, TEXAS

GENERATORS EYED

Space Engines Going Electric?

The time may not be too far away when space ships will be powered by small electric generators.

Developments could come inside the next few years, says Dr. W. B. Nottingham, one of the world's foremost authorities on thermionics, the heating of a metal to a high temperature after which it would give off electricity.

The electric generator will in all probability be very small. Dr. Nottingham says the ideal sized one would be about 10 square centimeters.

The Massachusetts Institute of Technology professor told Dallas newsmen of the generator and its possibilities here Monday. He is attending meetings of the American Institute of Mining, Metallurgical and Petroleum Engineers.

He said there will be a score of problems to be solved before a workable generator can be put into operation. And it is going to be costly.

"Nobody in his right mind would try to develop one of the generators for earth use. It is really for space machines," Dr. Nottingham said.

The MIT professor said refractory metals such as tungsten and rhenium could be put in a nuclear reactor and heated to 2,000 degrees centigrade. The large amounts of electricity hurled off by the heat could then be wired into an ion engine as a contender for rocket propulsion.

Traveler (e)
BOSTON, Mass.
Circ. 161,453

DEC 9 1964

Dr. Wayne W. Nottingham

Ex-MIT Prof Dies In Europe

Dr. Wayne B. Nottingham, 65, who retired last July as professor of physics at Massachusetts Institute of Technology, died Friday, Dec. 4, in Aerdenhout, The Netherlands, it was announced last night by MIT.

Dr. Nottingham, a former resident of Cambridge, had made his home in Stowe, Vt., since his retirement. With him at the time of his death, was his wife, Evaline (van Berkum). They had been touring Europe following a series of free lectures by Dr. Nottingham.

He was a leading authority on physical electronics and thermionics. In 1935 he organized and conducted the first M.I.T. Physical Electronics Conference which provided a unique forum for the exchange of information in this special field. These conferences became highly successful and have been held annually at M.I.T. each spring except for the World War II years.

Born in Tipton, Ind., he was graduated from Purdue University in 1920. The following year he studied at the University of Uppsala, Sweden, as a Benjamin Franklin fellow of the American-Scandinavian Foundation. Upon his return he joined the staff of what later became the Bell Telephone Laboratories in New Jersey. He then continued his graduate education at Princeton University where he received his master's degree in 1926 and his doctorate in 1929, having done his thesis on metallic arcs under Karl Compton.

He also was awarded the degree of electrical engineer in 1929 by Purdue, and from 1926 to 1931 he was a Bartol Research Fellow of the Franklin Institute.

Dr. Nottingham joined the M.I.T. faculty in 1931 as assistant professor of physics, was appointed associate professor in 1936 and professor in 1942. He retired in July 1964. He contributed more than fifty papers and articles to symposia and journals in his field, and developed a number of electronic measuring devices. During World War II he served as a special representative of the M.I.T. Radiation Laboratory to the federal Office of Scientific Research and Development in Washington.

A fellow of the American Academy of Arts and Sciences, he was also a member of the Institute of Electrical and Electronics Engineers, the Optical Society of America and the American Physical Society. He belonged to Eta Kappa Nu and Sigma Xi, and held the Louis E. Levy Award of the Franklin Institute.

Professor Nottingham is also survived by his son, Marsh W., of Roswell, New Mexico.

Chronicle Sun
CAMBRIDGE, Mass.
Weekly Circ. 13,238

DEC 10 1964

Dr. W. B. Nottingham

Dr. Wayne B. Nothingham, 65, professor emeritus of physics at M.I.T. and a former Cambridge resident, died Friday in Aerdenout, Holland.

The professor and Mrs. Nottingham, the former Eveline (van Berkum) were touring Europe following a series of lectures he had delivered abroad earlier this fall.

A leading authority on electronics, he was a graduate of Purdue University in 1920 and received his master's and doctorate degrees from Princeton University. He later was awarded a degree of electrical engineering by Purdue.

Dr. Nottingham joined the M.I.T. faculty in 1931 as assistant professor of physics, was appointed associate professor in 1936 and professor in 1942. He was retired last July.

During World War II, he served as a special representative of the M.I.T. Radiation Laboratory to the Federal Office of Scientific Research and Development in Washington.

In 1935, he had organized and conducted the first M.I.T. Physical Electronics Conference.

Well known as a skiing enthusiast, he owned the Stowe - Tok Ski Inn at Stowe, Vt. Besides his wife, he leaves a son, Marsh W. Nottingham of Roswell, New Mexico.

Morning Globe
BOSTON, Mass.
Circ. 202,711

1964

Dr. Wayne Nottingham, MIT Electronics Expert

Dr. Wayne B. Nottingham, professor emeritus of physics at Massachusetts Institute of Technology and a leading authority on electronics, died Friday in Aerdenout, Holland, it was learned Tuesday.

Prof. and Mrs. Nottingham, who formerly lived in Cambridge, were touring Europe following a series of lectures he had delivered abroad earlier this Fall.

Dr. Nottingham, 65, contributed widely to symposia and journals in the fields of physical electronics and thermionics, and developed a number of electronic measuring devices.

In 1935 he organized and conducted the first M.I.T. Physical Electronics Conference. These meetings became highly successful and are held annually at the institute.

A graduate of Purdue University in 1920, Dr. Nottingham received his master's and doctorate degrees from Princeton University, and was later awarded the degree of electrical engineer at Purdue.

He joined the M.I.T. faculty in 1931 as assistant professor of physics, was appointed associate professor in 1936 and professor in 1942. He retired last July.

DR. WAYNE B. NOTTINGHAM

During World War II, he served as a special representative of the M.I.T. Radiation Laboratory to the Federal Office of Scientific Research and Development in Washington.

A Fellow of the American Academy of Arts and Sciences, he was also a member of the Institute of Electrical and Electronics Engineers, and Optical Society of America, and the American Physical Society.

An avid and accomplished skiier, he owned the Stowe-Tok Ski Inn at Stowe, Vt.

He is survived by his wife, Eveline (van Berkum) of Stowe, and a son, Marsh W. Nottingham of Roswell, N. Mex.

Technology Review July 1931.

DR WAYNE B. NOTTINGHAM , Assistant Professor in the Department of Physics

Electrical Engineer and Scandanavian-Americal Fellow at the University of Upsala. After his fellowship he returned t o America to join the research staff of the Bell Telephone Company and later was put in charge of certain developments at the Hawthorne Plant of the Western Electric Company. Following this, he received his Doctor's Degree on the basis of research on the properties of matallic arcs at Princeton. Since then he has been a research fellow of the Bartol Foundation, and has done notable work, first on arcs, and more recently on photo-electric phenomena, electron emission, and the properties of metallic surfaces. He has at the same time been a consultant in the design of new apparatus involving amplifiers

Tech.Rev.,July 1932, Vol34 ,No.9,p.i

Dr. Wayne B. Nottingham, Assistant Professor of Physics at Technology, was awarded the Levy gold medal of the Franklin Institute in Philadelphia on May 18. Dr. Nottingham is noted for distinguished contributions in various fields of physical research.

The paper which won for him the Levy award was based on a study of small grid-contolled hot-cathode mercury arcs or thryatrons, in which the flow of enormous electric currents is controlled by devices of extremely low power, in some cases of the order of a millionth of a watt. Previously Dr. Nottingham has conducted notable studies in electron emission, photo-electric phenomena, and properties of metallic surfaces. He joined the staff of Technology in 1931.

NY World Telegram and Sun, Oct. 11, 1954

Boston, Oct. 11
Announcement of appointment of Dr. Wayne B. Nottingham as vice president for research of the Electronics Corp. of American was made here today by Arthur G. ~~N~~ B. Metcalf, president. He also announced appointment of Dr. Raymond H. McFee as director of research. Dr. Nottingham continues as a full professor and head of the course of physical electronics at M.I.T.

Publishers' Weekly, NYC, Jan. 15, 1955:

NOTTINGHAM, Wayne B. and others
BIBLIOGRAPHY ON PHYSICAL ELECTRONICS. 437 p. (M.I.T. Research Lab. of Electronics pubn.) c'54 (Cambridge, Mass., Addison-Wesley) $8.50. (Listings of papers published from 1930-50, and some important later ones, in the field of physical phenomena related closely to the "free" electron.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

OFFICE OF THE PRESIDENT

December 8, 1964

To Members of the Faculty:

I regret to announce the death of Professor Emeritus Wayne B. Nottingham on Friday, December 4, in Aerdenhout, Holland. Professor and Mrs. Nottingham were touring Europe following a series of lectures he had delivered earlier this fall.

Professor Nottingham was a leading authority on physical electronics and thermionics. In 1935 he organized and conducted the First M.I.T. Physical Electronics Conference which provided a unique forum for the exchange of information in this special field. These conferences became highly successful and have been held annually at M.I.T. each spring except for the World War II years.

Born in 1899 in Tipton, Indiana, Professor Nottingham was graduated from Purdue University in 1920. The following year he studied at the University of Uppsala, Sweden, as a Benjamin Franklin Fellow of the American-Scandinavian Foundation, and upon his return to the United States he joined the staff of the Bell Telephone Laboratories. He then continued his graduate education at Princeton University where he received his Master's degree in 1926 and his doctorate in 1929, having done his thesis on metallic arcs under Karl Compton. He also was awarded the degree of Electrical Engineer in 1929 by Purdue, and from 1926 to 1931 he was a Bartol Research Fellow of the Franklin Institute.

Dr. Nottingham joined the M.I.T. faculty as an Assistant Professor of Physics in 1931, was appointed Associate Professor in 1936, and Professor in 1942. He contributed more than fifty papers and articles to symposia and journals in his field, and developed a number of electronic measuring devices. During World War II, he served as a special representative of the M.I.T. Radiation Laboratory to the federal Office of Scientific Research and Development in Washington. A Fellow of the American Academy of Arts and Sciences, he was also a member of the Institute of Electrical and Electronics Engineers, the Optical Society of America and the American Physical Society. He belonged to Eta Kappa Nu and Sigma Xi, and held the Louis E. Levy Award of the Franklin Institute.

Professor Nottingham is survived by his wife, Mrs. Eveline van Berkum Nottingham of Rindge, New Hampshire, and his son, Marsh W. Nottingham of Roswell, New Mexico.

J. A. STRATTON

From the Office of Public Relations
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Telephone: UN 4-6900, Ext. 2705

FOR IMMEDIATE RELEASE

More than 200 electronics engineers and scientists are meeting this week at the Massachusetts Institute of Technology for the 25th annual M.I.T. Conference on Physical Electronics sponsored by the M.I.T. Research Laboratory of Electronics.

The conferences were started prior to World War II by Professor Wayne B. Nottingham, M.I.T. Professor of Physics, a pioneer in physical electronics, who died last December while on a lecture tour in Europe. Professor Nottingham started the conferences primarily for former students to help keep them up to date on changes in the burgeoning field of electronics.

Attendance is still by invitation only and the total number is purposely kept low to ensure free exchange of information and views. Attendees represent government, industry and university laboratories throughout the U.S.

Emphasis of the conference is on informality of presentations. No strict time limits are placed on scheduled presentations and lines of discussion are continued as long as they are productive.

Conference co-chairmen this year are Robert E. Stickney, M.I.T. Assistant Professor of Mechanical Engineering, and J. F. Waymouth of Sylvania Electric Products, Inc., Danvers, Mass. Session chairmen include D. B. Langmuir, Space Technology Laboratories, Inc.; A. U. MacRae, Bell Telephone Laboratories; H. D. Hagstrom, also of

(more)

Bell Labs; R. Brietweiser, Lewis Research Center, National Aeronautics and Space Administration; and R. E. Fox, Westinghouse Research Laboratories.

Dr. W. Crawford Dunlap of the NASA Electronics Research Center in Cambridge, will address a conference banquet at the M.I.T. Faculty Club Thursday evening. The conference opened Wednesday and ends Friday.

-- 30 --

March 24, 1965

Meeting

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Nottingham, W.B.

Crystallographic Non-Uniformity and its Influence on the Thermionic Emission Properties of Clean Surfaces

Symposium on the Physics of Surface Phenomena

Am. Phys. Soc., Washington, May, 1947

Meeting

Nottingham, W.B. and Mutter, W.E.

Photoelectric Technique for Spectral Emissivity Determination Illustrated by Result on Tungsten.

Am. Phys. Soc, Madison, Wisc., June, 1948

Nottingham, Wayne B. T.R. 110

Survey of Methods Used to Determine the Optical Properties of Phosphors.

May 10, 1949

Journal (T.R. 110)

Nottingham, W.B.

A Survey of Present Methods Used to Determine the Optical Properties of Phosphors

J. Opt. Soc. Am. 39, No. 8, 641 (1949) Aug.

Meeting Paper

Nottingham, W. B.

Quantitative Measurements of Field Emission from Tungsten Crystals

Field Emission Conf., Linfield College, Jan. 2-4, 1952, McMinnvill, Oregon

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Meeting Paper

Nottingham, W. B.

The Measurement of High Vacuum

Field Emission Conf., Linfield College, Jan. 2-4, 1952, McMinnvill, Oregon

Meeting ②

Nottingham, W. B.

Design and properties of the M.I.T. modified Bayard-Alpert gauge

Symposium on Vacuum Technology, Asbury Park, N. J. June 17, 1954

Spec. Pub.

Nottingham, W. B.

Thermionic Emission, Handbuch der Physik, 1955

---

meeting

Nottingham, W. B.

Application of space-charge theory to the determination of electron emitter properties

1955 August Meeting of the American Physical Society, University of Mexico, Aug. 29-31, 1955

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meeting

Nottingham, W. B.

The application of the Fowler and Richardson thermionic equations in their relation to thermionic emission from oxide cathodes

Sixteenth Annual Conference on Physical Electronics M.I.T., Cambridge, Marbh 22-24, 1956

TR 321

Wayne B. Nottingham

Thermionic Emission

December 10, 1956

Meeting

Nottingham, W. B.

Properties of the plasma determined by Langmuir probe measurements in low-pressure mercury arcs

Third International Conference on Ionization Phenomena in Gases, Fondazione Giorgio Cini, Venice, June 11-15, 1957 journal article

(3)

Nottingham, W. B.

Review of "ElectronImpact Phenomena and the Properties of Gaseous Ions"by F.H. Field and J.L. Franklin

Science

J. Art.

Nottingham, W. B.

Comments on "Electrostatic Potential in Crystals

Am. J. Phys. Vol. 26, No. 1, 33-34, Jan. 1958

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letter to the editor

Nottingham, W. B.

Comments on "Electrostatic potential in crystals"

Am. J. Phys. accepted Jan-Feb 1958

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journal article

Nottingham, W. B.

The thermionic diode as a heat-to-electric-power transducer

J. Appl. Phys., Vol. 30, No. 3, 413-417, March, 195

W.B. Nottingham Journal

Cesium Plasma Diode as a Heat-to-Electrical-Power Transducer

J. Appyl. Phys. Vol. 30, No. 3, March 1959
413-17

---

meeting

Nottingham, W. B.

The thermionic diode as a heat-to-electrical-power transducer

Nineteenth Annual Conference on Physical Electroni
Massachusetts Institute of Technology, Cambridge,
Massachusetts. March 26-28, 1959

④

journal

Nottingham, W. B.

A simplified method for the computation of the electrical properties of a close-spaced thermionic converter

J. Appl. Phys.

---

special publication

Nottingham, W. B.

The thermionic diode as a heat-to-electrical-power transducer

(Report on Nineteenth Annual Conference on Physical Electronics, Massachusetts Institute of Technology, March 26-28, 1959, pp. 71-82)

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letter to the editor

Nottingham, W. B.

Comments on the Barnes cold-cathode guage

Rev. Sci. Instr. Acc.

TR 379

Nottingham, W. B., and Torney, F. L., Jr.

A detailed examination of the principles of ion gauge calibration

Oct. 25, 1960

TR 373

Nottingham, W. B.

The Thermionic Energy Converter

Sept. 9, 1960

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letter to the editor

Nottingham, W. B.

Comments on "Heat to Electricity by Thermionic Emission"

J. Appl. Physics acc;

spec. pub.

⑤

Nottinghma, W. B.

Cesium plasma as a heat-to-electrical power transducer (Proc. Fourth International Conference on Ionization Phenomena in Gases, Uppsala, Sweden, Aug. 17-21, 1959)

---

spec. pub.

Nottingham, W. B.

The thermionic conversion of heat to electricity (Proc. Fifth National Conference on Tube Techniques)

---

journal paper

Nottingham, W. B., Hatsopoulos, G. N., and Carabateas, E. N.

Thermionic conversion of heat to electricity

Aerospace Engineering

---

spec. pub.

Nottingham, W. B.

A simplified method for the computation of the electrical properties of a close-spaced thermionic converter (Report on Twentieth Annual Conference on Physical Electronics) Masssachusetts Institute of Technology, Cambridg
Mass., March 24-26, 1960)

---

spec. pub.

Nottingham, W. B.

The thermionic diode as a heat-to-electrical-power transducer (Report on Nineteenth Annual Conference on Physical Electronics, Massachusetts Institute of Technology, March 26-28, 1959, pp. 71-82.

---

meeting paper

Nottingham, W. B.

Electron emission (invited)

Fall Meeting, New York Section, American Physical Society, Niagara Falls, New York
October 13-14, 1961

meeting paper

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Nottingham, W. B.

Design parameters' influence on M. I. T. - Bayerd-Alpert Gauge sensitivity (invited)

Fall Meeting, American Vacuum Society,
Washington, D. C.
October 16-18, 1961

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letter

Nottingham, W. B.

Comments on "Heat to Electricity by Thermionic Emission"

J. Appl. Phys.

---

special publication

Nottingham, W. B. , Candidus, E. S. and Koller, L. R.

Quantitative analysis of a photoemissive solar-energy converter (Report on Twenty-first annual conference on Physical Electronics, M. I. T., Cambridge, Mass., March 29-31, 1961

---

meeting paper

Nottingham, W. B.

Analysis of typical voltage-current curves (
(invited)

Power Information Center, Jet Propulsion Laboratory, Pasadena, California
December 6-7, 1961

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letter

Nottingham, W. B.

Comments on the Barnes cold-cathode gauge

Rev. Sci. Instr. Vol. 32, No. 4, 464-465, April 1961

Meeting Paper

Nottingham, W. B.

Ionization of cesium at surfaces
The energy distribution for electrons in a thermionic diode plasma

Symposium on Thermionic Power Conversion,
Colorado Springs, Colorado

May 14-16, 1962

TR 405

⑦

Nottingham, W. B.

I. Ionization of Cesium at Surfaces

II. The Energy Distribution for Electrons in a Thermionic Diode Plasma Cannot Be Truly Maxwellian

July 31, 1962

Special Publication

W. B. Nottingham

The Energy Distribution for Electrons in a Thermionic Diode Plasma Cannot Be Truly Maxwellian

Reprinted from Advanced Energy Conversion,
Vol. 2, pp. 467-479, Pergamon Press 1962

Special Publication

Nottingham, W. B.

Ionization of Cesium at Surfaces

Reprinted from Advanced Energy Conversion,
Vol. 3, pp. 245-253, Pergamon Press,
Oxford, England, 1963

Special Publication

W. B. Nottingham

Design parameters' influence on M. I. T. Bayerd Alpert Gauge Sensitivity

Reprinted from 1961 Transactions of the
Eighth Vacuum Symposium and Second Internatio
Congress, Pergamon Press, 1962 pp. 494-498

Meeting Paper

W. B. Nottingham, Electron Emitting Materials

Symposium on Metallurgy of Electron Emitting
Materials, Dallas, Texas
February 25, 1963

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letter to the editor

Nottingham, W. B.

Energy Levels of the Cesium Atom
Proc. IEEE, 51, 12, December 1963

Publications - Professor W. B. Nottingham

W. B. Nottingham, "Normal Arc Characteristic Curves: Dependence on Absolute Temperature of Anode," Phys. Rev. 28, 764 (1926).

W. B. Nottingham, "Probe Measurements in the Normal Electric Arc," J. Franklin Inst. 206, No. 1 (1928).

W. B. Nottingham, "Instruction on the Making of Potassium-Hydride Photo-Electric Cells," J. Franklin Inst. 206, No. 5 (1928).

W. B. Nottingham, "Probe and Radiation Measurements in the Copper Arc," J. Franklin Inst. 207, No. 3 (1929).

W. B. Nottingham, "A Note on the High Grid Resistor Amplifier," J. Franklin Inst. 208, No. 4 (1929).

W. B. Nottingham, "Measurement of Small D.C. Potentials and Currents in High Resistance Circuits by Using Vacuum Tubes," J. Franklin Inst. 209, No. 3 (1930).

W. B. Nottingham, "Influence of Accelerating Fields on the Photoelectric and Thermionic Work-Function of Composite Surfaces," Phys. Rev. 35, 1126 (1930).

W. B. Nottingham, "Characteristics of Small Grid-Controlled Hot-Cathode Mercury Arcs or Thyratrons," J. Franklin Inst. 211, No. 3 (1931).

W. B. Nottingham, "Photoelectric and Thermionic Emission from Composite Surfaces,"Phys. Rev. 41, 793 (1932).

W. B. Nottingham, "Thermionic Emission from Tungsten and Thoriated Tungsten Filaments," Phys. Rev. 49, 78 (1936).

T. S. Gray and W. B. Nottingham, "Half-Cycle Spot-Welder Control," Rev. Sci. Instr. 8, 65 (1937).

A. B. White, W. B. Nottingham, H. E. Edgerton, and K. J. Germeshausen, "The Strobotron - II," Electronics, March, 1937.

W. B. Nottingham, "Electrical and Luminescent Properties of Willemite Under Electron Bombardment," J. Appl. Phys. 8, 762 (1937).

W. B. Nottingham, "Ionization and Excitation in Mercury Vapor Produced by Electron Bombardment," Phys. Rev. 55, 203 (1939).

W. B. Nottingham, "Electrical and Luminescent Properties of Phosphors Under Electron Bombardment," J. Appl. Phys. 10, 73 (1939).

W. B. Nottingham, "Starting Characteristics of a "Trigger" Tube with a Radioactive Cathode," Rev. Sci. Instr. 11, 2 (1940).

W. B. Nottingham, "Optimum Conditions for Maximum Power in Glass A Amplifiers," Proc. IRE 29, 620 (1941).

MASS. INST. TECH.
DEC 8 1964
LIBRARIES
Archives

Reprinted from — 18th Annual Proceedings — Power Sources Conference — May 19, 20, 21, 1964

Session on Thermal Energy Conversion

EMITTER MATERIALS FOR HIGH TEMPERATURE ENERGY CONVERSION

W. B. Nottingham
Massachusetts Institute of Technology

Introduction

Energy derived from a heat source can be converted directly to electrical energy by the proper application of the principles of thermionic electron emission. To utilize this method of energy conversion, three elements are indispensable. First, electrons must be emitted from a conducting surface maintained at a high temperature. Second, the electron current must be carried by means of some transport mechanism across a gap to a collector. And third, an electron collector must be present which is maintained at a considerably lower temperature than the emitter and have a low enough work-function in comparison with that of the emitter to permit the device to deliver power to an external circuit.

The device described in these most general terms is a thermionic diode. It is not to be implied that the thermionic device which is finally shown to have the greatest utility as an energy converter will be a simple diode. At the outset, stress must be placed on ultimate objectives from an overall systems point of view. For example, one user may wish to have a converter which operates at the maximum possible efficiency, whereas another application may call for a converter which delivers the maximum amount of power per unit weight of the entire system. It is almost certain that the construction which gives the maximum power per unit weight will not be the same construction as the one that gives the maximum efficiency.

It is always the ambition of a true scientist to utilize basic knowledge in order to accomplish a specific objective. The indispensable background of information which here is classified as "fundamental" really relates to at least three basic scientific areas. One may be identified as the fundamental physics of "microscopic" phenomena. This term is used for lack of a better one to indicate the need for detailed information concerning the physical processes involved in the actual thermionic emission of electrons from a surface. The transport phenomena depend on detailed information concerning ion generation, electron and ion space-charge and other properties associated with general concepts of plasma generation and maintenance. The work-function of the collector is again a microscopic quantity in that knowledge concerning the means by which the most suitable collector work-function can be maintained is needed. In contrast to these considerations are the "macroscopic" aspects of the problem. The designer of a converter needs to make detailed studies of the heat and electrical conduction of materials. He needs to design macroscopic configurations of these materials to minimize the heat losses and minimize the losses in power due to the ohmic resistance of the electrical conductors that serve as terminals of this energy converter. Radiation losses must be minimized and these depend on macroscopic considerations and "engineering" design. Still a third area of comparable importance has to do with the "material" problems. Long life of the device may be of extreme importance and efficiency and power per unit weight may have to be sacrificed in order to select materials that will not disintegrate or evaporate under the conditions that are dictated by the need to have extreme reliability for long periods of time.

Inportant though these last two areas involving fundamentals are, this discussion will be directed exclusively to the fundamentals related to the "microscopic" phenomena. Even to deal with this area comprehensively would require a book instead of an article; therefore, this treatise will simply highlight some of the problems and indicate the approach that forms the basis of extensive research programs now directed toward the achievement of energy conversion through thermionics.

An Interrelation Between Component Parts

In order to bring forward the interrelation between the components of a thermionic energy converter, Figure 1 has been prepared. It first calls attention to the fact that the difference between the heat energy put in and the heat energy taken out is the only heat available for conversion directly to electrical power. Since this converter is thermodynamically a heat engine, the Carnot efficiency defined by $(T_1 - T_2)/T_1$ sets an absolute upper limit to the efficiency of the device. It goes without saying that this efficiency can never be attained in any practical structure. Electrical power can always be defined as the product of *current* and *voltage.* The diagram

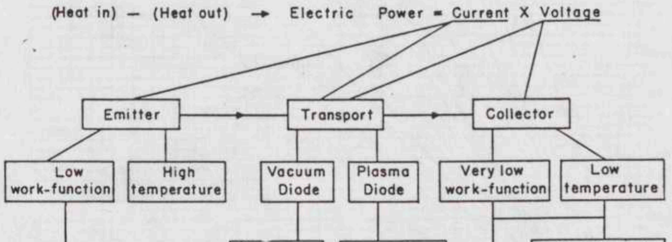

Figure 1. Block diagram to show interrelation between elements of a thermionic converter.

of Figure 1 shows that the emitter and the transport mechanism predominate in the determination of the available current. The transport and the collector properties predominantly determine the voltage available. To attain the desired current density from the emitter, it must have a suitably low work-function and operate at a relatively high temperature. Unless ultra close spacing is used, electrons cannot be transported efficiently over to the collector unless positive ions are provided to neutralize the electron space-charge. Unless the collector work-function is appreciably less than the work-function of the emitter, the output voltage when the device is operating under the condition of maximum power will be extremely low. In fact, it will be the voltage equivalent of temperature which can be computed directly as $\overline{V} = 8.616 \times 10^{-5} T_1$. At 2000°K, this voltage is 0.17 volt. To achieve a high power density, therefore, the current would have to be very large. If the difference between the emitter work-function and the collector work-function is 1.0 eV, then the available voltage could approach 1.2 volts to give six times the power for the same current.

To operate at such a high temperature at 2000°K calls for a very refractory material such as tungsten or rhenium. Either of these materials alone would yield a current density of less than 0.01 A/cm². Such a low current density would be hopelessly small for a practical device. The fundamental studies of Langmuir and Taylor[1] established the fact that the work-function of a refractory material can be reduced so greatly in the presence of a cesium film maintained by the equilibrium between condensation and evaporation to give an emission current density at the specified temperature higher than 10 A/cm².

In schematic, the diagram of Figure 1 calls attention to the importance of having cesium present in the converter in order to establish the required low work-function for the emitter and provide for an adequately great thermionic emission current density. Clearly, if cesium will reduce the work-function of the emitter, it will also reduce that of the collector. Studies to be mentioned here show that this reduction does in fact take place by the suitable choice of materials and temperatures so that an emitter-to-collector work-function difference of at least 1 eV can be maintained as desired.

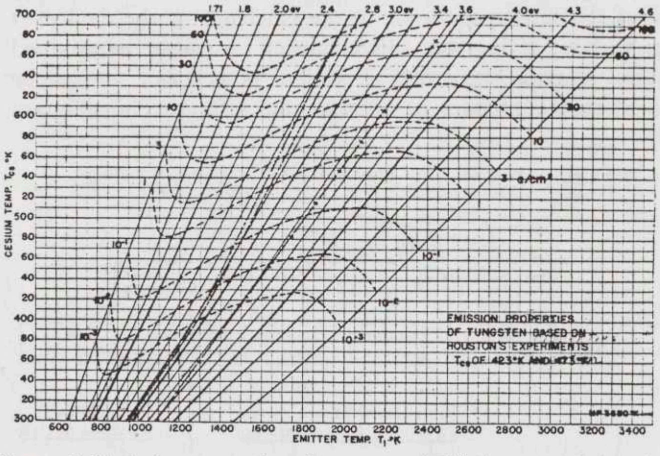

Figure 2. Emission properties of tungsten. Solid lines: work-function related to emitter temperature and cesium temperature. Dotted lines: current density in A/cm². Double dot-dash line: demarcation between electron-rich sheath on the left and ion-rich sheath on the right as given by Langmuir-Saha equation. Plus-dash line demarcation between stable and unstable region. To the right of line ions must be returned to the emitter to obtain stable results.

Cesium also has the property of being easily ionized. The ionization procedure depends on a combination of fundamental mechanisms. An important one is the production of ions at the emitter surface by thermal ionization. The anticipated yield of ions is well approximated by the Langmuir-Saha[2] theory. Evidence is strong that under suitably chosen operational conditions many more ions are produced by electron collisions with the cesium atoms in the interelectrode space. Generally speaking, this is not accomplished by the simple impact of an energetic electron with a neutral cesium atom. Cumulative processes are clearly evident and the fundamentals, although under present investigation, are not clearly established.

Thermionic Emission In the Presence of Cesium

Most specimens of tungsten are fabricated from polycrystalline material. Before extensive heat treatment, the crystals are very small, but the maintenance of the specimen at a high temperature results in recrystallization and the formation of much larger crystals. In order to achieve stability in the operation of thermionic converters, part of the processing should involve the maintenance of the emitter at a high temperature and for a sufficiently long period of time so that the major part of the recrystallization will have been completed.

Studies made of single crystals of tungsten reveal that the true thermionic work-function is very dependent on the exposed crystallographic direction[3]. The surface characterized by the 110 direction has a very high work-function of at least 5.3 eV and holds a cesium layer at a higher equilibrium density than any of the other surfaces. Other tungsten areas have work-functions as low as 4.3 eV. In spite of this non-uniformity in the properties of the various crystallographic faces of tungsten, the quantitative results that describe the electron emission, current density as a function of the emitter temperature and the cesium bath temperature have been in remarkably good agreement even though the specimens used for those studies have had different heat treatment and geometrical configuration.[4]

It is important to the efficiency of a thermionic converter to have a very uniform work-function over the surface as it is operated. It is not easy to determine that the emitter work-function is uniform and a number of researches are now in progress designed to evaluate the non-uniformity associated with individual specimens operated under conditions that simulate, to some extent at least, ones likely to be found in an actual converter.

For design purposes, it is important to have available the best knowledge concerning the thermionic properties of refractory materials; therefore, the available data on tungsten used to form the chart[5] shown in Figure 2. The independent variables are the emitter temperature and the cesium bath temperature, both expressed in degrees Kelvin. Associated with these two temperatures, an observer can determine an electron emission current density under a wide range of conditions. The Richardson type formula can be solved in terms of the emitter temperature and the observed current density to give the effective work-function. This equation is

$$\phi_1 = \overline{V}\ (14.0 + 2 \ln T_1 - \ln Jo). \qquad (1.)$$

It is essentially by this means that the map of tungsten-cesium properties in Figure 2 is made. The solid lines establish then a correlation between cesium temperature and emitter temperature to accomplish a specific effective work-function. The dotted lines that form "S" curves represent the emission capability expressed in A/cm^2. Across this chart, in the general region of the work-function 2.8 to 2.6 eV, are some lines that divide the chart into two important regions. The region to the left of these lines is one identified as being "electron-rich," whereas the one to the right of these lines is "ion-rich." Thus, in the absence of ions being generated in the space between the emitter and the collector, an electron space-charge sheath depresses electron emission for the electron-rich region, whereas on the right part of the diagram, an ion sheath accelerates the electrons into the inter-electrode space and suppresses the available ion production.

If the zero of the cesium temperature and the zero of the emitter temperature had not been suppressed in the layout of the coordinate scales, it would be seen that the lines tend to go through the origin of the coordinate system. It is this tendency that encourages some observers to maintain that the work-function is dependent only on the ratio (T_1/T_{Cs}). The fact that the lines do not go through the origin exactly, demonstrates that this assumed dependency on the ratio is simply a useful approximation.

Some data are available that describe the properties of molybdenum and tantalum in a similar manner[5]. The properties of rhenium are being investigated, but the details are not as yet published. Because of the dearth of well-documented information concerning the emission properties of potentially good thermionic emitters, it is still impossible to identify the emitter material most likely to be used. Not only will it be necessary to discover the most favorable emitter material, but it will be equally important to discover the best way to process this material in order to obtain the desired uniformity.

Desirable Collector Properties

Some of the desirable collector properties may be enumerated.

1. The collector work-function should be as low as possible consistent with the overall systems requirements. This point will be discussed later.
2. The collector work-function should be uniform.
3. The collector work-function should not change with time.
4. The collector work-function should not be dependent on the flow of electron current to it.
5. If the collector work-function is lowered by the presence of a complex molecular structure the film must have a negligible electrical resistance.

The collector work-function is dependent on the structure of the base material, the density of the partial monomolecular layer of cesium and on the temperature. In certain applications, specifically related to the direct conversion of heat to electricity in outer space, it will be desirable to operate the collector at a relatively high temperature in order to minimize the weight of the radiator used to discharge the excess heat. This is one of the factors that makes is exceedingly difficult to generalize concerning the most desirable work-function properties of the collector.

Analysis of Voltage Current Curves

One of the first steps that must be taken to evaluate a thermionic converter design depends on the acquisition of a voltage-current curve. For any particular test vehicle, such a curve depends on controllable parameters such as emitter temperature, cesium bath temperature, collector temperature and spacing. Uncontrolled parameters often include the detailed surface structure of the emitter and the collector, and the presence of spurious discharges that may possibly be initiated between other elements of the test vehicle such as the surrounding walls, the emitter or collector support, and other elements that may be present in a particular device. In order to acquire information concerning fundamental mechanisms active in determining a voltage-current characteristic, it is necessary to devise a test vehicle which minimizes spurious phenomena. Such a test vehicle has been under investigation by Breitwieser[6] and has yielded valuable information. His studies have not been confined to the limited region in the voltage-current curve that corresponds to power conversion. In his studies, the collector potential may be made quite negative with reference to the Fermi level of the emitter. Under this condition at close spacing, the ion-current yield may be observed and thanks to the presence of supporting guard-rings, leakage currents may be minimized. Two typical voltage current curves are shown in Figure 3. One applies to the very close spacing of 10 microns and the other to the larger spacing of 460 microns. Data may be analyzed in terms of the Schottky[7] theory as it relates to ion production. Figure 4 is presented as illustrative of these results. At the close spacing of 10 microns, the observed data follow close to the theoretical line associated with that small spacing. At the larger

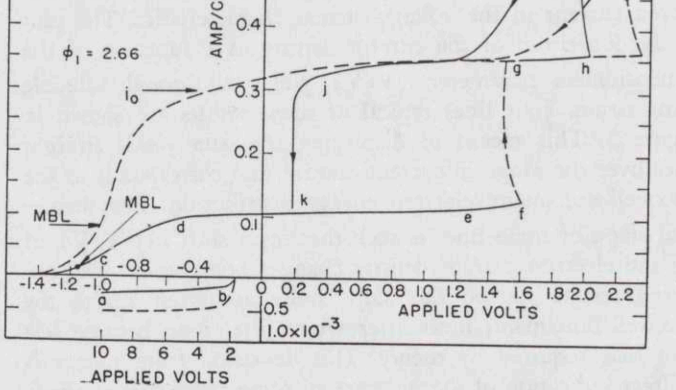

Figure 3. Two voltage-current curves taken by Breitwieser. Emitter temperature 1500°K, cesium condensation 500°K. Solid line spacing: 460 microns. Dash line spacing: 10 microns. Note change in voltage scale for ion currents shown negative. Current density anticipated from chart of Figure 2 is i_o. MBL limit of Maxwell-Boltzmann distribution. Passive mode range d to e quasi saturation due to limiting barrier. Ignition at f. Range g to h: ignited mode before arc mode at i. Ignited mode returned toward passive mode j to k. Line may be retraced if k remains 5 percent above passive mode line.

spacings, the figure shows lines of steeper slopes than those observed at close spacing, and these indicate directly that the Schottky theory is not applicable within the range of applied voltage available before sputtering effects and other interferferences set in.

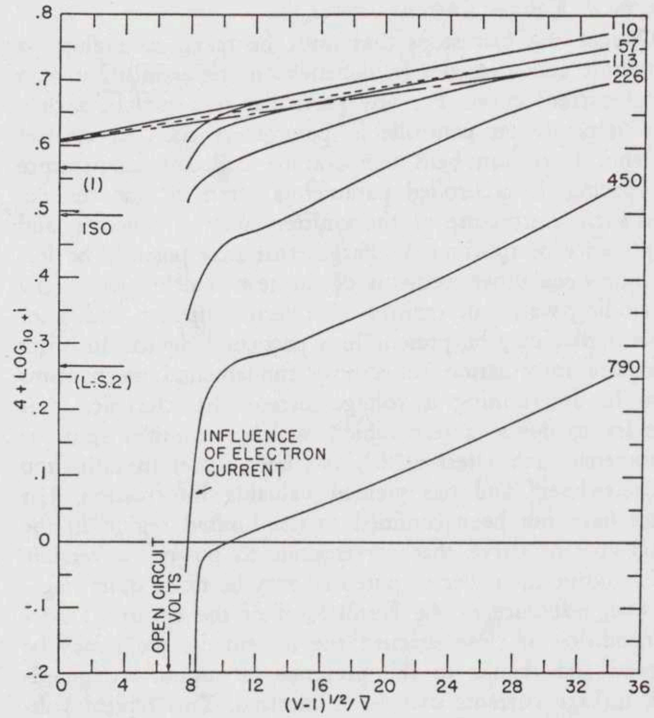

Figure 4. Ion currents plotted on the basis of the Schottky mirror-image theory for ion current increase with applied voltage. Six spacings shown from 10 microns to 790 microns. (L-S • 2): anticipated ion current based on Langmuir-Saha theory. ISO: random current in isothermal diode. (1): Langmuir-Saha equation with statistical weight of 2 omitted.

The analysis of the ion-current data, combined with possible electron emission from the collector, serves as the means of separating out the electron current itself from the total observed current in the voltage-current characteristics. The plot of the logarithm of the current density as a function of the dimensionless parameter $(V/\overline{V})$ yields additional valuable information. Four lines typical of these results are shown in Figure 5. This means of displaying the data yields straight lines over the range in current density that corresponds to the Maxwell-Boltzmann electron energy distribution. The theoretical slope of these lines is such that for a shift in $(V/\overline{V})$ of 2.3 the electron current density changes one decade. The observed results yielded this slope quite accurately up to the Maxwell-Boltzmann limit after which the slope became less than that required by theory. This deviation from theory is a direct indication of the presence of some space-charge effect. At the very close spacing of 10 microns, the knowledge of the current density at a particular value on the Boltzmann line permits the accurate calculation of the effective work-function of the collector as given by the following formula:

$$\phi_2 = \overline{V}\ (14.0 + 2 \ln T_1 - \ln J_v) + V_{app}. \qquad (2.)$$

Figure 5 would seem to indicate that the collector work-function increases with the spacing even though its temperature and the other controllable parameters, namely, the emitter temperature and the cesium temperature, are held constant. It is our opinion that this displacement of the Boltzmann line is not a true indication of a change in the collector work-function but simply shows that a certain fraction of the electrons, which normally in the absence of collisions with cesium atoms or ions would have crossed the interelectrode space, are turned back in the "electron-retarding" field and thus reenter the emitter and are lost to the electron collector.

Another interesting point illustrated by the curves of Figure 5 is that at very close spacings, the apparent saturation current is very close to 0.28 A/cm². This value is remarkably close to that expected on the basis of the chart of Figure 2. Note, however, that the apparent saturation when the spacing is increased to 790 microns is 7×10^{-2} A/cm². The flatness of this curve indicates two things: first, a space-charge effect is limiting the current; secondly, the modulation of the space-charge by the variation of the surface potential of the collector is hardly noticeable. This means that a complex motive diagram must be assumed to exist in the interelectrode space. Quantitative evaluation of the apparent saturation establishes the location of the space-charge minimum relative to the Fermi level of the emitter.

As the applied potential is made slightly positive and the

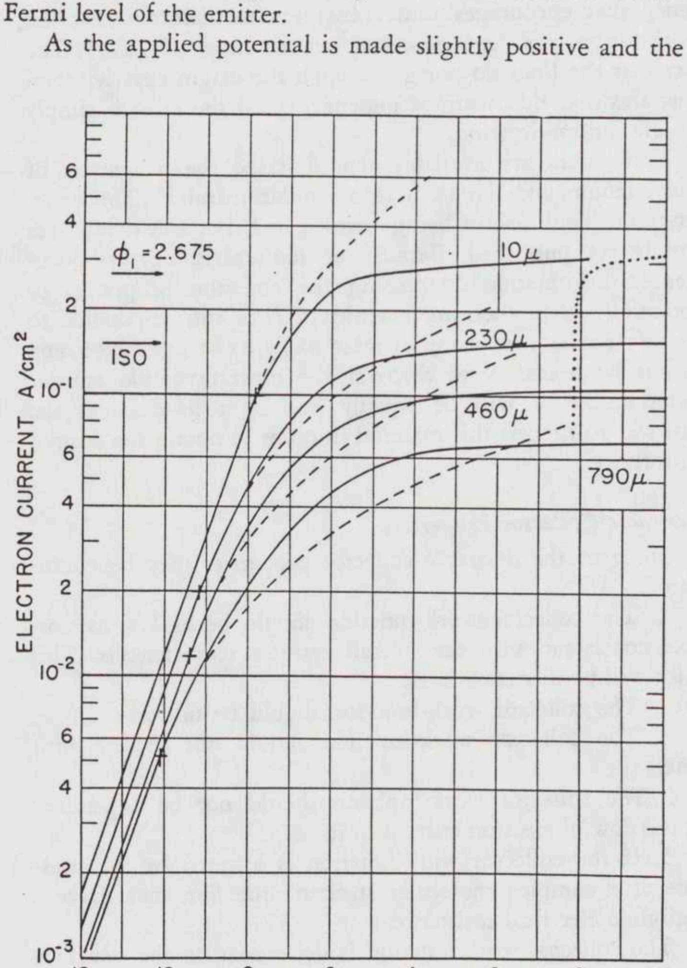

Figure 5. Electron currents plotted according to Maxwell-Boltzmann energy distribution analysis. Emitter 1500°K, cesium 500°K. Limit of Maxwell-Boltzmann range shown by +. Dashed lines: space-charge theory applied to an ion-free electron emitter. Dotted line: return from ignited mode toward passive mode for the spacing 790 microns. ISO: random current density expected in an isothermal diode.

surface potential of the collector is only slightly negative with respect to the Fermi level of the emitter, ignition takes place. Inspection of the motive diagram shown here as Figure 6 would seem to indicate that this generation of ions near the collector surface is established at a very copious rate when the electron energy available barely exceeds 2.6 eV. This is a specific example of the transfer from the "passive" mode of diode operation, in which a negligible space ionization is taking place, over to the "ignited" mode for which space ionization is dominant.

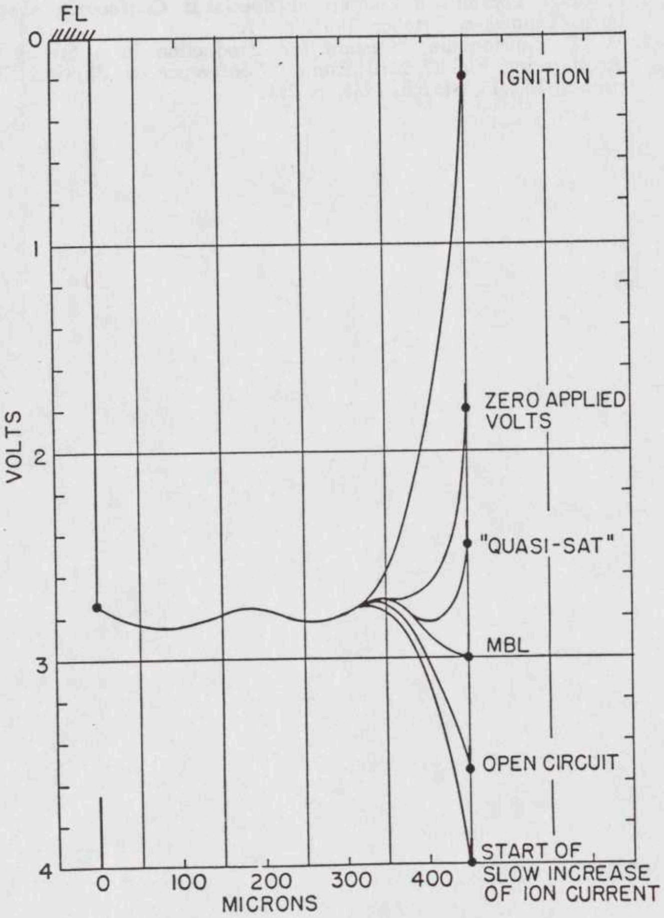

Figure 6. Hypothetical motive diagrams applicable to spacing of 450 microns, temperatures 1500°K and 500°K. Surface potential of the emitter relative to its Fermi level shown by left-hand dot. Collector surface potentials shown for six different values of applied potential. Collector work-function 1.8 eV. Note intermediate space-charge barriers not easily modulated. Important changes in the collector sheath are shown.

After ignition, the applied potential may be made less positive and the current observed remains practically equal to the emission capability of the emitter, as illustrated by the dotted line of Figure 5. Very close to zero applied voltage, it is evident that the current falls very sharply. In spite of the steepness of this curve, it is retraceable as long as the minimum current transferred across the diode does not become less than 7.5×10^{-2} A/cm^2. The ignited mode is lost when the electron current transmitted across the diode approaches within 5 percent of the current observed while it was still operating in the passive mode.

It has been the objective of this discussion to indicate that valuable information concerning thermionic diode operation can be acquired as the result of the detailed study of the voltage-current curve. To obtain this information, it is necessary to study over a very wide range of applied potentials, so that the various components of current can be separated. It is not easy to make this separation in a completely unambiguous manner. Small details should not be overlooked since they may have a very important bearing on the determination of the real mechanisms controlling the converter performance.

Conclusions

It has been the purpose of this presentation to stress the need for further research to establish the fundamental "microscopic" properties of the materials useful in thermionic energy converters. The factual data presented serve mainly as an indication of the researches now in progress and the research results anticipated in the near future. Important decisions basic to the successful development of practical energy converters cannot be made on anything but a cut-and-try basis without the necessary back-up of fundamental information. Even when this is available, there will still be important problems to be solved that relate both to the properties of the materials useful in this area and to the design and construction of units best adapted to fit into an overall converter system. The thermionic converter itself is only a component even though an important one and in the long run cannot be divorced from the other components which include the source of heat and the means of discharging the unused thermal energy into some form of heat sink. In terrestrial applications, this heat sink might very well be another energy converter and in that sense, the thermionic converter would be a "topping unit." In space applications, the heat sink will probably have to be a radiator and in order to minimize its weight, it will be necessary to operate this radiator at the highest possible temperature consistent with a reasonable overall efficiency of the system as a whole.

GLOSSARY OF SYMBOLS

k	Boltzmann's constant 1.380×10^{-23} joule/°K.
J_o	Electron current density at zero field in A/m^2. Eq. 1.
J_v	Current density in A/m^2 at any applied potential V_{app} on the Boltzmann line. Eq. 2.
q	Electron charge 1.602×10^{-19} C.
T_1	Temperature of emitter in °K. Eq. 1.
T_2	Temperature of collector.
T_{Cs}	Cesium reservoir temperature °K.
V_{app}	Applied potential to establish collector Fermi level relative to that of the emitter. Generally negative. Eq. 2.
$\overline{V}$	Electron volt equivalent of temperature (kT/q).
ϕ_1	Emitter true work-function. Eq. 1.
ϕ_2	Collector true work-function. Eq. 2.

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