ADVANCED THERMIONIC TECHNOLOGY PROGRAM
Summary Report

October 1984

Work Performed Under Contract Nos. AC02-76ET11292
AC21-83MC20352

For
U. S. Department of Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Thermo Electron Corporation
Waltham, Massachusetts

and

Rasor Associates, Inc.
Sunnyvale, California

Technical Information Center
Office of Scientific and Technical Information
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PREFACE

This report summarizes the progress made by the Advanced Thermionic Technology Program during the past several years. This Program, sponsored by the U.S. Department of Energy, has had as its goal adapting thermionic devices to generate electricity in a terrestrial (i.e., combustion) environment. The technology has previously been developed for astronautical applications.

The report is organized in four volumes, each focused as much as possible on the needs of a particular audience. Volume 1 contains Part A, the Executive Summary. This Executive Summary describes the accomplishments of the Program in brief, but assumes the reader's familiarity with the thermionic process and the technical issues associated with the Program. For this reason, Volume 1 also contains Part B, a minimally technical overview of the Advanced Thermionic Technology Program. It is suggested that readers just being introduced to the Program review both portions of Volume 1 before consulting the more technical volumes which follow.

Volume 2 (Part C) concentrates on the progress made in developing and fabricating the "current generation" of chemical vapor deposited hot shell thermionic converters and is addressed to those primarily concerned with today's capabilities in terrestrial thermionic technology. Volume 3 (Part D) contains the results of systems studies of primary interest to those involved in identifying and evaluating applications for thermionics. Volume 4 (Part E) is a highly technical discussion of the attempts made by the Program to push

the state-of-the-art beyond the current generation of converters and is directed toward potential researchers engaged in this same task. These technical discussions are complemented with Appendices where appropriate.

TABLE OF CONTENTS

VOLUME 4

PART E
PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

	<u>Page</u>
Preface	i
Table of Contents	iii
List of Exhibits	v
 1. CONVERTER PHYSICS ANALYSES	 4-2
1.1 Introduction	4-2
1.2 Electrode Surface Physics	4-14
1.3 Ignited Mode Analysis	4-44
1.4 Auxiliary Ion Source Analysis	4-70
1.5 Knudsen Mode Analysis	4-83
SECTION 1 - REFERENCES	4-91
 2. CONVERTER DESIGN EXPERIMENTATION	 4-93
2.1 Introduction	4-93
2.2 Oxygen Additive Converters	4-97
2.3 Structured Electrode Converters	4-119
2.4 Divergent Plasma Converters	4-130
2.5 Auxiliary Ion Source Converters	4-146
2.6 SAVTEC Converters	4-171
2.7 Large Converters	4-184
2.8 Cold-Seal Converters	4-198

TABLE OF CONTENTS

VOLUME 4
(Continued)

PART E
PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

	<u>Page</u>
2.9 Inductive Power-Coupled Converters	4-206
2.10 Cesium-Graphite Reservoir Converters	4-213
2.11 Miscellaneous Development Efforts	4-215
SECTION 2 - REFERENCES	4-220
3. HEAT TRANSFER RESEARCH AND TECHNOLOGY	4-222
3.1 Introduction	4-222
3.2 Fire-Tube Cogeneration Burner	4-223
3.3 High Current (HC) Series Heat Transfer Development	4-227
3.4 Ball Matrix Heat Exchangers	4-240
3.5 Finned Heat Exchangers	4-242
SECTION 3 - REFERENCES	4-256
APPENDICES TO VOLUME 4, PART E	4-257
APPENDIX 4-A THE IGNITED DIODE ANALYTICAL MODEL IMD-4	4-258
APPENDIX 4-B THE AUXILIARY ION SOURCE ANALYTICAL MODEL "AIS-1"	4-285
APPENDIX 4-C KNUDSEN MODE DIODE PROGRAM (KMD-1)	4-309

LIST OF EXHIBITS

VOLUME 4

PART E
PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-1.1 DEPENDENCE OF CONVERTER EFFICIENCY ON TEMPERATURE AND INTERNAL LOSSES (V_B)	4-5
EXHIBIT E-1.2 CURRENT DENSITY VS. ELECTRODE SPACING IN A "VACUUM" CONVERTER	4-9
EXHIBIT E-1.3 VOLTAGE LOSSES COMPARED IN THE UNIGNITED AND IGNITED MODES	4-13
EXHIBIT E-1.4 TRANSITION ENERGIES AMONG THE VARIOUS ADSORBED AND GASEOUS SPECIES	4-19
EXHIBIT E-1.5 ILLUSTRATION OF LOCAL ELECTRIC FIELD AT AN ADSORBED PARTICLE DUE TO THE SURROUNDING DIPOLE ARRAY, AND OF PARTIAL PENETRATION OF DIPOLE LAYER POTENTIAL FIELD BY ADSORBED IONS . . .	4-26
EXHIBIT E-1.6 COMPARISON OF COMPUTED AND OBSERVED [3] COVERAGE DEPENDENCE OF FRACTIONAL PENETRA- TION, BY ADSORBED IONS, OF DIPOLE LAYER POTENTIAL FIELD	4-28
EXHIBIT E-1.7 COMPARISON OF COMPUTED AND OBSERVED WORK FUNCTIONS FOR SURFACES IMMERSSED IN CESIUM VAPOR	4-30
EXHIBIT E-1.8 COMPARISON OF COMPUTED AND OBSERVED [4] TEMPERATURE DEPENDENCE OF THE CHANGE IN WORK FUNCTION $\Delta\phi$ OF POLYCRYSTALLINE TUNGSTEN IMMERSSED IN OXYGEN AT VARIOUS PRESSURES P_{O_2}	4-33
EXHIBIT E-1.9 RELATIVE COADSORPTION OF ATOMIC OXYGEN θ_{O_1} AND MOLECULAR OXYGEN θ_{O_2} FOR OXYGEN PRESSURE 6×10^{-9} TORR	4-34
EXHIBIT E-1.10 ARRHENIUS PLOTS OF EMISSION CURRENT DATA FOR (100) TUNGSTEN CRYSTAL IN MIXED CESIUM AND OXYGEN VAPOR AS OBTAINED BY ALLEAU AND BACAL [5]	4-36

LIST OF EXHIBITS

VOLUME 4
(Continued)

PART E
PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-1.11 WORK FUNCTION VS. T/T_{Cs} FOR (100) TUNGSTEN CRYSTAL IN MIXED CESIUM AND OXYGEN VAPOR AS OBTAINED BY ALLEAU AND BACAL [5]	4-37
EXHIBIT E-1.12 ARRHENIUS PLOTS OF EMISSION CURRENT DATA FOR (100) TUNGSTEN CRYSTAL IN MIXED CESIUM AND OXYGEN VAPOR AS OBTAINED BY DENISOT [6]	4-38
EXHIBIT E-1.13 WORK FUNCTION VS. T/T_{Cs} FOR (100) TUNGSTEN CRYSTAL IN MIXED CESIUM AND OXYGEN VAPOR AS OBTAINED BY DENISOT [6]	4-39
EXHIBIT E-1.14 USE OF THE ANALYTICAL MODEL TO DEFINE THE BASIC ORIGIN OF THE OBSERVED BEHAVIOR OF ELECTRODES WITH COADSORBED OXYGEN AND CESIUM	4-42
EXHIBIT E-1.15 COMPARISON OF RESULTS OF PHENOMENOLOGICAL MODEL TO EXPERIMENTAL DATA [9]	4-46
EXHIBIT E-1.16 FLOW CHART FOR IMD-1	4-47
EXHIBIT E-1.17 FLOW CHART FOR IMD-2 AND IMD-3	4-49
EXHIBIT E-1.18 COMPARISON OF J-V CURVES FOR IMD-2 AND IMD-1	4-50
EXHIBIT E-1.19 COMPARISON OF J-V CURVES FOR IMD-3 and IMD-1	4-51
EXHIBIT E-1.20 PLASMA DENSITY PROFILES FROM VARIOUS IGNITED MODE MODELS	4-52
EXHIBIT E-1.21 FLOW CHART FOR THE COMPUTER PROGRAM LOGIC IN IMD-4 ANALYTICAL CONVERTER MODEL	4-54
EXHIBIT E-1.22 COMPARISON BETWEEN CALCULATED RESULTS FROM IMD-4 AND EXPERIMENTAL DATA FROM A PLANAR CONVERTER	4-56
EXHIBIT E-1.23 VARIATION OF PLASMA DENSITY IN INTERELECTRODE SPACE	4-58

LIST OF EXHIBITS

VOLUME 4 (Continued)

PART E PROSPECTS FOR FURTHER TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-1.24 VARIATION OF ELECTRON TEMPERATURES IN INTERELECTRODE SPACE	4-59
EXHIBIT E-1.25 EFFECT OF RADIATION LOSS ON A CALCULATED J-V CURVE IN THE IMD-4 MODEL	4-61
EXHIBIT E-1.26 COMPARISON BETWEEN EXPERIMENTAL DATA AND RESULTS OF IMD-4 MODEL WITH RESONANCE RADIATION INCLUDED	4-62
EXHIBIT E-1.27 DEPENDENCE OF CONVERTER PERFORMANCE ON COLLECTOR AREA RATIO IN IMD-4 CALCULATIONS	4-64
EXHIBIT E-1.28 DEPENDENCE OF CONVERTER PERFORMANCE ON EMITTER AREA RATIO IN IMD-4 CALCULATIONS	4-65
EXHIBIT E-1.29 COMPARISON OF CALCULATED PLANAR AND RADIAL IGNITED MODE PERFORMANCE USING IMD-4 AND IMD-4R	4-67
EXHIBIT E-1.30 COMPARISON OF CALCULATED PLANAR AND RADIAL PLASMA ELECTRON TEMPERATURES, DENSITIES, AND VOLTAGE IN INTERELECTRODE SPACE USING IMD-4 AND IMD-4R	4-68
EXHIBIT E-1.31 ARC DROP REDUCTION	4-69
EXHIBIT E-1.32 BOUNDARY CONDITIONS FOR AUXILIARY ION SOURCE MODEL	4-73
EXHIBIT E-1.33 SCHEMATIC J-V CURVE FOR AUXILIARY ION SOURCE CONVERTER	4-74
EXHIBIT E-1.34 PROGRAM FLOW CHART FOR AIS-1	4-75
EXHIBIT E-1.35 MEASURED PLASMATRON CHARACTERISTICS FOR $T_E = 1300 \text{ K}$, $T_C = 900 \text{ K}$	4-76

LIST OF EXHIBITS

VOLUME 4
(Continued)

PART E
PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-1.36 CALCULATED PLASMATRON CHARACTERISTICS FOR $T_E = 1300 \text{ K}$, $T_C = 900 \text{ K}$ FOR AIS-1 MODEL	4-77
EXHIBIT E-1.37 MOTIVE DIAGRAM AT $J \sim 10 \text{ A/cm}^2$ FOR XENON PLASMATRON	4-79
EXHIBIT E-1.38 PERFORMANCE OF XENON PLASMATRON WITH EMITTER WORK FUNCTION OF 2.0 EV ACCORDING TO AIS-1 MODEL	4-81
EXHIBIT E-1.39 PERFORMANCE OF XENON PLASMATRON WITH EMITTER WORK FUNCTION OF 2.2 EV ACCORDING TO AIS-1 MODEL	4-82
EXHIBIT E-1.40 KMD-1 CALCULATION SHOWING EFFECT OF EMITTED IONS	4-90
EXHIBIT E-2.1 EVOLUTION OF THE CESIATED WORK FUNCTION MINIMUM WITH THE PREADSORBED OXYGEN COVERAGE AT ROOM TEMPERATURE	4-99
EXHIBIT E-2.2 WORK FUNCTION VS. CESIUM EXPOSURE FOR ADSORPTION ON OXIDIZED W(110) FOR DIFFERING OXYGEN COVERAGES	4-100
EXHIBIT E-2.3 COMPARISON OF EXPERIMENTAL DATA ON WORK FUNCTION MINIMA-TEMPERATURE RELATIONSHIP TO PREDICTIONS OF SIMPLE THERMAL DISTURBANCE MODEL	4-103
EXHIBIT E-2.4 EVOLUTION OF THE WORK FUNCTION DURING SIMULTANEOUS EXPOSURE TO CESIUM AND OXYGEN FLUXES	4-104
EXHIBIT E-2.5 EMISSION CHARACTERISTICS OF 2D-OXIDE-W(110), OXYGENATED ELECTROPOLISHED CVD RE AND OXY- GENATED ELECTROETCHED CVD W SURFACE IN 2 MILLITORR OF CESIUM	4-106

LIST OF EXHIBITS

VOLUME 4 (Continued)

PART E PROSPECTS FOR FURTHER TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-2.6 CURRENT DENSITY FROM MO(110) IN CESIUM VAPOR WITH AND WITHOUT CESIUM MONOXIDE VAPOR	4-108
EXHIBIT E-2.7 RASOR-WARNER PLOTS FOR MO(110) IN MIXED CESIUM AND CESIUM MONOXIDE VAPORS, AT A GIVEN CESIUM PRESSURE	4-110
EXHIBIT E-2.8 COMPARISON OF LOWEST WORK FUNCTIONS OBTAINED ON MO(110) WITH CS ₂ O VAPOR IN THE DIODE TO THE WORK FUNCTION MINIMUM OF THE W(110)-2D-OXIDE CS SURFACE	4-111
EXHIBIT E-2.9 RASOR-WARNER PLOTS FOR W(110) IN MIXED CESIUM AND CESIUM MONOXIDE VAPORS, AT A GIVEN CESIUM PRESSURE	4-113
EXHIBIT E-2.10 HIGH TEMPERATURE EMISSION CHARACTERISTICS FOR W(110) AND MO(110) IN MIXED CESIUM AND CESIUM MONOXIDE VAPORS	4-114
EXHIBIT E-2.11 CORRELATION OF OPTIMUM COLLECTOR TEMPERATURE TO THE OXYGEN CONTENT OF MOLYBDENUM OXIDE COLLECTORS	4-118
EXHIBIT E-2.12 DEPENDENCE OF THE OUTPUT CHARACTERISTICS OF STRUCTURED OSEC-3 AND SMOOTH OSEC-2 CONVERTERS ON COLLECTOR TEMPERATURE T _C	4-121
EXHIBIT E-2.13 COMPARISON OF DEPENDENCE OF BARRIER INDEX ON COLLECTOR TEMPERATURE FOR STRUCTURED AND UN- STRUCTURED COLLECTORS IN THE <u>UNIGNITED</u> MODE	4-122
EXHIBIT E-2.14 COMPARISON OF DEPENDENCE OF BARRIER INDEX ON COLLECTOR TEMPERATURE FOR STRUCTURED AND UN- STRUCTURED COLLECTORS IN THE <u>IGNITED</u> MODE	4-123
EXHIBIT E-2.15 COMPARISON BETWEEN STRUCTURED CONVERTER SPC-10 AND SMOOTH CONVERTER SPC-9 PERFORMANCE ENVELOPES	4-125

LIST OF EXHIBITS

VOLUME 4 (Continued)

PART E PROSPECTS FOR FURTHER TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-2.16 COLLECTOR TEMPERATURE OPTIMIZED PERFORMANCE ENVELOPES FOR $T_E = 1700$ K FOR COMBINATIONS OF STRUCTURED AND SMOOTH ELECTRODES AT A CURRENT DENSITY OF 10 AMPERES/CM ²	4-127
EXHIBIT E-2.17 LEAD INPUT POWER AND LEAD EFFICIENCY VS. TOTAL CURRENT FOR $T_E = 1700$ K FOR COMBINATIONS OF STRUCTURED AND SMOOTH ELECTRODES	4-128
EXHIBIT E-2.18 BARRIER INDEX (V_B) VS. TOTAL CURRENT FOR COMBINATIONS OF STRUCTURED AND SMOOTH ELECTRODES	4-129
EXHIBIT E-2.19 THE DIVERGENT GEOMETRY CONVERTER	4-132
EXHIBIT E-2.20 CONVERTER ARRAY MODEL USED TO COMPUTE CORREC- TION FOR FINITE RESISTANCE OF EMITTER WIRE IN DIVERGENT GEOMETRY CONVERTER	4-134
EXHIBIT E-2.21 CESIUM VAPOR PRESSURE FAMILY #1 FOR DIVERGENT GEOMETRY CONVERTER AT $T_E = 1730$ K	4-135
EXHIBIT E-2.22 CESIUM VAPOR PRESSURE FAMILY #2 FOR DIVERGENT GEOMETRY CONVERTER AT $T_E = 1730$ K	4-136
EXHIBIT E-2.23 PERFORMANCE CURVE FOR FAMILY #1 DIVERGENT GEOMETRY CONVERTER AT $T_E = 1730$ K	4-137
EXHIBIT E-2.24 PERFORMANCE CURVE FOR FAMILY #2 DIVERGENT GEOMETRY CONVERTER AT $T_E = 1730$ K	4-138
EXHIBIT E-2.25 PHOTOGRAPH OF EMITTER PIN ASSEMBLY AND COLLECTOR HOLE STRUCTURE FOR DIVERGENT GEOMETRY TEST CONVERTER	4-140
EXHIBIT E-2.26 ENERGY BALANCE FOR DIVERGENT GEOMETRY THERMIONIC CONVERTER USING PIN ARRAY	4-141

LIST OF EXHIBITS

VOLUME 4 (Continued)

PART E PROSPECTS FOR FURTHER TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-2.27 LEAD POWER, LEAD EFFICIENCY, AND ELECTRODE VOLTAGE AS A FUNCTION OF EMITTER PLATE TEMPERATURE FOR PIN ARRAY DIVERGENT GEOMETRY CONVERTER	4-142
EXHIBIT E-2.28 LEAD POWER, LEAD EFFICIENCY, AND ELECTRODE VOLTAGE AS A FUNCTION OF PIN LENGTH FOR PIN ARRAY DIVERGENT GEOMETRY CONVERTER	4-143
EXHIBIT E-2.29 LEAD POWER, LEAD EFFICIENCY, AND ELECTRODE VOLTAGE AS A FUNCTION OF EMITTER CURRENT FOR PIN ARRAY DIVERGENT GEOMETRY CONVERTER	4-144
EXHIBIT E-2.30 MOTIVE DIAGRAM FOR THE PLASMATRON	4-147
EXHIBIT E-2.31 POTENTIAL DIAGRAM DURING DECAY OF ELECTRODE PULSE	4-150
EXHIBIT E-2.32 CURRENT AS FUNCTION OF TIME FOLLOWING PULSE IN PULSED CONVERTER	4-152
EXHIBIT E-2.33 DEMOUNTABLE PLASMATRON TEST CONVERTER WITH PLANE PARALLEL ELECTRODES	4-154
EXHIBIT E-2.34 DEMOUNTABLE PLASMATRON TEST CONVERTER WITH CYLINDRICAL ELECTRODES	4-155
EXHIBIT E-2.35 EXPERIMENTAL AND THEORETICAL PERFORMANCE OF CESIUM PLASMATRON	4-157
EXHIBIT E-2.36 EXPERIMENTAL AND THEORETICAL PERFORMANCE OF ARGON PLASMATRON	4-158
EXHIBIT E-2.37 AMPLIFICATION FACTOR AS A FUNCTION OF ARGON PRESSURE IN ARGON PLASMATRON	4-160
EXHIBIT E-2.38 ENHANCEMENT DISTRIBUTION IN THE CYLINDRICAL PLASMATRON	4-162

LIST OF EXHIBITS

VOLUME 4
(Continued)

PART E
PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-2.39 MAGNETIC CUT-OFF IN THE CYLINDRICAL PLASMATRON	4-163
EXHIBIT E-2.40 MAGNETIC DISPLACEMENT OF THE ENHANCED DISTRIBUTION IN THE CYLINDRICAL PLASMATRON	4-165
EXHIBIT E-2.41 DC OUTPUT CHARACTERISTICS IN A XENON ATMOS- PHERE AS A FUNCTION OF EMITTER-COLLECTOR SPACING IN A RING TRIODE CONVERTER	4-168
EXHIBIT E-2.42 BARRIER INDICES AND EQUIVALENT ARC DROPS FOR PULSED DIODE AS FUNCTION OF XENON PRESSURE (IGNITED MODE)	4-170
EXHIBIT E-2.43 ELECTRODE EFFICIENCY VS. EMITTER TEMPERATURE FOR DIFFERENT ELECTRODE SPACINGS	4-172
EXHIBIT E-2.44 ELECTRODE EFFICIENCY VS. OUTPUT POWER DENSITY FOR DIFFERENT EMITTER TEMPERATURES	4-174
EXHIBIT E-2.45 THE SAVTEC CONVERTER	4-175
EXHIBIT E-2.46 CHARACTERISTIC CURVE FOR AN EARLY SAVTEC	4-178
EXHIBIT E-2.47 CHARACTERISTIC CURVE FOR AN EARLY SAVTEC AT $T_E = 1200$ K	4-179
EXHIBIT E-2.48 CHARACTERISTIC CURVE FOR A SEVEN ELEMENT SAVTEC OPERATING WITH EMITTER TEMPERATURE 1270 K	4-181
EXHIBIT E-2.49 CHARACTERISTIC CURVE FOR A SEVEN ELEMENT SAVTEC CONVERTER OPENING WITH AN EMITTER TEMPERATURE OF 1350 K	4-182
EXHIBIT E-2.50 NINETEEN ELEMENT SAVTEC ARRAY	4-183
EXHIBIT E-2.51 ZEPO ASSEMBLY PRIOR TO WELDING	4-189

LIST OF EXHIBITS

VOLUME 4
(Continued)

PART E
PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-2.52 RANGE OF MEASURED CURRENT DURING ZEPO TEST TWO	4-192
EXHIBIT E-2.53 COMPUTER PLOT OF COLLECTOR TEMPERATURE, VOLTAGE PROFILE AND CURRENT DISTRIBUTION FOR ZEPO TEST TWO	4-193
EXHIBIT E-2.54 CUTAWAY SECTION OF HC-2 CONVERTER SHOWING VARIOUS ELEMENTS	4-195
EXHIBIT E-2.55 EMITTER-COLLECTOR-FLEXIBLE CONNECTOR FROM HC-2	4-196
EXHIBIT E-2.56 CROSS-SECTIONAL DRAWING OF COLD SEAL CONVERTER	4-200
EXHIBIT E-2.57 OPERATING CHARACTERISTICS OF A COLD SEAL CON- VERTER AS A FUNCTION OF ARGON OVERPRESSURE	4-203
EXHIBIT E-2.58 COLD SEAL CONVERTER OUTPUT CHARACTERISTICS MEASURED AT THE ELECTRODES	4-204
EXHIBIT E-2.59 FLUX RESET OPERATING CHARACTERISTICS	4-208
EXHIBIT E-2.60 PUSH-PULL OPERATING CHARACTERISTICS	4-210
EXHIBIT E-2.61 FLUX RESET CIRCUIT SCHEMATIC	4-212
EXHIBIT E-2.62 OSCILLOSCOPE TRACING OF A FLUX RESET SYSTEM	4-214
EXHIBIT E-2.63 CESIUM PRESSURE VS. LIQUID-CESIUM AND GRAPHITE-CESIUM RESERVOIR TEMPERATURES	4-216
EXHIBIT E-3.1 FIRE-TUBE CONVERTER DESIGN	4-225
EXHIBIT E-3.2 THERMIONIC COMBUSTOR CONTAINING SIX CONVERTERS	4-226

LIST OF EXHIBITS

VOLUME 4
(Continued)

PART E
PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-3.3 EFFECTIVE HEAT TRANSFER COEFFICIENT AND NUSSELT NUMBER VS. REYNOLDS NUMBER, ILLUS- TRATING ENHANCEMENT BY JET IMPINGEMENT	4-228
EXHIBIT E-3.4 JET IMPINGEMENT HEAT TRANSFER SYSTEM DESIGN CHART	4-230
EXHIBIT E-3.5 SILICON CARBIDE JET SHELL ASSEMBLY	4-231
EXHIBIT E-3.6 HEAT REJECTION SYSTEM JET IMPINGEMENT ARRAY FOR ZEPO	4-233
EXHIBIT E-3.7 EFFECT OF TAILORING HEAT FLUX PROFILE ON TEMPERATURE BY USING JET IMPINGEMENT	4-234
EXHIBIT E-3.8 CONCEPTUAL DRAWING OF RADIANT HEAT TRANSFER FROM CELLULAR CERAMIC	4-235
EXHIBIT E-3.9 COMPARISON OF RADIANT HEAT TRANSFER CO- EFFICIENTS FOR NATURAL GAS/AIR COMBUSTION PRODUCTS AND CELLULAR CERAMIC	4-237
EXHIBIT E-3.10 ANGULAR VARIATION OF HEAT FLUX FROM CELLULAR CERAMIC RADIATOR	4-238
EXHIBIT E-3.11 COMPARISON OF JET IMPINGEMENT AND CELLULAR CERAMIC HEAT TRANSFER FOR A 1973 K SOURCE	4-239
EXHIBIT E-3.12 BALL MATRIX HEAT EXCHANGER	4-241
EXHIBIT E-3.13 "FIN I" HEAT EXCHANGER	4-243
EXHIBIT E-3.14 REQUIRED PUMPING POWER VS. HEAT REMOVED FOR "FIN I" COOLER AND "FIN II" COOLER	4-244
EXHIBIT E-3.15 REQUIRED HEAT TRANSFER COEFFICIENT VS. COLLECTOR-AIR TEMPERATURE DIFFERENCE FOR "FIN II" DESIGN	4-246

LIST OF EXHIBITS

VOLUME 4
(Continued)

PART E
PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

	<u>Page</u>
EXHIBIT E-3.16 INITIAL RESULTS ON "FIN II" COLLECTOR HEAT EXCHANGER TEST SERIES	4-247
EXHIBIT E-3.17 "FIN III" COLLECTOR HEAT EXCHANGER DESIGN	4-249
EXHIBIT E-3.18 "FIN III" COLLECTOR HEAT EXCHANGER MOUNTED IN CONVERTER	4-250
EXHIBIT E-3.19 PRESSURE DROP VS. HEAT REMOVED FOR COLLECTOR HEAT EXCHANGER "FIN II"	4-252
EXHIBIT E-3.20 PRESSURE DROP VS. HEAT REMOVED FOR COLLECTOR HEAT EXCHANGER "FIN III"	4-253
EXHIBIT E-3.21 PRESSURE DROP VS. HEAT REMOVED FOR COLLECTOR HEAT EXCHANGERS "FIN II AND "FIN III"	4-254
EXHIBIT E-3.22 PARAMETRIC PLOT OF "FIN III" HEAT EXCHANGER PERFORMANCE	4-255

PART E

PROSPECTS FOR FURTHER
TECHNOLOGY ADVANCEMENT

1. CONVERTER PHYSICS ANALYSES

1.1 Introduction

The performance of the thermionic converters available today is far below the performance which can be expected from an ideal device. This can best be appreciated by examining the essential electron emission and heat transfer processes that occur in the converter and the non-essential losses present in currently available devices.

Consider an ideal converter operating at about 10 Amperes/cm^2 , with an emitter temperature of 1700 K and a collector temperature of 950 K. To move from the emitter into the interelectrode gap, an electron nominally "bound" to the emitter surface must overcome a potential barrier ϕ_E , known as the emitter work function. A similar barrier ϕ_C , the collector work function, exists at the collector.

In such an ideal converter, the electron is not affected by anything in the gap except the unperturbed electric field between plane-parallel electrodes. Thus, to move an electron from the emitter across the gap, an additional energy barrier $V + \phi_C$ must be overcome if the applied electrode potential difference V is greater than the "contact potential" $V_O \equiv \phi_E - \phi_C$. If A is the Richardson constant (i.e., $120 \text{ Amperes/cm}^2\text{-K}$) and k is the Boltzman constant, then the current density of the ideal diode is given by the Richardson-Dushman equation:

$$J = \begin{cases} AT_E^2 \exp\left(-\frac{V+\phi_C}{kT_E}\right) & \text{for } V > V_0 \\ AT_E^2 \exp\left(-\frac{\phi_E}{kT_E}\right) & \text{for } V < V_0 \end{cases} \quad \begin{matrix} \text{(E-1.1)} \\ \text{(E-1.2)} \end{matrix}$$

In the example case, this forward current density is approximately 12 Amperes/cm², while a current of about 2 Amperes/cm² is back-emitted from the collector, leaving a net output current density of 10 Amperes/cm². The emitter work function is 2.5 eV and the collector work function is 1.5 eV. Thus, the output voltage is 1.0 Volts and the output power density is 10 Watts/cm². If the only energy required to run the converter were that needed to emit electrons, the input power requirement would be $(Q_E + 2kT_E) \times J = 28 \text{ Watts/cm}^2$. The electric efficiency would be 36%.

In fact, other losses exist which are almost unavoidable, particularly radiation losses between the emitter and collector electrodes, electrical resistive heating (I^2R) and thermal losses in the electric lead to the emitter. Typically, an effective emissivity of .2 is observed for radiation between emitter and collector. In the example, this results in a requirement for 8.4 Watts/cm² of additional thermal input. In an optimized design, thermal losses down the electric lead can be shown to approximate ten percent of the total thermal input power. Thus, a total lead thermal input power of $(28 + 8.4) \times 1.1 = 40 \text{ Watts/cm}^2$ will be required. Other small losses may exist as well, for example, about 1 Watt/cm² for cesium conduction. It can also be shown that resistive losses in an emitter electric lead of optimum design will be about 10% of the output power, reducing total output to 9 Watts/cm². Thus, in an "ideal" converter with realistic radiation and lead losses, we might expect an efficiency of 22%.

By contrast, under the operating conditions of this example, present ignited mode thermionic converters have an optimized lead efficiency of, at best, 12%. The reason for this is the loss in current and energy experienced by the flow of electrons between the emitter and collector. This loss is equivalent to .5 eV and cuts the output voltage of the converter, and its efficiency, approximately in half. Thus, a primary emphasis in the Advanced Thermionic Technology Program has been the reduction of this loss in the inter-electrode space, since success holds the promise of nearly doubling the performance of the converter.

There is a second approach to potentially doubling converter performance: lowering the collector work function from 1.5 eV to 1 eV, thereby increasing the output voltage of the converter by .5 Volts. However, to achieve this, the back-emission of electrons from the collector must be held near or below an Ampere per square centimeter. This constraint sets an upper limit on collector temperature of only 650 K.

As discussed in Part B, the collector work function, the voltage losses across the interelectrode space, and the voltage equivalent of any losses in current density across the interelectrode space sum to give an overall figure-of-merit, V_B , called the barrier index, or back-voltage, for a particular converter and operating point. The best of presently available converters are typified by a V_B near 2.0 eV. Exhibit E-1.1 shows the lead efficiency which can be anticipated from such converters as a function of emitter temperature. Also shown is the efficiency to be expected when V_B is lowered to 1.5 eV by reducing interelectrode losses, collector work function, or a combination of these two. Ultimately $V_B = 1.0$ eV may be approached by fully reducing both interelectrode and collector losses.

Exhibit E-1.1
Dependence of Converter Efficiency on
Temperature and Internal Losses (V_B)

There are two primary constraints which must be considered in all attempts to achieve such performance improvement. First, both the emitter and collector must have low work functions (i.e., one to three electron Volts.). A partial monolayer of cesium is normally used to give the desired work functions. This layer is maintained using a low pressure (i.e., about one torr) cesium gas in the interelectrode space. Care must be taken to avoid increasing the collector work function if other methods than cesium are used to obtain a low emitter work function.

Second, the higher the emitter temperature, the higher must be the operating current density. This requirement is set by the level of radiation losses between the emitter and collector. High efficiencies can theoretically be obtained with less than an Ampere per square centimeter at 1200 K. Current densities of 5-10 Amperes/cm² are required at 1900 K in order to avoid large penalties in efficiency. Several approaches to improving performance while meeting these constraints have been addressed within the context of the Program.

The current which can flow from the emitter to the collector in a vacuum diode is severely limited by space-charge effects. With a normal interelectrode gap (i.e., three millimeters), current will be limited to 10⁻² Amperes/cm² by these effects, a current far too low to provide efficient power generation in even the lowest temperature converter.

Space-charge limits on current density can be eliminated if the electron cloud is neutralized with heavy positive ions. This is the method used in the conventional ignited mode of operation; i.e., a spontaneous cesium discharge is ignited in the interelectrode space. Electrons leaving the emitter are accelerated into the slightly positive (i.e., about one Volt) cesium plasma. Those

electrons with the highest energy produce cesium ions which make up for ions lost due to combination in the plasma or at the electrodes.

At first glance this would seem to be a very efficient process. Cesium is a very heavy atom, and, as a consequence, has a thermal velocity of only about $1/500$ that of an electron. Thus, one cesium atom can serve to neutralize the passage of 500 electrons before it, too, is lost at an electrode and must be replaced. The ionization potential of cesium is low, only 3.9 eV. If each passing electron contributes an average of only $1/500$ of this energy, then the voltage lost across the gap to supply this energy need only be $3.9/500$ eV, or about 0.01 Volt, and such a voltage loss would be inconsequential.

In fact, each electron does not contribute to the ionization of cesium atoms. Only those of highest energy do. To thermally supply enough electrons on the high energy tail of the Boltzmann distribution, the electron temperature in the plasma must also be very high -- typically 3200 K near the emitter and over 2000 K at the collector. The existence of this high-temperature electron gas in the interelectrode spaces results in large thermal losses to both emitter and collector as the hot electrons enter these electrodes. These losses must be replaced electrically, resulting in the voltage drop across the interelectrode plasma already referred to. This loss, a result of the inefficiency of producing cesium ions with high-temperature thermalized electrons, is the major source of energy loss in the conventional converter.

In the first approach to eliminating this loss considered within the Program, both the emitter and collector areas are roughened, or structured, to give them a surface area much larger than that of their planar cross-section.

On the emitter side, the additional area permits emission of a given total current with a higher surface work function. This permits use of lower cesium pressures. On the collector side, the large area results in a lower current density at the collector surface, corresponding to a higher barrier potential and higher output voltage. The structured surfaces do have higher emissivity, resulting in larger radiation losses. However, analytical models predict an improvement of about .1 Volt using this technique.

In a second approach, a divergent plasma is used. An example is a small cylindrical converter in which a wire is used as the emitter and the inner diameter of a cylinder serves as the collector. As current flows from the emitter to the collector the electron "gas" expands and can work against a retarding potential gradient. This results in increased power output for a given emitter current density, equivalent to a .15-.2 Volt increase in output voltage. Efficiencies are significantly higher despite slightly higher radiation losses between emitter and collector.

Another alternative being pursued is to reduce the interelectrode space instead of producing ions. Exhibit E-1.2 shows that a spacing of 10^{-3} cm is needed to allow current densities of several amperes per square centimeter. Under these conditions, interelectrode losses could be reduced to the equivalent of .15 Volt or less.

While only a factor of three below the spacings achieved in converter designs of the past, a spacing of 10^{-3} cm has proven extremely difficult to achieve in practice. A new design approach with this objective, SAVTEC (Self-Adjusting Versatile Thermionic Energy Converter), was created as part

Exhibit E-1.2
Current Density vs. Electrode Spacing in a "Vacuum" Converter

of the Program. The essence of this approach is to divide the emitter into small segments. Each segment is supported by its own electric lead and is heated by radiation. By using such small emitters and isolating them structurally from the rest of the converter structure, it is hoped that short-circuit problems found in earlier design approaches can be avoided.

Since the inefficiency of the ignited mode stems from the fact that ions are created thermally, using the same electrons which form the converter output current, several types of converters have been investigated in which a "cold" converter plasma is maintained by an auxiliary discharge current separate from the output current. This auxiliary discharge is powered by an external power supply which can be optimized specifically for the production of ions. Because the electrons which carry the converter current no longer produce ions, they need only suffer scattering losses as they transit the gap. However, enough power must be obtained from the external circuit to run the auxiliary discharge and this load corresponds to a pseudo-arc drop in the gap.

Early emphasis in the Program was given to the development of converters with cesium plasmas which used auxiliary ion sources. Two types of converters were studied, plasmatron-type devices and pulsed devices. In the plasmatrons small local auxiliary discharge regions were established, regularly spaced between the emitter and collector. Typically a third electrode was used for this purpose. Ions produced by the discharge filled the interelectrode space, allowing high currents to flow. In the pulsed converters, a short pulse at a higher optimum voltage applied to the converter periodically would be used to generate ions. Again high currents could flow until loss of the ions required repulsing. However, a fundamental problem was found to exist with the auxiliary

ion source converter using a cesium plasma. The average electron temperature was lower in these converters, minimizing plasma energy losses and consequent voltage drops across the gap, but the electron scattering cross-section of cesium for the low-temperature electron was very high, giving, in effect, a high plasma resistance. Such a device using cesium is, as a consequence, only of interest at very low current densities and temperatures.

Since an auxiliary discharge can be created in any gas, a plasma gas can be chosen which has a very low scattering cross-section for low-temperature electrons. Inert gases, particularly xenon, have low cross-sections. The use of such gases was studied extensively and analytical models were developed which accurately predict the performance characteristics of actual devices. The projected converter performance levels are very high. However, inert gas converters present another problem. In these converters the cesium pressure must be kept low, typically near or below 10^{-2} torr, to avoid excessive electron scattering. Yet it is this same cesium which, as a partial monolayer in the electrode surfaces, gives the needed emitter and collector work functions. Without sufficient cesium to supply these coatings, it has been necessary to develop new electrode surface materials. Conventional oxide cathode materials (BaO, CaO, etc.) suitable for emitter use all evaporate to some degree, coating the collector with material that has a 2.0-2.2 eV work function compared to the 1.5 eV cesiated collectors normally used. This results in a .5-.7 Volt loss in output voltage, a loss which completely offsets the gains made in the interelectrode plasma. As a result, a substantial effort is being made to develop emitter surfaces with the desired work function in 10^{-2} torr of cesium which are compatible with a 1.5 eV collector. Surfaces generated from a very low pressure $\text{Cs-Cs}_x\text{O}_y$ mixture appear from early test

results to satisfy this need. The next step is to use these surfaces in an auxiliary ion source converter, a step not yet accomplished in a practical converter geometry.

Still another approach might be based on the idea that, at sufficiently high emitter temperatures, cesium atoms hitting the emitter are thermally ionized. This source of ions, right near the emitter electrode, can be effective in reducing adverse space charge effects. As shown in Exhibit E-1.3, in the unignited mode the converter operates with about .4-.5 Volts higher output, demonstrating the elimination of most of the arc drop seen in the ignited mode. However, practical current densities are typically achieved in this mode only with emitter temperatures near 2000 K. The Soviets have published results suggesting practical operation at an emitter temperature of 1800 K using structured emitters to generate more ions. A temperature of 1800 K is at the upper range of hot shell performance to date, however, and as a consequence no work has yet been performed with this approach in this Program.

These various approaches have been pursued both through experiment and through the development of theoretical, analytical models as indicated above. The experimental activities are the subject of Part E, Section 2, while the analytical work is described in the remainder of this section and in Appendices 4-A through 4-C. The models created during this Program, and the results derived from them, should be of fundamental value in the continuing effort to bring thermionic technology to maturity.

Exhibit E-1.3
Voltage Losses Compared in the Unignited and Ignited Modes

1.2 Electrode Surface Physics

The surface properties of electron emitters and collectors in a conventional thermionic converter are primarily determined by a layer of adsorbed cesium atoms. This surface layer is continuously renewed by steady-state exchange of the adsorbed cesium atoms with the cesium vapor in the interelectrode space. In principle, this unique restorative capacity of thermionic devices could allow them to operate continuously at emission currents on the order of ten amperes per square centimeter for years without any degradation in performance due to changes in electrode properties.

Early basic understanding of the physics of this adsorbed layer, and the resulting correlation of its properties with the properties of the refractory metal surface on which it was adsorbed, led to control and stabilization of the electrode properties for substantial improvement of converter performance and lifetime. However, the cesium pressure used in such converters, which is at or above one torr, has required designs with small interelectrode spacings that impose close mechanical tolerances on the electrode structure, adversely affecting the cost and long-term stability of these structures. In addition, advanced modes of converter operation that greatly reduce power losses in the interelectrode plasma cannot be practically utilized at these relatively high cesium pressures. Alternative emitters that do not depend on cesium adsorption have been explored, but none have approached practicality.

Langmuir and co-workers in the 1920's found that the cesium pressure required to obtain high electron emission currents could be greatly lowered by first oxidizing the electrode surface. Also, in the same period, it was

found that very low work functions, i.e., about one electron Volt, could be obtained on surfaces covered with cesium oxide. In the mid-1960's it was discovered inadvertently that admission of oxygen to cesium vapor thermionic converters could greatly increase their performance. Many subsequent attempts were made in the U.S. and USSR to practically utilize this effect, including controlled addition of oxygen and cesium oxide vapor to the converter cesium vapor, and coating of the converter collector with tungsten oxide. Although some of these attempts had limited success, the beneficial effects were difficult to maintain over extended periods, were difficult to reproduce, and/or imposed severe constraints on practical converter fabrication and operation.

This instability, irreproducibility and inflexibility very likely arises from two related causes. One of these is that the amount of oxygen required to produce the desired effects is extremely small (i.e., 10^{-8} to 10^{-6} torr), and long-term control of such a trace of a highly active impurity in a high-temperature device is difficult to achieve practically. The other cause is the many competing chemical and physical processes which exist in the converter that can strongly affect its behavior.

During this Program, an analytical model for two-state adsorption of cesium on various surfaces, which has been valuable in guiding past practical development of converter electrode surfaces, has been extended to include oxygen adsorption and coadsorption of cesium and oxygen. This work has provided a basic framework for correlating the many experimental variables to aid in identifying, organizing, and interpreting the oxygen effects observed in converters, and to permit their control and optimization. Among the options provided by this general formulation is the potential enlightened use of

chalcogens other than oxygen (e.g., sulfur, selenium, or tellurium vapor) to obtain the desired effects at partial pressures well above the impurity level, an approach pioneered by the USSR but not yet employed in the U.S.

The method employed is an extension of highly successful work originated by Langmuir, Becker and DeBoer in the 1930's. By considering only surfaces immersed in vapors of known composition, the general and powerful methods of statistical mechanics can be applied to a highly simplified physical model of the adsorbed particles and the surface. The absence of structural detail in the analysis is justified by the fact that such detail has much less effect on the state of the surface than the adsorption energies, temperatures and particle fluxes which characterize conditions in an experimental or practical thermionic device. Furthermore, the structural detail that can be determined by surface-diagnostic instruments at low temperatures, the typical subject of most current surface physics investigations, disappears at the high operating temperature of thermionic electrodes; in effect, the adsorbed layer becomes more like a two-dimensional gas than like a two-dimensional crystal.

This "Langmuir surface phase postulate" assumes that the vapor phase in which the surface is immersed is in complete thermodynamic equilibrium, and that the two-dimensional adsorbed phase also is in complete thermodynamic equilibrium at a different temperature. Although the two phases, therefore, are not in complete equilibrium with each other, equal fluxes of atoms are exchanged between the two phases at steady state. This postulate is valid whenever the rate of interaction among particles within the individual phases is much greater than the rate of vaporization, a condition amply fulfilled under all practical conditions in thermionic devices.

The general equilibrium reaction of two species M and X to form a combined species is represented by

At equilibrium the second law of thermodynamics requires that the chemical potentials of the reactants must equal the chemical potential of the products.

$$\bar{\mu}_{MX} = n\bar{\mu}_M + m\bar{\mu}_X \quad (E-1.4)$$

$$\bar{\mu}'_{MX} = n\bar{\mu}'_M + m\bar{\mu}'_X \quad (E-1.5)$$

where [1]

$$\bar{\mu}_j = kT \ln(\Lambda_j^3 n_j / q_j) - V_j \quad (E-1.6)$$

for species j in the vapor phase (j = M, X or MX) and

$$\bar{\mu}'_j = kT \ln(b_j \theta_j / q_j) - V_j - \phi_j + kT\theta / S_f \quad (E-1.7)$$

for species j in the adsorbed phase on a metal surface, with

$\Lambda_j = h / (2\pi \bar{M}_j kT)^{1/2}$ is the thermal DeBroglie wavelength.

$$b_j = \Lambda_j^2 \sigma_j f_j h / kT S_f,$$

T = surface temperature,

n_j = number density of species j in the vapor,

q_j = statistical weight of species j,

V_j = dissociation energy of species j in the vapor phase,
 ϕ_j = desorption energy of species j ,
 σ_j = density of adsorption sites for species j on surface,
 $\theta = \sum_j \theta_j$ = fraction of adsorption sites occupied by all species
 S_f = fraction of available adsorption sites
 $= (1 - 1.307\theta^3 + .307\theta^4) / (1 + 1.81\theta + 2.57\theta^2)$

$$\approx 1 - \frac{3}{2} \theta + \frac{1}{2} \theta^2, \quad (\text{E.1.8})$$

f_j = vibration frequency of adsorbed species normal to surface,
 $\bar{M}_j$ = mass of species j , and
 h and k = Planck and Boltzman constants.

Exhibit E-1.4 illustrates the transitions and transition energies possible among the various adsorbed and gaseous species. The first law of thermodynamics requires that the adsorption and dissociation energies are related by:

$$E_{MX} + n\phi_M + m\phi_X = \phi_{MX} + V_{MX} \quad (\text{E-1.9})$$

where E_{MX} is the dissociation energy of species M_nX_m in the adsorbed phase. Note that $V_j = E_j = 0$ for the products M and X , that the chemical potential of the electron $\bar{\mu}_e$ is zero in the vapor phase and that $\bar{\mu}_e = -\phi_e$ in a metal with work function ϕ_e .

Exhibit E-1.4
Transition Energies Among the Various Adsorbed and Gaseous Species

The number density n_j , the partial pressure p_j and the arrival rate μ_j (not to be confused with the chemical potential $\bar{\mu}_j$) of species j at the surface are related via kinetic gas theory by:

$$n_j = p_j/kT = (2\pi\bar{M}_j/kT)^{1/2}\mu_j \quad (\text{E-1.10})$$

Furthermore, the surface phase postulate requires that the evaporation rate v_j from the equilibrium surface phase at temperature T must equal the arrival rate μ_j from an equilibrium vapor phase at the same temperature, i.e., $v_j = \mu_j$ in Equation E-1.10.

Equations E-1.4 through E-1.10 combine, along with Equations E-1.1 and E-1.2, to give, for the neutral adsorbed species,

$$v_M^n v_X^m / v_{MX} = v_{oMX}^{n+m-1} \exp(-V_{MX}/kT) \equiv K_{MX} \quad (\text{E-1.11})$$

$$\theta_M^n \theta_X^m / \theta_{MX} = \theta_{oMX}^{n+m-1} \exp(-E_{MX}/kT) \quad (\text{E-1.12})$$

where

$$v_{oMX}^{n+m-1} = \frac{q_M^n q_X^m}{q_{MX}} \frac{M_M^n M_X^m}{M_{MX}} \frac{2\pi(kT)^2}{h^3} \quad (\text{E-1.13})$$

$$\theta_{oMX}^{n+m-1} = \frac{(\sigma f)_{MX}}{(\sigma f)_M^n (\sigma f)_X^m} \left(\frac{v_{oMX}}{\gamma} \right)^{n+m-1} \quad (\text{E-1.14})$$

$$\gamma = \exp(\theta/S_f)/S_f \quad (\text{E-1.15})$$

Equations E-1.4 through E-1.10 also combine to give, for the neutral species,

$$v_j = (\sigma f)_j \theta_j \exp(-\phi_j/kT) \quad (E-1.16)$$

Similarly, for the vapor above a reservoir of the condensed phase of $M_n X_m$ at the equilibrium temperature of the vapor T_{MX} (i.e., using $\theta = S_f = 1$ and $\phi_j = h_{MX}$ in Equation E-1.7),

$$\mu_M^n \mu_X^m = \mu_{oMX}^{n+m-1} \exp[(h_{MX} - v_{MX})/kT_{MX}] \equiv K_{MXv} \quad (E-1.17)$$

and

$$\mu_{MX} = (\sigma f)_v \exp(-h_{MX}/kT_{MX}) \quad (E-1.18)$$

where

$$\mu_{oMX}^{n+m-1} = (\sigma f)_{MXv} v_{oMX}^{n+m-1}, \quad (E-1.19)$$

$(\sigma f)_v$ is the product of the σ and f appropriate for $M_n X_m$ vaporization, and h_{MX} is its heat of vaporization.

For the charged species, Equations E-1.4 through E-1.10 give

$$e v_e = AT^2 \exp(-\phi_e/kT) \quad (E-1.20)$$

$$v_{j\pm} = v_j \frac{q_{j\pm}}{q_j} \exp\left(\pm \frac{\phi_e - v_{j\pm}}{kT}\right) \quad (E-1.21)$$

$$\theta_{j\pm} = \theta_j \frac{q_{j\pm}}{q_j} \exp\left(\mp \frac{E_{j\pm}}{kT}\right) \quad (\text{E-1.22})$$

where $E_{j\pm} = V_{j\pm} - \phi_e \pm \phi_j \mp \phi_{j\pm}$, (E-1.23)

and v_e is the electron emission rate,

$A = 4\pi\bar{m}ek^2/h^3$ is the Richardson constant,

v_{j+} and v_{j-} are the positive ion and negative ion emission rates,

θ_{j+} and θ_{j-} are the positive ion and negative ion surface coverage fractions,

V_{j+} and V_{j-} are the ionization potential and electron affinity,

ϕ_{j+} and ϕ_{j-} are the desorption energies of the positive ion and negative ion, and

e and $\bar{m}$ are the electron charge and mass.

The transition times among the ionic and neutral species is much shorter than the vibration period within, or the "hopping time" among, the adsorption sites. The adsorbed layer therefore should not be considered as a fixed array of ionic and neutral particles, but rather as an array in which all of the particles are rapidly fluctuating among the various charge states within their respective adsorption sites. The properties of the particles are a weighted average of these properties among the various charge states according to the relative probability of their occurrence.

Since the equilibrium temperature of the vapor T_{MX} generally is different than that of the surface T , the composition of the arriving and evaporating species is not the same. At steady state, however, the total rate of M atoms evaporating in any form Σv_M must equal the total rate of their arrival $\Sigma \mu_M$, and similarly for the X atoms, so that for $M_n X_m$ dissociation:

$$\Sigma v_M \equiv v_M + n v_{MX} = \mu_M + n \mu_{MX} \equiv \Sigma \mu_M \quad (E-1.24)$$

and

$$\Sigma v_X \equiv v_X + m v_{MX} = \mu_X + m \mu_{MX} \equiv \Sigma \mu_X \quad (E-1.25)$$

In these two equations and in the remainder of this presentation, the effect of ion emission and arrival is neglected for brevity, although it can be readily included in the analytical model. In general, it is negligible for all work functions ϕ_e less than the ionization potentials V_{j+} of all significant species -- the lowest is that for cesium, $V_{Cs+} = 3.9$ eV -- or greater than their electron affinities V_j -- the largest being considered here is for atomic oxygen, $V_{O-} = 1.4$ eV, and the largest reported is $V_{Cl-} = 3.7$ eV. When ion evaporation is not negligible, its space charge can have a profound effect on the properties of the interelectrode plasma, and the surface state can depend profoundly on whether or not the applied electrode potential traps the emitted ions.

Several of the equations in the above derivation are recognizable from other sources. Equation E-1.11 is the chemical equilibrium equation for dissociation in the gaseous phase, with K_{MX} being the equilibrium constant

and V_{MX} the enthalpy of dissociation for the molecule M_nX_m . Equation E-1.12 is the surface phase equivalent of Equation E-1.11. Equation E-1.17, and K_{MXv} and $h_{MX} - V_{MX}$, have the same significance for evaporative dissociation. While it is possible to estimate these quantities from first principles -- for example, via Equation E-1.13 -- it is more accurate and reliable to obtain them from tabulated thermochemical data -- i.e., from the Gibbs free energy -- if such data are available.

Continuing with this interpretation, Equation E-1.16 is the equation for neutral particle emission. Equation E-1.20 is the Richardson-Dushman equation for electron emission. Equation E-1.21 is the Saha-Langmuir equation for ion emission, and Equation E-1.22 is its surface phase equivalent.

Adsorbed particles, together with their electrostatic images in the conducting surface plane, constitute a dipole layer at the surface, across which there is a potential difference that changes the desorption energies of the electron and ionic species by amounts $\Delta\phi_e$, $\Delta\phi_{j+}$, and $\Delta\phi_{j-}$, such that

$$\phi_e = \phi_{eo} + \Delta\phi_e \quad (E-1.26)$$

$$\phi_{j+} = \phi_{jo\pm} + \Delta\phi_{j\pm} \quad (E-1.27)$$

where ϕ_{eo} and $\phi_{jo\pm}$ are the values at $\theta = 0$. It is assumed here that the adsorption energies of the neutral species are independent of coverage, an assumption that is found to be adequate for representing the experimental data.

From elementary electrostatic theory the potential change across this dipole layer is 2π times the dipole moment per unit area, so that the change in electron work function is the sum of the moment of all species, or

$$\Delta\phi_e = -2\pi e \sum_j \sigma_j \theta_j M_j \quad (\text{E-1.28})$$

where M_j is the dipole moment of adsorbed species j normal to the surface and e is the electronic charge.

This dipole moment consists of a permanent dipole moment M_{j0} associated with each particle and its adsorption site plus a dipole moment induced by the resultant electric field ϵ from all the surrounding dipoles, or

$$M_j = M_{j0} + \alpha_j \epsilon \quad (\text{E-1.29})$$

where α_j is the polarizability of the system consisting of the adsorbed particle and the local surface structure upon which it is adsorbed.

The electron passes completely through the dipole layer as it enters the metal surface. The charge of the adsorbed ions, however, does not enter the metal, but is spaced an effective distance R_i (i.e., approximately equal to the particle radius) away from the surface. As a result, its charge only penetrates a fraction $\bar{f}$ of the dipole layer such that

$$\Delta\phi_{j\pm} = \bar{f} \bar{f} \Delta\phi_e \quad (\text{E-1.30})$$

as shown in Exhibit E-1.5.

Exhibit E-1.5
 Illustration of Local Electric Field at an Adsorbed Particle Due
 to the Surrounding Dipole Array, and of Partial Penetration of
 Dipole Layer Potential Field by Adsorbed Ions

Since a potential difference $(1-\bar{f}) \Delta\phi_e/e$ exists across the distance R_i at the particle, the average electric field there is

$$\epsilon = g \Delta\phi/eR \quad (\text{E-1.31})$$

where $g = 1-\bar{f}$.

Exhibit E-1.6 summarizes the dependence of $\bar{f}$ on the coverage θ_i by the species which are primarily producing the electric field, as computed [1,2] from electrostatic theory, and as indicated by experimental values [3] of $\bar{f} = \Delta\phi_{\text{Cs}^+}/\Delta\phi_e$. For analytical convenience,

$$g = .18 + .20 \theta_i \quad (\text{E-1.32})$$

is used in the analytical model as an adequate representation of both computed and experimental results. Since g is relatively insensitive to the nature and state of the adsorbed species and to temperature, Equation E-1.32 is used for all species and temperatures.

Equations E-1.26 through E-1.31 can also be combined to give

$$\Delta\phi_e = \frac{-2\pi e \sum_j M_{jo} \sigma_j \theta_j}{1 - \frac{2\pi g}{R_i} \sum_j \sigma_j \alpha_j \theta_j} \quad (\text{E-1.33})$$

The values of v_M and v_X from Equations E-1.24 and E-1.25 for each species can be substituted into Equation E-1.11, which can then be solved iteratively

Exhibit R-1.6
 Comparison of Computed and Observed [3] Coverage Dependence
 of Fractional Penetration, by Adsorbed Ions, of
 Dipole Layer Potential Field

to give the evaporation rates v_M , v_X and v_{MX} for all species as functions of temperature and vapor phase arrival rates μ_j . The μ_j can be obtained from Equations E-1.17 and E-1.18 for a given reservoir temperature T_{MX} and condensed phase composition. The surface coverage by each species θ_j can be computed via Equation E-1.16 from the values of $(\sigma f)_j$, v_j and ϕ_j for that species. Since γ is a function of $\theta = \sum_j \theta_j$, it must be determined by iteration.

The work function ϕ_e of a surface immersed in the vapor above the $M_n X_m$ reservoir then can be computed explicitly from these θ_j via Equations E-1.26 and E-1.27 if neutral adsorbed species predominate. If a significant fraction of the adsorbed species are in an ionic state, Equation E-1.33 must be solved by iteration since the ionic adsorption energies $\phi_{j\pm}$, and therefore the $\theta_{j\pm}$, are functions of $\Delta\phi_e$ according to Equations E-1.22, E-1.27 and E-1.30, i.e.,

$$E_{j\pm} = v_{j\pm} - \phi_{eo} \pm \phi_j \mp \phi_{jo\pm} - g\Delta\phi_e \quad (E-1.34)$$

The dissociation energies v_j , ionization energies v_{j+} and electron affinities v_{j-} are independent of the substrate and often are well-known. The adsorption energies ϕ_j and $\phi_{jo\pm}$, and the bare work function ϕ_{eo} are dependent on the structure and composition of the bare electrode surface. Because ϕ_{eo} characterizes the affinity of the surface for electrons, its affinity for the ionic charge and bound electrons of the adsorbed particles should be closely related to ϕ_{eo} . It has been found [2], therefore, that the emission and adsorption properties of any surface can be uniquely and conveniently characterized by its bare work function ϕ_{eo} . The adsorption energies and work function of the bare surface can be independently measured experimentally by well-established

Exhibit E-1.7
Comparison of Computed and Observed Work Functions for
Surfaces Immersed in Cesium Vapor

methods, but their estimation from first principles is difficult. (It should be noted, however, that the elementary model of charged particles adsorbed on a conducting plane gives $\phi_{j\text{ot}} \cong e^2/4R$ for monovalent ions with closed-shell core configurations, e.g., ϕ_{Cs^+}). When analytically estimated or independently measured experimental values are not available, the adsorption energies can be chosen to best characterize and correlate the experimental data on emission from surfaces immersed in vapors of known composition.

If the adsorbed layer is dominated by positive ions, and if it predominantly evaporates as neutral particles (as is the case for emitters with adsorbed cesium), Equations E-1.16, E-1.18, and E-1.22 give (for $\mu_{\text{Cs}} = \nu_{\text{Cs}}$),

$$\Delta\phi_e = -\frac{1}{g} \left[\nu_{\text{Cs}^+} - \phi_{\text{eo}} - \phi_{\text{Cs}^+} + h_{\text{Cs}} \frac{T}{T_{\text{Cs}}} + kT \ln \left(\frac{2(\sigma f)_{\text{Cs}}}{(\sigma f)_v} \gamma \theta_{\text{Cs}^+} \right) \right] \quad (\text{E-1.35})$$

The work function ϕ_e , therefore, should be primarily dependent on T/T_{Cs} in the mid-coverage range where the logarithmic term is negligible. The correlation by the parameter T/T_{Cs} also should be valid for negative ion domination, but should not be valid for surfaces in which the surface is dominated by adsorbed neutral particles (i.e., as is the case for surfaces immersed in pure oxygen).

Since a number of experimental measurements of work functions have been published, it has been possible to test this model for surfaces immersed in pure cesium vapor, pure oxygen vapor, and cesium oxide vapor.

Exhibit E-1.7 compares the values of ϕ_e computed from Equation E-1.33 with the experimental values for polycrystalline tungsten in cesium vapor at

several temperatures. The values that characterize the data are:

$M_{\text{CsO}} = .4 \times 10^{-18} \text{ esu}$, $M_{\text{CsO}^+} = 1.3 \times 10^{-18} \text{ esu}$ (which corresponds via $M_{\text{Jo}^+} = 2eR_i$ to a classical image-plane radius $R_{\text{Cs}^+} = 1.4 \text{ Angstroms}$, about .8 the ionic radius of cesium), $\alpha_{\text{Cs}^+} = 38$ and $\alpha_{\text{Cs}} = 6 \times 10^{-24} \text{ esu}$ (which are intermediate to the ionic and atomic polarizabilities for cesium, 2.7 and $50 \times 10^{-24} \text{ esu}$ respectively), $\sigma_{\text{Cs}} = 3.6 \times 10^{14} \text{ cm}^{-2}$ (the value used by Langmuir), $f_{\text{Cs}} = 10^{12} \text{ sec}^{-1}$, (the diatomic cesium molecule vibration frequency is $1.3 \times 10^{12} \text{ sec}^{-1}$), $\phi_{\text{CsO}^+} = 2.04 \text{ eV}$ (the value observed by Taylor and Langmuir, corresponding to $R_{\text{Cs}^+} = 1.7 \text{ Angstroms}$), $\phi_{\text{Cs}} = 1.7 \text{ eV}$ (as found in [2] for W), and $V_{\text{Cs}^+} = 3.89 \text{ eV}$. The fit between measured and computed values is more than adequate to guide further converter design efforts.

Exhibit E-1.8 compares the values of $\Delta\phi_e$ computed from Equation E-1.33 with measured values [4] for a polycrystalline tungsten surface immersed in oxygen at various pressures. Exhibit E-1.9 shows the corresponding relative coverage by atomic and molecular oxygen, θ_{01} and θ_{02} , respectively, indicated by Equation E-1.12. The curves in Exhibits E-1.8 and E-1.9 are characterized by $(\sigma M_o)_{01} = -0.31(\sigma M_o)_{\text{Cs}^+}$, $(\sigma\alpha/R)_{01} = 6.8 (\sigma\alpha/R)_{\text{Cs}^+}$, $(\sigma f)_{01} = 50(\sigma f)_{\text{Cs}^+}$, and $\phi_{01} = 6.0 \text{ eV}$, a generally accepted value, for atomic oxygen, and by $(\sigma M_o)_{02} = -0.62(\sigma M_o)_{\text{Cs}^+}$, $(\sigma\alpha/R)_{02} = 4.5(\sigma\alpha/R)_{\text{Cs}^+}$, $(\sigma f)_{02} = 40(\sigma f)_{\text{Cs}^+}$, $\phi_{02} = 5.6 \text{ eV}$ and $V_{02} = 5.1 \text{ eV}$, an accepted value for molecular oxygen. These values are physically reasonable in view of the 2.5-fold smaller radius, 8.3-fold greater mass and three-fold greater adsorption energy of the oxygen atom compared with the cesium ion (e.g., the diatomic oxygen molecule vibration frequency is $2.1 \times 10^{13} \text{ sec}^{-1}$).

Exhibit E-1.8
Comparison of Computed and Observed [4] Temperature Dependence
of the Change in Work Function $\Delta\phi_e$ of Polycrystalline Tungsten
Immersed in Oxygen at Various Pressures p_{O_2}

Exhibit E-1.9
 Relative Coadsorption of Atomic Oxygen θ_{o_1} and Molecular
 Oxygen θ_{o_2} for Oxygen Pressure 6×10^{-9} torr

The oxides of cesium and their dissociation energies V_j are CsO (3.04 eV), Cs_2O_2 (9.17 eV), Cs_2O (5.70 eV), Cs_2O_3 and CsO_2 . At this time there is considerable uncertainty as to which of the several apparently contradictory thermochemical values found in the literature should be used for determination of the constants in Equations E-1.11, E-1.17 and E-1.18. Without confident knowledge of these values, along with the wholly unknown desorption energies, the use of the theory to determine the dominant species by comparison with experimental data involves too many arbitrarily adjustable constants for practically or physically meaningful representation of the data. Therefore, although the inclusion of all species is possible with the theory, exploration has so far been confined to the use of only Cs, Cs^+ , O, O_2 and CsO as the adsorbed species. The separate behavior and physical properties of the first four already have been established, and the major features of their interaction via the simplest compound CsO should guide the subsequent introduction of the others.

Another severe difficulty is the absence of appropriate experimental data for confident evaluation of the theory. Exhibits E-1.10 through E-1.13 show data obtained by Alleau and Bacal [5], and subsequently by Denisot [6], using a monocrystal of tungsten immersed in oxygen at very low pressures and simultaneously exposed to a beam of cesium vapor. The data are well-correlated for interpretation by plotting the work function versus T/T_{Cs} . The Alleau-Bacal and Denisot data show what is probably the major qualitative phenomenology associated with the variables for Cs-O coadsorption emitters. Its quantitative validity is in question, however, because it is unlikely that a true steady-state condition was obtained at the low pressures and rates of cooling employed.

Exhibit E-1.10
 Arrhenius Plots of Emission Current Data for (100)
 Tungsten Crystal in Mixed Cesium and Oxygen Vapor
 as Obtained by Alleau and Bacal [5]

Exhibit E-1.11
 Work Function vs. T/T_{Cs} for (100) Tungsten
 Crystal in Mixed Cesium and Oxygen Vapor
 as Obtained by Alleau and Bacal [5]

Exhibit E-1.12
 Arrhenius Plots of Emission Current Data for (100)
 Tungsten Crystal in Mixed Cesium and Oxygen Vapor
 as Obtained by Denisot [6]

Exhibit E-1.13
Work Function vs. T/T_{cs} for (100) Tungsten Crystal
in Mixed Cesium and Oxygen Vapor as Obtained by Denisot [6]

Recently, Desplat has obtained data for a monocrystal of molybdenum immersed in a quasi-equilibrium cesium oxide vapor [7]. The Desplat data has directly demonstrated that practical emission currents can be approached at steady-state by emitters immersed in low-pressure cesium oxide vapor. However, the constraints of the measurements have prevented exploration of the phenomenology over a wide range of variables, and the composition of the vapor is still in doubt.

These existing data do suggest the following phenomenology that is to be explained and practically utilized via the developed theory:

- o At high T/T_{Cs} and sufficiently high oxygen (or oxide) pressure, oxygen is first adsorbed as the temperature is lowered, increasing the work function ϕ_e .
- o At lower T/T_{Cs} , cesium adsorption begins to lower ϕ_e well below the value for no oxygen. The amount of such lowering depends on the oxygen pressure, but the amount and nature of the effect of pressure is ambiguous among the Alleau-Bacal, the Denisot and the Desplat data, presumably because of differences in degree of departure from steady state.
- o Below a critical value of T/T_{Cs} , which ambiguously depends on the oxygen pressure, the effect of oxygen is suppressed, and ϕ_e approaches the zero-oxygen value. This is presumed to result from the combination of adsorbed oxygen with adsorbed cesium to form adsorbed cesium oxide.

- o At the lowest T/T_{Cs} , ϕ_e progresses through several minima to very low values, i.e., one electron Volt or less, as $T/T_{Cs} = 1$ (i.e., complete equilibrium) is approached. This presumably results from formation of multiple oxide layers.

Exhibit E-1.14 shows the computed value of ϕ_e when only the species Cs, Cs^+ , O and O_2 are included in the model (i.e., when cesium oxide in any form is formally excluded from the computation). Very low pressures of oxygen have a large effect by abruptly increasing ϕ_e above the zero oxygen value as T/T_{Cs} is lowered below a critical value that depends on the oxygen pressure. At sufficiently high oxygen pressure and low cesium pressure, the oxygen-only increase in ϕ_e is, of course, obtained.

When CsO is introduced into the model as an allowed species, ϕ_e is lowered below the zero oxygen value by an amount which depends on the assumed values of $(\sigma M_o)_{CsO}$ and $(\sigma \alpha/R)_{CsO}$, and which first appears at values of T/T_{Cs} that depend strongly on the values assumed for ϕ_{CsO} and V_{CsO} . Below a critical value of T/T_{Cs} , ϕ_e abruptly increases to above the zero-oxygen value.

The abrupt increase in ϕ_e occurs when either the coverage by adsorbed oxygen θ_{O1} or by adsorbed cesium oxide θ_{CsO} approaches unity and literally pushes the adsorbed cesium off of the surface. It can be seen that behavior of this form actually occurs in the Alleau-Bacal data (curves 5 and 6 in Exhibit E-1.11). This behavior appears in the theory as a consequence of assuming that all species compete equally for the same adsorption sites.

Exhibit E-1.14
 Use of the Analytical Model to Define the Basic Origin of
 the Observed Behavior of Electrodes with Coadsorbed Oxygen
 and Cesium. ($M_{CsO} = 0.5 M_{Cs+}$ and $\alpha_{CsO} = 0.16 \alpha_{Cs+}$ assumed)

In the remainder of the Alleau-Bacal and Denisot data, however, the abrupt increase does not occur, and ϕ_e smoothly approaches the zero-oxygen value. This can only occur if the cesium and oxygen do not compete for the same sites, i.e., only if two or more classes of sites, p and q, are defined such that,

$$\theta_p = \sum_j^p \theta_j \quad (E-1.36)$$

and

$$\theta_q = \sum_j^q \theta_j \quad (E-1.37)$$

where p and q refer to exclusive subsets of the set of j species and, in general, the sum of θ_p and θ_q is not θ . This results in two classes of γ via Equations E-1.8 and E-1.14, i.e., γ_p and γ_q .

In at least one physical circumstance this phenomenon can be easily understood. The oxygen atom radius (.66 Angstroms) is much smaller than that of the cesium atom (2.6 Angstroms) or cesium positive ion (1.7 Angstroms), and has a much higher adsorption energy. The oxygen atom therefore can be buried deep in adsorption sites not accessible to cesium, and cesium can be adsorbed on top of the oxygen atom adsorbed in such sites. Different types of surfaces, depending on their method of preparation, can exhibit different types of behavior depending on the existence of such deep adsorption sites. In fact, oxygen adsorption itself is known to cause transformation of the substrate surface structure under certain conditions ("burrowing"). Alternately, the large negative $\Delta\phi_e$ produced by cesium adsorption favors the existence of the negative oxygen ion according

to Equations E-1.22 and E-1.34. This ion has an atomic radius (1.4 Angstroms) that approaches that of the cesium ion. The existence of two classes of adsorption sites might be precluded by the coexistence of these ions under certain conditions on a given surface structure, and be allowed under others.

The species required to be included in the coverage subsets in order to characterize the existing data needs to be defined by an appropriately modified coadsorption analytical model. Also, the inclusion of adsorbed species other than CsO is needed to permit definition of their unique characteristics for identification in subsequent experimental data, and for definition of the optimum practical reservoir composition and operating points. This work is now underway using private funding.

1.3 Ignited Mode Analysis

Analytical models of the physical processes governing ignited mode behavior are also of major importance to obtaining enhanced converter performance. These analytical tools have been continually updated during the Program to reflect new understanding and are used to explain experimentally observed behavior and to predict new approaches to better the design. Four such models have been developed.

The first model [8], denoted the Phenomenological Model, has many characteristics of a correlation rather than a fundamental theory. It has primarily been used in organizing parametrical results of well-established experimental measurements. Adjustable physical constants in the model can be set to correlate with experimental data. The model then provides good approximations of converter operating characteristics (i.e., current-voltage curves)

over at least the range of parameter variations in which the linkage of model assumptions to the experimental situation remains valid. A recent version of the model incorporated expressions for the work functions of both emitter and collector materials in cesium vapor, as well as a treatment of plasma radiation losses. The capabilities of the model in this type of task are illustrated by Exhibit E-1.15, in which experimental data [9] for various cesium reservoir temperatures (Exhibit E-1.15a) is compared with values calculated with the Phenomenological Model (Exhibit E-1.15b). Other examples of the model's capabilities are given in [10].

A first effort oriented at producing a more fundamental, comprehensive ignited mode model was denoted IMD-1. However, this model did not take into account either the variation of electron temperature in the plasma or ion recombination. The plasma profile was also assumed to be sinusoidal, an assumption not justified by results. Thus, while the uniform electron temperature calculation was sufficiently simple to permit its use on small computers, and it gave the first calculated results indicating the benefits of structured electrodes for performance improvement, it ignores many phenomena which may be important and in some cases gives incorrect results. A flow chart of model algorithms is shown in Exhibit E-1.16.

In order to address these weaknesses, additional models were created. IMD-2 uses a closed form approximation of the plasma density profile for the solution of the nonlinear differential equation for ion production. Recombination is included as well as a simplified treatment of electron temperature variation in the plasma. A third model, IMD-3, uses a numerical calculation (Rungge-Kuta) to obtain the plasma density profile from the complete differential equation for ion production. The electron temperature is obtained in both

Exhibit E-1.15
Comparison of Results of
Phenomenological Model to
Experimental Data [9].

Exhibit E-1.16
Flow Chart for IMD-1

models with a simplified calculation that assumes a spatially uniform average value of the thermal conductivity for electrons.

A flow chart for the calculational routine of IMD-2 and IMD-3 is shown in Exhibit E-1.17. The same simplified flow chart is applicable to either model since the only difference between them is the method of calculating the plasma density profile, $n(x)$.

Both IMD-2 and IMD-3 produce current density-voltage curves of similar shape to those obtained with IMD-1, but with an arc drop about .15 eV larger. Also, these later models can operate at larger values of plasma and current density without producing unrealistic results. These models, like IMD-1, have provisions to include electrode area ratios, reflectivity and collector back-emission. The production of ions and the loss by recombination in all of the models are treated with the source and recombination coefficients calculated by Norcross and Stone [11].

Comparisons of the current density-voltage curves produced by IMD-2 and IMD-3 with those produced by IMD-1 are shown in Exhibits E-1.18 and E-1.19, respectively. Calculated profiles of the plasma density at the ten Amperes per square centimeter point of the curves in these exhibits are shown for all three calculational models in Exhibit E-1.20. The values of the plasma density obtained by the Rungge-Kutta calculations in IMD-3 are shown as "+" signs in this exhibit. Note that the +'s representing the more precise calculation tend to lie between the IMD-2 curves for $N(x)$ and $N_T(x)$. This fact verifies the validity of the approximations used in IMD-2. Furthermore, the end values and the slopes at the boundaries match in these two models, which

Exhibit E-1.17
Flow Chart for IMD-2 and IMD-3

Exhibit E-1.18
Comparison of J-V Curves for IMD-2 and IMD-1

Exhibit E-1.19
 Comparison of J-V Curves for IMD-3 and IMD-1

Exhibit R-1.20
 Plasma Density Profiles from Various Ignited Mode Models

means that the computed values of the particle fluxes and the sheath voltage for the approximate function are in agreement with the numerical calculation.

All three analytical models were eventually replaced with a more general model, IMD-4. The IMD-4 analytical model is a complete one-dimensional solution of the thermionic converter using the "shooting method." Five simultaneous equations are solved numerically in order to carry out calculations with IMD-4. Two transport equations describe the currents for electrons and ions, respectively. Total energy transport, production of electron-ion pairs, and production of heat within the plasma are described by the others. All of the equations were originally derived by Wilkins and Gyftopoulos [12].

Terms of the three transport equations (i.e., electron current, ion current, and energy) are retained and included in the solution to permit the study of thermal diffusion effects without approximation. The ion drag term is also included. Boundary conditions for these equations have monotonic electron retaining sheaths in the quasi-saturation region of the current density-voltage characteristic and a double-sheath barrier at the emitter side of the plasma in the obstructed portion of the characteristic. Electrode area ratios and electron reflectivities are also included in the boundary conditions. Electron back-emission from the collector was accounted for in the collector side boundary condition, but ion emission from the emitter has been neglected. Radiation loss and partially inelastic collision terms are also dropped from the conservation equations.

A flow chart which shows the calculational logic for solution of the IMD-4 computer program is given in Exhibit E-1.21. The calculation begins by guessing a value for the temperature at the collector edge of the plasma, T_{eC} , and for

Exhibit E-1.21
Flow Chart for the Computer Program Logic in
IMD-4 Analytical Converter Model

the plasma density at the collector edge n_C . Using these guesses, equations describing the boundary conditions at the collector are solved for parameters in the transport equations describing the interelectrode space. The transport equations are then integrated across the interelectrode space and emitter boundary conditions -- either appropriate to a double-sheath condition or a Schottky effect condition -- are determined. If the heat flux calculated from the transport equations does not match the known (i.e., from input) heat flux at the emitter boundary, T_{eC} is modified and the calculations repeated. If heat flux does match, the electron current density at the emitter-sheath interface is similarly used to test the original guess for plasma density. The entire procedure, with heat flux tests nested inside current density tests, is repeated iteratively. Finally, both values of n_C and T_{eC} achieve sufficiently small errors and the results are calculated, plotted and printed for a given current density-voltage characteristic point. The next point on the curve is then calculated by incrementing the current density.

The algorithm employs several features to permit increased stability and efficiency. The first feature of the improved algorithm is a "smart guess" which helps choose initial values for T_{eC} and n_C based upon earlier results and leads to a rapid solution. The second feature is a "smart step" which improves the iterative search by retaining the convergence values from earlier results. If all the iterated variables remain well-behaved, the solution is rapidly obtained by a secant method search routine to direct the iteration efficiently to convergence. However, there are some special circumstances where convergence is difficult [13]. The model is discussed in much greater depth in Appendix 4-A.

Exhibit E-1.22
 Comparison Between Calculated Results from IMD-4 and
 Experimental Data from a Planar Converter

An example of an IMD-4 model solution is presented in Exhibit E-1.22. This plot compares an experimental current density-voltage curve (dashed line) with a computed curve (solid line). The calculated motive diagram at various points along the curves is also shown in the exhibit as indicated. For points 1 to 4 in the obstructed region of the curve, there is a double-sheath barrier at the emitter edge of the plasma. The emitter sheath in this region of the characteristic is approximately constant in size, equal to about .81 to .83 Volts. The collector sheath does not vary much either in this region. It remains at about .26 to .30 Volts. Points 5 to 7 are in the quasi-saturation region of the J-V curve, and monotonic sheaths are present on both sides of the plasma. Schottky effects on the emitter are included in the calculation in this region which, along with the ion currents, give the slope to the characteristic in the quasi-saturation region. In quasi-saturation both the sheath and the collector sheath increase in size as the current is raised and the plasma becomes more dense. The plasma drop is negative in this region of the curve and growing in magnitude, whereas the plasma drop in the obstructed region is very small and actually has a positive value for the very lowest current densities.

Plasma density profiles for the seven operating points of Exhibit E-1.22 are shown in Exhibit E-1.23. As operating current is increased, the plasma density also increases monotonically, and the position of the maximum shifts slightly toward the emitter side. Corresponding electron temperature profiles are shown in Exhibit E-1.24. The value of the electron temperature is highest overall for the lowest current, i.e., at operating point 1. As the current is increased, the electron temperature at the collector decreases by about 200 K and the slope of electron temperature at the emitter edge begins to rise as shown for operating points 6 and 7.

Exhibit E-1.23

Variation of Plasma Density in Interelectrode Space;
for Identification of Curves, see Exhibit E-1.22

Exhibit E-1.24
 Variation of Electron Temperature in Interelectrode
 Space; for Identification of Curves, see Exhibit E-1.22

The data in these exhibits correspond to a near-optimum value of the product of pressure and interelectrode spacing of approximately 20 mil-torr. The IMD-4 model can also be used to solve cases with a high plasma density. Despite the existence of a region where there is approximate local thermodynamic equilibrium in such cases, the model obtains stable solutions, mainly due to the improvements incorporated into the search routines in the iteration logic.

The slope of the model's characteristic curves agrees well with experimental data in the quasi-saturation region. However, the slope of the curves is too small in the obstructed region. The calculated curves have the approximate shape of a Boltzmann line in the obstructed portion of the characteristic curve, whereas the experimental curve is steeper. Indeed, all of the one-dimensional calculation models investigated in the Program exhibited a Boltzmann line shape in this part of the characteristic curve.

One possible explanation for the discrepancy between computed and experimental results could be attributed to neglecting the resonance radiation loss from the plasma. The major portion of this loss is the radiation arising from the 6p to 6s transition. An analysis of the arc drop indicated that plasma radiation loss could account for the slope difference.

Consequently, radiation losses were added to the IMD-4 code using the expression formulated by Norcross [14]. As shown in Exhibit E-1.25, the radiation loss increases the slope in the obstructed region and leads to better agreement with experimental data at intermediate current densities (about three Amperes per square centimeter) as shown in Exhibit E-1.26. The calculated value of the arc drop, .52 volts, is also in very good agreement with experimental results.

Exhibit E-1.25
 Effect of Radiation Loss on a Calculated J-V Curve in the IMD-4 Model

Exhibit E-1.26
 Comparison Between Experimental Data and Re-
 sults of IMD-4 Model with Resonance Radiation
 Included

However, at high current densities, radiation loss still does not account for the differences between model and data. It has been proposed that constriction of the discharge during the applicable experiments may be responsible for the discrepancy in the slope. Plasma constriction has been observed visually beginning at the knee in all the planar converters examined for this phenomenon. If the constriction phenomenon is responsible for the difference in the slope, only a multi-dimensional model, which has both radial and axial variables, may yield complete agreement with experimental results.

IMD-4 was used to suggest new approaches to converter performance improvement as the result of systematic examination of the effects of varying system parameters. The first of these, structured electrodes, arose from the observation that increasing the collector area ratio has the effect of improving the output voltage by about one-tenth of a volt at a given current, as shown in Exhibit E-1.27. In this exhibit, A_c is the collector area, and A_p is the projection of the plasma area upon the electrode. On the basis of this theoretical prediction, a series of test converters was fabricated with various structured surfaces. The results have confirmed that there is a small performance gain (see Part E, Section 2.3).

Interestingly, the effect of increasing the emitter area ratio is quite different, as shown in Exhibit E-1.28; it raises the saturation current with a small loss of output voltage in the vicinity of the knee.

Another approach to converter performance gain was also "discovered" with IMD-4: divergence in the plasma geometry creates an electric field in the plasma in such a direction as to increase the converter output voltage.

Exhibit E-1.27
Dependence of Converter Performance on Collector Area Ratio in IMD-4 Calculations

Exhibit E-1.28
Dependence of Converter Performance on Emitter Area Ratio in IMD-4 Calculations

To further explore this effect, a radial geometry version of the analytical model, designated IMD-4R, was created to analyze cylindrical geometry converters with various differential electrode diameters. Calculated characteristic curves obtained with IMD-4R suggested that greater performance could be obtained with a divergent geometry cylindrical converter, in which the emitter is smaller than the collector.

A computed comparison between equivalent planar and radial converters is shown in Exhibit E-1.29. The improvements in both output voltage and maximum efficiency (18.0% vs. 15.7%) are evident. Conditions at $J = 15 \text{ Amperes/cm}^2$ (as measured from the emitter surface) are summarized in Exhibit E-1.30, showing the following:

- o The electron temperature has a steeper gradient for the radial than for the planar converter. The radial case has a lower electron temperature over most of the interelectrode space.
- o The plasma density in the radial case is lower over the entire gap and reaches its maximum closer to the emitter. As a result, the average value of $(dn/dx)/n$ is more negative than for the planar case.
- o The major voltage improvement in the radial case occurs in the plasma, not at the sheaths. This is primarily due to the $(dn/dx)/n$ term of the plasma electric field.

Exhibit E-1.31 summarizes the various components of the arc drop at 15 Amperes/cm^2 and shows what percentage of the improvement occurs for each

Exhibit E-1.29
 Comparison of Calculated Planar and Radial Ig-
 nited Mode Performance Using IMD-4 and IMD-4R

$$J = 15 \text{ A/CM}^2$$

Exhibit E-1.30
Comparison of Calculated Planar and Radial Plasma Electron Temperatures,
Densities, and Voltage in Interelectrode Space Using IMD-4 and IMD-4R

(CALCULATED AT $J = 15 \text{ A/cm}^2$)

	PLANAR	RADIAL	% IMPROVMENT (OF TOTAL V_d)
$V_d =$	<u>.4947</u>	<u>.3837</u>	<u>22.4</u>
$+ 2kT_{eC} - 2kT_E$	.1670	.1261	8.3
$+ \frac{J_{BS}}{J_o} (2kT_{eE} - 2kT_E)$	.1696	.1086	12.3
$+ \frac{A_C}{A_E} \frac{J_C}{J_o} (2kT_{eC} - 2kT_C)$	.0141	.0365	-4.5
$+ \frac{J_{iE}}{J_o} (2kT_{eE} + 2kT_{iE} - 2kT_E + V_E - V_B + V_i)$	.0909	.0571	6.8
$+ \frac{A_C}{A_E} \frac{J_{iC}}{J_o} (2kT_{eC} + 2kT_{iC} - 2kT_C + V_C + V_i)$	.0363	.0350	0.3
$+ \text{PLASMA RADIATION, ION TRANSPORT}$	.0169	.0204	-0.7

Exhibit E-1.31
Arc Drop Reduction

component. As can be seen, the major contributions are due to reduction of the electron temperature at the collector and reduction of hot electron and ion losses at the emitter. The loss due to back-emission is greater for the radial case than for the planar case, implying that the performance of a divergent converter would be more sensitive to back-emission.

A divergent geometry converter was constructed to experimentally test the predictions of improvement indicated by the calculations. The performance in the divergence converter tests (see Part E, Section 2.4) has verified the existence of such improvement.

1.4 Auxiliary Ion Source Analysis

An analytical model of a converter with a spatially uniform source of ionization has been developed to analyze and predict performance for thermionic devices in which there is an auxiliary source of ions. The analytical model computer code was first developed to analyze characteristics of a plasmatron (a form of ignited triode). Eventually it was extended to allow examination of the unignited mode of the cesium diode, where the ions originate at the surface of the emitter by thermal surface ionization.

One detailed analysis of the plasmatron is described in [15]. This analysis of the plasmatron has been used to describe the behavior of the weakly ionized plasmatron. A second analytic description of the plasmatron, applicable to both weakly and strongly ionized plasmas, has also been reported [16]. While formulated slightly differently, it agrees very closely in analytic form with the first analysis in the weakly ionized plasma case. Thus, because of its

greater generality, this second description was adopted for the model. A detailed description of the model, denoted AIS-1, is contained in Appendix 4-B along with the actual computer code, while only a brief overview is presented here.

The analytical model considers an essentially neutral plasma of density n , with a uniformly distributed source of ions throughout its volume, contained between two planar electrodes with work functions ϕ_E (emitter) and ϕ_C (collector). The emitter is operated at a temperature T_E while the collector at temperature T_C is spaced some distance from the emitter.

Simplified forms of the transport coefficients for both electrons and ions are used, i.e., for electrons:

$$\Gamma_e = -D_e \nabla n - \mu_e E n, \quad (\text{E.1.38})$$

and for ions,

$$\Gamma_i = -D_i \nabla n - \mu_i E n, \quad (\text{E.1.39})$$

where $\Gamma_e(x)$ and $\Gamma_i(x)$ are the electron and ion current densities, D_e and D_i are the electron and ion diffusion coefficients, μ_e and μ_i are the electron and ion mobilities, respectively, and E is the electric field strength.

The boundary conditions at the emitter and collector depend on the plasma potential relative to the surface of the electrodes. The definitions of the

electrode sheath conditions are implicit in the specification of the electrode boundary conditions. These boundary conditions are summarized in Exhibit E-1.32. The terminology of a "down condition" (D) and an "up condition" (U) refers to whether the plasma sheath retains ions or electrons, respectively, and, therefore, increases or decreases the potential barrier of the sheath.

Calculation of a characteristic curve is accomplished by specifying the current density, J , and solving for the output potential, V . A typical J-V curve is computed by starting at a value of J near zero, and moving up the curve toward higher values of the current density. The typical sequence of sheath conditions encountered in this way is illustrated in Exhibit E-1.33. As shown in the exhibit, the curve begins in the DU (Down-Up) condition at low currents. It then passes through an intermediate range of currents with either DD (Down-Down) or UU (Up-Up) sheaths, depending on the strength of the ion source. The J-V curve may then saturate in the UD (Up-Down) condition. Consequently, it is necessary to consider four sets of equations appropriate to each of the four sheath conditions. The details of this algebra are shown in Appendix 4-B and the flow chart for the computer program is shown in Exhibit E-1.34.

An argon pressure family of current-voltage curves measured on a cylindrical plasmatron device at an emitter temperature of 1300 K is given in Exhibit E-1.35. A set of model-generated curves intended to represent the same device is shown in Exhibit E-1.36 for comparison. Parameters used in the model were either measured from the actual device or, as in the case of work functions which were not available for direct measurement, adjusted for best fit using manufacturer's specifications as a guide. The comparison indicates that the

EMITTER SIDE SHEATH BOUNDARY CONDITIONS

$$\Gamma_{eE} = J_S \exp\left(\frac{-V_E}{kT_E}\right) - \frac{n_E v_e}{4}$$

$$\Gamma_{iE} = J_i - \left(\frac{n_E v_i}{4}\right) \exp\left(\frac{-V_E}{kT_{iE}}\right)$$

COLLECTOR SIDE SHEATH BOUNDARY CONDITIONS

$$\Gamma_{iC} = \left(\frac{n_C v_i}{4}\right) \exp\left(\frac{-V_C}{kT_{iC}}\right)$$

$$J = \frac{n_e v_e}{4} - J_C \exp\left(\frac{-V_C}{kT_C}\right)$$

$$\Gamma_{eE} = J_S - \left(\frac{n_E v_e}{4}\right) \exp\left(\frac{-V_E'}{kT_{eE}}\right)$$

$$\Gamma_{iE} = J_i \exp\left(\frac{-V_E'}{kT_{iE}}\right) - \frac{n_E v_i}{4}$$

$$\Gamma_{iC} = \frac{n_C v_i}{4}$$

$$J = \left(\frac{n_C v_e}{4}\right) \exp\left(\frac{-V_C'}{kT_{eC}}\right) - J_C$$

In the equations describing the boundary conditions:

J_S $\equiv$ Saturation emission current density from the emitter surface;

J_i $\equiv$ Ion emission current density from emitter surface;

J_C $\equiv$ Electron saturation emission current density from the collector surface;

J $\equiv$ Net electron current density reaching the collector;

n_e and n_C are the respective plasma density values at the emitter and collector sides of the gap.

Exhibit E-1.33
Schematic J-V Curve for Auxiliary Ion Source Converter

Exhibit E-1.34
Program Flow Chart for AIS-1

Exhibit E-1.35
Measured Plasmatron Characteristics for $T_E = 1300 \text{ K}$, $T_C = 900 \text{ K}$

P_{argon}

4-77

Exhibit E-1.36

Calculated Plasmatron Characteristics for $T_E = 1300 \text{ K}$, $T_C = 900 \text{ K}$ for AIS-1 Model

computational model is quite accurate in predicting operating characteristics based on converter parameters.

In most experimental auxiliary electrode plasmatron devices the interelectrode spacing has been large (i.e., about three millimeters) to accommodate the auxiliary electrode, which was generally a wire emitter. Because of the large spacing, a high probability of electron-ion scattering (Coulomb scattering) and electron-ion recombination exists despite the relatively low plasma densities. Both effects produce a plasma potential drop linear with converter current and subtract from the output voltage. While neither effect is significant at low current densities, they appear to suggest high current plasmatron operation would be inefficient.

Since both effects decrease with increasing electron temperature the model was modified to include a variation in electron temperature. It was found [17] the Joule heating resulting from electron-ion scattering raised the electron temperature at current densities above 10 Amperes/cm² and produced a plasma potential loss less than .1 eV. Subsequently, the recombination effect was found to be negligible. The motive diagram for a xenon plasmatron for $T_E = 1600$ K, $J = 10$ Amperes/cm² and spacing $d = .02$ inches shown in Exhibit E-1.37 illustrates the small plasma potential drop.

Very encouraging results have been obtained using the computer program that portend advanced performance in a xenon plasmatron. A xenon plasmatron with an emitter work function $\phi_E = 2.0$ eV and collector work function $\phi_C = 1.3$ eV operated at $T_E = 1600$ K would operate with $V_B = 1.75$ eV at $J = 10$ Amperes/cm². The required electrode surfaces are at present not

Exhibit E-1.37
Motive Diagram at $J \sim 10 \text{ A/cm}^2$ for Xenon Plasmatron

available; however, such surfaces are not considered beyond the range of development.

The characteristic curve calculated by AIS-1 for this device is shown in Exhibit E-1.38, and that for a less advanced device, i.e., one with an emitter work function of 2.2 eV and a saturation current density at the emitter surface of 36 Amperes/cm², is shown in Exhibit E-1.39. At an output current density of 10 Amperes/cm², both devices are predicted to have a barrier index of about 1.75 eV.

In addition to computing noble gas plasmatron behavior, the model has the capability of computing characteristics for the unignited cesium diode. The cesium version treats ion emission from the emitter so that structured electrode effects on the cesium unignited mode can be studied. This ability has shown an important distinction between voltage gains caused by collector area effects and changes in collector work functions. The model indicates that increasing the collector area relative to that of the plasma causes a voltage gain in the ignited mode, but a small voltage loss (accompanied by a small increase of current) in the unignited characteristic. This is in contrast with the effect of a change in work function, which would cause a uniform translation of both the ignited and unignited curves.

A question always exists when the collector has been modified by slotting or other structuring as to whether this procedure modifies the surface work function in addition to increasing the collector area. Performance comparisons of structured and unstructured surfaces do not in general resolve this question. However, the new theoretical insight of different behavior in the ignited and

unignited modes may make it possible to discriminate between work function and area effects.

1.5 Knudsen Mode Analysis

The Knudsen mode of thermionic converter operation is that in which the interelectrode gap is so small, or the cesium pressure so low, that almost all the electrons cross the gap without making collisions with other particles. The build-up of electron space charge, which can greatly reduce the amount of current, can be treated in two different ways. For emitter temperatures less than about 1700 K, the interelectrode gap must be kept very small, i.e., less than 13 microns. Almost no ions are produced, and the cesium vapor is used only to produce low work functions on the electrodes. For emitter temperatures higher than about 1700 K to 1800 K, cesium ions produced by surface ionization on the emitter can neutralize the space charge, enabling the interelectrode gap to be larger than for the low-temperature Knudsen mode converter. The Knudsen mode offers two important performance advantages over the ignited mode. First, there is no arc drop arising from the necessity of making cesium ions by electron-atom collisions. Secondly, there is no loss of current by electrons backscattering to the emitter. The difficulties are that either extremely close interelectrode gaps or extremely high emitter temperatures must be achieved.

Two different analytical descriptions of the Knudsen mode have been developed in order to analyze experimental data and study the potential performance of such converters. The first follows Langmuir's treatment of a space-charge limited vacuum diode [18]. Knudsen mode converters are not technically vacuum diodes, since they have cesium vapor in the interelectrode space.

However, if there are very few cesium ions formed, i.e. due to a low emitter temperature, and very few collisions in the gap, the vacuum diode treatment may still be used.

Langmuir's treatment also ignores the effect of collector back emission. Under these assumptions, the only particles contributing space-charge are electrons ejected from the emitter. The interelectrode potential distribution can then be found from Poisson's equation,

$$\frac{d^2V}{dx^2} = \frac{e}{\epsilon_0} n_e(x), \quad (E-1.40)$$

where n_e is the electron density. This equation can be integrated twice, where the last integration must be done numerically. The result is a table of dimensionless potential (η) vs. dimensionless distance (ξ) which has been compiled by Langmuir.

This theory is implemented in the LVD (Langmuir Vacuum Diode) computer program. The LVD program uses a set of best-fit polynomial curves to approximate Langmuir's tables. In order to plot a volt-ampere curve, a value of current density J is specified, which along with the known value for the saturation current density, J_s , gives the height of the electron-retarding barrier. Using Langmuir's tables, plus the known value of the interelectrode spacing, gives the collector potential and hence the output voltage and power. Converter efficiency is calculated by taking into account the contributions of electron cooling, radiation, cesium conduction, and lead conduction to the thermal input power. The program has the advantage of simplicity and fast execution, even on a small computer.

In regimes where back emission or emitted cesium ions are important, the simple Langmuir theory is inadequate. The interelectrode potential must be found by solving Poisson's equation with all charged particles included. This can be a complicated problem. Many different types of potential distribution are possible, each requiring a different mathematical formulation. For conditions where the space charge is almost exactly neutralized by the ions, the distribution can be oscillatory. "Wells" can exist in the distribution which trap charged particles. The present treatment of the Knudsen mode theory, therefore, makes some simplifying assumptions. First, spatially oscillatory modes are not treated. Secondly, incomplete neutralization of space-charge (the electron-rich condition) is assumed. Finally, the effect of trapped particles is ignored. This treatment is used in the KMD-1 computer model.

In this formulation, the particle velocity distributions are integrated over limits appropriate to a specified potential distribution. This gives expressions for the dependence of the particle densities on potential. Substituting these into Poisson's equations gives

$$\frac{d^2V}{dx^2} = \left[\frac{e}{\epsilon_0} n_i(\eta) - n_e(\eta) \right], \quad (\text{E-1.41})$$

where $\eta = eV/kT_E$. This can also be written as

$$\frac{d^2V}{dx^2} = \left[\frac{e}{\epsilon_0} n_{i0}N_i(\eta) - n_{e0}N_e^+(\eta) - n_{ec}N_e^-(\eta) \right], \quad (\text{E-1.42})$$

where n_{i0} is the density of emitted ions, n_{e0} is the density of emitted electrons, and n_{ec} is the density of back-emitted electrons. These are given by the relations:

$$J_i = en_{io} \sqrt{\frac{2kT_E}{\pi m_i}}, \quad (E-1.43)$$

$$J_s = en_{eo} \sqrt{\frac{2kT_E}{\pi m_e}}, \quad (E-1.44)$$

and

$$J_c = en_{ec} \sqrt{\frac{2kT_c}{\pi m_e}}, \quad (E-1.45)$$

where m_i and m_e are the masses of ion and electron, respectively.

Equation E-1.42 can be written in dimensionless form by defining:

$$\xi = \frac{x}{x_o}, \quad (E-1.46)$$

and

$$x_o = \sqrt{\frac{\epsilon_o kT_E}{2e^2 n_{eo}}}, \quad (E-1.47)$$

which gives

$$\frac{2d^2\eta}{d^2\xi} = \beta N_i(\eta) - N_e^+(\eta) - \alpha N_e^-(\eta), \quad (E-1.48)$$

$$\text{or} \quad \frac{d}{d\xi} \left[\left(\frac{dn}{d\xi} \right)^2 \right] = \beta N_i(\eta) - N_e^+(\eta) - \alpha N_e^-(\eta) \quad \frac{dn}{d\xi} \quad (E-1.49)$$

Here β (the ion richness ratio) is n_{i0}/n_{e0} and α is n_{ec}/n_{e0} . The exact functional form of Equation E-1.49 depends on the type of potential distribution. However, for all distributions a first integral of Equation E-1.49 can be done analytically giving

$$\frac{d\eta}{d\xi} = F(\eta), \quad (\text{E-1.50})$$

for some $F(\eta)$.

This results in the integral equation:

$$\xi_c = \int_0^{\eta_c} \frac{d\eta}{F(\eta)}, \quad (\text{E-1.51})$$

where $\eta_c = eV_c/kT_E$, and V_c is the change in potential from the emitter surface to the collector surface. The parameter $\xi_c = d/x_0$. If a motive peak $V_{\max}$ occurs then Equation E-1.51 becomes

$$\xi_c = \int_0^{\eta_m} \frac{d}{\sqrt{F_1(\eta)}} - \int_{\eta_m}^{\eta_c} \frac{d}{\sqrt{F_2(\eta)}}. \quad (\text{E-1.52})$$

These integrals must be solved numerically. An additional complication is that the integrand is singular at $\eta = \eta_m$. This difficulty is handled in the model by evaluating the integrals as

$$\int \frac{d\eta}{\sqrt{F(\eta)}} = \int \left[\frac{1}{\sqrt{F(\eta)}} - \frac{C}{\sqrt{\eta}} \right] d\eta + \int \frac{d\eta}{\sqrt{\eta}} \quad (E-1.53)$$

The parameter C is chosen so that $1/\sqrt{F(\eta)} - C/\sqrt{\eta}$ is well-behaved over the interval of the integration. A Simpson's rule integration scheme can then be used on the transformed integrand.

The computer program begins its computation by solving Equation E-1.51 for the critical point (i.e., zero electric field at the collector) and for the saturation point (i.e., zero field at the emitter). Linear extrapolation is used to find a value of η_c which will give the correct value of ξ_c .

The critical and saturation points are the bounds of the region in which a space charge barrier exists in the interelectrode space. In this region of the current-voltage curve, Equation E-1.52 is solved for η_m , giving $V_{\max}$ and hence, the current density J for a specified value of η_c . The output voltage is

$$V_o = \phi_E - \phi_c + (kT_E/e)\eta_c \quad (E-1.54)$$

The converter efficiency can also be calculated.

The program has proved useful for analysis of converters which have an ion richness ratio β of less than about .1. Above this value, the transformation used to eliminate singularities in the integrands is ineffective. New integration schemes are being investigated. A listing of the KMD-1 program is given in Appendix 4-C.

A comparison between a characteristic curve calculated with no ions and one in which ions have been introduced is shown in Exhibit E-1.40. Even a small value of the ion richness ratio reduces the effect of space charge, moving the curve in the direction of ideal diode performance.

$T_E = 1600 \text{ K}$
 $T_C = 800 \text{ K}$
 $T_R = 551 \text{ K}$
 $\phi_E = 2.4 \text{ eV}$
 $\phi_C = 1.5 \text{ eV}$
 $d = 0.5 \text{ mils}$

Exhibit E-1.40
 KMD-1 Calculation Showing Effect of Emitted Ions

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2. CONVERTER DESIGN EXPERIMENTATION

2.1 Introduction

In addition to the analytical work described in Part E, Section 1, attempts to advance thermionic technology beyond today's capabilities have also proceeded along a parallel path of design experimentation. Certain of these design approaches -- oxygen additive converters, structured electrode converters, divergent plasma converters, auxiliary ion source converters, and SAVTEC (i.e., the Self-Adjusting Versatile Thermionic Energy Converter) -- have been closely coordinated with theoretical model developments achieved during the Advanced Thermionic Technology Program, and the rationale for experimental effort in these areas has been explained in Section 1. However, other experimental approaches have been attempted as well, usually on the basis of recognizable engineering opportunities in matching converter design to power systems for particular applications.

Thus, a major portion of design experimentation has involved a review of the basic converter approach in light of prospective design applications to create new concepts which could increase life, reduce cost or otherwise improve the system design. These new concepts have included the fire-tube cogeneration burner -- which will be discussed in Part E, Section 3 because of its intimate connection with heat transfer aspects of the Program -- and large converters, the cold seal converter, inductive power-coupled converter, cesium-graphite reservoir converter, and some miscellaneous designs. The rationale for these latter approaches are discussed briefly in the following paragraphs.

In larger scale applications (i.e., central station power plants), the use of more than a million small converters, each generating hundreds of watts, may not be optimum. Larger converters, each generating many kilowatts, have several potential advantages. First, the component count can be reduced, increasing reliability and potentially reducing cost. Second, very high currents can be generated. This permits replacement of the normal ceramic seal in the converter with a resistive metal seal, because current losses through the seal can now be made relatively inconsequential relative to the total output current. Finally, the larger converters permit more individualized control of cesium pressure, load, etc., and consequently higher overall system performance. The primary disadvantages of large converters are the massive electrodes needed to conduct high currents (this is particularly expensive for the emitter electrode); the relatively large thermal expansion of the electrodes; and the possible difficulty of maintaining uniform thermionic emission over the large electrode surfaces (particularly in the presence of magnetic fields produced by the high currents). A very large nickel converter, eighteen inches in diameter, was built and tested to confirm the feasibility of uniformly generating high currents. A short-circuit converter generated 6500 Amperes DC current and remained stable during operation, demonstrating basic feasibility.

A second converter, HC-2, incorporated innovations designed to solve other problems. Small electric leads distributed over the emitter surface permitted use of a relatively thin emitter electrode. A segmented, spring-loaded collector structure with ceramic pads in the interelectrode space permitted use of a small interelectrode gap despite the large thermal expansion inherent in the design. Thin-walled, metal bellows replaced ceramic insulators employed in earlier designs.

Thermionic converters typically operate with a low pressure of cesium in the interelectrode space. In addition, the emitter must be electrically insulated from the collector. Thus, each converter must have an insulating region in its envelope which is compatible with both air and cesium at temperatures near 650 K. The alumina insulators developed for this purpose are relatively expensive and fragile, and they can be a weak point in the design. This ceramic seal can be replaced with low-temperature, low-cost seals (plastic, O-rings, etc.) if a means can be found for isolating the seal from the cesium environment. This objective was successfully accomplished in this program by using the cold seal converter, a concept first described by Musa et. al. [1].

In this concept a portion of the converter envelope acts as a small, inert gas-buffered cesium heat pipe. The converter is located in the cesiated portion of the pipe and the seal is located in the cesium-free, inert gas-filled portion of the pipe. Tests on two prototype converters confirmed the practicality of the concept and revealed two performance advantages. First, contamination of the converter due to leaks, etc., had no adverse effects since the contaminants were removed from the electrode region of the converter by the "diffusion-pump" action of the heat pipe region. Secondly, oxidation of the cesium, followed by the concentration of cesium oxide at the electrode end of the heat pipe section of the converter, resulted in substantially improved converter output.

The low-voltage output of a single thermionic converter is inappropriate for most applications. Typically, a series of converters would be used to reach 10-20 volts, where conventional solid-state switches and transformers could be used to efficiently produce high-voltage alternating current.

However, the thermionic converter's "unignited" mode is effectively an open circuit. Thus, a converter could act as its own switch. By using this ability, converters could be directly connected to the primary of a transformer and higher voltage output could be obtained from the secondary.

In this inductive power coupling concept, it would no longer be necessary to series-connect converters prior to generating high-voltage output, a distinct advantage with respect to system reliability and design simplicity. This is especially true since preliminary computer simulations have shown that array operation is much more vulnerable to temperature variations with series connections than with parallel connections (see Part C, Section 5). Two converters operating push-pull in the primary circuit could be used to produce high-voltage AC. Alternatively, a single converter in the primary circuit could be operated in the flux-reset mode to generate high-voltage pulsed DC. The characteristics of both coupling approaches were analyzed in the Program, and the practicality of the novel flux-reset approach was demonstrated.

The motivation for attempting to develop a converter using a cesium-graphite reservoir is one of design simplicity. By charging a graphite slug with cesium gas to form a variable ratio alloy, the use of a separately heated liquid cesium reservoir can be avoided. Experiments during the Program have shown that a cesium-graphite reservoir can stably maintain the proper cesium pressure for optimal converter operation at a given collector temperature and is a viable alternative to the liquid cesium reservoir.

The remainder of Section 2 describes in detail the results of the tests and development efforts on advanced converters, both those which were closely

related to the analytical models described in Section 1 and those which were not.

2.2 Oxygen Additive Converters

Oxygen additive converters are thermionic converters in which oxygen is introduced into the interelectrode space to improve performance. Oxygen has been found to lower the emitter and collector work functions to allow a lower optimum cesium pressure to be used in a variety of experimental studies, many predating this Program. Indeed, the coadsorption of cesium and oxygen has been shown in the past to provide work functions around one electron Volt on semi-conducting or metallic substrates. Tungsten (110) and molybdenum (110) single crystal surfaces were chosen as substrates for most of the studies reported in this regard because the (110) orientation is the most stable, and because extensive studies of oxygen adsorption on these single crystals were becoming available.

Within this Program itself, the basic structure of co-deposited cesium and oxygen layers on tungsten was explored in ultra-high vacuum where modern surface diagnostic techniques can be employed. This work was remarkably successful in defining the conditions for achieving very low work function on coadsorbed Cs-O surfaces, resolving a long-standing uncertainty and controversy over whether a monolayer or multiple layers are required. More recently, this work was extended to explore these conditions in a discharge using mixed cesium and oxygen vapors, more nearly approaching the practical conditions in a thermionic converter. Finally, the Program addressed practical design methods for introducing oxygen into the converter and controlling

its impact on converter performance, the step which has proven the most difficult in translating the knowledge of oxygen's desirable additive properties into actual improvements in converter performance.

In experiments in ultra-high vacuum, static adsorption states were studied by a variety of surface analytical techniques. The experimental set-up, located at NASA-Ames, allowed work function measurements by a Kelvin probe or by thermionic emission. Coverage and structure determinations could also be made, respectively, by Auger Electron Spectroscopy (AES) and Low Energy Electron Diffraction. Identification of desorption products and estimation of their binding energies by thermal desorption spectroscopy was also possible. The sample studied was W(110) [2].

Preadsorbing oxygen on the W(110) sample results in a substantial reduction in the cesiated work function minimum ϕ_m . This is illustrated in Exhibit E-2.1, which shows the work function as a function of the oxygen coverage θ_o . The lowest ϕ_m , around 1.05 eV measured by the Kelvin method at room temperature, is obtained for an oxygen coverage around one oxygen atom for each tungsten atom in the (110) plane. The oxygen layer for this optimum θ_o has a particular structure, identified as a two-dimensional oxide (2D-oxide) [3]. As seen in Exhibit E-2.1, beyond $\theta_o = 1$, when three-dimensional oxide crystallites begin to form, the work function minimum rises rapidly, and in fact is no longer visible on the work function versus cesium exposure plots for oxidized W(110) (Exhibit E-2.2), even after the deposition of several cesium layers where one might naively expect the availability of additional oxygen to have a beneficial effect. In Exhibit E-2.2, an exposure time of ten minutes is roughly equivalent to the deposition of six cesium layers. These results, along with other data on Cs-O-metal systems, suggest that, in order to be effective in creating a very

Exhibit E-2.1
Evolution of the Cesium Work Function Minimum with
the Preadsorbed Oxygen Coverage
at Room Temperature

Exhibit E-2.2
 Work Function vs Cesium Exposure for Adsorption on
 Oxidized W(110) for Differing Oxygen Coverages

low ϕ_m , oxygen atoms should form an independent chemisorbed layer and should not be combined with substrate atoms in a mixed layer, which is the case when reconstruction or oxidation occur [2].

The 2D-oxide-W(110) structure is thermally stable and does not desorb oxygen up to 1250 K [3]. This stability was further established after the 2D-oxide-W(110) surface had been subjected to several cesium adsorption-desorption cycles from 300 K to 1250 K [4], confirming the absence of any significant desorption of Cs-O compounds [2]. Another interesting feature of this particular oxygen structure from a technological point of view is that it might be formable by vacuum annealing at 1250 K of a WO_2 layer deposited onto the W(110) substrate at 300 K, this WO_2 layer being even able to withstand an air exposure prior to its introduction in vacuum. However, Program resources did not permit testing this technique.

The ability of the 2D-oxide (W(110) surface to create low ϕ_m at collector temperatures was tested in a crucial experiment in which the equilibrium effective work function minima were found to increase with temperature [4]. It was further observed that, after quenching the steady state obtained at 700 K, the Kelvin work function at 300 K returned to low values. This showed that the increase in the effective work function could not be attributed to a cesium coverage different from optimum. To explain this work function increase at constant cesium coverage, a simple model was introduced, assuming that the increase might arise from the effect on the mutual field depolarization of adjacent adatom dipoles of thermal distortion of the cesium adatom array [5]. The result of the thermal oscillations of one particular adatom and its neighbors is that this particular adatom spends most of its time closer to its neighbors than at lower temperatures, thereby experiencing a stronger depolarizing field. A comparison

between the experimental data from [4] and the calculated work function minima versus temperature is shown in Exhibit E-2.3. The polarizability of the adatoms in the experimental data is 15 cubic Angstroms. Considering the simplicity of the model, the agreement is good.

Because of the observed increase in the work function minimum with temperature, the use of a cesiated 2D-oxide-W(110) as a collector would have to be limited to temperatures below 600 K to be able to take full advantage of its low work function. From the cesium desorption spectra, the cesium desorption energy around the optimum coverage was estimated at 1.75 eV [2]: the cesium flux necessary to maintain the optimum coverage at 600 K would correspond to a cesium pressure around 4×10^{-8} torr. Operating a converter with such a low cesium pressure places severe constraints on the emitter. The use of thick cesium oxide layers on the collector is one potential approach to mitigating this problem.

The co-deposition of cesium and oxygen on W(110) to form thick cesium oxide layers was studied in the same apparatus, the work functions being determined by the Kelvin method at 300 K [6]. The thick layer properties depended on which of the two constituents was in excess in the incident flux. This is illustrated for the work function in Exhibit E-2.4. With an excess of cesium (curves 1 and 2), work functions between .9 and 1.0 eV were obtained for thicknesses around 30 Angstroms. Thermal desorption spectroscopy showed that the only significant cesium-carrying desorption products were, by order of importance, Cs_2O and Cs. With an excess of oxygen (curve 3) a constant work function around 2 eV was reached above 30 Angstroms, and there was more cesium desorbed than Cs_2O , but no evidence of Cs_2O_2 or CsO_2 . Exposure to additional

Exhibit E-2.3
Comparison of Experimental Data on Work Function Minima-Temperature
Relationship to Predictions of Simple Thermal Disturbance Model

cesium brought back all the characteristics of layers deposited with an excess of cesium. These results suggest that the chemical nature of the Cs-O compound is different in each case: 1) with an excess of incident cesium a near stoichiometric monoxide Cs_2O is grown; 2) with an excess of incident oxygen, the extra oxygen appears to be imbedded in a Cs_2O matrix, but it can eventually react with additional cesium.

The complex cesium desorption spectra, their evolution with the oxygen content of the Cs-O layer grown on the W(110) substrate and the existence of Cs desorption peak identical to the one observed after heavy cesiation of a thick WO_2 layer [2] also suggest that part of the Cs_2O layer reacts with the substrate to form some tungsten oxide at temperatures around 700 K and that this oxide might also react with cesium to form a bronze. This gives a glimpse of the complex reactions likely to occur when cesium and oxygen are both present in a converter.

Another type of experiment was conducted in which a steady state is achieved inside a diode filled with one or more vapors. The work function is determined by thermionic emission. As single crystals are expensive and poorly suited for industrial converters, a study was conducted to assess the performance of oxygenated, chemical-vapor-deposited samples, against that of the 2D-oxide-W(110) surface. A CVD tungsten sample, produced from WCl_6 and electroetched to reveal (110) facets, and a CVD rhenium sample, produced from ReCl_5 and electropolished, were tested after exposure to oxygen at high temperature (1250 K for the 2D-oxide-W(110) and the electroetched W sample, 900 K for the electropolished Re sample). The results are shown in Exhibit E-2.5 for a cesium pressure of two millitorr. While the maximum current density available

Exhibit E-2.5
Emission Characteristics of 2D-Oxide-W(110), Oxygenated
Electropolished CVD Re and Oxygenated Electroetched CVD W
Surfaces in 2 Millitorr of Cesium

from the oxygenated electroetched W was only one-third of that from the 2D-oxide, the oxygenated, electropolished Re provided nearly as much maximum current as the 2D-oxide. However, all these surfaces are only marginally suitable for use as emitters in low cesium pressures because oxygen desorption begins at 1250 K for the tungsten samples and is actually complete at 1350 K for the rhenium sample.

Repeated attempts to form a 2D-oxide on Mo(110) led to a progressive accumulation of cesium oxides in the diode, which was probably responsible for erratic but exceptionally good emission results. Thus, a systematic study of the work function of Mo(110) in mixed Cs and Cs₂O vapors was undertaken. Initially Cs₂O was formed in the diode by oxidizing a fraction of the cesium previously transferred out of its reservoir. In latter experiments, commercial Cs₂O, 99% pure, was loaded in a separate reservoir: no noticeable difference was observed. The vapor pressure of Cs₂O in torr is [7]:

$$\log P_{\text{Cs}_2\text{O}} = 7.71 - 6008/T_{\text{Cs}_2\text{O}} \quad , \quad (\text{E-2.1})$$

where $T_{\text{Cs}_2\text{O}}$ is the temperature in degrees Kelvin of the cesium monoxide. Solid Cs₂O does not appear to undergo any decomposition in vacuum up to at least 593 K [8].

The addition of Cs₂O vapor had dramatic effects on electron emission, as illustrated in Exhibit E-2.6 for Mo(110). At 1 millitorr of cesium, the maximum current density was increased 700 times and at 1250 K the current density was increased by a factor of 1×10^5 . In fact, at 1250 K, the current density was 10 times higher than for the 2D-oxide-W(110) surface.

Exhibit E-2.6
Current Density from Mo(110) in Cesium Vapor,
With and Without Cesium Monoxide Vapor

Rasor-Warner plots (i.e., cesiated work function ϕ versus the ratio of the emitter temperature T to the cesium reservoir temperature T_{Cs}) are shown in Exhibit E-2.7 for one cesium pressure and three cesium oxide pressures. In fact, a corrected T_{Cs}^* is used to take into account the cesium atoms brought by the incident Cs_2O molecules. The reservoir temperatures are shown in parentheses in the exhibit's legend. From the location of the quasi-linear ascending portion of the work function curves, one can infer the bare work function ϕ_0 to which they correspond: with Cs_2O added, ϕ_0 is about 6.5 eV, which makes the system $\text{Mo}(110)\text{-Cs}_2\text{O}$ the best emitter in cesium vapor reported to date. This high ϕ_0 and the overall similarity with results [9] on oxygen-exposed $\text{Mo}(110)$ strongly suggests that dissociation of Cs_2O molecules occurs on $\text{Mo}(110)$ at high temperatures, and leaves an oxygen layer on the substrate, the constant flux of incident Cs_2O counteracting the loss of oxygen by thermal desorption. A discussion of the respective influence of the vapor pressures on the work function curves can be found in [10].

Another interesting feature in Exhibit E-2.7 is the appearance of low work functions as the emitter temperature drops below 760 K ($T/T_{\text{Cs}}^* < 2$), which can be interpreted as resulting from the progressive build-up of a thick Cs_2O layer, probably containing a certain amount of metallic cesium. In normal operation, $T \geq T_{\text{Cs}_2\text{O}}$, which limits the Cs_2O layer thickness. If the emitter is cooled below the temperature of the cesium oxide, then extremely low work functions can be observed. They are not steady-state data, however. A compilation of the lowest work functions obtained in this manner, with the cesium oxide pressure limited to about 2×10^{-4} torr, shows a linear dependence on the substrate temperature, as seen in Exhibit E-2.8. The decrease in work function with temperature probably reflects the increase in the Cs_2O layer thickness. Also included in

Exhibit E-2.7
Rasor-Warner Plots for Mo(110) in Mixed Cesium and
Cesium Monoxide Vapors, at a Given Cesium Pressure

Exhibit E-2.8
 Comparison of Lowest Work Functions Obtained on Mo(110)
 with Cs₂O Vapor in the Diode to the Work Function
 Minimum of the W(110)-2D-Oxide Cs Surface

Exhibit E-2.8 is the change in the W(110)-2D-oxide-Cs work function minimum with substrate temperature (i.e., from Exhibit E-2.3). The thick Cs₂O layer provides lower work functions below 500 K. It is expected that increasing the Cs₂O pressure should result, at a given substrate temperature, in a thicker layer having a lower work function.

A similar study was undertaken for a W(110) substrate, with a better-controlled Cs₂O reservoir temperature allowing a much wider pressure range to be explored. At temperatures above 1200 K, where the data are quite reproducible, varying the Cs₂O pressure by over three orders of magnitude produced little difference, as shown in Exhibit E-2.9. It is likely that, even at the highest temperatures reached (i.e., around 1970 K) and with a Cs₂O pressure as low as 1×10^{-7} torr, the oxygen coverage is already a substantial fraction of a monolayer. Considerable scatter in the data, shown as hatched areas in the exhibit, was present at temperatures between 800 K and 1200 K, probably reflecting the complexity of the chemical reactions taking place between Cs₂O and the substrate, e.g., thick tungsten oxide and cesium-tungsten bronze formation. If a detailed understanding of such processes is needed, additional analytical techniques would have to be used to investigate them.

By comparing the Rasor-Warner plots of W(110) and Mo(110) in mixed cesium monoxide vapors, Exhibits E-2.7 and E-2.9, it can be seen that W(110) is an inferior emitter compared to Mo(110) for a given set of Cs and Cs₂O pressures, i.e., Mo(110) lies to the right of the W(110) on the Rasor-Warner plots. However, raising the cesium and the cesium monoxide pressures, respectively, into the 10^{-2} torr and 10^{-3} torr ranges brings back high-current densities, as shown in Exhibit E-2.10. The emission capabilities of Mo(110) and W(110) at

Exhibit E-2.9
 Rasor-Warner Plots for W(110) in Mixed Cesium and
 Cesium Monoxide Vapors, at a Given Cesium Pressure

Exhibit E-2.10
 High Temperature Emission Characteristics for W(110)
 and Mo(110) in Mixed Cesium and Cesium Monoxide Vapors

cesium and cesium monoxide pressures higher than the ones used in these studies, as well as the low work functions obtained below 800 K, have not been studied in sufficient detail to allow firm conclusions to be drawn.

Thus, at present, it is not possible to achieve in an operating converter more than a small portion of the potential improvement in performance hinted at by these experimental results. The experimental conditions described are, of course, highly artificial in respect to those that would exist for mass production of converters using, for example, CVD hot shell techniques. Thus, the key to translating these laboratory findings into advanced converters appears to lie in development of practical techniques for introducing Cs_2O or other forms of oxygen into the converter in a reproducible, controlled manner. Thus, even while experiments directed at gaining better understanding of how oxides lower surface work functions have been continuing, experiments have also been underway to empirically demonstrate lowering of work functions in alternative converter designs employing oxygen additive approaches.

Several techniques for introducing a controlled amount of oxygen to optimize performance have been tested in research converters. Lieb, et. al. [11] have described four techniques for oxygen addition termed the reflux reservoir, oxide flange, external reservoir and heated silver tube converters. The most recent investigations on oxygen additives have involved the heated silver tube, oxygen shower head, cesium carbonate reservoir and metal oxide collector converters.

A discussion of the heated silver tube technique can be found in [12]. The paper reports the results of converter tests using a tungsten emitter and

lanthanum hexaboride collector with a silver tube heated in air that selectively allowed oxygen to pass into the converter. A collector work function of 1.42 eV (retarding plot) at $T_C/T_R = 1.5$ and a barrier index of 2.0 eV at emitter temperatures of 1300 K and 1400 K were obtained. However, performance of this converter was not stable and deteriorated.

The oxygen shower-head technique was described in a paper by Goodale, et. al. [13] for a converter using a tungsten emitter and lanthanum hexaboride collector. Oxygen gas was slowly bled through the porous electrode collector into the interelectrode space. The best performance achieved with this technique was a barrier index of 2.20 eV at an emitter temperature of 1400 K.

In the cesium carbonate reservoir converter, a cesium carbonate reservoir was substituted for the cesium reservoir. At 870 K, cesium carbonate decomposes to form elemental cesium, cesium peroxide and carbon dioxide. Carbon dioxide was pumped out of the converter prior to testing. Collector work functions of 1.3 eV were obtained from back emission measurements. Emitter work functions varied between 1.4 eV at 700 K to 2.9 eV at 1450 K. However, this method required that the entire converter assembly be maintained above 870 K. Furthermore, operation of the converter in the ignited mode could not be achieved, suggesting that the cesium pressure was too small. Thus, this approach was abandoned.

Currently, the most promising design for an oxygen additive converter is the metal oxide collector converter. The improved performance achievable with this converter appears to be the result of the metal oxide decomposing at moderate collector temperatures (i.e., greater than 600 K) to form a cesium

oxide that lowers the emitter work function. Converters with collectors made from the oxides of tungsten and molybdenum now represent the most effective and stable technique for dispensing oxygen into the interelectrode space.

Research converter experiments on metal oxide collector converters have been performed to correlate converter performance with collector surface preparation and collector substrate. The thin metal oxide surfaces are produced by vapor depositing tungsten oxide in vacuum or vapor depositing pure molybdenum in a low pressure oxygen atmosphere onto a suitable substrate. The substrate material has been typically nickel or niobium.

The primary surface preparation variables found to affect performance were metal oxide surface thickness and oxygen vapor pressure during vapor deposition. While no correlation of barrier index to oxygen content of molybdenum oxide was found, Exhibit E-2.11 shows that the optimum collector temperature is inversely related to the oxygen content.

The oxygen additive collectors were formed from several metal oxides. The lowest barrier index of 1.92 eV was produced at an emitter temperature of 1600 K by a tungsten oxide collector and tungsten electropolished arc cast emitter [12]. Collector work functions as low as 1.37 eV, as measured by the retarding plot method, have been recorded, as has a lifetime of 2200 hours. Tungsten oxide has the advantage as a collector that it is compatible with the tungsten metal most commonly used as an emitter material. It has the disadvantage of requiring an activation period on the order of tens of hours during which the collector temperature must be held above 850 K before performance improvements appear.

Exhibit E-2.11
Correlation of Optimum Collector Temperature to the Oxygen Content
of Molybdenum Oxide Collectors

A molybdenum oxide collector with a tungsten electropolished arc cast emitter has produced a barrier index as low as 1.98 eV at an emitter temperature of 1650 K. This converter was successfully tested for 1160 hours. Another converter produced nearly the same V_B with a collector work function of 1.48 eV.

On the other hand, titanium oxide did not appear to dispense oxygen at all, although converters with such collectors exhibited barrier indices and work functions quite comparable to the tungsten and molybdenum oxide collector converters.

Additional details of converter performance and surface preparations can be found in reports by Goodale, et. al. [13], and Oettinger, et. al. [16].

Thermionic converters with metal oxide collectors are excellent candidates for further development for terrestrial flame-fired applications. These converters represent the best combination of performance, reproducibility and operating life that has been achieved to date. In addition, the output power is less sensitive to electrode spacing and optimizes at a larger spacing (i.e., typically 50 mm) than metal electrodes, which is advantageous for the fabrication of flame-fired converters.

2.3 Structured Electrode Converters

The analytical model for the ignited thermionic diode reviewed in Part E, Section 1.3 predicts that improved ignited mode performance would be expected if smooth electrode surfaces were replaced by structured ones. In particular, if the emitter were structured, higher emitter saturation currents would result.

If instead the collector were structured, the converter arc drop would be reduced, resulting in higher output voltage. Lastly, if both electrodes were structured, the resulting performance would be enhanced by both effects.

The effect on converter efficiency caused by structured electrodes is more subtle because the efficiency depends on the thermal input power as well as the electric output. The use of structured electrodes should produce enhanced output power level but could also exhibit an associated higher input power requirement to compensate for increased thermal radiation between electrodes.

Five different sets of experiments were conducted, therefore, to determine whether and to what extent the predictions of the analytical model could be translated into actual performance gains.

In the first set, electrodes were fabricated with grooves .76, .5 and .025 mm wide in nickel collectors and platinum, tungsten and molybdenum emitters. Performance improvements were not large in comparison to unstructured electrodes. In one investigation of a converter with a structured collector, a 20 to 60 mV improvement in output voltage was achieved over an identical unstructured (control) converter. However, since data between identical electrodes has been typically reproducible only to within 40 mV, the apparent improvement could not be regarded as definitive in and of itself.

In the second set of experiments, called OSEC, fixed-spacing cylindrical converters were constructed from commercial electronic tube shells. Results shown in Exhibits E-2.12 through E-2.14 indicate an improvement in output voltage in both the unignited and ignited mode of 100-200 mV. However, this

Exhibit E-2.12
 Dependence of the Output Characteristics of Structured OSEC-3
 and Smooth OSEC-2 Converters on Collector Temperature T_C

Exhibit E-2.13
Comparison of Dependence of Barrier Index on Collector
Temperature for Structured and Unstructured Collectors
in the Unignited Mode

Exhibit E-2.14
Comparison of Dependence of Barrier Index on Collector Temperature for Structured and Unstructured Collectors in the Ignited Mode

apparent improvement must be viewed with caution. It clearly is possible that converter to converter variation could explain some of the differences observed. This could be the case for the OSEC test because the same magnitude of improvement was witnessed in both the ignited and unignited modes. Since the plasma density differs by orders of magnitude, and the electron mean free path by an order of magnitude, in the two cases, the structured electrode effect (a plasma effect) is not expected to be the same. A difference in effective collector work function could explain the results.

In the third set of experiments, a fixed-spacing planar research converter was constructed having one smooth molybdenum electrode and one structured molybdenum electrode. Either electrode could act as the emitter or the collector. The emitter electrode temperature was held at 1100 K and the collector temperature maintained at 800 K in each test. The difference in the output voltage of the two configurations was of the order of 40 mV, the better result being observed when the structured electrode was the emitter. This improvement is hard to interpret since there could have been asymmetry in the converter. Such an asymmetry may have been caused by differences in the definition of the two electrodes active surfaces due to differences in guard ring implementation.

In the fourth set of experiments, variable-spacing planar research diodes were used. One of these, denoted SPC-9, had a smooth molybdenum collector, while another, denoted SPC-10, had a structured molybdenum collector. Otherwise, the two converters were identical.

Fully optimized performance curves were measured at several emitter temperatures for current densities up to 20 Amperes/cm² as shown in Exhibit E-2.15.

Exhibit E-2.15
Comparison Between Structured Converter
SPC-10 and Smooth Converter SPC-9 Performance Envelopes

There is an apparent improvement in performance at an emitter temperature of 1600 K with the structured collector (i.e., SPC-10) which increases with current density to as much as 20 mV at $J = 20$ Amperes/cm². At 1700 K, although measurements for SPC-9 are not available above $J = 10$ Amperes/cm², the improvement again grows with current density, reaching about 20 mV at the 10 Amperes/cm² level. However, at 1650 K, the behavior is less clear because the shape of the performance curves with the structured collector is at variance with the results at $T_E = 1600$ and 1700 K.

In the final set of experiments, a series of four fixed-spacing cylindrical diodes, each one containing a different combination of smooth and structured electrode surfaces, was built and tested in a joint effort with NASA/JPL. The emitter surfaces were coated with CVD rhenium and the collectors were molybdenum. Converter performance curves were measured for optimized cesium and collector temperatures at a fixed spacing of .01 inches. Lead performance curves for the four converters are shown in Exhibits E-2.16 and E-2.17, and barrier indices are shown in Exhibit E-2.18.

In summary, the evidence for improvement by structuring is suggestive, but ambiguous. Interpretation is made especially difficult because: 1) the model-predicted size of the effect is of roughly the same order as the repeatability of performance between two supposedly identical converters; and, 2) structuring can apparently affect the shape of the performance curves, with an effect again roughly of the same order as the expected bulk improvement. Consequently, while the effect is probably real, structuring appears to represent a much less promising approach to performance than the oxygen additive converter.

Exhibit E-2.16
 Collector Temperature Optimized Performance
 Envelopes for $T_E = 1700 \text{ K}$ for Combinations of
 Structured and Smooth Electrodes
 at a Current Density of 10 Amperes/cm^2

Exhibit E-2.17
Lead Input Power and Lead Efficiency vs Total Current
for $T_E = 1700 \text{ K}$ for Combinations of Structured and
Smooth Electrodes

Exhibit E-2.18
 Barrier Index (V_B) vs Total Current for Combinations
 of Structured and Smooth Electrodes

2.4 Divergent Plasma Converters

The ignited mode analytical model described in Part E, Section 1 also predicted that some benefit could be derived by making the emitter dimensions much smaller than those of the collector, a relationship between the two electrodes which is referred to as divergent geometry. In cylindrical geometry, for example, the divergence is accomplished by centering a thin wire emitter inside a larger diameter tube collector. In this geometry there should be a large reduction in scattered electrons returning to the small emitter and an enhancement in the radial density gradient over a non-divergent cylindrical geometry (i.e., one in which the spacing/emitter diameter ratio is very small). In Exhibit E-1.30 (see Section 1), comparative calculations at $T_E = 1730$ K showed that, at a collector to emitter ratio of 3:1 and an interelectrode spacing of .02 inches, the improvement over non-divergent geometry with the same spacing is over 100 mV at $J = 10$ Amperes/cm². At an output voltage of .55 Volts the output current density would increase from 10 Amperes/cm² to 25 Amperes/cm², more than doubling the output power. A comparison at $T_E = 1730$ K of the peak efficiencies of the two types of converters indicates a 15% increase in the efficiency (from 15.7% to 18.0%) of the divergent converter over the planar type. This would occur despite an increase in the power input to the divergent converter due to increased emitter radiative losses. The emitter radiative heat transfer to the collector would be 50% higher for the divergent configuration over the planar configuration. All of the calculational (and experimental) results discussed in this context define the converter current density using the emitter surface area.

A converter was designed and fabricated to test these predictions of the effect of divergent geometry on converter performance. A drawing of the device is shown in Exhibit E-2.19. The emitter is a resistively heated .02 inch tungsten wire centered in a .06 inch bore in a nickel collector block. A direct view of the wire for pyrometric temperature measurements is provided by a sapphire window mounted on an extension tube welded into the collector block. The hot portion of the tungsten wire outside the collector region is surrounded by ceramic radiation shields which suppress converter current outside the region defined by the collector. During characteristic measurements the emitter heater is "on" except for the duration of a single sweep at 60 Hz to obtain data. The drop in the emitter temperature during the sweep was less than 5 K.

The characteristic curves which are directly measured are actually plots of the converter current I_C versus the voltage V_E at the other end of the emitter. The interelectrode voltage decreases from V_E to V_E' along the length of the emitter because of finite emitter resistance. The opposite is true of the current density; it increases along the wire as the interelectrode voltage decreases because the J-V curve has a negative slope. The measured data were unfolded to deduce the electrode J-V curves for a wire with zero resistance in the following way:

The current measured is

$$I_C = \int_0^L J(x) dx \quad (E-2.2)$$

where L is the emitter length and $J(x)$ is the spatially varying current density.

Emitter: Tungsten - 20 mil DIA - 0.5 cm^2

Collector: Nickel - 60 mil DIA - 1.5 cm^2

Exhibit E-2.19
The Divergent Geometry Converter

The average current density $J = I_C/A_E$ is the quantity that is represented in the measured J-V curves.

The performance of the converter can be approximated by treating it as a group of short converters in parallel separated in the emitter interlink by equal resistors, whose sum is the measured resistance of the emitter wire $R_E = 0.06$ Ohms (see Exhibit E-2.20). The output current of the array, I_C , is computed and J plotted versus the voltage V_1 . This plot represents a measured curve. Also, the quantity $J_D = n(I_1)/A_E$, where n = number of segmented converters in the model, is computed and plotted versus V_1 . The difference in the two curves represents the best approximation of the correction to the measured curves to establish the true J-V curve for the divergent converter with a zero resistance emitter.

A pair of measured cesium vapor families for this test divergence converter are shown in Exhibits E-2.21 and E-2.22. Also shown, on the horizontal scales below the exhibit legends, are barrier indices which can be read against the location of the characteristic curves at the 10 Amperes/cm^2 current density level. For example, in Exhibit E-2.21, at a reservoir temperature of 577 K, the barrier index is slightly less than 2.0.

Perhaps the most interesting thing about these exhibits is that two very different performance curves were observed for apparently identical converter parameters. No explanation for this behavior has yet been put forward. Envelopes of the performance curves for these exhibits, corrected for finite emitter resistance, are shown in Exhibits E-2.23 and E-2.24. At a current

Exhibit E-2.20
 Converter Array Model used to Compute Correction for
 Finite Resistance of Emitter Wire in Divergent Geometry Converter

Exhibit E-2.21
 Cesium Vapor Pressure Family #1 for Divergent Geometry
 Converter at $T_E = 1730 \text{ K}$

Exhibit E-2.22
 Cesium Vapor Pressure Family #2 for Divergent Geometry
 Converter at $T_E = 1730 \text{ K}$

Exhibit F-2.23
Performance Curve for Family #1 Divergent Geometry
Converter at $T_E = 1730 \text{ K}$

Exhibit E-2.24
 Performance Curve for Family #2 Divergent Geometry
 Converter at $T_E = 1730 \text{ K}$

density of about 15 Amperes/cm², the barrier index ranges from 1.8 to 1.9 eV at an output level of about 10 Watts/cm².

The model prediction that divergent geometry would produce an improvement in diode efficiency was also investigated in a parametric study in a more practical converter configuration. The electrode design consists of a large number of short tungsten pins mounted in a planar block. These are centered within a matching array of blind holes in a collector block. The ratio R of the hole diameter to the pin diameter determines the divergence. The electrode spacing is given by $d_{\text{gap}} = .02$ inches. The converter cells are arranged in a close pack hexagonal pattern. The portion of the emitter block between the pins in this design is shielded by a series of foils to suppress emission and reduce bypass heat transfer to the collector. Exhibit E-2.25 is a photograph of the pin design.

Exhibit E-2.26 shows the energy flows considered in computing converter efficiency. All energy enters the system through the emitter planar block. This energy finally exits through the collector as rejected heat and electric power. Rejected heat is the sum of heat passing through the foil shield, heat radiated from the pin to the shield and collector, and energy carried by emitted electrons.

A parametric survey of the efficiency for a single cell in a densely packed array was made as a function of emitter temperature, pin length, and emitter current. The results are shown in Exhibits E-2.27 through E-2.29. The efficiency increases as a function of emitter plate temperature and reaches a broad maximum. A broad maximum also appears around a pin length

Exhibit E-2.25
Photograph of Emitter Pin Assembly and
Collector Hole Structure for Divergent Geometry
Test Converter

Exhibit E-2.26
 Energy Balance for Divergent Geometry
 Thermionic Converter Using Pin Array

Exhibit E-2.27
 Lead Power, Lead Efficiency, and Electrode Voltage
 as a Function of Emitter Plate Temperature
 for Pin Array Divergent Geometry Converter

Exhibit E-2.28
 Lead Power, Lead Efficiency, and Electrode Voltage
 as a Function of Pin Length for Pin Array
 Divergent Geometry Converter

NET EMITTER CURRENT

$L=.25$ GAP=.0508 $F_0=1.75$ J=VARIABLE $R1=3$ $R2=.8$
 $V_b=1.7$ $N=2$ $\Phi I_c=1.5$ $T_e=1751$ $T_c=900$

Exhibit E-2.29
 Lead Power, Lead Efficiency, and Electrode Voltage
 as a Function of Emitter Current for Pin Array
 Divergent Geometry Converter

of .25 cm. The efficiency increases with pin length as a larger fraction of input heat is converted to output power rather than waste heat. Eventually the average temperature of the pin drops, reducing the electrode voltage and the rate of increase in output power. Similar behavior is observed as a function of emitter current with a very broad maximum above $J = 10 \text{ Amperes/cm}^2$.

Calculations also showed that the incremental insulating ability of a foil layer is high as foils are first added, but the advantage of adding successive foils quickly diminishes. The first foils increase efficiency by stopping heat loss from the planar emitter surface to the collector. As the thickness of the foil layer grows, the area available for emission decreases and the pin temperature drops, as does the efficiency.

Finally, the dependence of the converter efficiency on the divergence ratio (i.e., collector diameter to emitter diameter) was computed for both a fixed gap and a fixed collector diameter. The maximum efficiency for the fixed gap case is nearly constant for a divergence ratio of three to ten while in the latter case it is constant for a ratio of two to four. At high ratios, when the emitter diameter is fixed, a large spacing gap leads to low performance and degradation in efficiency. When the ratio is high, and the collector diameter is fixed, the resulting emitter diameter is small; the average emitter temperature decreases due to poor power transmission along emitter pins, and the performance is again reduced.

Based on these results, the design for a practical converter was established with the following parameters incorporating a divergence ratio of three:

Pin Length	=	.10 inch
Pin Diameter	=	.02 inch
Hole Diameter	=	.06 inch
Number of Foils	=	2

The test converter shown in Exhibit E-2.25 was fabricated by installing an emitter pin assembly and collector hole structure in a standard variable spacing test converter body in order to demonstrate construction feasibility. A limited amount of testing was performed, but results were mixed, and inadequate resources were available to pursue the issues raised by the tests in any detail.

2.5 Auxiliary Ion Source Converters

Auxiliary ion source converters maintain space charge neutralization through dependence upon an externally powered discharge distinct from the main power-producing discharge of the converter. These two discharges must be separated either in time or by location. In the latter case, discrete additional electrode ionizers are distributed throughout the interelectrode gap. Investigations of this type of device have focused on a form known as the plasmatron.

Exhibit E-2.30 shows a motive diagram illustrating the general operation of the plasmatron. In the exhibit, V_A is the auxiliary electrode voltage bias, V is the output voltage at the converter, and ϕ_E , ϕ_C , and ϕ_A are the emitter, collector, and auxiliary electrode surface work functions, respectively. The auxiliary electrode is biased negative with respect to the emitter. Electrons

Exhibit E-2.30
Motive Diagram for the Plasmatron

from the auxiliary electrode accelerate into the interelectrode space, ionize the gas, and generate a plasma which fills the interelectrode space. The interelectrode space then has sufficient conductivity for a large current to pass from the main emitter to the collector.

One means of judging plasmatron performance is the effectiveness of output current enhancement by the auxiliary discharge current. This can be expressed in terms of a current amplification factor A which is the ratio of converter current to auxiliary electrode current:

$$A = \frac{I}{I_A} . \quad (E-2.3)$$

The significance of this factor is most evident if an equivalent arc drop V_d^* is also defined. The equivalent arc drop is convenient for performance comparison with the standard ignited mode converter. The equivalent arc drop V_d^* is defined, for the plasmatron, as the auxiliary power required to produce a given output current I , divided by that current itself, i.e.,

$$V_d^* = \frac{\text{auxiliary power}}{\text{output current}} = \frac{I_A V_A}{I} = \frac{V_A}{A} . \quad (E-2.4)$$

The auxiliary electrode bias potential V must be somewhat larger than the ionization potential of the gas. Thus, for best performance the plasmatron should use a gas with a low ionization potential in order to be able to use a low bias and produce a large current amplification factor. Unless the resulting equivalent arc drop V_d^* is much less than the ignited mode arc drop of approximately one-half volt, there is little motivation to add the complication of the auxiliary electrode.

After a suitable gas has been chosen, the next consideration is to select the geometrical relationship of the main converter and the auxiliary electrode. Current density of the converter decreases markedly with distance away from the auxiliary electrode. Hence, if the auxiliary probes are widely separated from one another, little benefit is realized from their use. If many auxiliary probes are employed, too much energy goes into these probes, which reduces the converter efficiency.

An entirely different approach is taken in order to separate the power and auxiliary discharges in time. With separation in time, a transient pulse produces the ions for operation. It is possible to have a pulsed converter with either diode or triode configurations. However, a pulsed diode is the simplest system. Despite the fact that a pulsed triode provides some advantages in transmitting the pulse to the converter, most of the research work to date has been performed on pulsed diodes. Pulsed diode research has included both cesium plasmas and inert gas plasmas as well as mixed cesium and inert gas plasmas.

The sequence of events occurring during and after a forward pulse are represented by the potential diagram shown in Exhibit E-2.31. Before the pulse there is an electron-rich space charge between the electrodes. At the beginning of the pulse, the potential of the collector side is suddenly lowered as in position 1 of the exhibit.

Electrons are accelerated by this large electric field and produce ions by collisions with gas atoms. The formation of a dense population of ions modifies the potential during the pulse as shown in positions 2 and 3. At position 4, the pulse is terminated. Within several microseconds, the plasma

Exhibit E-2.31
Potential Diagram During Decay
of Electrode Pulse

relaxes to an ambipolar, diffusion-limited distribution and decays by ion losses at the boundaries as shown in positions 4 through 6. After the potential has reached position 7, there is a transition in the decay rate because ion-retaining sheaths are formed at the electrodes and reduce the loss. Thus a longer time constant is observed as the plasma decays from 7 to 8 and 9.

The same sequence can also be seen in the diagram of the time behavior of current as shown in Exhibit E-2.32. The pulse is too short to be depicted on this time frame so positions 1, 2, and 3 appear as a vertical line. Rapid decay occurs in the current from 4 through 6. At this point there is a transition in the decay time and the current decreases much more slowly from 7 to 9.

It is possible to characterize pulsed converters by an equivalent arc drop just as can be done for plasmatrons. In this case, the equivalent arc drop is given by the ratio of pulse power to diode current [17], which can be approximately expressed as:

$$V_d^* = \frac{\sigma_s}{2\alpha k} \frac{J}{J_s} Q(V_P, V_I, d/\lambda). \quad (E-2.5)$$

where k = rate of change of ionization cross-section with energy at the threshold (Angstroms²/eV),
 σ_s = electron scattering cross-section (Angstroms²),
 J_s = saturation current density of the emitter (Amperes/cm²),
 J = converter output current density (Amperes/cm²), and
 α^2 = M/m (i.e., the ion/electron mass ratio).

Exhibit E-2.32
Current as Function of Time Following
Pulse in Pulsed Converter

The function $Q(V_p, V_I, d/\lambda)$ contains the dependence on pulse voltage, V_p , ionization potential, V_I , and ratio of spacing to atom mean free path, d/λ . At optimum conditions, the numerical value of $Q(V_p, V_I, d/\lambda)$ is about one. All of the dependence on the parameters for the type of gas is contained in the quantity $\sigma_s/2\alpha k$. Thus, this quantity may be considered as a figure of merit for different gases in a pulsed converter, with small values being superior.

At optimum conditions, the equivalent arc drop is only .08 eV for xenon compared to .17 eV for cesium, and .18 eV for argon. This is the primary reason why xenon is so often chosen as a plasma in pulsed diodes. In non-mathematical terms, xenon's large atomic mass ensures that both gas thermal conductivity and ion diffusion rates will be small enough to eliminate parasitic heat loss and give a low ion loss rate. The electron collision cross-section for xenon is small at the energies of electron drift in a converter, but it is larger at the energy of the pulsed discharge. Furthermore, by using xenon as a gas for the plasma instead of cesium, which modifies the work function, it is possible to separately study the characteristics of the plasma independent of the behavior of the electrode surface. Since xenon is an inert gas, it does not adversely affect the electrode surface.

The participants in this Program have experimented with both plasmatrons and pulsed converters in order to improve thermionic performance.

Two plasmatron converters were built and tested, one a plane-parallel device, the other a cylindrical device. The plane-parallel converter is shown in Exhibit E-2.33, the cylindrical converter in Exhibit E-2.34. Both converters

Exhibit E-2.33
Demountable Plasmatron Test Converter with
Plane Parallel Electrodes

Exhibit E-2.34
Demountable Plasmatron Test Converter with
Cylindrical Electrodes

had molybdenum structures with a dispenser emitting surface heated by hot filaments. In the plane parallel device the auxiliary electrode was a straight, heated tungsten wire and the collector had three probes (auxiliary collectors) to measure the output current distribution. The cylindrical device had an azimuthal auxiliary electrode and a series of seven probes in the collector body to obtain the current distribution.

A unique feature of the cylindrical device was the double-ended emitter lead. Current could be passed lengthwise along the emitter, generating an azimuthal magnetic field in the interelectrode space. This allowed evaluation of the effect of magnetic field on the magnitude and the distribution of the output current. Magnetic effects could be significant in large-current, practical devices.

The use of dispenser emitters in both experimental converters had the advantage that their work function is independent of gas pressure. Therefore, the plasma properties of the plasmatron could be studied independent of electrode phenomena.

The saturation output current, I_s , versus auxiliary current for cesium and argon plane parallel plasmatrons is shown in Exhibits E-2.35 and E-2.36. Constant values of amplification factor A appear as converging straight lines in those exhibits, which also correspond to constant values of equivalent arc drop V_d^* . For the biases given in the figure, the corresponding arc drops are listed for each of the converging lines.

The cesium plasmatron might be expected, a priori, to have greater amplification factors and lower equivalent arc drops because of the lower mobility

Exhibit E-2.35
 Experimental and Theoretical Performance of
 Cesium Plasmatron

Exhibit F-2.36
 Experimental and Theoretical Performance of Argon Plasmatron

of the heavier cesium ions and because of the lower ionization potential for cesium. In practice, however, argon gives significantly better performance. The equivalent arc drop for the cesium plasmatron is no better than the arc drop typical for today's standard ignited mode converter.

The experimental data agree reasonably well with the predictions of the model (i.e., the curves shown as "theory" in the exhibits) discussed in Part E, Section 1.4. However, the data show a drop-off in amplification at high converter currents greater than that found in the calculations. This could be due, for example, to energy relaxation in the ionizing electron beam from the auxiliary electrode. As the converter current increases, the plasma density increases, and accordingly, the relaxation rate for this beam also increases. The beam therefore becomes less efficient in ionizing the argon. Such an effect is not included in the calculations.

The amplification is shown in Exhibit E-2.37 as a function of argon pressure. For a given bias, the amplification increases with pressure due to the increase in the density of ionization target atoms and reaches a maximum when the low-energy electron mean free path is the order of the interelectrode spacing. Further increase in pressure leads to increased back-scattering of the low-energy electrons because of excess ion density and is accompanied by a drop in amplification as pressure continues to increase. The pressure dependence of the amplification was also observed in the cylindrical converter, where the peak saturation current also occurs near two torr.

With argon, back-scatter limitation is less serious than with cesium as ion generation is optimized, because the ionization cross-section for argon at

Exhibit E-2.37
Amplification Factor as a Function of Argon Pressure
in Argon Plasmatron

the high electron injection energy is greater than the electron-neutral cross-section at the lower, plasma-conduction electron energy. This advantageous cross-section ratio does not occur with cesium, where back-scatter does become important for cesium before the pressure is high enough to optimize ion generation.

Current distribution is a function of many effects: the width of the ion generation region, the extent of spreading of the ions along the interelectrode gap, ion recombination, and the effect of these ions on the converter current density. An example of the net effect is shown in Exhibit E-2.38. In this case, no current was observed at the central probe (i.e., directly under the auxiliary electrode), so current density in that region was estimated from the total integrated current of the device. Except for the inferred rapid drop-off close to the auxiliary electrode, the current density falls about a factor of two for every two electrode spacings away from the auxiliary electrode. The ion mean free path in this case is also the same order of magnitude as the interelectrode spacing. It is not known yet whether it is the spacing or the mean free path which most affects the current drop-off. The relative narrowness of the enhancement region indicates that auxiliary electrodes must be closely spaced in a practical device.

Because the plasmatron is inherently a low-pressure device, it is more sensitive to magnetic cut-off than the usual ignited mode converter. This magnetic cut-off for the plasmatron was measured with the cylindrical converter. The observed effect is shown in Exhibit E-2.39 where total converter current is plotted versus magnetic flux density. Reduction to 20% of full current occurs at 70 Gauss, which corresponds to about 200 Amperes of axial

Exhibit E-2.38
Enhancement Distribution in the Cylindrical Plasmatron

Exhibit E-2.39
Magnetic Cut-Off in the Cylindrical Plasmatron

current. The circular path of an electron with average thermal velocity in a magnetic field would have a diameter equal to the spacing at only 10-20 Gauss. That the cut-off is more sluggish than this is probably due to a small amount of interelectrode scattering. Even so, for large advanced mode devices with large currents, this magnetic cut-off could be a serious problem, requiring attempts at solution through appropriate geometric design.

Another magnetic effect, less important for design optimization, is the distortion of the enhanced current distribution due to magnetic pumping of the plasma. This is shown by the normalized distributions in Exhibit E-2.40. It is interesting to note that the distortion also allows current into the central probe. It would be desirable for the pumping to spread the current enhancement down the length of the emitter, since this would reduce the number of auxiliary electrodes needed. Unfortunately, the observed pumping effect is too small to accomplish that.

Computed equivalent potential drops in plasmatron current-voltage curves are on the order of .1 Volt at low current densities -- a significant improvement over the arc drop in the cesium ignited mode -- although the densities are too low to be practical. A resistance voltage drop which increases with current density reduces the performance at higher current densities.

The output voltage recorded by the experimental data is deceptively low because the contact potential between electrode surfaces is unfavorable. However, the computer generated curves, which match the experiment, illustrate that voltage drop in plasma is responsible for only a small portion of the observed voltage loss.

Exhibit E-2.40

Magnetic Displacement of the Enhanced Distribution in the Cylindrical Plasmatron

Thus, it appears feasible to build a plasmatron type of thermionic converter with a plasma arc drop of less than .3 Volt. However, suitable materials for an adequate emitter and a compatible low work function collector must be available for use in an inert gas plasma in order to boost current density. Furthermore, the auxiliary input power used for ion production must be considered as an additional loss, equivalent to greater arc drop. Fortunately, the auxiliary power requirement appears to be small. Large values of current amplification have been demonstrated. At the higher emitter temperatures, the auxiliary power requirement is no more than 15% of the estimated output power from a practical plasmatron converter.

Work has also proceeded on pulsed diodes and triodes.

Early results [18] showed that a pulsed xenon diode with a small amount of cesium sufficient to produce only a low collector work function and a barium oxide cathode yielded operation with $V_B = 1.6$ eV at approximately 1 Ampere/cm². This high level of performance could only be maintained for a short time, however, until barium evaporated from the emitter. The evaporation contaminated the collector, increasing its work function and degrading its performance.

In experiments conducted within the Program more recently, converters were tested with a grid electrode between the emitter and collector and a ring electrode circumscribing the interelectrode space. During converter operation, the triode was given frequent high-voltage pulses, typically 100 Volts for 10^{-6} second, to ionize a cesium-noble gas (i.e., argon or xenon) mixture in the interelectrode space. The converter emitter was a Philips Type M dispenser and the collector was nickel. Performance characteristics of the converter were studied as a

function of pulse length, triode potential, noble gas pressure, cesium pressure, spacing emitter temperature and collector temperature.

Results from the auxiliary electrode converter experiments showed the maximum current output of the pulsed ring triode that could be achieved was limited to current densities less than 1.0 Ampere/cm^2 at an emitter temperature of 1550 K. A typical current-voltage curve is shown in Exhibit E-2.41. The power output of the pulsed ring triode was higher than that observed from the pulsed grid triode since a smaller spacing could be used. The discharge from the ring triode was observed to penetrate the emitter-collector region at spacings greater than .02 inches. The pulse operation could be maintained in xenon-cesium gas with cesium partial pressures up to .5 torr. The highest output was obtained with a xenon pressure of ten torr.

Another set of experiments involving a pulsed inert gas diode with a strontium reservoir was performed in conjunction with the University of Saint-Jerome in Marseilles, France [19]. More recently some pulsed diode experiments have been carried out which study the effects of cesium with xenon and cesium oxide in a combined mixture for pulsed diode plasmas.

If cesium vapor is present in an inert plasma of an auxiliary ion source converter, it tends to dominate the characteristics of the discharge. This is because cesium has such a large low-energy electron-atom cross-section. The amount of cesium partial pressure necessary to maintain coverage on the collector will not dominate the behavior, but the larger pressure required for cesiated emitters usually does cause excessive electron scattering. Work described in Part E, Sections 1.2 and 2.2 above, however, indicates that the

Exhibit E-2.41
DC Output Characteristics in a Xenon Atmosphere as a Function of
Emitter-Collector Spacing in a Ring Triode Converter

use of Cs_2O vapor in converters may lead to low surface work functions (i.e., less than 1.4 eV on the collector) with cesium partial pressures in the 10^{-3} to 10^{-2} torr region, permitting emission currents of some tens of Amperes per square centimeter. This should permit favorable conditions to be met for auxiliary ion source converters.

Pulsed diode investigations using these new low Cs pressure emitters were conducted both with and without xenon. Characteristic curves were obtained at a Cs pressure of 4×10^{-3} torr, both without Xe and with various Xe pressures. Exhibit E-2.42 shows the barrier indices and arc drops obtained at a current density of one Ampere per square centimeter.

The arc drop without Xe was substantially smaller than was expected from the Tschersich and Niekisch [20] correlation of V_d^* with the pressure-distance product obtained at much higher Cs pressures. The decline in V_d^* as the Xe pressure is increased is also more pronounced at this low Cs pressure.

The pulse-enhanced barrier index without Xe was 1.70 eV, which indicates that the arc drop in the enhanced mode was nearly completely suppressed. Introducing Xe at the lowest pressure, .64 torr, did not modify V_B , but at a higher P_{Xe} , V_B increased slightly.

It therefore appears that new low Cs pressure emitters will be suitable for auxiliary ion source converters with inert gas plasmas. However, several practical problems which were encountered remain important. It is difficult to maintain both high current densities and long decay times because the diffusion rates of Cs or Cs_2O are very slow in high xenon pressure. Thus,

EXHIBIT E-2.42

BARRIER INDICES AND EQUIVALENT ARC DROPS FOR
PULSED DIODE AS FUNCTION OF XENON PRESSURE
(IGNITED MODE)

$$P_{Cs} = 4 \times 10^{-3} \text{ torr}, \phi_c = 1.6 \text{ (eV)}$$

P_{Xe} (torr)	0	0.64	2.6	7.0
V_B (eV)	3.02	2.67	2.2	2.15
V_d^* (eV)	1.42	1.07	0.60	0.55

equilibration times are long, and cesium flux to replenish the absorbed coverage is small. Sputtering of the adsorbed Cs or Cs_2O by the pulsed discharge is a problem. And of course, a practical system must be engineered to provide an efficient way of transmitting the pulses into the interelectrode space.

Nevertheless, if the use of Cs_2O vapor or other techniques can be developed which produce low surface work functions and if such techniques can be applied in ways that permit large enough current densities to be practical, the incorporation of such techniques into auxiliary ion source converters may be the most effective approach to thermionic converter improvement now in sight.

2.6 SAVTEC Converters

The SAVTEC (Self-Adjusting Versatile Thermionic Converter) is a novel, recently developed structure which has already demonstrated enhanced performance over ignited mode converters. The basis of this converter is the use of very close emitter-collector gap spacings to reduce or eliminate space charge losses. Spacings less than ten microns are preferred.

It has long been known that interelectrode voltage and current losses could be largely eliminated if sufficiently close interelectrode spacing could be achieved. Recent advances in developing electrodes with low surface work functions can further enhance the benefits of close spacing.

The efficiency expected from close-spaced converters as a function of temperature is shown in Exhibit E-2.43. The general measure of performance of a conventional converter, the barrier index, is also shown on the exhibit

Exhibit E-2.43
Electrode Efficiency vs Emitter Temperature
for Different Electrode Spacings

for comparison. Efficiency is plotted against output power density in Exhibit E-2.44 as a function of emitter temperature. Expected performance in both exhibits was calculated by the approach described in Part E, Section 1.5. The reduction of space charge by emitter cesium ions at emitter temperatures above 1750 K to 1800 K was not included in this model; therefore, the computed performance curves do not extend to these temperatures. It should also be noted that the collector was not optimized in this case, resulting in a collector work function of 1.86 eV. With optimized performance, the output voltage would be about .30 Volts higher.

The close-spaced converter efficiency depends strongly on the inter-electrode spacing, and weakly on emitter temperature. At emitter temperatures less than 1500 K, this efficiency is better than typical ignited mode efficiencies, even for a spacing as large as 12.7 microns (.0005 inches). The electrode efficiency is better than 10% even for T_E as low as 1200 K. Output power density, however, depends strongly on the emitter temperature.

Attempts in the past to develop converters with small electrode spacing have been frustrated by a number of technical problems, such as maintaining electrode spacing, integrity, and uniformity during start-up and operation. The SAVTEC design incorporates a number of features to minimize or to eliminate these problems.

The key point of the design is to make individual converters very small in size. The schematic is shown in Exhibit E-2.45. The size reduction makes it easier to keep both emitter and collector parallel. Thermal expansion of the emitter in the radial direction causes it to slide over the collector surface

Exhibit E-2.44
 Electrode Efficiency vs Output Power Density
 for Different Emitter Temperatures

One Experimental Thermionic Converter Arrangement - SAVTEC

Exhibit E-2.45
The SAVTEC Converter

and may plough up chips of material. However, if expansion is held to dimensions less than the interelectrode gap, radially ploughed chips, should they occur, cannot curve upward to fill the gap and initiate electrical shorts. Thus, SAVTEC converters are sized so that the maximum radial expansion of the emitter is less than the expected interelectrode gap.

The emitter is heated by radiation to eliminate uneven heating and to reduce thermal distortion. Radiation heating permits multiple assemblies in close proximity. This scheme enables a large number of small converters to be connected in a series-parallel array inside a common container. The radiation coupling then permits the emitters to be physically and electrically isolated from one another. An emitter-to-collector short in a single converter would not cause a failure of the entire array, as it would if a single, larger converter were used.

Close electrode spacing is obtained using differential thermal expansion. The emitter is connected to its base by a post, as shown in Exhibit E-2.45. Thermal expansion of this post during heating forces the emitter away from contact with the collector, establishing the proper position. This post also acts as the electrical connector.

Because of SAVTEC's very small size, many converters can be connected in series, raising the voltage output and reducing the resistive (i.e., I^2R) losses. This allows small, light buses which reduce the system mass. It also provides a sufficient number of converters that a series-parallel array becomes feasible within a single envelope itself, thereby increasing the reliability of the device. Placing the converters in a single envelope further

allows reduced bus material by close-packing the converters tighter than would be possible with individually enclosed converters.

The original SAVTEC tests involved single thermionic converters. These converters had disc-shaped molybdenum electrodes which were .4 inches thick and polished to within 2 interference fringes (.6 microns) flatness. A ceramic insulator was brazed between the collector and the emitter base. Volt-ampere curves from one converter are shown in Exhibit E-2.46. These data are for an emitter temperature of approximately 1800 K and a spacing of about 12 microns. Under these conditions, the space charge is nearly compensated by the ion emission. Maximum lead power is 4.2 Watts/cm^2 at about 1 Volt. This is about the same power density that a conventional converter with a barrier index of 1.74 eV would produce at this temperature and current density. A volt-ampere curve for a lower emitter temperature case, $T_E = 1200 \text{ K}$, is shown in Exhibit E-2.47. This device delivers approximately $.3 \text{ Watts/cm}^2$ of power. Here space-charge effects are reduced by the small spacing, rather than by emitted ions.

Four converters of the test series have achieved spacings of less than 12.7 microns (.0005 inches). Three of these converters used thermal expansion to set the interelectrode gap, the other used ceramic spacers. These devices were designed to be shorted at cold conditions and transiently unshorted at start-up to provide the expected electrical output. Repeatable shorting and unshorting of the converters during start-up was typically observed between $T_E = 1000 \text{ K}$ to 1400 K , depending on the electrical lead length.

The tests of the single converters were followed with a test of a multiple SAVTEC array incorporating seven converters. Typical volt-ampere curves for

Exhibit E-2.46
Characteristic Curve for an Early SAVTEC

Exhibit E-2.47
Characteristic Curve for an Early SAVTEC
at T_E = 1200 K

emitter temperatures of 1270 K and 1350 K are shown in Exhibits E-2.48 and E-2.49, respectively. These devices operated in the power quadrant and supplied .28 Watts/cm² and .55 Watts/cm², respectively. Post-test examinations revealed that the converters suffered from fabrication difficulties (i.e., braze-flow shorting of the emitter lead, etc.).

A nineteen array converter, shown in Exhibit E-2.50, was also built and tested. During the tests, the thermal conductance of the support post was lower than anticipated, which resulted in high collector temperatures. The high collector temperature had two adverse effects. First, it resulted in lower converter performance due to the back emission of electrons from the collector. Second, the higher collector temperature resulted in a smaller interelectrode gap, which would eventually cause a short between emitter and collector. To avoid these problems during data acquisition, the hot shell and emitter were taken from a cold start to operating temperature as rapidly as possible, which opened the interelectrode gap of most of the converters. The thermal mass of the collector-substrate structure resulted in a relatively slow increase in collector temperature. During the interim between test start and shorting of the electrodes, it was possible to obtain data. Unfortunately, it was not possible to obtain performance stability data.

Post-test examination showed evidence (i.e., discolorations were similar to the collectors) indicating the emitters for three of the individual converters remained near collector temperature throughout the test series. Although the cause of this behavior has not been definitely established, it has been suggested, based on experience with earlier converters, that emitter leads had been inadvertently brazed to the collector due to braze wicking. The other 16 devices successfully generated electricity.

Exhibit E-2.48
Characteristic Curve for a Seven Element SAVTEC
Operating with Emitter Temperature 1270 K

Exhibit E-2.49
Characteristic Curve for a Seven Element SAVTEC
Converter Operating with an Emitter Temperature of 1350 K

Exhibit E-2.50
Nineteen Element SAVTEC Array

Thus, the design, development and testing done to date indicates that the SAVTEC approach to improved converter performance is feasible. However, much further development is required before that potential will be realized in practical devices. Experience has taught that meticulous care during assembly is necessary to develop successful assemblies. Fabrication techniques and procedures must be prepared along with the devices to increase the probability of success.

2.7 Large Converters

Although small converters have been developed and have operated for thousands of hours, high-current, high-power converters for terrestrial fossil-fuel power applications have not been developed nor tested prior to this Program. Large-scale thermionic converters are expected to be modular in design. Each cell would typically be 10-100 times larger than more conventional converters. However, larger power levels would introduce a new design uncertainty. While characteristics of the large converters might be extrapolated from experience with smaller converters, some phenomena which are relatively unimportant in small converters may play a large role in determining the operating characteristics of large devices. Ignition characteristics and magnetic field effects are examples. Other scaling effects are not completely known. The high-current (HC) series of experiments was performed to confirm the extrapolated behavior and to examine other characteristics of large converters.

Two high-current, large converters were developed and tested [21,22]. These two high-current converters are referred to as HC-1 and HC-2. The first

of these, HC-1 was also known as ZEPO, an acronym for "zero power output." HC-2 extended ZEPO technology to a high-current, power-generating converter.

In order to accomplish these studies, it was necessary to develop a test facility. This facility met several new and significantly different requirements than normal converter testing conditions. First, the facility was capable of providing large amounts of thermal input power (i.e., 100 kW to the emitter surface) over a wide emitter temperature range (i.e., 1500 K to 2000 K) at high-power densities (i.e., 20 Watts/cm²). It was possible to tailor the heat flux profile over the surface to meet the particular requirements of specific converter designs. Similarly, the facility provided for the removal of reject heat from the converter over a broad range of collector temperatures (i.e., 530 K to 810 K), at high-power densities (i.e., 20 Watts/cm²). The ability to deliver any desired heat rejection profile was also available.

A natural gas-fired furnace was selected for use as the heat source because it can easily provide the total thermal power required while simulating the combustion environment in large power plants. The furnace was a vertical cylinder with a burner at the bottom and exhaust gas exit at the top. The furnace walls were constructed from high-alumina refractory backed by a thick insulating refractory to minimize heat loss through the walls. The furnace could operate at pressures up to 1.37×10^4 Pascals (2 psi). The system could deliver 732 kW (2.5×10^6 Btu/hr) of thermal power with an exit gas temperature of 2030 K.

Jet impingement heat transfer was selected for use with the furnace since it could provide the high heat fluxes required while providing a tailored heat

flux profile across the emitter surface by proper design of the jet pattern. A cylindrical jet shell containing 5000 holes, 1.60 mm (.063 inches) in diameter, was fabricated from silicon carbide (SiC). The jet shell sat over the open top of the furnace and the emitter surrounded it. The hot exit gases from the furnace entered the jet shell and were forced, under pressure, through the holes against the inner surface of the emitter. By reducing the spacing between holes, the heat transfer rate was increased in the lead region of the converter where the heat input requirement was largest.

The inner diameter of the cylindrical emitter would expand over 6.35 mm (.25 inches) when it was raised to the operating temperature. To accommodate this expansion, the jet shell was made from 96 rectangular sheets of SiC positioned within the emitter, using 16 equally spaced vertical SiC rods. Slip joints were used between each plate and adjacent support rod, permitting the gas pressure in the furnace to force the jet shell outward against the emitter diameter as it expanded.

Heat rejection was accomplished by jet impingement cooling using room air. After balancing various parameters, the necessary heat transfer coefficient was achieved by utilizing 1200 jets of 11.11 mm (.438 inches) diameter. Cooling air, under pressure from a centrifugal blower, was directed to the individual jets.

Development of this heat transfer system is further described in Part E, Section 3.

ZEPO, the first converter tested, was designed specifically to study the problem of high-current flow, while using converter performance available with

only low-temperature metal construction materials. The objective was achieved by designing the converter to operate under nearly short-circuit conditions, i.e., with less than one-tenth Volt of output. ZEPO was capable of generating currents up to 6500 Amperes into a short circuit. This permitted the direct study of large converter structural design, magnetic field effects, current uniformity and ignition propagation. A cylindrical geometry was selected with an emitter area of 3000 cm^2 .

Nickel was used as the material for both the emitter and collector because of its high corrosion resistance, good electrical and thermal conductivity, and relatively low cost. The major disadvantage of nickel is its poor creep strength and its low-temperature limitation as a flame barrier or an emitter.

Nickel creep tests indicated that the emitter and collector would short-circuit due to induced creep in only a few hours at operating temperatures. To avoid this, 750 alumina pads, 6.35 mm (.25 inches) in diameter and .5 mm (.02 inches) thick, were spaced over the collector surface. An interlayer of molybdenum was placed between the nickel collector and the alumina pads to moderate differential thermal expansion. A mock-up test showed that the pads could serve to maintain the design gap for at least 100 hours.

To acquire the maximum possible current within the temperature limits of nickel, it was necessary to achieve the flattest possible emitter temperature profile. Normally, the large heat loss to the ends of the converter would result in a temperature peak at the middle of the emitter. By providing less input power at the middle, this peak could be reduced, permitting a higher average emitter temperature. The input power profile needed to produce this

flat emitter temperature profile was determined by a thermal model of this basic ZEPO configuration utilizing an existing in-house engineering analysis program.

Two nickel plates, one inch thick, were rolled and longitudinally welded to form the emitter and collector cylinders. The collector cylinder was then cut in half and all three cylinders, two collector halves and the emitter, were machined to the finished dimensions. Following cleaning, the 750 alumina pads were plasma-sprayed onto the two collector halves. The halves were placed onto the emitter, as shown in Exhibit E-2.51, and the circumferential welds at the ends of the converter were completed.

Initial tests showed that converter outgassing during operation could result in the accumulation of undesirable gases (H_2 , N_2 , etc.) during operation. To avoid this, a cesium still was designed into the cesium system to permit continuous removal of the contaminants. The status of the inter-electrical discharge within the large converter was determined using igniters as collector probes. Separate heaters and thermocouples were provided for four igniters, as were current leads and voltage probes. Each could be used to analyze the condition of the electrode surfaces as well as to ignite the interelectrode gap. Characteristic curves from each igniter were digitally stored with a waveform recorder to permit later simultaneous comparison on an oscilloscope. Real-time acquisition and reduction of key converter data was mandatory to ensure safe operation. A computerized data acquisition system to provide this capability was used.

Voltage differences between various probes on the surface were used to calculate the current density profile of the converter. Because higher current

4-189

Exhibit E-2.51
ZEPO Assembly Prior to Welding

densities result in higher heat flux, the uniformity of current generation could also be estimated by determining the collector temperature profile. Eighty voltage probes mounted in a rectangular array on the collector were used to obtain the voltage data. Forty thermocouples were used to provide collector temperature data and ten thermocouples were used to continuously measure the emitter temperature. Typically, a full scan of data channels could be accomplished in five seconds. The data processing required for the ZEPO test took an additional 45 seconds before a plot of the converter's operating conditions could be completed.

Two major tests have been performed with the ZEPO converter. During the first testing period, the converter was baked slowly, under vacuum, over a period of two weeks. During this period, several leaks developed. Both the bellows material and the bellows weld were repaired numerous times. The second test took place following these structural corrections to the unit. Supportively small converter tests had shown that oxygenating the nickel electrodes improved performance. Consequently the electrode surfaces were oxygenated by filling the interelectrode space with about 250 torr of oxygen and then heating the emitter to 1220 K and the collector to 820 K over a period of 37 minutes. The converter was then evacuated and cesiated.

Immediately following cesiation, current could be drawn with the igniters. Shortly after the igniter characteristic curves broke into the power quadrant, current flow was detected with the collector voltage probes. At all times the current was stable and easily controlled, responding smoothly to changes in emitter, collector, and reservoir temperatures. No evidence of unexpected variations in current was observed.

After the appropriate preparations were made, ZEPO was tested a second time for a duration of roughly one hour. The bottom half of the converter ignited first, but the upper half produced equal current levels within seven minutes. The highest and lowest current levels measured in any of the eight converter sections are shown in Exhibit E-2.52. The two halves became more and more similar as the test proceeded. For most of the test, the current variations around the converter were $\pm 20\%$. Emitter temperature variations, only ± 15 K, based on thermocouple data, are too small to explain the current variation. Similarly, spacing variations are an unlikely explanation. The most likely cause is variations in the properties of the surfaces. An emitter work function variation of .03 eV would explain the current variation, for example. Collector work function variations could have a similar effect for operation near the optimum cesium pressure. Such surface variations would be expected to result from any residual contaminants left from the first test. Computer plots of collector temperature, voltage profiles, and current distribution in the sixteen collector sections during peak current are shown in Exhibit E-2.53.

The peak current and emitter temperatures obtained, 6500 Amperes and 1450 K, respectively, were limited by furnace operation. No unexpected magnetic field effect or other instabilities were observed. ZEPO demonstrated that large thermionic converters can be stably operated and easily controlled and this conclusion led to the development and testing of the next high-current converter, HC-2.

HC-2 was designed to function as a power generating converter. The basic design philosophy was to maintain as many desirable design features from ZEPO

Exhibit E-2.52
Range of Measured Current During ZEPO Test Two

Exhibit E-2.53
Computer Plot of Collector Temperature, Voltage Profile
and Current Distribution for ZEPO Test Two

as possible and address a number of other problems associated with large-scale converters.

The first crucial difference was to replace the welded end (shorted end) of the converter with a thin-walled metal bellows. The bellows provided vacuum and both electrical and thermal isolation. The long path length and the thin walls of the bellows allowed the bellows to act as a high impedance path for current flow. The bellows construction permitted independent thermal expansion of both the emitter and collector and also protected the interelectrode vacuum. Exhibit E-2.54 shows a schematic diagram of HC-2.

Secondly, the collector was changed from a single structure to a segmented design with eight equal parts. Each collector segment was designed with backing springs to enable the collector and the emitter to move with thermal expansion and creep, while maintaining a constant interelectrode spacing. Spacing was maintained by eight alumina pads placed in machined recesses in each collector surface, as shown in Exhibit E-2.55. The pads continually made contact with the emitter. These alumina pads were positioned inwards 1.5 cm (.6 inches) from the outer edge, four on each side along its length. However, this proved to be a design weakness during testing. The emitter itself was a continuous cylinder of nickel, with a 21.6 cm (8.5 inches) outside diameter.

The third new design feature was a means of distributing the electrical connections to the two electrodes. Recall that both electrodes are made of nickel and the electrodes deliver high electric currents. Hence, if only one electrical contact was made on each electrode, large resistive losses would result. In order to avoid this problem, multiple connections were made and

Exhibit E-2.54
 Cutaway Section of HC-2 Converter Showing
 Various Elements

Exhibit E-2.55
Emitter-Collector-Flexible Connector from HC-2

distributed over the collector to reduce the local current. Additionally, because both electrodes expand and contract, these connectors had to be flexible. The distributed flexible connector concept is also shown in Exhibit E-2.55.

The emitter was connected to the emitter bus via flexible pieces of bent nickel welded to the emitter. The collector connectors were fabricated by lamina of copper foil coated with a molybdenum disilicide coating which allowed the foil to slide over its neighbors. This same connector also provided heat conduction from the collector to the collector bus, a monolithic piece of OFHC copper which backed the collector. Testing also showed these elements to be a weakness in the design. Heat was to be transferred by the laminated foils to the collector bus. The collector bus, in addition to being an electrical bus, also housed the cooling lines for heat removal. Large copper slabs formed the remainder of the connectors and bus.

Testing of HC-2 consisted of a prolonged period of baking out the converter while under vacuum, followed by six hours of running with cesium in the system. Igniters were used to start ignition of the plasma in the interelectrode space. The igniters consisted of small diameter wires which were set at the top of the collector segments. Following a gradual heat-up, ignition was accomplished. However, the converter operated sporadically. The eight collectors did not operate in unison and most operated outside the power quadrant. Those that did deliver power did so with a very low power density, primarily due to a very high collector temperature. The source of the problem was the electrical collector connector which also was intended to cool the device. However, this connector exhibited excessively high thermal resistance and did not adequately remove heat from the collector.

Following shutdown and disassembly, a second problem was identified. Two of the collector units became cocked during operation and short circuited to the emitter. This short-circuit created exceptionally high currents and collector temperatures. This problem could have been easily avoided by moving the outermost alumina stand-offs closer toward the edge.

Results from HC-1 and HC-2 show promise in the development of large-scale, high-current converters. ZEPO confirmed the feasibility of scale-up to high current and large emitter areas in a single cell. HC-2 confirmed the viability of the distributed lead - segmented collectors concept. Further work is clearly required to optimize the thermal design of the collector portions of the converter, however, before the ultimate potential of large converters can be fully evaluated.

2.8 Cold-Seal Converters

The cold seal converter was designed to eliminate high-temperature ceramic sealing by using heat pipe technology. Cesium confinement for this converter is accomplished by arranging the chamber to act as a cesium heat pipe with a region of argon gas at its upper end. A refluxing action of the cesium vapor is maintained by evaporation of the cesium in the bottom (i.e., the hot end) of the converter chamber, and condensation of the vapor at the cold end onto a wick that lines the inner wall. The liquid cesium from the condenser region then returns via capillary action and gravity through the wick back to the bottom of the chamber to be evaporated once again. This refluxing cycle pumps argon gas out of the bottom region toward the upper end and a transition interface is established between the cesium vapor and the inert gas. The cesium is

adequately confined using this technique and does not escape into the upper end of the chamber. The lower temperatures at the upper end permit the use of low-temperature plastic insulator seals in this region.

Exhibit E-2.56 is a schematic of a cold seal converter. Heaters are mounted on the outside of the chamber near the bottom and a cooling coil is brazed to the chamber near its upper end. This provides a heat flow to drive the heat pipe action and produce the required interface region. The temperature at the bottom end is kept above the cesium condensation temperature by the heaters located in that region. The temperature in the upper argon region is typically near room temperature. A tubing manifold connected to the heat pipe in the upper argon region provides access to a vacuum pump and a supply of argon used to evacuate and fill the device. The closure at the top of the device is made with a Plexiglass disk sealed with "Viton-A" O-ring.

The cesium is continually cleansed by the refluxing action through the wick. Because cesium is repeatedly evaporated and recondensed in the wick, gaseous contaminants are continually transported toward the top-most region away from the active electrodes. Any gas build-up which might occur in the converter region is thus removed. As a consequence, admission of air or water vapor during disassembly or reassembly is not a critical problem. In fact, experience with the cold seal device has shown that large amounts of contamination from air and even liquid water do not adversely affect operation of the cold seal converter [23].

Initial tests of this gas-buffered cesium heat pipe were made with a clear plastic plate at the top to permit visual observation of the cesium flow

Exhibit E-2.56
Cross-sectional Drawing of Cold Seal Converter

characteristics. A variety of vapor flow conditions were observed. Unless the argon overpressure was properly adjusted, it was possible to lose control of the cesium-inert gas interface and have cesium droplets splattered up onto the plastic plate at the top. However, proper adjustment of the heater power and the argon overpressure could produce a stable interface.

In order to accurately determine the location of the interface, a hot-filament cesium detector mounted on a movable probe was inserted axially through a compression fitting located at the top of the device. Data obtained with the cesium detector probe verified conclusively that the cesium vapor region existed in the bottom of the chamber while an "argon-only" region existed in the upper part of the chamber. For cesium pressures in the 1 to 10 torr range in the evaporator section, the cesium partial pressure in the argon region was below 10^{-4} torr, the limit of detectability.

Emitter temperature was measured via a thermocouple located on the inside of the hollow emitter. A bombardment filament was used to heat the emitter during operation. The diameter of the emitter was one-half inch and the length of the active region was approximately one and one-quarter inch. The collector was made of stainless steel, and the interelectrode gap was .5 mm (.02 inches).

The ease with which the emitter could be removed and reinstalled illustrated the value of this technique for providing access to the electrodes. To remove the emitter it was only necessary to keep the cooled heat pipe chamber oriented in the vertical direction and then fill it with argon to slightly above atmospheric pressure. At this point the emitter and top plate were lifted slowly so as not to create secondary air currents within the assembly.

Because argon is heavier than air, very little atmospheric air was introduced during withdrawal or subsequent reinsertion of the emitter. Pumping the argon pressure down to the desired operating cesium pressure (i.e., approximately 1 to 4 torr) and reheating completed installation.

The converter was tested with a variety of emitter temperatures and cesium pressures and showed controllable behavior. A cesium pressure family with the emitter temperature at 1600 K and the collector temperature at 930 K is shown in Exhibit E-2.57. These characteristics are shown as a function of argon overpressure, since, in practice, this argon pressure was used to control cesium pressure. During testing at low argon pressures (i.e., less than 0.5 torr), it was found that the buffer gas-cesium vapor interface became poorly defined and cesium was lost during the buffer gas evacuation.

After the device was fully optimized, exceptionally high output power density was produced at 1600 K with a collector temperature of 800 K, an argon overpressure of 1 torr (i.e., with cesium pressure approximately the same as argon pressure) and an interelectrode spacing of .5 mm (.02 inches). The output characteristics at 1600 K are shown in Exhibit E-2.58. The maximum measured power output was 72 Watts. This represents a peak power density of 6 Watts/cm². The maximum power occurred at $J = 20$ Amperes/cm² and $V = 0.3$ Volts. The barrier index at this point was 1.98 eV. The minimum barrier index of 1.92 eV occurred at $V = 0.5$ volts and $J = 8$ Amperes/cm². The peak power density was twice that of conventional hot shell converters operated at the same temperature.

This superior performance was attributed to oxygen and water contamination of the electrodes. Substantial amounts of both oxygen and water were present

Exhibit E-2.57
Operating Characteristics of a Cold Seal
Converter as a Function of Argon Overpressure

Exhibit E-2.58
Cold Seal Converter Output Characteristics
Measured at the Electrodes

in the device. It is postulated that two previously reported effects may have acted to lower the work function of the collector [24]. First, molybdenum from the emitter may have been deposited on the stainless steel collector surface by the "water cycle" experienced in other thermionic converters. Furthermore, the molybdenum may have been deposited on the collector in the form of moly-oxides. Superior performance of cesium converters with Mo_xO_y collector surfaces has been observed. Second, cesium oxides may have been adsorbed on the collector. Work functions as low as 1.0 eV have been produced by codeposition of cesium and oxygen in the proper proportions.

The cold seal converter may have fortuitously achieved a nearly optimum oxygen partial pressure for cesium oxide collector conditions. Oxygen in the converter would react with cesium, producing cesium oxide in the condenser region of the wick. As the cesium and the cesium oxide mixture flows from the condenser region back to the evaporator, the cesium would be preferentially evaporated, increasing the concentration of the cesium oxide. The cesium oxide would decompose as the mixture reaches the hottest section in the vicinity of the active electrodes. This could result in an unusually high partial pressure of oxygen in the electrode region, which would give a high oxygen coverage on the collector surface. This phenomenon is of possible interest in connection with the study of techniques for producing low surface work functions with cesium oxide mixtures. However, Program resources have not permitted any systematic study of its potential.

Oxygen effects in the cold seal converter were also evidenced by its unusually high electron emission. The maximum output power occurred at a current density substantially higher than would be expected from a cesiated

polycrystalline molybdenum surface under similar conditions. In fact, the emission corresponds to a line on a T_E/T_R plot equivalent to a bare work function above 4.8 eV (i.e., compared to 4.3 eV expected for molybdenum). Oxygen is a well-known cause for such an effect.

Exhibit E-2.57 is also of interest in another regard. The characteristic curves show a pronounced hysteresis effect. The cause of this behavior is unknown, but it has been speculated that it represents a switching between ignited and unignited modes of operation.

The experience with the cold seal converter has shown that this method of cesium confinement is feasible. Although these studies did not address the question of converter lifetime, it is believed that a cold seal type of converter could be designed in such a way as to have an adequate lifetime for topping cycle applications.

2.9 Inductive Power-Coupled Converters

Inductive power coupling refers to the electrical connection of thermionic converters so as to deliver AC power through a transformer. Two modes of inductive coupling, flux-reset and push-pull, have been examined. Both of these methods couple the converters to their load inductively by switching converters between two characteristic operating states (i.e., high-current, low-impedance ignited mode and low-current, high-impedance unignited mode). However, both flux-reset and push-pull systems operate at decreased baseline efficiency because the converter operates at a reduced duty cycle.

The flux-reset method is one where a single converter drives the primary of a transformer as shown schematically in Exhibit E-2.59. The converter is alternately switched between its low-impedance, power-producing state and its high-impedance state with aid of a short duration electrical pulse. A small amount of energy supplied by this generator is used to reverse the flux in the transformer, switching it between states. A short while later, an opposite polarity pulse is created to switch the converter back to the first state.

Exhibit E-2.59 shows the input and output waveforms and the converter operating points for flux-reset output coupling. At point 1, power is delivered to the load until the transformer core begins to saturate. A pulse at point 2 de-ignites the converter and disconnects the load from the circuit. The converter is driven out of the power quadrant at point 3 to reset the flux in the transformer. Finally, a pulse at point 4 re-ignites the converter and re-connects the load. The output from the transformer secondary is interrupted DC with a high-duty cycle (i.e., 80-85%). The output voltage is determined by the turns ratio used in the transformer.

Although the duty cycle is high, there are losses in efficiency associated with the amount of time the converter is not producing power. If an 85% duty cycle is assumed along with an emitter temperature of 1650 K and a current density of 10 Amperes/cm^2 , the ratio of the flux-reset efficiency to the base-line efficiency is .96 according to equations derived in [25]. Furthermore, because the required pulse power must be about 6% of the total output power [26], the efficiency ratio must be further reduced to about .90, i.e., the input power must be increased by a factor of 1.11 to compensate for these losses.

- ① Power Delivery
- ② Turn Off
- ③ Reset
- ④ Fire

TRANSFORMER INPUT WAVEFORMS

TRANSFORMER OUTPUT WAVEFORM

Exhibit E-2.59
Flux Reset Operating Characteristics

Proper utilization of flux-reset requires that the reset and ignition voltages extend out of the power quadrant by an amount many times the operating voltage to ensure discontinuance of the switch state. As the reset and ignition voltages approach a value equal to the output voltage, the duty cycle decreases to 50%, and the efficiency decreases to the value reported for push-pull below.

There is no lower theoretical limit to the frequency at which a converter may be switched on and off. As the frequency decreases, the transformer does become larger, and hence physical size and weight introduce a practical lower limit. The turn-off time of one millisecond is much longer than the ignition time of less than ten microseconds and thus controls the upper frequency limit. In general, increasing the switching frequency decreases the duty cycle and, hence, the system efficiency.

Another simple inductive output coupling method is the push-pull-type, where two converters are connected to the center-tapped primary winding of a transformer, as shown in Exhibit E-2.60. While one converter is producing power, the other converter is operating in its high-impedance, unpowered state. The converters are switched simultaneously between operating states by means of a short pulse connected to the transformer secondary, by reversing the flux in the transform core. Again, a pulse generator is used to perform the switching. The output waveform, using this coupling method, is a square-wave AC, with the voltage determined by the transformer turns ratio.

The duty cycle of each converter in a push-pull power conditioning system is 50%. Thus, twice as many converters as the baseline design are required to

- ① Operating Point Of Power Delivering Diode
- ② Operating Point Of Nonconducting Diode

SWITCHING WAVE FORM

OUTPUT WAVE FORM

Exhibit E-2.60
Push-Pull Operating Characteristics

produce the same output power. However, it is not necessary to fully double the input power to compensate for the loss in output power. Instead, it has been shown [25] that a push-pull system is capable of achieving a maximum efficiency which is about 83% of baseline efficiency. To obtain the same output power as the baseline system, the input power must then be increased by roughly 20%.

Because flux-reset has a potentially higher efficiency than push-pull, experiments within the Program have concentrated on evaluation of the former method. A small cylindrical ignited mode converter with an emitter surface area of 7.5 cm^2 (1.2 inches^2) was designed for this evaluation. A circuit schematic is presented in Exhibit E-2.61.

The emitter was made from molybdenum, and a thin (i.e., .002 inches) layer of platinum was used in the active region to provide a low cesiated work function. The collector was stainless steel. The interelectrode space was .05 inches.

A high-vacuum flange was provided between the emitter and collector to facilitate disassembly and modifications. A stainless steel vacuum chamber was welded on top of the converter to provide the necessary vacuum environment for an electron bombardment filament. This allowed operation of the converter in air. The cesium was contained at the bottom of a nickel tube extending down from the collector. Cesium reservoir temperature control was accomplished by varying the thermal conductance of the reservoir tube by changing the position of a surrounding copper sleeve. For a given position of this sleeve the reservoir tended to run at a constant temperature difference below the collector temperature.

Exhibit E-2.61
Flux Reset Circuit Schematic

A single 120 Volt AC transformer with two secondary windings for both filament heating and electron bombardment provided the input power for the converter. Only one variable transformer control was required. Partial saturation of the transformer by the DC electron bombardment current provided negative feedback to the filament heater which provided emitter temperature stabilization at an operating point.

The system was successfully fabricated and tested. Exhibit E-2.62 shows actual voltage and current traces for one full cycle period as recorded on an oscilloscope. The cycle frequency was 53 Hz, and a power of 2.5 Watts was generated during 66% of each cycle. The converter behaved reliably and its performance actually improved during testing. This improvement may have been due to evaporation of platinum onto the collector, since the change of performance was consistent with a change in collector work function.

2.10 Cesium-Graphite Reservoir Converters

Tests on cesium-graphite reservoir converters were conducted to determine if equivalent performance could be achieved with the use of a cesium-graphite reservoir in place of the normal cesium reservoir. Experiments by Yates and Fitzpatrick [27] showed that cesium-graphite compounds can act as a dispenser of cesium at collector temperatures. A passive cesium-graphite reservoir could then replace a separately heated and controlled cesium reservoir in thermionic converters.

Initial converter tests used both a separately heated cesium and cesium-graphite reservoir for experimental flexibility. In a later converter

Exhibit E-2.62
Oscilloscope Tracing of a Flux Reset System

design the cesium-graphite reservoir was made integral with the collector. In each converter, the cesium reservoir was heated to charge a graphite slug at a cesium pressure to give optimum performance. The cesium reservoir was then pinched off and the cesium-graphite reservoir was heated to collector temperatures.

Results from cesium-graphite reservoir converters were favorable and demonstrated the ability of the reservoir to maintain the cesium vapor pressure in the converter. The functional relationship between cesium vapor pressure and cesium-graphite reservoir temperature is similar to that of a cesium reservoir as shown by Exhibit E-2.63. One converter was tested for 300 hours with no significant change in performance. Thus, although this technique offers no real hope of performance improvement, it does offer hope of a much simpler and potentially more economical converter design.

2.11 Miscellaneous Development Efforts

In addition to the development and performance improvement experiments described in the previous portions of this section, a number of miscellaneous efforts were carried out at various times during the Program.

A set of bare metal electrode converter tests was primarily designed to obtain performance characteristics of new emitter materials (e.g., LaB_6 , Re, Pt and graphite) and, under controlled laboratory conditions, electrode materials used in combustion converters. A further discussion on iridium and lanthanum hexaboride electrodes is contained in a paper by Goodale [13].

Exhibit E-2.63
Cesium Pressure vs Liquid-Cesium and Graphite-
Cesium Reservoir Temperatures

Investigations were also conducted on converters that were fabricated with collector surfaces that do not dispense oxygen but which were nonetheless predicted by previous laboratory work to have very low work functions (i.e., 1.1 to 1.5 eV) and would, therefore, be expected to give good converter performance. The oxides of barium, zinc, and strontium were tested. These surfaces were typically prepared by spraying thin coatings onto nickel substrates and outgassing binder materials. However, the work functions of these materials in converters, as measured by back emission and retarding plot methods, could not duplicate laboratory measurements at the same cesium pressures. Similarly, the barrier indices of these converters were larger than anticipated. Additional information can be found in a report by Lieb, et. al. [12].

A research converter was also instrumented to measure the electron heating rate to the collector in order to investigate fundamental mechanisms coupling the plasma to the electrodes in the ignited mode. The electron heating rate to the collector is composed of the incident electron kinetic energy and the heat generated as the electrons drop through the potential associated with the collector work function, ϕ_C . Thus,

$$Q_C = J(\phi_C + 2kT_e), \quad (E-2.6)$$

where J is the current density, k is the Boltzmann constant and T_e is the electron temperature. By carefully controlling the temperatures of all the converter's components, it is possible to measure the electron heating rate to the collector over a range of converter current densities.

The converter tested had a tungsten emitter and a nickel collector. An auxiliary heater positioned .75 mm (.03 inches) from the collector surface

provided a nulling thermal input. Current-voltage characteristics for the converter, along with the collector work function, were measured. Collector heat flux determinations were made at an emitter temperature of 1700 K, a cesium reservoir temperature of 577 K and over a range of collector temperatures from 750 K to 900 K at interelectrode spacings from .25 to 2 mm (.01 to .1 inch). The electron heating to the collector was found to be constant over the range of current densities from 0.05 Amperes/cm² to 9.0 Amperes/cm². Measurements were also made at various collector work functions, produced by varying the collector temperature for a constant cesium reservoir temperature. The value of electron heating minus collector work function as determined from retarding plots was $.54 \pm .04$ eV over the collector work function range from 1.70 to 1.94 eV. This value corresponds to an electron temperature of 3100 K. Measurements of collector electron heating showed a pronounced increase at spacings less than .5 mm (i.e., .02 inches).

Finally, so-called particle thermionic converters were designed to mitigate detrimental space charge in the interelectrode space by positioning a thin, porous layer of semiconducting material in contact with the electrodes. Each pore of the semiconductor would act like a thermionic converter that would conduct electrons but, because of its small size, would be free of any appreciable space charge. Several such pores in a layer between the emitter and collector would form a series of converters able to transport electrical current. A low work function semiconductor was required to insure high current emission and the electrical resistance of the bulk material was small to limit voltage losses. Experiments with a 25 micron thick layer of barium, strontium and calcium oxides containing pores between one and ten microns in diameter produced a short-circuit current of .5 Amperes/cm² and an open circuit voltage

of .47 V at emitter and collector temperatures of 1373 and 1118 K, respectively. The maximum output power density achieved was .06 Watts/cm². In addition, semiconducting layers of magnesium oxide and alumina oxide were tested. Particle thermionic converters, normally operated under vacuum, were also tested under low pressure cesium vapor which gave no significant improvement in output power. The marginal performance of these converters was later attributed to "whisker" formation on the molybdenum collector substrate that tended to short the electrodes.

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3. HEAT TRANSFER RESEARCH AND TECHNOLOGY

3.1 Introduction

The electrical output of a thermionic converter is a direct function of the thermal energy flux through the converter. Efficient heat transfer to the emitter and from the collector are of primary importance to the proper operation of the converter, and the development of practical thermionic systems. Within the Advanced Thermionic Technology Program, therefore, attention has been given to balance-of-system considerations as well as to the thermionic converters themselves.

Cogeneration designs typically require air at near atmospheric pressure as the working fluid in the collector heat exchanger. Thermal energy removed from the collector is used to preheat the combustion air for the cogeneration burner. This imposes pressure drop and temperature constraints on the collector heat exchanger. The cooling pressure head must be provided by the combustion blower, and there are severe equipment cost and power consumption penalties for exceeding the pressure capabilities of that device. The optimum collector temperature and achievable heat transfer rates also place a practical upper limit on the outlet air temperature which can be produced for combustion air preheating. Work on cogeneration converter collector heat exchange design, therefore, is chiefly concerned with balancing these trade-offs to develop a configuration which satisfies heat flux, temperature, and size constraints while minimizing the pressure drop.

By contrast, a topping cycle for a gas and steam turbine plant would use high-pressure air from the turbine as the working fluid. This imposes very different constraints on cooling system design.

In short, much of the work on heat transfer conducted by the Program has been carried out in the context of system applications. This type of effort has reached its greatest detail in economic feasibility assessments of the kind discussed in Part D. Thus, portions of Part D address issues of heat transfer.

However, the Program has also addressed questions of heat transfer where they were of importance to particular thermionic converter concepts -- such as the large converters discussed in Part E, Section 2.7, and the fire-tube cogeneration burner -- or where they were concerned with general concepts of heat transfer as applicable to thermionics. In this latter regard, methods for improving collector cooling heat transfer which have been examined have included ball matrix heat exchangers and finned heat exchangers. The remainder of Section 3 discusses the heat transfer research carried-on by the Program outside the context of the system economic studies described in Part D.

3.2 Fire-Tube Cogeneration Burner

As indicated above, cogeneration imposes design constraints on conventional thermionic converters which can limit their performance. The fire-tube burner design attempts to meet these constraints by combining a separate burner with each converter.

The fire-tube cogeneration burner refers to a converter design in which the combustion flame is encased in a hollow tube which forms the emitter. This design uses these converters to produce both electrical power and high temperature flue gas. A schematic drawing of the fire-tube converter design is shown in Exhibit E-3.1. Since combustion occurs within the cylindrical emitter of each converter, the emitters are in close proximity to the combustion gases and have minimal surface area. The emitters are molybdenum tubes with CVD silicon carbide on their inner surface. Each tube is one inch in diameter and twelve inches long.

Locating the collector concentrically around the emitter allows geometric divergence to reduce the temperature drop through the collector, since increased surface area for heat transfer exists on the outside surface of the collector. This increases the acquired temperature of the coolant air. The collectors for this converter are made of copper, suitably plated with nickel or chromium to reduce oxidation. Conventional ceramic-metal seals are used. This burner design releases about 35,000 Watts within each tube, a volumetric burning rate of 21 Watts/cm³. The burner delivers 20 Watts/cm² into the emitter at a temperature of 1700 K.

Six fire-tube converters are designed to be mounted in an array within a thermionic combustor as shown in Exhibit E-3.2. DC power is delivered from the front end of the combustor and process heat is discharged from the opposite end. During operation, combustion air is blown into the plenum formed by the enclosure. It then flows to the center of each converter through channels in their collectors. Having been preheated to near collector temperature, the air is then ducted to the burner end where it is introduced with fuel into the combustion region. The converters are electrically connected in a series-parallel

Exhibit E-3.1
Fire-Tube Converter Design

Exhibit E-3.2
Thermionic Combustor Containing Six Converters

array to obtain the desired output voltage and current. Two such converters were built and operated during the test period, both individually and in a combustor. Additionally, a single emitter tube was operated in a life test accumulating 1200+ hours at a temperature of 1750 K. Two converters were also operated for a total of slightly over 7 hours duration with their emitter temperatures between 1550 K and 1620 K.

3.3 High Current (HC) Series Heat Transfer Development

High heat fluxes can be achieved by a high velocity jet impinging on a surface. The jet strikes the surface, breaks up the boundary layer and thereby increases the local heat transfer. In addition, jet-impingement heat-transfer can be easily controlled, and by proper design of the pattern of jets, provides the preferred heat transfer profile across the surface. The engineering trade-off here is that additional pump work is required to form and maintain these jets. The increased heat transfer is manifested as additional power output. Generally, pump work is smaller than the increase in power output, so the trade-off is worthwhile.

Beneficial effects of jet impingement on Stirling engine operation were studied by the NASA Lewis Research Center [1]. Their results are presented non-dimensionally in the traditional manner, namely plots of Nusselt number versus Reynolds number in Exhibit E-3.3. An increased Nusselt number reflects an increased effective heat transfer coefficient. "Jet impingement" clearly exhibits a higher heat transfer coefficient.

Because jet impingement provided a fundamental means of generating higher heat rates, it was incorporated into the design of the first of the HC converter

Exhibit E-3.3
Effective Heat Transfer Coefficient and Nusselt Number
vs Reynolds Number, Illustrating Enhancement by
Jet Impingement

series, i.e., ZEPO, described above in Part E, Section 2.7. A computer code was developed based upon data from [1], [2], and [3] to optimize spacing between jets, uniformity of temperature, jet velocity, distance between jet nozzle and heat transfer surface, and gaseous transport properties. Parametric design charts were generated, as shown in Exhibit E-3.4. These data, coupled with preferred temperature and converter response, permitted the design of the gas impingement heat and cooling system used in the HC series.

The computer code and subsequent calculations showed that the proper heat transfer rate and profile for the first large converter (i.e., ZEPO) test could be obtained with an array of 5000 jets, each 1/16 inch in diameter, spaced approximately 1/8 inch from the inner diameter of the emitter. A flue gas temperature of about 2000 K would be required from a 2,500,000 Btu/hr furnace. The furnace would have to operate at a positive pressure of 17 inches of H₂O to obtain the desired jet velocity.

Silicon carbide (SiC) was selected as the material most capable of providing the required strength in the flue gas environment at the design temperature. It was clear that a single large cylinder of SiC would be very expensive, fragile and unable to maintain the proper jet-to-emitter spacing. Consequently, a flexible house-of-cards approach to the jet shell design was selected. In this design, shown in Exhibit E-3.5, the cylinder of SiC is composed of 96 rectangular 1/8 inch thick sheets of SiC positioned inside the emitter using 16 equally spaced vertical SiC rods. The internal pressure of the flue gases forces the rods against the emitter, thereby maintaining jet spacing during temperature cycles. The "prebroken" design of the shell eliminates bad stress points, minimizing failures. Plates or rods that do fail are relatively inexpensive and easy to replace.

Exhibit E-3.4
Jet Impingement Heat Transfer System Design Chart

Exhibit E-3.5
Silicon Carbide Jet Shell Assembly

This jet shell, as used in the tests of ZEPO, provided 61 Watts/cm^2 at 1175 K to the emitter of the thermionic converter. The array of jets provides a means for tailoring the heat flux to meet specific design objectives.

Jet impingement was also used to cool the collector. In ZEPO, 1050 nozzles were placed around the collector. Exhibit E-3.6 shows this assembly. Room temperature air was pumped through a double plenum into the jet manifolds. The resulting temperature profiles for a shorted high-current converter test for the bottom halves of the two electrodes are shown in Exhibit E-3.7. Note that temperatures are relatively constant and vary by less than 14% in this section, indicating the uniformity of heat flux. As illustrated in Exhibit E-3.7, the jet impingement system provided the required heat flux profile to maintain uniform operating temperatures for the range of heat transfer coefficients required for a thermionic converter.

The jet impingement technique does have two major disadvantages: the heat transfer coefficient is very dependent on the jet-to-substrate distance, and the heated substrate is subject to a high local heat flux and resulting erosion from the jets. To avoid these problems, a cellular ceramic radiant-heat transfer system was also considered.

In this design, a ceramic is extruded into the form of 25 parallel square flow passages per square centimeter. Each extruded body is square in cross-section and is approximately one inch in width. Combustion gas passes through the channels in the ceramic as shown schematically in Exhibit E-3.8. The ceramic heats up and acts as a radiator to the converter.

Exhibit E-3.6
Heat Rejection System Jet Impingement Array
for ZEPO

Exhibit E-3.7
Effect of Tailoring Heat Flux Profile on
Temperature by Using Jet Impingement

Exhibit E-3.8
Conceptual Drawing of Radiant Heat Transfer
from Cellular Ceramic

The cellular wall exhibits a high emissivity and has a higher radiant heat transfer efficiency than a typical furnace. The large hole-depth/hole-diameter ratio of the channels makes the cellular ceramic approximate an array of black-body cavities. Furthermore, the large surface area of the channel walls gives a much larger area for heat transfer from the combustion gases to the radiating intermediate wall. Exhibit E-3.9 shows the effective heat transfer coefficient for a cellular ceramic system compared to combustion gas radiation for the same gas and receiver temperatures.

Unique to the cellular ceramic radiant system is its directional radiating characteristics. As shown in Exhibit E-3.10, there is a definite peak in the radiant flux. The minimum at normal incidence is due to viewing through the cells. However, when viewed slightly off normal, a deep, nearly isothermal cavity is seen with an emissivity approaching unity.

Several tests were performed to find a suitable material for the cellular structure. Several samples for testing were supplied by Corning's Ceramic Products Division. Based on these tests and jet shell experience, silicon carbide was selected; it exhibits excellent thermal shock resistance, high-temperature strength, and long life at high operating temperatures.

A cellular silicon carbide radiator was constructed and tested with the high-current thermionic converter HC-2. In these tests, the design heat flux of 20 Watts/cm² to a 1500 K surface was readily obtained.

Exhibit E-3.11 compares the heat fluxes to be expected for jet impingement and for ceramic radiation for a 1973 K source. Both median and upper and lower

Exhibit E-3.9
Comparison of Radiant Heat Transfer Coefficients for
Natural Gas/Air Combustion Products and Cellular Ceramic

Exhibit E-3.10
Angular Variation of Heat Flux from
Cellular Ceramic Radiator

Exhibit E-3.11
Comparison of Jet Impingement and Cellular Ceramic
Heat Transfer for a 1973 K Source

bound values are shown for the two approaches. Jet impingement tends to be more effective at lower temperatures (i.e., below about 1075 K), and cellular ceramic radiation is superior at elevated temperatures. However, the radiant system may be the only reasonable alternative when jet impingement ablates or distorts the surface, when local hot spots are undesirable, or when pumping power losses are critical.

3.4 Ball Matrix Heat Exchangers

Early in the Program [4] ball matrix heat exchangers were examined for application to collector cooling, but the results were generally disappointing. Ball matrix heat exchangers suffered from two drawbacks in this application. First, the small contact area between the collector and the balls -- and between adjacent balls -- limited the conduction of heat from the collector. The interior balls remained cooler and were, therefore, less effective in transferring heat to the air. Even brazing the balls together did not sufficiently increase the conduction to improve heat transfer.

The second problem was nonuniform flow through the matrix, resulting in partial stagnation of certain areas. Reversing the air flow pattern improved the flow characteristics, but did not correct the poor conduction to the interior balls. A schematic of a ball matrix heat exchanger is shown in Exhibit E-3.12.

A second ball matrix cooler utilized a plate to force the air flow through the hotter exterior balls adjacent to the collector. This improved performance slightly, but was still not as effective as finned coolers.

Exhibit E-3.12
Ball Matrix Heat Exchanger

3.5 Finned Heat Exchangers

Several finned heat exchangers have been designed and tested in the course of the Program.

The first finned design (i.e., "Fin I") utilized an inner ring of 12 fins and an outer ring of 24 fins, brazed to the inner surface of the collector (Exhibit E-3.13). The fins were of constant height and the air flow channels of constant dimension for ease of fabrication. Despite lack of design refinement, this heat exchanger provided higher heat removal than the plate-ball matrix cooler, and so the finned approach was pursued. The second finned design (i.e., Fin II) used 18 fins on the inner ring and 36 fins on the outer ring, for increased area and heat removal. This finned cooler performed within acceptable limits, although the required pumping power was higher than desirable (see Exhibit E-3.14).

Information developed during the testing of the second finned design was incorporated into the heat transfer section of a computer model for optimizing the design of thermionic topping of a combined gas and steam turbine power plant [5]. The computer model was studied to determine if it could accurately describe the behavior of the finned collector, and it was discovered that both the heat transfer coefficients and the pressure drops predicted by the code were higher than would normally be expected for this type of heat exchanger. Since the existing code could not be used with confidence in this application, a new experimental study was undertaken to establish the baseline performance of the finned heat exchanger and formulate a more suitable design model.

Exhibit E-3.13
"Fin I" Heat Exchanger

Exhibit E-3.14
Required Pumping Power vs Heat Removed for
"Fin I" Cooler and "Fin II" Cooler

A set of preliminary calculations was performed to determine the required heat transfer coefficient, h , as a function of collector-air temperature difference, given the Fin II collector design and air at atmospheric pressure. The results are indicated in Exhibit E-3.15. Film coefficients above $570 \text{ Watts/m}^2\text{-K}$ ($100 \text{ Btu/Hr-Ft}^2\text{-F}$) are difficult to achieve; therefore, the minimum temperature difference between collector and air for this application was taken to be about 280 K (500 F). Since a typical collector temperature is 850 K , this sets upper temperature limit for inlet air at about 570 K .

In the experiments themselves, a known quantity of electrical energy was dissipated through a resistance heating element brazed to the face of the collector. The assembly was thoroughly insulated, and the inlet and outlet air temperatures and flow rate were monitored. The test setup was allowed to reach thermal equilibrium after each change in input power or air flow rate. The results are summarized in Exhibit E-3.16.

The results of these experiments indicated that the computer model was producing reasonable estimates of heat transfer coefficients, but was over-estimating the pressure drop and pumping power losses. The problem was ultimately traced not to errors in the computer code, but to errors in the experimental data recorded in the initial tests of the Fin II design, i.e., the data incorporated into the computer program.

Further analysis indicated that close to 70% of the pressure drop through the heat exchanger was occurring in the inner ring of fins, although only 30% of the heat removed from the collector was rejected by the inner fins. This observation suggested that a more efficient design could be achieved by arranging

Exhibit E-3.15
Required Heat Transfer Coefficient vs Collector-Air
Temperature Difference for "Fin II" Design

Exhibit E-3.16
Initial Results on "Fin II" Collector Heat Exchanger Test Series

the collector heat exchanger geometry such that the pressure drop in each ring of fins was proportional to the heat to be rejected by those fins.

A new computer program was written with this design task in mind. The dimensions and arrangement of fins and air flow channels were specified separately for each ring of fins. The inlet air temperature and pressure, the input heat flux, and the desired collector operating temperature were also input parameters. The program then calculated the required air flow rate, resulting pressure drop, and outlet air temperature. The amount of heat removed by each ring and its associated pressure drop were also reported. By varying the fin and air flow channel geometry a "balanced" design could be generated.

A third collector heat exchanger design, denoted Fin III, was developed with the aid of this computer model. A schematic of the design is shown in Exhibit E-3.17. Its installation in a standard hot shell converter is shown in Exhibit E-3.18. The width of the air flow channels in the inner ring was increased to reduce the pressure drop. The width of the flow channel in the outer ring was reduced to increase the pressure drop and the heat transfer coefficient. The length of the outer fins was increased to provide more heat transfer surface, as the fin-air temperature difference was lower in that section.

For this design, the computer program predicted a large decrease in pressure drop and required pumping power for a given amount of heat rejected from the collector. In addition, the improved collector heat exchanger was composed of two parts rather than three, as in the previous design. This is expected to result in stock, machining and assembly savings as well as better thermal performance.

Exhibit E-3.17
"Fin III" Collector Heat Exchanger Design

Exhibit E-3.18
"Fin III" Collector Heat Exchanger Mounted in Converter

The improved finned collector heat exchanger has been fabricated and tested. The results and a comparison with the previous design are indicated in Exhibits E-3.19 through E-3.21.

The improved design reduces both the required air flow and the required pumping pressure to achieve proper cooling at the desired collector temperature. This reduces the total required pumping power for collector cooling by a factor of four, to less than one Watt per converter in a full-scale thermionic module. Pumping losses will be somewhat higher for single converters due to heat flux through the sides of the hot shell, which would normally not be exposed.

The performance of Fin III has been replotted parametrically in Exhibit E-3.22. This exhibit shows the heat removed from the collector with constant air inlet flow. The outlet air temperature is also shown. To remove 400 Watts from the collector with a collector cooling air temperature of 688 K, the pressure loss is seen to be only 1 inch of water or 200 Pascals. This parametric plot can be used to match the collector cooling air requirements to the available blower pressure and desired hot air temperature for each application.

Exhibit E-3.19
Pressure Drop vs Heat Removed for Collector Heat Exchanger "Fin II"

Exhibit E-3.20
Pressure Drop vs Heat Removed for Collector Heat Exchanger "Fin III"

Exhibit E-3.21
Pressure Drop vs Heat Removed for Collector Heat
Exchangers Fin II and "Fin III"

Exhibit E-3.22
Parametric Plot of "Fin III" Heat Exchanger Performance

SECTION 3 - REFERENCES

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APPENDICES TO VOLUME 4,
PART E

NOMENCLATURE

d	=	interelectrode gap width	(cm)
e	=	electron charge	(coulombs)
E	=	electric field	(volt/cm)
$E(o)$	=	electric field at the emitter surface	" "
E_p	=	electric field at the emitter sheath-plasma interface	" "
J_R	=	Richardson current	(Amps/cm ²)
J_E	=	net electron current emitted into the plasma from the emitter	" "
J_C	=	electron back emission from the collector	" "
J_{pE}	=	ion emission from the emitter	" "
J_{eE}	=	net forward electron current at the emitter sheath-plasma interface (computed from boundary conditions)	" "
J_{eC}	=	net forward electron current at the collector sheath-plasma interface	" "
J_{iE}	=	net forward ion current at the emitter sheath-plasma interface	" "
J_{iC}	=	net forward ion current at the collector sheath-plasma interface	" "
$J_e(o)$	=	net forward electron current at the emitter sheath-plasma interface (computed from transport equations)	" "
J	=	net current through the diode	" "
k	=	Boltzmann's constant	(erg/°K)
$k_e T$	=	electron thermal diffusivity	-dimensionless-
$k_i T$	=	ion thermal diffusivity	-dimensionless-
K_e	=	electron thermal conductivity	(watt/cm °K)
m_e	=	electron mass	(gm)
m_i	=	cesium ion mass	(gm)
n_e	=	electron density	(cm ⁻³)
n_i	=	ion density	"
n	=	charged particle density	"
n_E	=	charged particle density at the emitter sheath-plasma interface	"
n_C	=	charged particle density at the collector sheath-plasma interface	"

n_a	=	neutral atom density	(cm ⁻³)
P	=	cesium gas pressure	(torr)
			(degrees/cm ²)
q_e	=	electron kinetic energy flux	(watt/cm ²)
Q_e	=	total electron energy flux	" "
Q_{eE}	=	electron energy flux at the emitter sheath-plasma interface (calculated from the boundary conditions)	" "
Q_{eC}	=	electron energy flux at the collector sheath-plasma interface	" "
$Q_e(o)$	=	electron energy flux at the emitter sheath-plasma interface (calculated from transport equations)	" "
R_{ie}	=	ion drag term	(volt/cm ⁵)
S	=	ion source coefficient	(cm ³ /sec)
T_e	=	electron temperature	(°K)
T_i	=	ion temperature	"
T_a	=	neutral gas temperature	"
T_{eE}	=	electron temperature at the emitter sheath-plasma interface	"
T_{eC}	=	electron temperature at collector sheath-plasma interface	"
T_E	=	emitter temperature	"
T_C	=	collector temperature	"
T_R	=	cesium reservoir temperature	"
U_+	=	initial energy of ions entering the emitter sheath from the plasma	(erg)
U_-	=	initial energy of electrons entering the emitter sheath from the emitter	(erg)
v_e	=	electron thermal velocity	(cm/sec)
v'_i	=	effective ion velocity at the sheath-plasma interface	" "
V	=	electron potential	(volts)
V_E	=	emitter sheath height	"
V_C	=	collector sheath height	"
V_p	=	plasma drop	"
V_d	=	arc drop	"

V_B	=	double sheath barrier height	(volts)
V_O	=	output voltage	"
V_i	=	cesium ionization potential	"
x	=	spatial coordinate in interelectrode gap	(cm)
α	=	recombination coefficient	(cm ⁶ /sec)
Γ_e	=	electron particle flux (= J_e/e)	(1/cm ² -sec)
Γ_i	=	ion particle flux (= J_i/e)	" "
Γ_{eE}	=	electron particle flux at emitter sheath-plasma interface (= J_{eE}/e)	" "
Γ_{eC}	=	electron particle flux at collector sheath-plasma interface (= J_{eC}/e)	" "
Γ_{iE}	=	ion particle flux at emitter sheath-plasma interface (= J_{iE}/e)	" "
Γ_{iC}	=	ion particle flux at collector sheath-plasma interface (= J_{iC}/e)	" "
ζ_E	=	emitter sheath attenuation factor	-dimensionless-
ζ_C	=	collector sheath attenuation factor	-dimensionless-
μ_e	=	electron mobility	(cm ² /volt-sec)
μ_i	=	ion mobility	" " "
ϕ_E	=	field-free emitter work function	(volts)
ϕ'_E	=	effective emitter work function	"
ϕ_C	=	collector work function	"

ALGORITHM

The ignited mode thermionic converter is described by a set of five transport equations and their associated boundary conditions. The transport equations are those derived by Wilkins and Gyftopoulos. Charge neutrality in the plasma is assumed, so that $n_e = n_i$. The particle fluxes are

$$\vec{\Gamma}_e = -\mu_e \left[\frac{k}{e} T_e \nabla n + n \vec{E} + (1 + k_e^T) n \frac{k}{e} \nabla T_e \right] \quad (1)$$

for the electrons, and

$$\vec{\Gamma}_i = -\mu_i \left[\frac{k}{e} T_i \nabla n - n \vec{E} + (1 + k_i^T) n \frac{k}{e} \nabla T_i - \vec{R}_{ie} \right] \quad (2)$$

for the ions, where the ion drag term $\vec{R}_{ie}$ is

$$\vec{R}_{ie} = -g_1 \left(\frac{k}{e} T_e \nabla n + n \vec{E} \right) + (g_2 - g_1) n \frac{k}{e} \nabla T_e. \quad (3)$$

Here g_1 and g_2 are functions of the electron collision frequency and are evaluated by Wilkins and Gyftopoulos.

The kinetic energy flux $\vec{q}_e$ is given by

$$\vec{q}_e = \vec{\Gamma}_e (5/2 + k_e^T) k T_e - K_e \nabla T_e. \quad (4)$$

The total energy flux is just

$$\vec{Q}_e = \vec{q}_e + \vec{\Gamma}_e V, \quad (5)$$

where V is the electron potential. The ion source equation gives

$$\nabla \cdot \vec{\Gamma}_e = \nabla \cdot \vec{\Gamma}_i = S n_a n - \alpha n^3, \quad (6)$$

where n_a is the neutral particle density and S and α are the ionization and recombination coefficients, respectively. Completing the set of differential equations is

$$\nabla \cdot \vec{q}_e = -\vec{\Gamma}_e \cdot \vec{E} - V_i \nabla \cdot \vec{\Gamma}_e + \Delta E_{\text{rad}} + \Delta E_{\text{elas}}. \quad (7)$$

Here ΔE_{rad} and ΔE_{elas} represent energy transfer by radiation loss and elastic collisions, respectively. These terms will be ignored in this analysis. Combining Eqns. (7) and (5) gives

$$\nabla \cdot \vec{Q}_e = (V - V_i) \nabla \cdot \vec{F}_e. \quad (8)$$

In this analysis, all equations will be solved in one dimension only.

The boundary conditions at the emitter for an electron retaining sheath are

$$\Gamma_{eE} = \frac{J_E}{e} - \frac{n_E v_e(0)}{4} \exp\left(-\frac{eV_E}{kT_{eE}}\right), \quad (9)$$

$$\Gamma_{iE} = \frac{J_{pE}}{e} \exp\left(-\frac{eV_E}{kT_E}\right) - \frac{n_E v_i'(0)}{2}, \quad (10)$$

and

$$Q_{eE} = \frac{J_E}{e} (2 kT_E + V_E + V_P) - \left(\frac{J_E}{e} - \Gamma_{eE}\right) (2 kT_{eE} + V_E + V_P). \quad (11)$$

Here the zero of electron potential is taken at the collector edge, so that V_P represents the change in the electron potential in going from the collector to the emitter. The ion emission from the emitter, J_{pE} will be neglected. The ion velocity $v_i'(0)$ is the ion Bohm velocity evaluated at the emitter edge.

The collector boundary conditions are

$$\Gamma_{eC} = \frac{n_C v_e(d)}{4} \exp\left(-\frac{eV_C}{kT_{eC}}\right) - \frac{J_C}{e}, \quad (12)$$

$$\Gamma_{iC} = \frac{n_C v_i'(d)}{2}, \quad (13)$$

and

$$Q_{eC} = \left(\Gamma_{eC} + \frac{J_C}{e}\right) (2 kT_{eC} + V_C) - \frac{J_C}{e} (2 kT_C + V_C). \quad (14)$$

In order to treat either the Schottky effect or a double sheath barrier at the emitter, which both modify J_E , the electric field at the emitter must be evaluated. Solving Laplace's equation in the emitter sheath results in the McKeown equation:

$$\begin{aligned} E(0)^2 - E_p^2 = 8\pi e \left\{ \sqrt{\frac{2 m_i V_E}{e}} \left[(-\Gamma_i E) f\left(\frac{U_+}{V_E}\right) \right. \right. \\ \left. \left. - \frac{nk T_e E}{e} \left[1 - \exp\left(-\frac{eV_E}{kT_e E}\right) \right] - \frac{J_E}{e} \sqrt{\frac{m_e}{m_i}} f\left(\frac{U_-}{V_E}\right) \right] \right\} \end{aligned} \quad (15)$$

$$\text{where } f(x) = \sqrt{1+x} - \sqrt{x}. \quad (16)$$

The terms U_+ and U_- represent the initial energies of ions arriving from the plasma and emitted electrons, respectively.

The final equation necessary for the solution of the problem is the conservation of current

$$\frac{J}{e} = \Gamma_e - \Gamma_i. \quad (17)$$

Preparing to integrate the equations in one dimension, Eqs. (1), (2), (4), (6), and (7) must be solved explicitly for

$\frac{dJ_e}{dx}$, $\frac{dT_e}{dx}$, $\frac{dn}{dx}$, $\frac{dV}{dx}$, and $\frac{dQ_e}{dx}$. Eq. (6) gives

$$\frac{dJ_e}{dx} = e (S \dot{n}_a n - \alpha n^3). \quad (18)$$

Combining (4) and (5) gives

$$Q_e = \Gamma_e [(5/2 + k_e^T) k T_e + V] - K_e \frac{dT_e}{dx}. \quad (19)$$

Solving for $\frac{dT_e}{dx}$ yields

$$\frac{dT_e}{dx} = \frac{J_e [(5/2 + k_e^T)kT_e + V] - Q_e}{K_e} . \quad (20)$$

Eqs. (1) and (2) can be used to eliminate E , giving

$$\frac{dn}{dx} = \frac{-\left[\frac{\Gamma_e}{\mu_e} + \frac{\Gamma_i}{\mu_i} + (1 + k_e^T) n \frac{k}{e} \frac{dT_e}{dx} + (1 + k_i^T) n \frac{k}{e} \frac{dT_i}{dx} - R_{ie}\right]}{\frac{k}{e} (T_e + T_i)} . \quad (21)$$

Using Eq. (17) to eliminate Γ_i and rewriting gives

$$\begin{aligned} \frac{dn}{dx} = - \left[\frac{J_e}{e} \left(\frac{1}{\mu_e} + \frac{1}{\mu_i} \right) - \frac{J}{e} \frac{1}{\mu_i} + (1 + k_e^T) n \frac{k}{e} \frac{dT_e}{dx} \right. \\ \left. + (1 + k_i^T) n \frac{k}{e} \frac{dT_i}{dx} - R_{ie} \right] / \frac{k}{e} (T_e + T_i) \end{aligned} \quad (22)$$

Solving Eq. (1) for E yields

$$\frac{dV}{dx} = E = - \left[\frac{J_e}{e} \frac{1}{\mu_e n} + \frac{kT_e}{e} \frac{1}{n} \frac{dn}{dx} + (1 + k_e^T) \frac{k}{e} \frac{dT_e}{dx} \right] . \quad (23)$$

Finally, (8) gives

$$\frac{dQ_e}{dx} = (V - V_i) \frac{dJ_e}{dx} . \quad (24)$$

The coefficients S and α in Eq. (18) are evaluated as functions of T_e and n based on the results of Norcross and Stone. The ion temperature T_i is assumed to be equal to the neutral gas temperature, which varies linearly between the electrode temperatures. Thus,

$$T_i = T_E + (T_C - T_E) \frac{x}{d} , \quad (25)$$

and

$$\frac{dT_i}{dx} = \frac{T_C - T_E}{d} . \quad (26)$$

The neutral density n_a is given by the ideal gas law;

$$P = n_a k T_a + n k T_i + n k T_e , \quad (27)$$

which can be rewritten as

$$n_a = \frac{P}{k T_i} - n \left(1 + \frac{T_e}{T_i} \right). \quad (28)$$

Here the relationship $T_i = T_a$ has been used.

The ion drag term R_{ie} is found by using Eqs. (3) and (1) to give

$$R_{ie} = g_1 \left(\frac{J_e}{e \mu_e} + k_e^T n \frac{k}{e} \frac{dT_e}{dx} \right) + g_2 n \frac{k}{e} \frac{dT_e}{dx} . \quad (29)$$

The electron transport coefficients μ_e , k_e and k_e^T are evaluated using the results of Stoenescu and Heinicke, for Nighan's best guess elastic collision cross section. The coefficients μ_i , k_i^T , g_1 , and g_2 are evaluated according to the formulation of Wilkins and Gyftopoulos, using a cross section of $1.0 \times 10^{-13} \text{ cm}^2$ for the ions and $3.5 \times 10^{-14} \text{ cm}^2$ for the electrons.

Eqs. (18), (20), (22), (23), and (24) are integrated using a standard fourth-order Runge-Kutta algorithm, using a step size of $d/50$.

II. COMPUTATIONAL ALGORITHM

The computational model operates by specifying a value for J , the output current density, which specifies a position on the volt-ampere characteristic. The output voltage, V_o , is the value to be calculated.

Values are also specified for the emitter temperature T_E , the collector temperature T_C , the reservoir temperature T_R , the cesiated emitter work function ϕ_E , the collector work function ϕ_C , and the interelectrode spacing d .

The saturation and back-emission current densities are calculated by the Richardson-Dushman equation:

$$J_R = 120 T_E^2 \exp \left(- \frac{\phi_E}{kT_E} \right), \quad (30)$$

and

$$J_C = 120 T_C^2 \exp \left(- \frac{\phi_C}{kT_C} \right). \quad (31)$$

The gas pressure P is calculated from the cesium reservoir temperature by

$$P = \frac{2.45 \times 10^8}{\sqrt{T_R}} \exp \left(- \frac{8910}{T_R} \right), \quad (32)$$

which is an empirical formula.

The system of equations is solved using the shooting method. This method involves guessing those values which are unknown in the boundary conditions at one side, integrating over to the other side using a standard stepping technique, and iterating on the unknown values until the boundary conditions at the far side are satisfied within a specified degree of accuracy. This method is useful when the differential equations to be integrated are strongly nonlinear. In this model, integration is begun at the collector edge and proceeds toward the emitter.

The values to be guessed are n_C and T_{eC} . The iteration on T_{eC} is rested within that for n_C .

To begin propagating the equations across the gap, values of parameters at the collector edge are calculated first. The ion and electron velocities at the collector edge are calculated:

$$v_e(d) = \sqrt{\frac{8k T_{eC}}{\pi m_e}}, \quad (33)$$

and

$$v_i'(d) = \sqrt{\frac{8k(T_C + T_{eC})}{\pi m_i}}. \quad (34)$$

The collector ion current is given by Eq. (13),

$$J_{iC} = \frac{en_C v_i'(d)}{2}. \quad (35)$$

The collector electron current is now found from Eq. (17),

$$J_{eC} = J + J_{iC}. \quad (36)$$

A value for the collector sheath barrier factor is also required.

This is defined to be

$$\zeta_C \equiv \exp \left(- \frac{eV_C}{kT_{eC}} \right), \quad (37)$$

and using Eqn. (12) gives

$$\zeta_C \equiv \frac{4 (J_{eC} + J_C)}{en_C v_e(d)} \quad (38)$$

Thus, the collector sheath is

$$V_C = kT_{eC} \ln(1/\zeta_C). \quad (39)$$

The energy flux carried by electrons is given by Eq. (14), which can be rewritten for the collector edge as

$$Q_{eC} = J_{eC} (2kT_{eC} + V_C) + J_C 2k(T_{eC} - T_C). \quad (40)$$

Values have now been either found or guessed for all parameters at the collector side. Values of n_C , T_{eC} are guessed and J_{eC} and Q_{eC} are calculated. The electron potential is taken to be zero at the collector edge. Numerical integration of the differential equations can now proceed.

At the end of the integration, values are available for $J_e(0)$, T_{eE} , n_E , $V(0)(=V_p)$, and $Q_e(0)$ at emitter edge. The emitter boundary conditions are now solved.

The ion and electron velocities at the emitter side are found by

$$v_i'(0) = \sqrt{\frac{8k(T_E + T_{eE})}{\pi m_i}} , \quad (41)$$

and

$$v_e(0) = \sqrt{\frac{8k \cdot T_{eE}}{\pi m_e}} . \quad (42)$$

The ion flux is found using Eq. (10);

$$J_{iE} = - \frac{en_E v_i'(0)}{2} . \quad (43)$$

Eqns. (17) gives

$$J_{eE} = J + J_{iE} . \quad (44)$$

A value for J_E is now guessed. The value of J_E will be iterated in order to solve either the case of a double sheath barrier or Schottky modification of J_E .

Defining

$$\zeta_E \equiv \exp \left(- \frac{eV_E}{kT_{eE}} \right) , \quad (45)$$

and using Eq. (9) gives

$$\zeta_E \equiv \frac{4(J_E - J_{eE})}{en_e v_e(0)} . \quad (46)$$

The emitter sheath is given by

$$V_E = \frac{kT_{eE}}{e} \ln \left(\frac{1}{\zeta_E} \right) . \quad (47)$$

The electric field at the emitter, $E(0)$, is evaluated using Eq. (15), with

$$U_+ = 3/2 k(T_E + T_{eE}) \quad (48)$$

$$\text{and } U_- = 3/2 kT_E. \quad (49)$$

The value of E_p in Eq. (15) comes from evaluation of Eq. (23). All quantities in the right hand side of Eq. (15) are first converted to Gaussian units, which results in a value for $E(0)$ in statvolts/cm. This value is then converted to the practical units of volt/cm.

For the case of a double sheath barrier, J_E is iteratively adjusted by the secant method to make $E^2(0) = 0$ in Eq. (48). The sheath barrier height V_B is found by

$$V_B = kT_E \ln \left(\frac{J_R}{J_E} \right). \quad (50)$$

If the current J is too high for the existence of a double sheath barrier, this procedure will find a negative value for V_B . In this case, a procedure is used to evaluate the Schottky effect. This procedure is similar to that just described, except that a J_E is found using a false position method that will make

$$\Delta J_E \equiv J_E - J_R \exp \left(\frac{4.4\sqrt{E(0)}}{T_E} \right) = 0, \quad (51)$$

where $E(0)$ is again calculated with Eq. (15). The energy flux Q_{eE} is now found using Eq. (11).

$$Q_{eE} = J_E 2k(T_E - T_{eE}) + J_{eE} (2k T_{eE} + V_E + V_P). \quad (52)$$

Where J_{eE} was obtained from Eq. (44) and $J_e(0)$ comes from the numerical integration of Eq. (18).

Two functions are formed which are the bases of iteration on T_{eC} and n_C . The first of these is

$$F(T_{eC}) = Q_{eE} - Q_e(0), \quad (53)$$

where Q_{eE} comes from Eq. (52) and $Q_e(0)$ is obtained from the numerical integration of Eq. (24). The second function is

$$F(n_C) = J_{eE} - J_e(0), \quad (54)$$

where J_{eE} was obtained from Eq. (44) and $J_e(0)$ comes from the numerical integration of Eq. (18).

The value of T_{eC} must be adjusted to make $F(T_{eC})$ small. In general, $F(T_{eC})$ will be positive for values of T_{eC} which are too large and negative for T_{eC} too small. This is complicated by the fact that for values of n_C and T_{eC} which are much larger than the converged values the integration of $n(x)$ results in a negative value before reaching the emitter and therefore cannot proceed. This is handled by assigning $F(T_{eC})$ a positive default value when $n(x)$ is less than zero. The value of T_{eC} is adjusted in order to find two non-default values for $F(T_{eC})$ which are of opposite sign. The solution of T_{eC} is then found by using the secant method.

The iterative solution of n_C , which has the T_{eC} iteration nested inside of it, proceeds in a much more straight forward way. The secant method is used to find the value of n_C which will make $F(n_C)$ zero. The parameter $F(n_C)$ is always evaluated after T_{eC} has converged. This process will finally lead to a simultaneous solution for T_{eC} and n_C .

It should be noted that a problem occurs if the order of the nested iterations is changed. For certain values of T_{eC} , no possible adjustment of n_C will result in $F(n_C) = 0$.

Upon convergence, the output voltage is calculated. The effective emitter work function ϕ_E' is given by

$$\phi_E' = \phi_E + V_B \quad (55)$$

in the case of a double sheath, and by

$$\phi_E' = \phi_E - kT_E \ln(J_E/J_R) \quad (56)$$

in the Schottky region. The arc drop is given by

$$V_d = V_E - V_C + V_p. \quad (57)$$

Finally the output voltage is calculated;

$$V_o = \phi_E' - \phi_C - V_d. \quad (58)$$

The current J is changed, and the calculation process begins again.

```

1: "M44P 2/23/82":
2: "INCLUDES REVISED BOUNDARY CONDITIONS":
3: "AND RESONANCE RADIATION LOSS":
4: dim P[5],F[5],S[5],Y[5]
5: dim P[7],C[7],D[7],G[7],H[7],I[7],J[7]
6: dim G[7],R[7],U[7],V[7],W[7],Z[7]
7: dim E[31],K[31],L[31],M[31]
8: prt "ELECTRON-ATOM CROSS SECTION"
9: ent "ENTER NIGHAN (1) OR KARULE (2)",P
10: if B=2:prt "KARULE'S THEORY":spc 3:gto +5
11: if B#1:gto -2
12: if 1.B[-],C[-],D[-],G[-],H[-],I[-],J[-],G[-],R[-],U[-],V[-],W[-],Z[-]
13: prt "NIGHAN'S BEST GUESS":spc 3
14: gto +2
15: if 15.B[-],C[-],D[-],G[-],H[-],I[-],J[-],G[-],R[-],U[-],V[-],W[-],Z[-]
16: if 2.E[-],K[-],L[-],M[-]
17: ldk 3
18: "DATA ENTRY":
19: ent "TE".r0,"TC".r1,"TR".r2
20: fxd 0
21: prt "TE".r0,"TC".r1,"TR".r2
22: ent "OE".r3,"OC".r4
23: fxd 3
24: prt "OE".r3,"OC".r4
25: ent "d(mils)".r5
26: fxd 1:prt "d(mils)".r5
27: ent "AE/AP".r59,"1-RE".r60,"AC/AP".r61,"1-RC".r62
28: prt "AE/AP".r59,"1-RE".r60,"AC/AP".r61,"1-RC".r62
29: ent J,"Jinc".0:prt "J".J,"Jinc".0:spc 5
30: flt 5
31: "BEGIN":
32: "INITIAL COMPUTATIONS":
33: r5=2.54e-3/D
34: 120r0r0exp(-11605*r3/r0)}r6
35: 120r1r1exp(-11605*r4/r1)}r7
36: 2.45e8/\r2-exp(-8910/r2)}r8
37: 1333*r8/P
38: 1.6022e-19/E:8.617e-5/K
39: r59r60/r11:r61r62/r14
40: "GUESS":
41: 1.2r0/r12
42: \((8+1.3807e-16*r12/((9.1095e-28)))r57
43: 4*(J/r14+r7)/Er57exp(-1)/r9
44: ent "TEC".r12,"NC".r9
45: ent "TEC".r12,"NC".r9
46: .05r9/r56:.5r9/r67
47: 0/r55/r71:sfg 7
48: "AGAIN":
49: "NC LOOP":
50: "NC1":sfg 1:0/r69:gto "NC3"
51: "NC2":if r71#0:abs(r42/r71):r66
52: -9/r10:r42:r43
53: -9-99(r42/r56):r9
54: "NC3":r59+1:r59:if r59>20:prt "Max N iter":stp
55: "TEC LOOP":0/r70:cfg 9
56: if r59>2:r12+r81(r9-r10)/r12
57: r59=2:100/r54:gto "TEC3"
58: "TEC2":if r55=0 and r40=444:abs(r40/r55):r64

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56: "TEC3":r12-r11:-40-r41
57: r12=sgn(r40)*r54-r12
58: sfg=1
59: "TEC3":r70+1:r70:if r70>20:prt "Max T iter":sto
60: "SOLVE COLLECTOR SIDE BOUNDARY CONDITIONS":
61: \((4-1.381e-16+r12/(1.661e-24+133.2))/r15
62: \((8-1.381e-16-r12/(3.1416*9.1095e-28))/r16
63: r61Er9r15/2)r17
64: J+r17)r18
65: 4(r18/r14+r7)/Er9r16)U
66: if U<0 or U>1:prt "Vc less than 0":stp
67: Kr12ln(1/U))r19
68: r18(2Kr12+r19)+r14r7+2K(r12-r1))r20
69: r18)Y[1]:r12)Y[2]:r9)Y[3]:0)Y[4]:r20)Y[5]
70: -D/50)H:D)X:0)M
71: "INTEGRATE DIFFERENTIAL EQUATIONS":
72: "R":
73: RUNGE1)R
74: if R=1:goto "NEXT"
75: if Y[3]<=0:444)r40:sfg 9:goto "Z"
76: if Y[2]<=100:-333)r40:sfg 9:goto "Z"
77: 'S'(Y[2],Y[3]))S
78: 'ALPHA'(Y[2],Y[3]))A
79: r0+(r1-r0)X/D)r53
80: P/(1.381e-16+r53)-Y[3](1+Y[2]/r53))Q
81: 2-Q/'PART'(Y[2]))r86
82: 4r86*exp(-1.42/(K+Y[2]))r87
83: 1.72e-14r87*.4/\D)r88
84: 'EMOB'(Y[3],Y[2],r53,0)r21
85: 'KTE'(Y[3],Y[2],r53,0)r23
86: 'COND'(Y[3],Y[2],r53,0)r22
87: 'IMOB'(Y[3],Y[2],r53,0)r24
88: 'KTI'(Y[3],Y[2],r53,0)r25
89: E(Sr86Y[3]-AY[3]^3))F[1]
90: (Y[1](2.5+r23)KY[2]+Y[4])-Y[5])/r22)F[2]
91: -(Y[1]/E*(1/r21+1/r24)-J/Er24+(1+r23)Y[3]KF[2]+(1+r25)Y[3]K(r1-r0)/D):r5
92: r54/K(Y[2]+r53))F[3]
93: -(Y[1]/EY[3]r21+KY[2]F[3]/Y[3]+(1+r23)KF[2]))F[4]
94: (Y[4]-3.89)F[1]-r88)F[5]
95: goto "R"
96: "NEXT":
97: if X>0:0)M:goto "R"
98: "SOLVE EMITTER SIDE BOUNDARY CONDITIONS":
99: Y[1]:r51:Y[2]:T:Y[3]:r46:Y[4]:r49:Y[5]:r50
100: F[4]:r68
101: \((4-1.381e-16+T/(1.661e-24+133.2))/r26
102: \((8-1.381e-16+T/(3.1416*9.1095e-28))/r27
103: -r59+Er46r26/2)r28
104: J+r28)r29
105: 100(r29-r51):r42
106: "BKNEE":
107: (1+.0002sgn(r29))+r29/r11)r30
108: "JE1":sfg 3:0)r76:goto "JE3"
109: "JE2":r30)r31:r34)r35
110: (1-.0001sgn(r29))+r29/r11)r30
111: "JE3":r76+1:r76:if r76>30:prt "Max JE iter":stp
112: r70ln(r5/r30):r36
113: 6:r31
114: 4(r30-r29/r11)/Er46r27:Z:if Z>1 or Z<0:444:r40:goto "OSAT"
115: r12=sgn(r40)*r31
116: -30D'(r33,r36,r0,T,r5,r31,r46,r38):r34

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120.  if a0=(r14)<.5:goto "OUT1"
121.  if flag1:goto "UE2"
122.  r30=(r30-r31)*r34/(r34-r35)*r32
123.  r30*r31:r34)r35:r32)r30:goto "UE3"
124.  "OUT1":if r36>=0:goto "OUT2"
125.  "OSAT":sfg 4:0)r76
126.  "JS1":(1+.0001sgn(r29))r29/r11)r30)r31:37)W:goto "JS3"
127.  "JS2":.9Er46r27/4+r29/r11)r30)r32:38)W
128.  "JS3":r76+1)r76:if r76>999:prt "Max Js iter":stp
129.  0)r91
130.  4(r30-r29/r11)/Er46r27)Z
131.  KTln(1/Z)r33
132.  ESOD(r33.0.r0.T.r30.r91.r46.r68)r34
133.  r6=exp(4.4+sgn(r34)*abs(r34)'.25/r0)r48
134.  r30-r48)rW
135.  if w=38 and r37r38>0:444)r40:goto "Z"
136.  if abs(rW)<1e-5*r30:goto "OUT2"
137.  if w=37:goto "JS2"
138.  if w=38:47)W:goto +3
139.  if r47r38>0:r30)r32:r47)r38:goto +2
140.  if r47r37>0:r30)r31:r47)r37
141.  (r31r38-r32r37)/(r38-r37)r30
142.  goto "JS3"
143.  "OUT2":
144.  r11r30*2K(r0-T)+r29(2KT+r33+r49)r39
145.  100(r39-r50)r40
146.  "Z":flt 3:fxd 2:dsp r12.10r40.r9.10r42
147.  if r70>10:prt r12.r40.r9.r42
148.  if flg9:0)r65
149.  if flg2:cfg 2:goto "TEC2"
150.  if flg6:goto +2
151.  goto "NEW T"
152.  if r65=0:goto +3
153.  if (r40-r41)(r12-r13)>0:goto "NEW T"
154.  goto "T2B"
155.  if r40r41>0:goto "T2B"
156.  if r40#444 and r40#-333:goto +3
157.  r64/3)r64
158.  r13-sgn(r41)r64)r12:goto "TEC3"
159.  if r41#444 and r41#-333:goto "NEW T"
160.  r64/3)r64
161.  goto "T2B"
162.  "NEW T":(r13r40-r12r41)/(r40-r41)C:cfg 6
163.  if abs((C-r12)/C)<1e-5:goto +2
164.  r12)r13:r40)r41:C)r12:goto "TEC3"
165.  (r40-r41)/(r12-r13)r65
166.  (r12-r92)/(r9-r10)r81:r12)r92
167.  if flg1:cfg 1:goto "NC2"
168.  (r10r42-r9r43)/(r42-r43)N
169.  r9/2)r67:N-r9)r75
170.  if abs(r75)>r67:r9+sgn(r75)r67)N
171.  if abs(r75/N)<1e-4:goto +2
172.  r9)r10:r42)r43:N)r9:goto "NC3"
173.  (r42-r43)/(r9-r10)r71
174.  "OUTPUT":
175.  if r36<0:r3-r6ln(r30/r6)r52:goto +2
176.  if r36>=0:r3+r36)r52
177.  r33-r19+r49)r45
178.  r52-r4-r45)V
179.  r10+2K(r0-T)-r29(r52+2KT)+r26(r33+3.89-r52)r77
180.  0)r76

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187: r7: (14-r77)/r75
188: x: 4:prt "Vc",V:fl: 5:fxd 5:prt "TeC",r12,"Vc",r9
189: fxd 2:prt "ELECTRODE POWER WATTS/CM2",r75
190: prt "INPUT POWER WATTS/CM2",r77+14
191: prt "ELECT. EFF. (%)",100r75
192: prt "*****":fxd 3
193: prt "*****":sdc 3
194: if J<=.5 and Q<0:end
195: if V<=0 and Q>0:end
196: J+Q*J
197: if flg7:gto +3
198: r2=Q/r74*(r9-r72)/N
199: r12+Q/r74*(r12-r73)/C
200: r12/r73:r9/r72:Q/r74
201: if not flg7:N:r9:C:r12
202: flg 7:gto "AGAIN"
203: "RANGE":
204: M=1
205: if M=1:gto "PASS1"
206: if M=2:gto "PASS2"
207: if M=3:gto "PASS3"
208: if M=4:gto "PASS4"
209: if M=5:gto "PASS5"
210: "PASS1":ret 1
211: "PASS2":ara Y)S
212: ara F)P
213: for I=1 to 5
214: S[I]+.5H*F[I])Y[I]
215: next I
216: Y+.5H)X
217: ret 1
218: "PASS3":for I=1 to 5
219: P[I]+2*F[I])P[I]
220: S[I]+.5H*F[I])Y[I]
221: next I
222: ret 1
223: "PASS4":for I=1 to 5
224: P[I]+2*F[I])P[I]
225: S[I]+H*F[I])Y[I]
226: next I
227: X+.5H)X
228: ret 1
229: "PASS5":for I=1 to 5
230: S[I]+H/6*(P[I]+F[I])Y[I]
231: next I
232: 0 M
233: ret 0
234: "ENDP":
235: p4/p1)p5
236: p2/500)p6
237: if p5<1:1)p6
238: if p5>6.9999:6.9999:p6
239: frc(p6)p7
240: frc(p5)p8
241: B[p8]+(B[p8+1]-B[p8])p7)p9
242: C[p8]+(C[p8+1]-C[p8])p7)p10
243: D[p8]+(D[p8+1]-D[p8])p7)p11
244: E[p8]+(E[p8+1]-E[p8])p7)p12
245: F[p8]+(F[p8+1]-F[p8])p7)p13
246: G[p8]+(G[p8+1]-G[p8])p7)p14
247: H[p8]+(H[p8+1]-H[p8])p7)p15

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241: c1=-c5(c13-c5(c14-c5p15))*p16
242: 1.5443e15+(p3+p5(p10-p11e5))/p16p1 p17
243: ret p17
244: "KTE":
245: p4/c1)p5
246: p2/500)p6
247: if p6<1:1)p6
248: if p6>6.9999:6.9999)p6
249: frc(p6))p7:int(p6))p8
250: Q[p8]+(Q[p8+1]-Q[p8])p7)p9
251: P[p8]+(P[p8+1]-P[p8])p7)p10
252: U[p8]+(U[p8+1]-U[p8])p7)p11
253: B[p8]+(B[p8+1]-B[p8])p7)p12
254: C[p8]+(C[p8+1]-C[p8])p7)p13
255: D[p8]+(D[p8+1]-D[p8])p7)p14
256: (p9+p5(p10+p5p11))/(p12+p5(p13+p5p14))p15
257: ret p15
258: "COND":
259: p4/c1)p5:p2/500)p6
260: if p6<1:1)p6
261: if p6>6.9999:6.9999)p6
262: frc(p6))p7:int(p6))p8
263: V[p8]+(V[p8+1]-V[p8])p7)p9
264: W[p8]+(W[p8+1]-W[p8])p7)p10
265: Z[p8]+(Z[p8+1]-Z[p8])p7)p11
266: G[p8]+(G[p8+1]-G[p8])p7)p12
267: H[p8]+(H[p8+1]-H[p8])p7)p13
268: I[p8]+(I[p8+1]-I[p8])p7)p14
269: J[p8]+(J[p8+1]-J[p8])p7)p15
270: p12+p5(p13+p5(p14+p5p15))p18
271: 3.146e-12*p2(p9+p5(p10+p5p11))/p18)p18
272: 'EMQB'(p1,p2,p3,p4))p16
273: 'KTE'(p1,p2,p3,p4))p17
274: p18-1.1897e-27*p2p1p17p16(2.5+p17))p18
275: ret p18
276: "IMQB":
277: ln(1.24e4*p3^1.5/\p1))p5
278: 1050.3*p4*1e-13*\p3)p6
279: 1.535e-3*p1p5/p3^1.5)p7
280: p7/p6)p8
281: (1+p8(4.2+2.86p8))/(1+p8(4.24+2.91p8))p9
282: .9*7.243e9*p9/p6)p10
283: ret p10
284: "VTI":
285: ln(1.24e4p3^1.5/\p1))p5
286: 1050.3*p4*1e-13*\p3)p6
287: 1.525e-3*p1p5/p3^1.5)p7
288: p7/p6)p8
289: -(1.18+.135p8)/(1+p8(4.2+2.86p8))p9
290: ret p9
291: "S":log(p2))p3
292: 10p3-119)p4
293: if p4<1:1)p4
294: if p4>30.9999:30.9999)p4
295: int(c4))p5
296: c4-c5)p6
297: L[p5]+(L[p5+1]-L[p5])p6)p7
298: E[p5]+(E[p5+1]-E[p5])p6)p8
299: c7exp(-11505p8/c1))p9
300: ret p9
301: "4.5kA":log(p2))p3

```

```

301: 10-1-10 p4
302: 10 p4/10 p4
303: 10 p4>30.9999:30.9999/p4
304: int(p4)/p5
305: p4-p5/p6
306: M[p5]+(M[p5+1]-M[p5])p6/p7
307: K[p5]+(K[p5+1]-K[p5])p6/p8
308: p7/p2*exp(-(11605/p1)*p8)/p9
309: ret p9
310: "PART":2+8exp(-11605*1.42/p1)/p2
311: p2+18exp(-11605*2.7/p1)+750exp(-11605*3.6/p1)/p2
312: ret p2
313: "ESQD":
314: p8/300/p9
315: p3/p4/p10
316: 11605p1/p3/p11;11605p2/p3/p12
317: p5/1.5022e-19*-(9.1095e-28/(2*1.3807e-16*p3)))/p13
318: 492.2*p6/p5/p14
319: p7/p13/p15
320: p15/2p10*(1+(p11/2p10)-1)/p16
321: exp(-p12)*(1+(p11)-1)/p17
322: p15/2p10*(1-exp(-p10p11))/p18
323: .5p14exp(p12)*(1-exp(-p11))/p19
324: p9p9+16(*1.3807e-16p3p13(p16-p17-p18+p19))/p20
325: 90000p20/p21
326: ret p21
+18994

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0: "IMD4HP RADIAL 4/19/82":
1: "INCLUDES REVISED BOUNDARY CONDITIONS":
2: "AND RESONANCE RADIATION LOSS":
3: dim P[5],F[5],S[5],Y[5]
4: dim B[7],C[7],D[7],G[7],H[7],I[7],J[7]
5: dim Q[7],R[7],U[7],V[7],W[7],Z[7]
6: dim E[31],K[31],L[31],M[31]
7: prt "ELECTRON-ATOM CROSS SECTION"
8: ent "ENTER NIGHAN (1) OR KARULE (2)",B
9: if B=2:prt "KARULE'S THEORY":spc 3;gto +5
10: if B#1:gto -2
11: ldf 1,B[7],C[7],D[7],G[7],H[7],I[7],J[7],Q[7],R[7],U[7],V[7],W[7],Z[7]
12: prt "NIGHAN'S BEST GUESS":spc 3
13: gto +2
14: ldf 15,B[7],C[7],D[7],G[7],H[7],I[7],J[7],Q[7],R[7],U[7],V[7],W[7],Z[7]
15: ldf 2,E[31],K[31],L[31],M[31]
16: ldk 3
17: "DATA ENTRY":
18: ent "TE",r0,"TC",r1,"TR",r2
19: fxd 0
20: prt "TE",r0,"TC",r1,"TR",r2
21: ent "OE",r3,"OC",r4
22: fxd 3
23: prt "OE",r3,"OC",r4
24: ent "emit. rad.(mils)",r5
25: ent "col. rad (mils)",r63
26: fxd 1;prt "em. rad.(mils)",r5,"col. rad.(mils)",r63
27: ent "J@ Emit. (A/cm2)",Y
28: ent "Jinc".0
29: prt "J",Y,"Jinc",Q:spc 5
30: flt 5
31: "BEGIN":
32: "INITIAL COMPUTATIONS":
33: r5=2.54e-3}F:r63=2.54e-3}G
34: 120r0r0exp(-11605*r3/r0)}r6
35: 120r1r1exp(-11605*r4/r1)}r7
36: 2.45e8/\r2+exp(-8910/r2)}r8
37: 1333*r8}P
38: 1.6022e-19}E:8.617e-5}K
39: "GUESS":
40: 1.2r0}r12
41: \ (8*1.3807e-16*r12/(i*9.1095e-28))}r57
42: FY/G}J
43: 4*(J+r7)/Er57exp(-1)}r9
44: dsp "TEC",r12,"NC",r9:stp
45: ent "TEC",r12,"NC",r9
46: .05r9}r66:.5r9}r67
47: 0:r65}r71:sfg 7
48: "AGAIN":
49: "NC LOOP":
50: "NC1":sfg 1:0}r69:gto "NC3"
51: "NC2":if r71#0:abs(r42/r71)}r66
52: r9:r10:r42}r43
53: r9=sgn(r42)r66}r9
54: "NC3":r69+1}r69;if r69>20:prt "Max N iter":stp

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55: "TEC LOOP":0:r70:cfg 9
56: if r69>2:r12-r81(r9-r10):r12
57: "TEC1":cfg 2:100:r64:gto "TEC3"
58: "TEC2":if r65#0 and r40#444:abs(r40/r65):r64
59: "T2B":r12:r13:r40:r41
60: r12-sgn(r40)*r64:r12
61: sfg 6
62: "TEC3":r70+1:r70:if r70>20:prt "Max T iter":stp
63: "SOLVE COLLECTOR SIDE BOUNDARY CONDITIONS":
64: FY/G)J
65: c11 'CSHEATH1'(r9,r12,r1,J,r7,r18,r17,r20,r19)
66: if r19>0:gto +3
67: c11 'CSHEATH2'(r9,r12,r1,J,r7,r18,r17,r20,r19)
68: if r19>0:dsp "NO COLLECTOR SHEATH SOLUTION":stp
69: r18)Y[1]:r12)Y[2]:r9)Y[3]:0)Y[4]:r20)Y[5]
70: (F-G)/50)H:G)R:0)M
71: "INTEGRATE DIFFERENTIAL EQUATIONS":
72: "R":
73: 'RUNGE')r80
74: if r80#1:gto "NEXT"
75: if Y[3]<=0:444)r40:sfg 9:gto "Z"
76: if Y[2]<=100:-333)r40:sfg 9:gto "Z"
77: FY/R)J
78: 'S'(Y[2],Y[3]))S
79: 'ALPHA'(Y[2],Y[3]))A
80: 'TA'(R,F,G,r0,r1,r82))r53
81: P/(1.381e-16*r53)-Y[3](1+Y[2]/r53))0
82: 2*0/'PART'(Y[2]))r86
83: 4r86*exp(-1.42/(K*Y[2]))r87
84: 1.72e-14r87*.4/\(G-F))r88
85: 'EMOB'(Y[3],Y[2],r53,0))r21
86: 'KTE'(Y[3],Y[2],r53,0))r23
87: 'COND'(Y[3],Y[2],r53,0))r22
88: 'IMOB'(Y[3],Y[2],r53,0))r24
89: 'KTI'(Y[3],Y[2],r53,0))r25
90: E(Sr86Y[3]-AY[3]^3)-Y[1]/R)F[1]
91: (Y[1]((2.5+r23)KY[2]+Y[4])-Y[5])/r22)F[2]
92: -(Y[1]/E*(1/r21+1/r24)-J/Er24+(1+r23)Y[3]KF[2]+(1+r25)Y[3]Kr82))r 4
93: r54/K(Y[2]+r53))F[3]
94: -(Y[1]/EY[3]r21+KY[2]F[3]/Y[3]+(1+r23)KF[2]))F[4]
95: (Y[4]-3.89)(F[1]+Y[1]/R)-Y[5]/R-r88)F[5]
96: gto "R"
97: "NEXT":
98: if R>F:0)M:gto "R"
99: "SOLVE EMITTER SIDE BOUNDARY CONDITIONS":
100: Y[1])r51:Y[2])T:Y[3])r46:Y[4])r49:Y[5])r50
101: F[4])r68
102: \((4*1.381e-16*T/(1.661e-24*133.2)))r26
103: \((8*1.381e-16*T/((9.1095e-28)))r27
104: -Er46r26/2)r28
105: J+r28)r29
106: 100(r29-r51))r42
107: "BKNEE":
108: (1+.0002sgn(r29))-r29)r30
109: "JE1":sfg 3:0)r76:gto "JE3"
110: "JE2":r30)r31:r34)r35
111: (1+.0001sgn(r29))-r29)r30
112: "JE3":r76+1)r76:if r76>30:prt "Max JE iter ":stp
113: Kr0ln(r6/r30))r36
114: 0)r91
115: 4(r30-r29)/Er46r27)Z:if Z>1 or Z<0:444)r40:gto "QSAT"

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116: VTln(1/Z)}r33
117: ESQD'(r33,r36,r0,T,r6,r91,r46,r68)}r34
118: if abs(r34)<.5:gto "OUT1"
119: if flg3:cfg 3:gto "JE2"
120: r30-(r30-r31)r34/(r34-r35)}r32
121: r30}r31:r34:r35:r32)r30:gto "JE3"
122: "OUT1":if r36>=0:gto "OUT2"
123: "QSAT":sfg 4:0}r76
124: "JS1":(1+.0001sgn(r29))r29)r30}r31;37}W:gto "JS3"
125: "JS2":.9Er46r27/4+r29)r30}r32;38}W
126: "JS3":r76+1}r76;if r76>999;prt "Max Js iter":stp
127: 0}r91
128: 4(r30-r29)/Er46r27}Z
129: VTln(1/Z)}r33
130: ESQD'(r33,r0,T,r30,r91,r46,r68)}r34
131: r6=exp(4.4*sgn(r34)*abs(r34)^(.25/r0))r48
132: r30-r48}rW
133: if W=38 and r37r38>0:444}r40:gto "Z"
134: if abs(rW)<1e-5>r30 or abs((r31-r32)/r30)<1e-7:gto "OUT2"
135: if W=37:gto "JS2"
136: if W=38:47}W:gto +3
137: if r47r38>0;r30}r32:r47}r38:gto +2
138: if r47r37>0;r30}r31:r47}r37
139: (r31r38-r32r37)/(r38-r37)}r30
140: gto "JS3"
141: "OUT2":
142: r30*2K(r0-T)+r29(2KT+r33+r49)}r39
143: 100(r39-r50)}r40
144: "Z":flt 3:fxd 2;dsp r12,10r40,r9,10r42
145: if r70>10;prt r12,r40,r9,r42
146: if flg9:0}r65
147: if flg2:cfg 2:gto "TEC2"
148: if flg6:gto +2
149: gto "NEW T"
150: if r65=0:gto +3
151: if (r40-r41)(r12-r13)>0:gto "NEW T"
152: gto "T2B"
153: if r40r41>0:gto "T2B"
154: if r40#444 and r40#-333:gto +3
155: r64/3}r64
156: r13-sgn(r41)r64)r12:gto "TEC3"
157: if r41#444 and r41#-333:gto "NEW T"
158: r64/3}r64
159: gto "T2B"
160: "NEW T":(r13r40-r12r41)/(r40-r41)}C;cfg 6
161: if abs((C-r12)/C)<1e-5:gto +2
162: r12}r13:r40}r41:C)r12:gto "TEC3"
163: (r40-r41)/(r12-r13)}r65
164: (r12-r92)/(r9-r10)}r81:r12}r92
165: if flg1:cfg 1:gto "NC2"
166: (r10r42-r9r43)/(r42-r43)}N
167: r9/2}r67:N-r9}r75
168: if abs(r75)>r67:r9+sgn(r75)r67}N
169: if abs(r75/N)<1e-4:gto +2
170: r9}r10:r42:r43:N}r9:gto "NC3"
171: (r42-r43)/(r9-r10)}r71
172: "OUTPUT":
173: if r36<0:r3-Kr0ln(r30/r6)}r52:gto +2
174: if r36>=0:r3+r36}r52
175: r33-r19+r49}r45
176: r52-r4-r45}V

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177: r30=2K(r0-r1)+r29(r52-2H7)+r28(r33+3.89-r52):r77
178: .2=5.67e-12(r04-r14):r83
179: r83+1.08e-6*\r0(r0-r1)/Fln(G/F):r83
180: YV)r78
181: r78/(r83+r77):r79
182: fxd 4:prt "J",Y,"Vo".V;flt 6:fxd 6:prt "TeC",r12,"NC",r9
183: fxd 2:prt "ELECTRODE POWER WATTS/CM2",r78
184: prt "INPUT POWER WATTS/CM2",r77+r83
185: prt "ELECT. EFF. (%)" .100r79
186: prt "*****":fxd 3
187: prt "*****":spc 3
188: if Y<=.5 and Q<0:end
189: if V<=0 and Q>0:end
190: Y+Q)Y
191: if flg7:gto +3
192: r9+Q/r74+(r9-r72)N
193: r12+Q/r74+(r12-r73)C
194: r12)r73;r9)r72:Q)r74
195: if not flg7:N)r9:C)r12
196: cfg 7:gto "AGAIN"
197: "RUNGE":
198: M+1)M
199: if M=1:gto "PASS1"
200: if M=2:gto "PASS2"
201: if M=3:gto "PASS3"
202: if M=4:gto "PASS4"
203: if M=5:gto "PASS5"
204: "PASS1":ret 1
205: "PASS2":for I=1 to 5
206: Y[I])S[I];F[I])P[I]
207: S[I]+.5H*F[I])Y[I]
208: next I
209: R+.5H)R
210: ret 1
211: "PASS3":for I=1 to 5
212: P[I]+2*F[I])P[I]
213: S[I]+.5H*F[I])Y[I]
214: next I
215: ret 1
216: "PASS4":for I=1 to 5
217: P[I]+2*F[I])P[I]
218: S[I]+H*F[I])Y[I]
219: next I
220: R+.5H)R
221: ret 1
222: "PASS5":for I=1 to 5
223: S[I]+H/6*(P[I]+F[I])Y[I]
224: next I
225: 0)M
226: ret 0
227: "EMOB":
228: p4/p1)p5
229: p2/500)p6
230: if p6<1:1)p6
231: if p6>6.9999:6.9999)p6
232: frc(p6)p7
233: int(p6)p8
234: B[p8]+(B[p8+1]-B[p8])p7)p9
235: C[p8]+(C[p8+1]-C[p8])p7)p10
236: D[p8]+(D[p8+1]-D[p8])p7)p11

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237: G[p8]+(G[p8+1]-G[p8])p7)p12
238: H[p8]+(H[p8+1]-H[p8])p7)p13
239: I[p8]+(I[p8+1]-I[p8])p7)p14
240: J[p8]+(J[p8+1]-J[p8])p7)p15
241: p12+p5(p13+p5(p14+p5p15))p16
242: 2.6443e15*(p9+p5(p10+p11p5))/p16p1)p17
243: ret p17
244: "KTE":
245: p4/p1)p5
246: p2/500)p6
247: if p6<1;1)p6
248: if p6>6.9999;6.9999)p6
249: frc(p6)p7:int(p6)p8
250: Q[p8]+(Q[p8+1]-Q[p8])p7)p9
251: R[p8]+(R[p8+1]-R[p8])p7)p10
252: U[p8]+(U[p8+1]-U[p8])p7)p11
253: B[p8]+(B[p8+1]-B[p8])p7)p12
254: C[p8]+(C[p8+1]-C[p8])p7)p13
255: D[p8]+(D[p8+1]-D[p8])p7)p14
256: (p9+p5(p10+p5p11))/(p12+p5(p13+p5p14))p15
257: ret p15
258: "COND":
259: p4/p1)p5;p2/500)p6
260: if p6<1;1)p6
261: if p6>6.9999;6.9999)p6
262: frc(p6)p7:int(p6)p8
263: V[p8]+(V[p8+1]-V[p8])p7)p9
264: W[p8]+(W[p8+1]-W[p8])p7)p10
265: Z[p8]+(Z[p8+1]-Z[p8])p7)p11
266: G[p8]+(G[p8+1]-G[p8])p7)p12
267: H[p8]+(H[p8+1]-H[p8])p7)p13
268: I[p8]+(I[p8+1]-I[p8])p7)p14
269: J[p8]+(J[p8+1]-J[p8])p7)p15
270: p12+p5(p13+p5(p14+p5p15))p18
271: 3.146e-12*p2(p9+p5(p10+p5p11))/p18)p18
272: 'EMOB'(p1,p2,p3,p4)p16
273: 'KTE'(p1,p2,p3,p4)p17
274: p18-1.1897e-27*p2p1p17p16(2.5+p17)p18
275: ret p18
276: "IMOB":
277: ln(1.24e4*p3^1.5/\p1)p5
278: 1050.3*p4*1e-13*\p3)p6
279: 1.535e-3*p1p5/p3^1.5)p7
280: p7/p6)p8
281: (1+p8(4.2+2.86p8))/(1+p8(4.24+2.91p8))p9
282: .9*7.243e9*p9/p6)p10
283: ret p10
284: "KTI":
285: ln(1.24e4p3^1.5/\p1)p5
286: 1050.3*p4*1e-13*\p3)p6
287: 1.535e-3*p1p5/p3^1.5)p7
288: p7/p6)p8
289: -(1.18+.35p8)/(1+p8(4.2+2.86p8))p9
290: ret p9
291: "S":log(p2)p3
292: 10p3-119)p4
293: if p4<1;1)p4
294: if p4>30.9999;30.9999)p4
295: int(p4)p5
296: p4-p5)p6
297: L[p5]+(L[p5+1]-L[p5])p6)p7

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298: E(p5)+(E(p5+1)-E(p5))p6.p6
299: p7exp(-11605p8/p1):p9
300: ret p9
301: "ALPHA":log(p2):p3
302: 10p?-119:p4
303: if p4<1:1:p4
304: if p4>30.9999:30.9999:p4
305: int(p4):p5
306: p4-p5:p6
307: M(p5)+(M(p5+1)-M(p5))p6:p7
308: K(p5)+(K(p5+1)-K(p5))p6:p8
309: p7/p2*exp(-(11605/p1)*p8):p9
310: ret p9
311: "PART":2+8exp(-11605*1.42/p1):p2
312: p2+18exp(-11605*2.7/p1)+750exp(-11605*3.6/p1):p2
313: ret p2
314: "ESQD":
315: p8/300:p9
316: p3/p4:p10
317: 11605p1/p3:p11;11605p2/p3:p12
318: p5/1.6022e-19*\((*9.1095e-28/(2*1.3807e-16*p3))):p13
319: 492.2*p6/p5:p14
320: p7/p13:p15
321: p15/2p10*(\((1+p11/2p10)-1)):p16
322: exp(-p12)*\((1+(p11)-1)/{}):p17
323: p15/2p10*(1-exp(-p10p11)):p18
324: .5p14exp(p12)*(1-exp(-p11)):p19
325: p9p9+16(*1.3807e-16p3p13(p16-p17-p18+p19)):p20
326: 90000p20:p21
327: ret p21
328: "TA":(p4-p5)/ln(p3/p2):p7
329: p2exp(p4ln(p3/p2)/(p4-p5)):p8
330: -p7/p1:p6
331: ret p7ln(p8/p1)
332: "CSHEATH1":Ep1\((1.381e-16*p2/(2(*9.1095e-28))):p10
333: Ep1\((1.381e-16*p2/(1.661e-24*133.2))):p7
334: (p4+p5+p7)/p10:p12
335: if p12<0 or p12>1;-99:p9:ret
336: p10p12-p5:p6
337: Kp2ln(1/p12):p9
338: p6(2Kp2+p9)+p5*2K(p2-p3):p8
339: ret
340: "CSHEATH2":Ep1\((1.381e-16*p2/(2(*9.1095e-28))):p10
341: Ep1\((1.381e-16*p2/(1.661e-24*133.2))):p11
342: (p10-p4)/(p11+p5):p12
343: if p12<0 or p12>0;99:p9:ret
344: p10-p5p12:p6
345: p11p12:p7
346: p6*2Kp2+p5*2K(p2-p3):p8
347: Kp3ln(p12):p9
348: ret
-28345

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THE AUXILIARY ION SOURCE ANALYTICAL MODEL "AIS-1"

I. Theoretical Description

The continuum equations used to describe the auxiliary ion source converter are

$$\vec{\Gamma}_e = -D_e \nabla n - \mu_e n \vec{E}, \quad (1)$$

$$\vec{\Gamma}_i = -D_i \nabla n + \mu_i n \vec{E}, \quad (2)$$

and

$$\nabla \cdot \vec{\Gamma}_e = \nabla \cdot \vec{\Gamma}_i = S, \quad (3)$$

where S is the auxiliary ion source term and, and is constant with space. Eliminating $\vec{E}$ from Eqs. (1) and (2) gives

$$\frac{\vec{\Gamma}_e}{\mu_e} + \frac{\vec{\Gamma}_i}{\mu_i} = - \left(\frac{D_e}{\mu_e} + \frac{D_i}{\mu_i} \right) \nabla n, \quad (4)$$

which can be rewritten as

$$- \frac{\mu_i \vec{\Gamma}_e + \mu_e \vec{\Gamma}_i}{\mu_i D_e + \mu_e D_i} = \nabla n. \quad (5)$$

Writing Eq. (5) in one dimension gives

$$- \frac{(\mu_i \Gamma_e + \mu_e \Gamma_i)}{\mu_i D_e + \mu_e D_i} = \frac{dn}{dx}. \quad (6)$$

Taking the derivative of both sides and ignoring the spatial dependence of the transport coefficients yields

$$\mu_i \frac{d\Gamma_e}{dx} + \mu_e \frac{d\Gamma_i}{dx} = - (\mu_i D_e + \mu_e D_i) \frac{d^2 n}{dx^2}. \quad (7)$$

Using Eq. (3) gives

$$S = - \left(\frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e} \right) \frac{d^2 n}{dx^2} . \quad (8)$$

The ambipolar diffusion coefficient D_a is defined as

$$D_a = \frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e} . \quad (9)$$

Substituting this into Eq. (8), we have

$$S = - D_a \frac{d^2 n}{dx^2} . \quad (10)$$

If S and D_a have no spatial dependence, then this is a second-order linear differential equation with constant coefficients, and can be solved analytically to yield $n(x)$.

Rewriting Eq. (10), we have

$$\frac{d^2 n}{dx^2} = - \frac{S}{D_a} . \quad (11)$$

Integrating and applying boundary conditions gives

$$\frac{dn}{dx} = - \frac{S}{D_a} x + \left. \frac{dn}{dx} \right|_0 . \quad (12)$$

Integrating again yields

$$n(x) = - \frac{Sx^2}{2D_a} + \left(\left. \frac{dn}{dx} \right|_0 \right) x + n_E , \quad (13)$$

where

$$\left. \frac{dn}{dx} \right|_0 = - \frac{(\mu_i \Gamma_{eE} + \mu_e \Gamma_{iE})}{\mu_i D_e + \mu_e D_i} \quad (14)$$

by Eq. (5).

The plasma voltage drop V_p can be found by first solving Eq. (1) for E ;

$$\vec{E} = - \left(\frac{\vec{r}_e}{\mu_e} \frac{1}{n} + \frac{D_e}{\mu_e} \frac{\nabla n}{n} \right). \quad (15)$$

Using the Einstein relations,

$$\mu_e = \frac{eD_e}{kT_e} \quad (16)$$

and

$$\mu_i = \frac{eD_i}{kT_i} \quad (17)$$

where T_e and T_i are the average values of the electron and ion temperatures respectively *

gives

$$\vec{E} = - \left(\frac{\vec{r}_e}{\mu_e} \frac{1}{n} + \frac{kT_e}{e} \frac{\nabla n}{n} \right) = \nabla V. \quad (18)$$

Since $V_p = -V(d)$, Eq. (17) gives

$$\frac{eV_p}{kT_e} = \int_0^d \frac{\Gamma_e}{D_e} \frac{dx}{n(x)} + \int_0^d \frac{dn}{n}. \quad (19)$$

* Note: At the boundaries of the plasma $T_i = T_e$ on the emitter side, and $T_i = T_c$ on the collector side.

$J_s \equiv$ Richardson Current to the Emitter,

and $J_C \equiv$ Collector Back Emission Saturation Current.

Here $a_E = \frac{A_E}{A_P} (1-r_E)$, where $\frac{A_E}{A_P}$ is the ratio of the convoluted emitter surface to the projected surface of the plasma, and r_E is the quantum mechanical electron reflectivity of the emitter surface. Similarly for the collector, $a_C = \frac{A_C}{A_P} (1-r_C)$.

Conservation of current implies that

$$\Gamma_{iC} - \Gamma_{iE} = \Gamma_{eC} - \Gamma_{eE}. \quad (27)$$

Integrating Eq. (3) gives

$$\Gamma_{iC} - \Gamma_{iE} = \Gamma_{eC} - \Gamma_{eE} = Sd. \quad (28)$$

For the DD case, the boundary conditions are

$$\Gamma_{eE} = a_E \left[\frac{J_s}{e} \zeta_E - \frac{n_E v_e}{4} \right], \quad (29)$$

$$\Gamma_{iE} = \frac{A_E}{A_P} \left[\frac{J_i}{e} - \frac{n_E v_i}{4} \zeta_E \right], \quad (30)$$

$$\Gamma_{eC} = a_C \left[\frac{n_C v_e}{4} - J_C \zeta_C \right], \quad (31)$$

and

$$\Gamma_{iC} = \frac{A_C}{A_P} \left(\frac{n_C v_i}{4} \right) \zeta_C; \quad (32)$$

where

$$\zeta_E = \exp \left(- \frac{eV_E}{kT_E} \right). \quad (33)$$

In discussing the boundary conditions, it will be convenient to introduce a shorthand notation:

UU - case of electron-retaining sheaths at both electrodes

DD - case of ion-retaining sheaths at both electrodes

DU - case of an ion-retaining sheath at the emitter and an electron-retaining sheath at the collector

UD - case of an electron-retaining sheath at the emitter and an ion-retaining sheath at the collector.

For the UU case the simplified boundary conditions are

$$\Gamma_{eE} = a_E \left[\frac{J_s}{e} - \left(\frac{n_E v_e}{4} \right) \zeta'_E \right], \quad (20)$$

$$\Gamma_{iE} = \frac{A_E}{A_p} \left[\frac{J_i}{e} \xi'_E - \frac{n_E v_i}{4} \right], \quad (21)$$

$$\Gamma_{eC} = a_C \left[\frac{n_C v_e}{4} \zeta'_C - \frac{J_C}{e} \right], \quad (22)$$

and

$$\Gamma_{iC} = \frac{A_C}{A_p} \frac{n_C v_i}{4}; \quad (23)$$

where $\zeta'_E = \exp \left(- \frac{eV_E}{kT_e} \right), \quad (24)$

$$\zeta'_C = \exp \left(- \frac{eV_C}{kT_e} \right), \quad (25)$$

$$\xi'_E = \exp \left(- \frac{eV_E}{kT_E} \right), \quad (26)$$

and

$$\zeta_C = \exp \left(- \frac{eV_C}{kT_C} \right). \quad (34)$$

For the DU case

$$\Gamma_{eE} = a_E \left[\frac{J_s}{e} \zeta_E - \frac{n_E v_e}{4} \right], \quad (35)$$

$$\Gamma_{iE} = \frac{A_E}{A_p} \left[\frac{J_i}{e} - \left(\frac{n_E v_i}{4} \right) \zeta_E \right], \quad (36)$$

$$\Gamma_{eC} = a_C \left[\left(\frac{n_C v_e}{4} \right) \zeta_C' - \frac{J_C}{e} \right], \quad (37)$$

and

$$\Gamma_{iC} = \frac{A_C}{A_p} \left(\frac{n_C v_i}{4} \right). \quad (38)$$

Finally, the UD case boundary conditions are

$$\Gamma_{eE} = a_E \left[\frac{J_s}{e} - \left(\frac{n_E v_e}{4} \right) \zeta_E' \right], \quad (39)$$

$$\Gamma_{iE} = \frac{A_E}{A_p} \left[\frac{J_i}{e} \zeta_E' - \frac{n_E v_i}{4} \right], \quad (40)$$

$$\Gamma_{eC} = a_C \left[\frac{n_C v_e}{4} - \frac{J_C}{e} \zeta_C \right], \quad (41)$$

and

$$\Gamma_{iC} = \frac{A_C}{A_p} \left(\frac{n_C v_i}{4} \right) \zeta_C. \quad (42)$$

II. Solution of the Equations

Evaluating Eq. (13) for $n(x)$ at $x = d$ and rearranging gives

$$n_E = n_C + \frac{Sd^2}{2D_a} - \left(\frac{dn}{dx} \right)_0 d. \quad (43)$$

Eq. (14) is substituted into Eq. (47) to give

$$n_E = n_C + \frac{Sd^2}{2D_a} + \left(\frac{\mu_i \Gamma_{eE} + \mu_e \Gamma_{iE}}{\mu_i D_e + \mu_e D_i} \right) d. \quad (44)$$

The diffusion coefficients and mobilities can be eliminated using the Einstein relations, Eqs. (16) and (17) and by

$$D_e = \frac{\lambda_e v_e}{3} \quad (45)$$

and

$$D_i = \frac{\lambda_i v_i}{3} \quad (46)$$

Here λ_e is the effective electron mean free path. It is a combination of the electron-neutral atom mean free path λ_{ea} and the coulombic mean free path λ_{ei} :

$$\frac{1}{\lambda_e} = \frac{1}{\lambda_{ea}} + \frac{1}{\lambda_{ei}}. \quad (47)$$

The electron-neutral mean free path is evaluated by

$$\lambda_{ea} = \frac{1}{n_a \sigma_{ea}} \quad (48)$$

where n_a is the neutral atom density and σ_{ea} is the elastic collision cross section. This cross section is a function of electron temperature.

For the coulombic mean free path:

$$\lambda_{ei} = \frac{3\gamma_E (2 kT_e)^{5/2}}{n v_e \pi^{3/2} m_e^{1/2} e^4 \ln \Lambda} \quad (49)$$

where $\gamma_E = .582$ is a parameter which accounts for the effect of electron-electron interaction, and $\ln \Lambda$ is the coulomb logarithm.

Using Eqs. (45), (46), (16), (17), and Eq. (9), Eq. (44) becomes

$$\begin{aligned} n_E = n_C + \frac{Sd^2}{2} \frac{3(\alpha\lambda_e + r\lambda_i)}{v_e \lambda_e \lambda_i (r+1)} \\ + \frac{3d}{(r+1)v_e \lambda_e} \left[r\Gamma_{eE} + \alpha \left(\frac{\lambda_e}{\lambda_i} \right) \Gamma_{iE} \right], \end{aligned} \quad (50)$$

where

$$r = \frac{\langle T_e \rangle}{\langle T_i \rangle} \quad (51)$$

and

$$\alpha = \frac{v_e}{v_i}. \quad (52)$$

Using Eq. (28), Eq. (50) becomes

$$\begin{aligned} n_E = n_C - \frac{Sd^2}{2} \frac{3(\alpha\lambda_e + r\lambda_i)}{v_e \lambda_e \lambda_i (r+1)} \\ + \frac{3d}{(r+1)v_e \lambda_e} \left[r\Gamma_{eC} + \alpha \left(\frac{\lambda_e}{\lambda_i} \right) \Gamma_{iC} \right]. \end{aligned} \quad (53)$$

The solution must now involve the specific boundary conditions (UU, DD, DU, or UD). In general, the boundary conditions for Γ_{eC} and Γ_{iC} are used to eliminate n_C and Γ_{iC} in Eq. (53). Then the boundary condition for Γ_{eE} is used along with Eq. (28) to eliminate n_E . This results in a relation of the form

$$\Gamma_{eC} = f [\zeta_E(\text{or } \zeta_E'), \zeta_C(\text{or } \zeta_C')] \quad (54)$$

At this point it is convenient to introduce the following quantities:

$$E \equiv \frac{3}{4} \left(\frac{r}{r+1} \right) \frac{d}{\lambda_e} \quad (55)$$

and

$$I \equiv \frac{3}{4} \left(\frac{1}{r+1} \right) \frac{d}{\lambda_i} \quad (56)$$

The boundary conditions, together with Eq. (28) can be manipulated to find a relationship between the sheath factors:

$$\zeta_C(\text{or } \zeta_C') = g[\zeta_E(\text{or } \zeta_E')]. \quad (57)$$

This relationship is now used to eliminate ζ_C (or ζ_C') from Eq. (54) and form an equation for ζ_E in terms of only known quantities. These are tested together with the various forms of Eq. (57) for each boundary condition case.

For UU:

$$A \zeta_E' (T_e/T_E + 1) + B \zeta_E' + C = 0 \quad (58)$$

where

$$A = \frac{J_i}{J_s} \frac{A_E}{A_P} \alpha \left(\frac{A_P}{A_C} + I \right) \quad (59)$$

$$B = \frac{eSd}{2J_s} \left(2 \alpha \frac{A_P}{A_C} + \alpha I - E \right) + \frac{e\Gamma_{eC} E}{J_s} \quad (60)$$

$$C = \left[\frac{e(J_{eC} - Sd)}{A_E J_s} - 1 \right] \left[1 + \frac{A_E}{A_P} \left(\frac{A_P}{A_C} + I \right) \right] \quad (61)$$

and

$$\frac{1}{\zeta_C} = \left[\frac{A_E}{A_P} \left(\frac{e\Gamma_{eC}}{a_E} - \frac{eSd}{a_e} - J_s \right) \frac{1}{\zeta_E} + \alpha \left(eSd + \frac{A_E}{A_P} J_i \zeta_E' \right) \right] \frac{A_C}{A_P} \left(\frac{e\Gamma_{eC}}{a_C} + J_C \right) \quad (62)$$

For DD:

$$A \zeta_E^2 + B \zeta_E + C = 0 \quad (63)$$

where

$$A = \frac{A_E}{A_P} I, \quad (64)$$

$$B = \left(\frac{eSd - e\Gamma_{eC}}{J_s} \right) \frac{I}{(1-r_E)} + 1, \quad (65)$$

$$C = \frac{eSd}{2J_s} \left(\frac{2}{a_E} + E - \alpha I \right) - \frac{e\Gamma_{eC}}{J_s} \left(\frac{1}{a_E} + \frac{1}{a_C} + E \right) - \frac{J_C \zeta_C}{J_s} - \alpha I \frac{J_i}{J_s} \frac{A_E}{A_P}, \quad (66)$$

and

$$\zeta_C = \left[\frac{A_C}{A_P} \left(\frac{e\Gamma_{eC}}{a_C} + J_C \zeta_C \right) \right]^{-1} \left[\frac{A_E}{A_P} \frac{(e\Gamma_{eC} - Sd)}{a_E} \zeta_E - J_s \frac{A_E}{A_P} \zeta_E^2 + \alpha \left(Sd + J_i \frac{A_E}{A_P} \right) \right]. \quad (67)$$

For DU

$$A \zeta_E^2 + B \zeta_E + C = 0 \quad (68)$$

where

$$A = \left(\frac{A_E}{A_C} + I \frac{A_E}{A_P} \right), \quad (69)$$

$$B = \frac{1}{(1-r_E)} \frac{e(Sd - r_{eC})}{J_s} \left(\frac{A_P}{A_C} + I \right) + 1, \quad (70)$$

$$C = \frac{eSd}{2J_s} \left(\frac{2}{a_E} + E - \alpha I - 2\alpha \frac{A_P}{A_C} \right) - \frac{e r_{eC}}{J_s} \left(\frac{1}{a_E} + E \right) - \frac{J_i}{J_s} \alpha \left(\frac{A_E}{A_C} + \frac{A_E}{A_P} I \right); \quad (71)$$

and

$$\frac{1}{\zeta_C} = \left[\frac{A_C}{A_P} \left(\frac{e r_{eC}}{a_C} + J_C \right) \right]^{-1} \left[\frac{A_E}{A_P} \left(\frac{e r_{eC}}{a_E} - \frac{eSd}{a_E} \right) \zeta_E - \frac{A_E}{A_P} J_s \zeta_E^2 + \alpha \left(Sd + J_i \frac{A_E}{A_P} \right) \right]. \quad (72)$$

For UD:

$$A \zeta_E^{(T_e/T_E+1)} + B \zeta_E + C = 0 \quad (73)$$

where

$$A = \frac{A_E}{A_P} \alpha I \frac{J_i}{J_s}, \quad (74)$$

$$B = \frac{e r_{eC}}{J_s} \left(\frac{1}{a_C} + E \right) - \frac{eSd}{2J_s} (E - \alpha I) + \frac{J_C}{J_s} \zeta_C, \quad (75)$$

$$C = \left(1 + \frac{A_E}{A_P} I\right) \left(\frac{e}{J_S a_E} - \frac{e S d}{J_S a_E} - 1\right); \quad (76)$$

and

$$\begin{aligned} \zeta_C = & \left[\frac{A_E}{A_P} \left(\frac{e \Gamma_{eC}}{a_E} - \frac{e S d}{a_E} - J_S \right) \frac{1}{\zeta_E} + \alpha S d \right. \\ & \left. + \frac{A_E}{A_P} \alpha J_i \xi_E \right] \left[\frac{A_C}{A_P} \left(\frac{e \Gamma_{eC}}{a_C} + J_C \zeta_C \right) \right]^{-1} \end{aligned} \quad (77)$$

The integral of Eq. (19) can be evaluated to give V_p . The equation gives

$$\frac{e V_p}{k T_e} = \int_0^d \frac{\Gamma_e}{D_e} \frac{dx}{n} - \ln \left(\frac{n_E}{n_C} \right) \quad (78)$$

The first term in the expression can be evaluated. From Eq. (13)

$$n(x) = a + b + c x^2 \quad (79)$$

where

$$a = n_E,$$

$$b = \frac{-(\mu_i \Gamma_{eE} + \mu_e \Gamma_{iE})}{\mu_i D_e + \mu_e D_i},$$

and

$$c = \frac{-S}{2Da}. \quad (80)$$

Solving Eq. (3) in one dimension with S constant gives

$$\Gamma_e = \Gamma_{eE} + Sx. \quad (81)$$

From Eqs. (45) and (47)

$$D_e = \frac{\lambda_e v_e}{3} = \frac{v_e}{3} \left(\frac{1}{\lambda_{ea}} + \frac{1}{\lambda_{ei}} \right)^{-1} \quad (82)$$

Using Eqs. (48) and (49) gives

$$D_e = (\delta n_a + \beta n)^{-1} \quad (83)$$

where $\delta = \frac{3 \sigma_{ea}}{v_e}$ (84)

and $\beta = \frac{\pi^{3/2} m^{1/2} e^4 \ln \Lambda}{\gamma_E (2 k T_e)^{3/2}}$ (85)

If $n_a(x)$ is approximated by a linear function, Eq. (83) becomes

$$D_e = (\delta_0 + \delta_1 x + \beta n)^{-1} \quad (86)$$

where

$$\delta_0 = \frac{3 \sigma_{ea}}{v_e} n_a(0) \quad (87)$$

and

$$\delta_1 = \frac{3 \sigma_{ea}}{v_e} \left(\frac{n_a(d) - n_a(0)}{d} \right) \quad (88)$$

Using Eqs. (81) and (86), the integral becomes

$$\int_0^d \frac{\Gamma_e}{D_e} \frac{dx}{n} = \int_0^d \frac{(\Gamma_{eE} + Sx)(\delta_0 + \delta_1 x + \beta n)}{n} dx \quad (89)$$

This can be rewritten as

$$\int_0^d \frac{\Gamma_e}{D_e} \frac{dx}{n} = \int_0^d \frac{(\Gamma_{eE} + Sx)(\delta_0 + \delta_1 x)}{n} dx + \int_0^d \beta (\Gamma_{eE} + Sx) dx \quad (90)$$

$$= \int_0^d \frac{(\Gamma_{eE} + Sx)(\delta_0 + \delta_1 x)}{n} dx + \beta \Gamma_{eE} d + \frac{\beta S d^2}{2} \quad (91)$$

Using Eq. (79) gives

$$\int_0^d \frac{\Gamma_e}{D_e} \frac{dx}{n} = \int_0^d \frac{(\Gamma_{eE} + Sx)(\delta_0 + \delta_1 x)}{a + b x^2 + c x^2} dx + \beta \Gamma_{eE} d + \beta \frac{Sd^2}{2} \quad (92)$$

This integral is solved to give

$$\begin{aligned} \int_0^d \frac{\Gamma_e}{D_e} \frac{dx}{n} = & \left(\delta_0 \Gamma_{eE} - \frac{\delta_0 S b}{2c} - \frac{\delta_1 \Gamma_{eE} b}{2c} \right. \\ & \left. + \frac{\delta_1 S b^2}{2c^2} - \frac{\delta_1 S a}{c} \right) \frac{1}{\sqrt{b^2 - 4ac}} \\ & \left[\ln \left(\frac{2cd(b + \sqrt{b^2 - 4ac}) + 4ac}{2D(b - \sqrt{b^2 - 4ac}) + 4ac} \right) \right] \\ & + \left(\frac{\delta_0 S}{2c} + \frac{\delta_1 \Gamma_{eE}}{2c} - \frac{\delta_1 S b}{2c^2} \right) \ln \left(1 + \frac{bd + cd^2}{a} \right) \\ & + \frac{\delta_1 S d}{c} + \frac{\beta S d^2}{2} + \beta \Gamma_{eE} d \end{aligned} \quad (93)$$

The values of Γ_{eE} , Γ_{iE} , and n_E in the parameters B and A can be evaluated using the boundary conditions and Eq. (28). This evaluation will depend on the sheath condition.

The electron temperature T_e can be calculated by an energy balance equation. It will be convenient to introduce the notation:

$$V_{E,C}^D = \begin{cases} 0 & \text{if the sheath is "up"} \\ V_{E,C} & \text{if the sheath is "down"} \end{cases}$$

and

$$V_{E,C}^U = \begin{cases} 0 & \text{if the sheath is "down"} \\ V_{E,C} & \text{if the sheath is "up"}. \end{cases}$$

And also

$$J_{S\text{eff}} = \begin{cases} J_S & \text{if emitter sheath is "up"} \\ J_S \zeta_E & \text{if emitter sheath is "down"}, \end{cases}$$

$$J_{C\text{eff}} = \begin{cases} J_C & \text{if collector sheath is "up"} \\ J_C \zeta_C & \text{if collector sheath is "down"}, \end{cases}$$

and

$$J_{i\text{eff}} = \begin{cases} J_i & \text{if emitter sheath is "down"} \\ J_i \zeta_E' & \text{if emitter sheath is "up"}. \end{cases}$$

The energy carried by electrons from the emitter into the plasma is

$$E_1 = a_E J_{S\text{eff}} (\phi_E + V_E^D + 2 \frac{k}{e} T_e). \quad (94)$$

The electron energy lost by the plasma to the emitter is

$$E_2 = (a_E J_{S\text{eff}} - e\Gamma_{eE}) (\phi_E + V_E^D + 2 \frac{k}{e} T_e). \quad (95)$$

The electron energy loss at the collector is

$$E_3 = (e\Gamma_{eC} + a_C J_{C\text{eff}}) (\phi_C + V_C^D + V_0 + 2 \frac{k}{e} T_e). \quad (96)$$

The energy input due to back emission is

$$E_4 = a_C J_{C\text{eff}} (\phi_C + V_C^D + V_0 + 2 \frac{k}{e} T_e) \quad (97)$$

The energy carried by ions from the plasma to the emitter can be written

$$E_5 = \left(\frac{A_E}{A_p} J_{i\text{eff}} - e\Gamma_{iE} \right) \left(\phi_{iE} + V_E^U + 2 \frac{k}{e} T_i(0) \right). \quad (98)$$

The energy input from the emitter due to returning atoms is

$$E_6 = \left(\frac{A_E}{A_p} J_{i\text{eff}} - e\Gamma_{iE} \right) \left(\phi_{iE} - V_i + \phi_E + 2 \frac{k}{e} T_E \right). \quad (99)$$

And that due to emitted ions is

$$E_7 = \frac{A_E}{A_p} J_{i\text{eff}} (\phi_{iE} + V_E^U + 2 \frac{k}{e} T_E). \quad (100)$$

These terms (E_5 , E_6 , and E_7) can be combined to give the net energy gain at the emitter due to ions and atoms:

$$\begin{aligned} E_{iaE} &= \frac{A_E}{A_p} J_{i\text{eff}} (\phi_a + 2 \frac{k}{e} T_E) \\ &\quad - e\Gamma_{iE} (\phi_E - V_i - V_E^U) \\ &\quad (\phi_a = \phi_E + \phi_{iE} - V_i). \end{aligned} \quad (101)$$

Using Eq. (28) this becomes

$$\begin{aligned} E_{iaE} &= \frac{A_E}{A_p} J_{i\text{eff}} (\phi_a + 2 \frac{k}{e} T_E) \\ &\quad - e\Gamma_{iC} (\phi_E - V_i - V_E^U) \\ &\quad + eSd (\phi_E - V_i - V_E^U). \end{aligned} \quad (102)$$

The energy loss at the collector due to ions is

$$E_8 = e\Gamma_{iC} (V_C^U + V_d + \phi_{iE} + 2 \frac{k}{e} T_i(d)) \quad (103)$$

where V_d is the arc drop.

Energy gained at the collector by returning atoms is

$$E_9 = e\Gamma_{iC} (\phi_{iE} + V_d + \phi_C + V_o - V_i + 2 \frac{k}{e} T_C) \quad (104)$$

Eqs. (103) and (104) can be combined to give

$$E_{iaC} = e\Gamma_{iC} (V_o + \phi_C - V_C^U - V_i) . \quad (105)$$

The energy carried into the plasma by the auxiliary ion source current is

$$E_{10} = eSd (V_i + 2 \frac{k}{e} T_i) \quad (106)$$

Combining Eqs. (102), (105), and (106) gives

$$E_{ia} = E_{iaE} + E_{iaC} + E_{10} \quad (107)$$

or

$$\begin{aligned} E_{ia} = & \frac{A_E}{A_p} J_{i\text{eff}} (\phi_a + 2 \frac{k}{e} T_E) \\ & + eSd (\phi_E - V_E^U + 2 \frac{k}{e} T_i) \\ & + e\Gamma_{iC} (V_E^U - V_C^U - V_d). \end{aligned} \quad (108)$$

The total energy gained by the plasma is

$$G = E_1 + E_4 + E_{ia}, \quad (109)$$

and the energy loss is

$$L = E_2 + E_3. \quad (110)$$

The electron temperature T_e is iteratively adjusted until

$$G \approx L. \quad (111)$$

```

1: "AUXILLIARY ION SOURCE W/RECOMB.":
2: dim AS[5],BS[9],CS[5],DS[5],A[6],E[8],M[3],W[3],S[3]
3: if flg5:gto +2
4: fxd 4:ldk 1:sfg 5
5: ent "argon ,xenon,or cesium?".BS
6: if BS="argon":2>K:cfg 8:prt "argon":gto +7
7: if BS="xenon":3>K:cfg 8:prt "xenon":gto +6
8: if BS="cesium":gto -3
9: "K:ent "cesiated emitter?-yes or no".CS
10: if CS="yes":sfg 8:gto +3
11: if CS="no":gto -2
12: cfa 8
13: ent "TE",r1,"TC",r2
14: if K=1:ent "TR",r13
15: if K=2 or K=3:ent "P(torr)",r8
16: if flg8:ent "00",r17
17: if not flg8:ent "0E",r3
18: ent "00",r4
19: if flg8:1.3r1/r13-.628r17+1.6>r3
20: 120r1r1exp(-11605r3/r1)>r18
21: prt "TE",r1,"TC",r2
22: if K=1:prt "TR",r13
23: if K=2 or K=3:prt "P(torr)",r8
24: if flg8:prt "00",r17
25: prt "0E",r3,"Js",r18,"00",r4
26: ent "Sd (A/cm^2)",r30,"Vbias",V,"D(cm)",r7:spc 4
27: prt "Sd (A/cm^2)",r30,"Vbias",V,"D(cm)",r7:spc 4
28: ent "Coulomb Scattering?".AS
29: if AS="yes":prt "Coul. Scat.":spc 2:gto +3
30: if AS="no":gto -2
31: cfg 7:prt "No Coul. Scat.":spc 2:gto +2
32: sfg 7
33: ent "structured electrodes?-yes or no",DS
34: if DS="no":1>A[1]>A[2]>A[3]>A[4]:gto +4
35: if DS="yes":gto -2
36: ent "AE/AP",A[1],"(1-RE)",A[2],"AC/AP",A[3],"(1-RC)",A[4]
37: prt "AE/AP",A[1],"(1-RE)",A[2],"AC/AP",A[3],"(1-RC)",A[4]:spc 4
38: ent "Jmax",r38,"Jint",r37,"Vmin",r40,"Vmax",r39,"Vint",r36
39: fxd 1:sc1 r40 r39,0.r38:xax 0,r36.r40.r39,1:fxd 0:yax 0,r37,0.r38,1:fxc 5
40: "RE PLT":
41: .07>M[1]:1.13>M[2]:.41>M[3]
42: 492>W[1]:270>W[2]:489>W[3]
43: (r1+r2)/2>r9
44: 1333r8/1.38e-16r9>r14
45: M[K]*2.69e19/r14*(600/r9)>r15
46: 1.96e7*(r9/1000)/W[K]>r11
47: 3e15r9/r11*8.616e-5>r61
48: 120r2r2exp(-11605r4/r2)>r51
49: A[1]A[2]A[5]:A[3]A[4]A[6]
50: "INIT":1>r20:-1>F
51: 10>I:5>E
52: r30>r19

```

```

32: r1=r5/r25
33: 0/r41:r42:.9)R:r34
34: r38/1000)r47
35: 0/r32:r32:3)r26:.1)X:cfg 10
36: 2e13)r49:r49:3)r74
37: "S":cfg 1:r5/r9)r0
38: 1.96e7\(.001r5)r10:r10/r11)c12:r12/\(r0+1)M:r12:M
39: c11 'EACRS'
40: 1/r14S[K])r48
41: "NQ1":sfg 12:gto +2
42: "NQ2":r74)r80:r82)r81:1.1r74)r74
43: "NQ3":
44: c11 'RECOM'
45: r30-r45r7:r19:if flg12:r30)r19
46: if flg7:gto +2
47: r48)r6:r61)r16:gto +6
48: ln(1.24e4r5 1.5/\r49)r50
49: 2.47e11r5 2.5/r49r10r50)r44:r48r44/(r44+r48)r6
50: if r=1:r61)r16:gto +3
51: W[K]*.267r9 1.5/r49r50)r59
52: r11r59)r50:r61r60/(r60+r61)r16
53: 3r0r7/4r6(r0+1)E
54: 3r7/4(r0+1)r16I
55: c11 'DU'
56: if (r21>0)(r23>0):1)r32:gto "PL"
57: c11 'DD'
58: if (r21>0)(r23>0):2)r32:gto "PL"
59: c11 'UU'
60: if (r21>0)(r23>0):3)r32:gto "PL"
61: c11 'UD'
62: if (r21>0)(r23>0):4)r32:gto "PL"
63: X-r47)Y:r47/3)r47:gto "S"
64: "PL":
65: c11 'VP'
66: r5/11605*(r27-ln(r26))r29
67: "NQB":r75
68: r75-r74)r82
69: if flg12:cfg 12:gto "NQ2"
70: r74-(r74-r80)r92/(r82-r81)r83
71: if abs((r83-r74)/r83)<.0001:r83)r74:gto +2
72: r82)r81:r74)r80:r83)r74:gto "NQ3"
73: if r32=0:c11 'NBAR'(X,r51)
74: if r32=1 or r32=3:c11 'NBAR'(X/T,r51/T)
75: if r32=2 or r32=4:c11 'NBAR'(X,r51R)
76: r3-r4+r31-r29)Y
77: "TCALC":rnp r32
78: sfg 3:cfg 4:A[3](X/A[6]+r51)/MT)r54:r180)r56:r51)r57:r55)r62:gto -4
79: sfg 3:sfg 4:A[3]R(X/A[6]+r51R)/M)r54:r180)r56:r51R)r57:r55)r62:gto +3
80: cfg 3:cfg 4:A[3](X/A[6]+r51)/MT)r54:r18)r56:r51)r57:7r55)r62:gto -2
81: cfg 3:sfg 4:A[3]R(X/A[6]+r51R)/M)r54:r18)r56:r51R)r57:Zr55)r62
82: c11 'EBAL'(r56,r57,r62)
83: r20(G-L)+r1+r5)r5:dsp "Te",r5,"G-L",G-L
84: if abs(r5-r25)>.0001r5:r5)r25:G-L)F:gto "S"
85: if flg6:V+r30/X)D:gto +2
86: 0)D
87: if not flg10:plt Y-D,X-r54:pen:sfg 10
88: plt Y-D,X-r54.2:pen
89: if r32=r33:gto +5
90: if r32=1:lbl "DU":gto +4
91: if r32=2:lbl "DD":gto +3
92: if r32=3:lbl "UU":gto +2

```



```

13: 151 "UD"
14: r32>r33:plt Y-D,X-r54,1
15: X+r47>X:gt0 "S"
16: "NEW":
17: "END":pen:pen# :end
18: "DD":A[1]I r12/M>A
19: 1-A(X-r19)/A[5]r18>B
20: (r19(2/A[5]+E-I r12)/2-(1/A[6]+1/A[5]+E)X-A[1]r55r12I)/r18>p1
21: "C1":p1-r51R/r18>C
22: (-B+\(BB-4AC))/2A>Q:if Q<0:-69>r21:gt0 +2
23: -r1/11605*ln(Q))r21
24: -M(r19+A[1]r55)+A[1]r18Q^2-Q(X-r19)/A[2])p2
25: if r51=0:-A[4]p2/X>R:gt0 +2
26: (-X/A[4]+\((X/A[4])^2-4A[3]r51p2))/2A[3]r51>R
27: if R<0:-69>r23:gt0 +4
28: R-r34>r41:if sgn(r41)#sgn(r42):(R+r34)/2>R
29: if abs(r41)>.0001R:R>r34:r41>r42:gt0 "C1"
30: -r2/11605*ln(R))r23
31: r21-r23>r31
32: ret
33: "UD":(A[1]r12I/M+1)((X-r19)/A[5]r18-1))C
34: (r19(r12I-E)/2+X(1/A[6]+E))/r18>p1
35: A[1]r55r12I/r18>A
36: "C2":p1+r51R/r18>B
37: if A#0:cll "NM"
38: if A=0:-C/B>S
39: S (r5/r1))Z
40: if S<0:-69>r21:gt0 +2
41: -r5/11605*ln(S))r21
42: -(A[1]((X-r19)/A[5]-r18)/S+M(r19+A[1]r55Z))p2
43: if r51=0:-A[4]p2/X>R:gt0 +2
44: (-X/A[4]+\((X/A[4])^2-4A[3]r51p2))/2A[3]r51>R
45: if R<0:-69>r23:gt0 +4
46: R-r34>r41:if sgn(r41)#sgn(r42):(R+r34)/2>R
47: if abs(r41)>.0001R:R>r34:r41>r42:gt0 "C2"
48: -r2/11605*ln(R))r23
49: -r21-r23>r31
50: ret
51: "DU":A[1](r12I/M+1/A[3])>A
52: A(r19-X)/A[5]r18+1>B
53: (r19(E-r12I+2/A[5]-2M/A[3])/2-X(1/A[5]+E)-A[1]r55(M/A[3]+I r12))/r18>C
54: (-B+\(BB-4AC))/2A>Q:if Q<0:-69>r21:gt0 +2
55: -r1/11605*ln(Q))r21
56: A[3](X/A[6]+r51)/((X-r19)Q/A[2]-A[1]r18Q^2+M(A[1]r55+r19))T
57: if T<0:-69>r23:gt0 +2
58: -r5/11605*ln(T))r23
59: r21+r23>r31
60: ret
61: "UU":(1+A[1](I r12/M+1/A[3]))((X-r19)/A[5]r18-1))C
62: r19(2M/A[3]+r12I-E)/2r18+XE/r18>B
63: A[1]r55(M/A[3]+r12I)/r18>A
64: if A#0:cll "NM"
65: if A=0:-C/B>S
66: S (r5/r1))Z
67: if S<0:-69>r21:gt0 +2
68: -r5/11605*ln(S))r21
69: A[3](X/A[6]+r51)/(A[1]((X-r19)/A[5]-r18)/S+M(r19+A[1]r55Z))T
70: if T<0:-69>r23:gt0 +2
71: -r5/11605*ln(T))r23
72: r23-r21>r31

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173: ret
174: "NM":(-B+\(BB-4AC))/2A>S>p1
175: r5/r1>p2
176: "C3":(AS (p2+1)+BS+C)/(A(p2+1)S p2+B)>p3
177: S-p3>S
178: if abs(S-p1)>.0001S>S>p1:gto "C3"
179: ret
180: "NRAR":(2(abs(o1)/A[6]+p2)(r26+1)+r19(E+r12I)/3)/1.602e-19r10>r49
181: ret
182: "EBAL":A[5]p1(r3+r21flg3+2r1/11605)>E[1]
183: (A[5]p1-(X-r19))(r3+r21flg3+2r5/11605)>E[2]
184: (X+A[6]p2)(r4+r23flg4+Y+2r5/11605)>E[3]
185: A[6]p2(r4+r23flg4+Y+2r2/11605)>E[4]
186: (r54-r19)(-r3+r21(not flg3))>E[5]
187: r54(r4+Y-r23(not flg4))>E[6]
188: r19+2r9/11605>E[7]
189: A[1]p3(2.5+2r1/11605)>E[8]
190: E[1]+E[4]+E[5]+E[6]+E[7]+E[8]>G
191: E[2]+E[3]>L
192: ret
193: "EACRS":if K=1:2e-14>S[1]:ret
194: 3/2>r5/11605>p1
195: if K=3:gto +3
196: if p1<=.71:(4.97p1p1-4.87p1+1.47)*1e-16>S[2]
197: if p1>.71:(2.19p1-1.04)*1e-16>S[2]
198: if p1<=.71:(34.38p1p1-48.82p1+19.33)*1e-16>S[3]
199: if p1>.71:(5.06p1p1-7.19p1+4.55)*1e-16>S[3]
200: ret
201: "VP":
202: if r32=1 or r32=2:4/r10*(r18Q-X/A[6]+r19/A[6])>r70
203: if r32=3 or r32=4:4/r10*(r18-X/A[6]+r19/A[6])/S>r70
204: if r32=1 or r32=3:4/r10*(X/A[6]+r51)/T>r71
205: if r32=2 or r32=4:4/r10*(X/A[6]+r51R)>r71
206: if r32=1 or r32=3:A[3](X/A[6]+r51)/MT>r54
207: if r32=2 or r32=4:A[3]R(X/A[6]+r51R)/M>r54
208: r70/r71>r26
209: r70/1.6022e-19>r70:r71/1.6022e-19>r71
210: -2(E+r12I)r19/r7r7r10/1.6022e-19>r68
211: -4(E(X-r19)+r12I(r54-r19))/r7r10/1.6022e-19>r69
212: 1333r8/(1.38e16+r1)>r72
213: 1333r8/(1.38e16+r2)>r73
214: "INTEGRAL">r27
215: ret
216: "INTEGRAL":
217: 3S[K]r72/r10>p3
218: 3S[K](r73-r72)/r7r10>p4
219: 3r50/2.47e11r5^2.5>p5
220: (X-r19)/1.6022e-19>p8
221: r19/(r7+1.6022e-19)>p9
222: \((r69r69-4r70r68)>p1
223: 1/p1*ln((2r68r7(r69+p1)+4r70r68)/(2r68r7(r69-p1)+4r70r68))>p10
224: p3p8-r69p9p3/2r68-r69p8p4/2r68+p9p4r69r69/2r68r68>p2
225: (p2-r70p9p4/r68)p10>p11
226: p11+p9r7r7p5/2+p8p5r7+p9p4r7/r68>p12
227: p9p3/2r68+p8p4/2r68-r69p9p4/2r68r68>p13
228: ret =13ln(1+(r69r7+r68r7r7)/r70)+p12
229: "RECOM":
230: jmp K
231: cll "CS":ret
232: cll "NG":ret+
233: cll "NG":ret

```

```

234: "CS":2.46e-24(3000/r5) 4.5)r58
235: 1.602e-19*r58*r74)r45
236: ret
237: "NG":if r5<=7500;tn (-22.17-8.54e-4r5):r58
238: if r5>7500;tn (-27.42-1.304e-4r5):r58
239: 1.602e-19*r58r74)r45
240: ret
241: "NQ8":
242: r68 3r7^5/7+r68r68r69r7 5/2+3(r68r68r70+r68r69r69)r7 4/5)p1
243: p1+(6r68r69r70+r69 3)r7^3/4+(r68r70r70+r69r69r70)r7r7:p2
244: p2+3r69r70r70r7/2+r70r70r70)p3
245: ret p3
+4604

```

Flow Chart for Auxiliary Ion Source
Computer Program

APPENDIX 4-C
KNODSEN MODE DIODE PROGRAM (KMD-1)

```

0: 'KNODSEN MODE DIODE PROGRAM (KMD1) - 6/17/82 (Revised 7/1)':
1: ent "TE (K)".T,"TC (K)".r0,"TR (K)".r1
2: fxd 0:pnt "TE",T,"TC".r0,"TR",r1;spc 1
3: ent "OE (eV)".r2,"OC (eV)".r3
4: fxd 3:pnt "OE".r2,"OC".r3;spc 1
5: ent "d (mils)".r4,"Electrode Area (cm2)".r38
6: fxd 2:pnt "d (mils)".r4,"Electrode Area (cm2)".r38;spc 6
7: enp "Effective emissivity",r8
8: ent "Vmax".r30,"Vmin".r31,"Vint",r32,"fxd-V".r33
9: ent "Jmax".r34,"Jint",r35,"fxd-J",r36
10: pclr;sc1 r31,r30,0,r34;pen# 2
11: fxd r33:xax 0,r32,r31,r30,1
12: fxd r36:yax 0,r35,0,r34,1;pen#
13: fxd 6;2.54e-3*r4}D
14: 120*T^2*exp(-11605r2/T)}r5
15: 120*r0^2*exp(-11605r3/r0)}r6
16: T/r0}r7
17: 2.45e8/\r1*exp(-8910/r1)}P
18: if Pr4>1;pnt "Pd (mil-torr)".Pr4;spc 5;dsp "DIODE NOT COLLISIONLESS";s
19: 2.207e-22}M:1.3807e-16}K:9.1095e-28}r14
20: 1.602e-19*1333.3P/\(2{MKr1)}r9
21: r9/(1+2exp(11605(3.89-r2)/T))}r10
22: r5*\((r14/2KT)/1.602e-19}r11
23: r6*\((r14/2Kr0)/1.602e-19}r12
24: r10*\((M/2KT)/1.602e-19}r13
25: r13/r11}B:r12/r11}A;pnt "ION RICHNESS RATIO ",B;spc 5
26: 4.8798\((T/r11)}X
27: D/X}C:1/11605}K
28: "CRITICAL POINT":
29: ln(DDr5/(7.729e-12*T^1.5))}r15
30: 'INT1A'(r15,r15)}r16
31: C-r16}r17:dsp "CP",r15,r17
32: r15+sgn(r17)*.5}r18
33: 'INT1A'(r18,r18)}r16
34: C-r16}r19:dsp "CP",r18,r19
35: if r17r19>0:r19}r17:r18}r15:gto -3
36: (r18r17-r15r19)/(r17-r19)}G
37: 'INT1A'(G,G)}r16
38: C-r16}r20:dsp "CP",G,r20;if abs(r20)<1e-5:gto +4
39: if r17r20>0:r20}r17:G}r15:gto +2
40: if r19r20>0:r20}r19:G}r18
41: gto -5
42: r5exp(-G)-r6-r10}r21
43: KTG+r2-r3}r22:G}r23
44: pen# 2
45: plt r22,r38r21,1:cplt -.33,-.25;lbl "+"
46: (r30+r3-r2)/KT}r28
47: for G=r23 to r28 by .1
48: KTG}Y
49: r2-r3+Y}V
50: r5exp(-G)-r6-r10}J
51: r5exp(-G)(r2+Y+2KT)-r6(r3+2Kr0):Q
52: Q+r10(3.89-r2)+r9-2K(T-r0)+r8*5.67e-12(T^4-r0^4)}Q
53: JV/0}Z
54: plt V,r38J

```

```

55: next G
56: pen;pen#
57: "SATURATION POINT":
58: -10)r15
59: 'INT3B'(0,r15)r16
60: C-r16)r17:dsp "SP",r15,r17
61: r15-sgn(r17)r18
62: 'INT3B'(0,r18)r16
63: C-r16)r19:dsp "SP",r18,r19
64: (r18r17-r15r19)/(r17-r19)G
65: 'INT3B'(0,G)r16
66: C-r16)r20:dsp "SP",G,r20
67: if abs((G-r18)/G)<1e-5:gto +2
68: r18)r15:r19)r17:G)r18:r20)r19:gto -4
69: KTG+r2-r3)r24:G)r25
70: r5-r6exp(r7r25)-r10exp(r25)S
71: pen# 2
72: plt r24,r38S.1;cplt -.33,-.25;lbl "+"
73: (r31+r3-r2)/KT)r29
74: for G=r25 to r29 by -.1
75: KTG)Y
76: r2-r3+Y)V
77: r5-r6exp(r7G)-r10exp(G)J
78: r5(r2+2KT)-r6exp(Gr7)(r3-Y+2Kr0)Q
79: Q+r10exp(G)(3.89-r2-Y)+r9*2K(T-r0)+r8*5.67e-12(T^4-r0^4)Q
80: JV/Q)Z
81: plt V,r38J
82: next G
83: pen;pen#
84: "REGION A":
85: r23/5)E;r23-E/2)U;cfg 1
86: for G=r23-E to 0 by -E
87: U)r15
88: 'INT1A'(r15,G)+'INT2A'(r15,G)r16
89: C-r16)r17:dsp r15,r17
90: r15+.1sgn(r17)r18
91: 'INT1A'(r18,G)+'INT2A'(r18,G)r16
92: C-r16)r19:dsp r18,r19
93: (r18r17-r15r19)/(r17-r19)U
94: 'INT1A'(U,G)+'INT2A'(U,G)r16
95: C-r16)r20:dsp U,r20
96: if abs((U-r18)/U)<1e-5:gto +2
97: r18)r15:r19)r17:U)r18:r20)r19:gto -4
98: r5exp(-U)-r6exp(r7(G-U))-r10J
99: KTG)Y:KTU)H
100: r2-r3+Y)V
101: r5exp(-U)(r2+H+2KT)-r6exp(r7(G-U))(r3+H-Y+2Kr0)Q
102: Q+r10(3.89-r2)+r9*2K(T-r0)+r8*5.67e-12(T^4-r0^4)Q
103: JV/Q)Z;fxd 3;prt 100Z
104: pen# 2;plt V,r38J.1;cplt -.33,-.25;lbl "+";pen#
105: if not flg1;sfg 1:U)L;1.1(G-E)U:gto +2
106: 2U-L)R;U)L:R)U
107: next G
108: "REGION B":
109: for G=-E to r25+E by -E
110: U)r15
111: 'INT1B'(r15,G)+'INT2B'(r15,G)+'INT3B'(r15,G)r16
112: C-r16)r17:dsp r15,r17
113: r15+.1sgn(r17)r18
114: 'INT1B'(r18,G)+'INT2B'(r18,G)+'INT3B'(r18,G)r16
115: C-r16)r19:dsp r18,r19

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116: (r18r17-r15r19)/(r17-r19):U
117: 'INT1E'(U,G)+'INT2E'(U,G)+'INT3E'(U,G)+r1E
118: C-r16)r20:dsp U,r20
119: if abs((U-r18)/U)<1e-5:gto +2
120: r18)r15:r19)r17:U)r18:r20)r19:gto -4
121: r5exp(-U)-r6exp(r7(G-U))-r10exp(G)}J
122: KTG}Y:KTU}H
123: r2-r3+Y}V
124: r5exp(-U)(r2+H+2KT)-r6exp(r7(G-U))(r3+H-Y+2Kr0)}Q
125: Q+r10exp(G)(3.89-r2-Y)+r9*2K(T-r0)+r8*5.67e-12(T^4-r0^4)}Q
126: JV/Q}Z:fxd 3:prt 100Z
127: pen# 2:plt V,r38J.1:cplt -.33-.25:lbl "+":pen#
128: if not flg1:sfg 1:U}L:gto +2
129: 2U-L}R:U}L:R}U
130: next G
131: end
132: "erf":if p1=0:ret 0
133: abs(p1)}p2
134: if p2<.1:gto "2"
135: "1":1/(1+.3275911p2)}p3
136: .254829592}p4:-.284496736}p5;1.421413741}p6
137: -1.453152027}p7;1.061405429}p8
138: 1-(p4p3+p5p3^2+p6p3^3+p7p3^4+p8p3^5)*exp(-p2p2)}p9
139: if p1<0:ret -p9
140: ret p9
141: "2":1}p10}p11}p12
142: (2p2p2)^p10/(p12(2p10+1)}p12)}p13
143: if p13/p11<1e-7:gto +2
144: p10+1}p10;p11+p13}p11:gto -2
145: 2/\{*p2exp(-p2p2)*p11}p9
146: if p1<0:ret -p9
147: ret p9
148: "H":exp(p1)(1+'erf'(\p1))-2\((p1/{}-1}p2;ret p2
149: "G":exp(p1)(1-'erf'(\p1))+2\((p1/{}-1}p2;ret p2
150: "L":exp(p1)'erf'(\p1)-2\((p1/{}-1}p2;ret p2
151: "INT1A":exp(-p1)+Aexp(r7(p2-p1))-Bexp(p1)(1-'erf'(\p1))}p3
152: 1/\p3}p3
153: 2p3\p1}p4:8}p5
154: p4+'SIMPSON'(0..9p1,p5,p1,p2,p3,1)}p6
155: 2p5}p5
156: p4+'SIMPSON'(0..9p1,p5,p1,p2,p3,1)}p7
157: if abs((p7-p6)/p7)>1e-5;p7}p6:gto -2
158: 8}p5
159: p7+'SIMPSON'(.9p1,.9999p1,p5,p1,p2,p3,1)}p8
160: 2p5}p5
161: p7+'SIMPSON'(.9p1,.9999p1,p5,p1,p2,p3,1)}p9
162: if abs((p9-p8)/p9)>1e-5;p9}p8:gto -2
163: ret p9
164: "INT2A":exp(-p1)+Aexp(r7(p2-p1))-Bexp(p1)(1-'erf'(\p1))}p3
165: 1/\p3}p3
166: 2p3\p1-p2}p4:8}p5
167: p4+'SIMPSON'(p2..9p1,p5,p1,p2,p3,2)}p6
168: 2p5}p5
169: p4+'SIMPSON'(p2..9p1,p5,p1,p2,p3,2)}p7
170: if abs((p7-p6)/p7)>1e-5;p7}p6:gto -2
171: 8}p5
172: p7+'SIMPSON'(.9p1,.9999p1,p5,p1,p2,p3,2)}p8
173: 2p5}p5
174: p7+'SIMPSON'(.9p1,.9999p1,p5,p1,p2,p3,2)}p9
175: if abs((p9-p8)/p9)>1e-5;p9}p8:gto -2

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176: ret p9
177: "INT1B":exp(-p1)+4exp(r7(p2-p1))/p3
178: p3-Bexp(p1)(1+'erf'(\(p1-p2))-2'erf'(\p1))/p3
179: 1/\p3}p3
180: 2p3\p1}p4;8}p5
181: p4+'SIMPSQN'(0,.9p1,p5,p1,p2,p3,3)}p6
182: 2p5}p5
183: p4+'SIMPSQN'(0,.9p1,p5,p1,p2,p3,3)}p7
184: if abs((p7-p6)/p7)>1e-5;p7}p6;gto -2
185: 8}p5
186: p7+'SIMPSQN'(.9p1,.9999p1,p5,p1,p2,p3,3)}p8
187: 2p5}p5
188: p7+'SIMPSQN'(.9p1,.9999p1,p5,p1,p2,p3,3)}p9
189: if abs((p9-p8)/p9)>1e-5;p9}p8;gto -2
190: ret p9
191: "INT2B":exp(-p1)+Aexp(r7(p2-p1))/p3
192: p3-Bexp(p1)(1+'erf'(\(p1-p2))-2'erf'(\p1))/p3
193: 1/\p3}p3
194: 2p3\p1}p4;8}p5
195: p4+'SIMPSQN'(0,.9p1,p5,p1,p2,p3,4)}p6
196: 2p5}p5
197: p4+'SIMPSQN'(0,.9p1,p5,p1,p2,p3,4)}p7
198: if abs((p7-p6)/p7)>1e-5;p7}p6;gto -2
199: 8}p5
200: p7+'SIMPSQN'(.9p1,.9999p1,p5,p1,p2,p3,4)}p8
201: 2p5}p5
202: p7+'SIMPSQN'(.9p1,.9999p1,p5,p1,p2,p3,4)}p9
203: if abs((p9-p8)/p9)>1e-5;p9}p8;gto -2
204: ret p9
205: "INT3B":exp(-p1)+Aexp(r7(p2-p1))/p3
206: p3-Bexp(p1)(1+'erf'(\(p1-p2))-2'erf'(\p1))/p3
207: 1/\p3}p3
208: 2p3(\(p1-p2)-\p1)}p4;8}p5
209: p4+'SIMPSQN'(p2,-.1,p5,p1,p2,p3,5)}p6
210: 2p5}p5
211: p4+'SIMPSQN'(p2,-.1,p5,p1,p2,p3,5)}p7
212: if abs((p7-p6)/p7)>1e-5;p7}p6;gto -2
213: 8}p5
214: 0}p10;if p1=0;-.0001}p10
215: p7+'SIMPSQN'(-.1,p10,p5,p1,p2,p3,5)}p8
216: 2p5}p5
217: p7+'SIMPSQN'(-.1,p10,p5,p1,p2,p3,5)}p9
218: if abs((p9-p8)/p9)>1e-5;p9}p8;gto -2
219: ret p9
220: "SIMPSON":if frc(p3/2)#0;dsp "Need even # for N";stp
221: (p2-p1)/p3}p8
222: 'EVAL'(p1,p4,p5,p6,p7)}p9
223: p9+'EVAL'(p2,p4,p5,p6,p7)}p9
224: p9+4'EVAL'(p2-p8,p4,p5,p6,p7)}p9
225: p1}p10;1}p11
226: 4'EVAL'(p10+p8,p4,p5,p6,p7)+2'EVAL'(p10+2p8,p4,p5,p6,p7)+p9;p9
227: p11+2}p11;p10+2p8}p10
228: if p11=p3-1;gto +2
229: gto -3
230: ret p8p9/3
231: "EVAL":'F'(p1,p2,p3,p5)/(p2-p1)}p6
232: 1/(\(p2-p1)*(1-p4p4p6)/(\p6*(1+p4\p6)))p7
233: ret p7
234: "F":if p4=1;gto "F1A"
235: if p4=2;gto "F2A"
236: if p4=3;gto "F1B"

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237: if p4=4:goto "F2B"
238: if p4=5:goto "F3B"
239: prt "INDEX ERROR":sto
240: "F1A":exp(-p2)*'H'(p2-p1)+A/r7*exp(r7(p3-p2))*'G'(r7(p2-p1))}p5
241: p5-B('G'(p2)-'G'(p1))}p5;ret p5
242: "F2A":exp(-p2)*'G'(p2-p1)+A/r7*exp(r7(p3-p2))*'H'(r7(p2-p1))}p5
243: p5-B('G'(p2)-'G'(p1))}p5;ret p5
244: "F1B":exp(-p2)*'H'(p2-p1)+A/r7*exp(r7(p3-p2))*'G'(r7(p2-p1))}p5
245: p5-B(exp(p3)('H'(p2-p3)-'H'(p1-p3))-2('L'(p2)-'L'(p1)))}p5;ret p5
246: "F2B":exp(-p2)*'G'(p2-p1)+A/r7*exp(r7(p3-p2))*'H'(r7(p2-p1))}p5
247: p5-B(exp(p3)('H'(p2-p3)-'H'(p1-p3))-2('L'(p2)-'L'(p1)))}p5;ret p5
248: "F3B":exp(-p2)*'G'(p2-p1)+A/r7*exp(r7(p3-p2))*'H'(r7(p2-p1))}p5
249: p5-B(exp(p3)('H'(p2-p3)-'H'(p1-p3))-2'L'(p2))}p5;ret p5
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