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EMITTER AND COLLECTOR SHEATHS FOR CESIUM THERMIONIC DIODES WITH POLYCRYSTALLINE TUNGSTEN ELECTRODES

by James F. Morris
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

Using electrode temperatures above and below those of thermally ionized plasmas, this analysis estimates sheath properties for polycrystalline tungsten emitters and collectors in cesium thermionic diodes. The fields of these positive-ion sheaths modify particle emissions from the plane electrodes; the sheath voltages affect cesium-arrival, hence contact-ionization rates. Cesium coverage dictates the work function, which is 4.59 volts for a bare electrode. In this study the assigned temperatures run from 1600 to 2400 K for plasmas with 10^{12} and 10^{13} electrons per cubic centimeter. Tabulations give results for diodes putting out from 0 to 1 ampere per square centimeter. Graphic trends of electrode and sheath characteristics also appear. The analysis applies to equilibria and near-equilibria.

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SUMMARY

Cesium plasmas and positive-ion sheaths strongly influence electrode properties in thermionic diodes. To indicate these effects this study uses a previously developed model for collisionless positive-ion sheaths on plane polycrystalline tungsten surfaces partially covered with cesium. At the electrode the sheaths change particle emission with their fields and voltages, and cesium on the tungsten lowers its work function from the 4.59 volts for no adsorption. With all other properties constant the cesium coverage increases electron ejection and decreases ion emission from an initially bare electrode. The cesium comes from thermally ionized plasmas with temperatures below those of the emitters and above those of the collectors. If these systems are at or near equilibrium, they submit satisfactorily to the present theory.

For this analysis the assigned temperatures range from 1600 to 2400 K with 10^{12} or 10^{13} electrons per cubic centimeter in the plasmas. Results for diodes delivering 0, 0.01, 0.1, 0.2, 0.5, and 1.0 ampere per square centimeter appear as a table. Graphs also present electrode and sheath properties. As electrode temperatures rise in these plots, sheath voltages climb; cesium arrival rates grow and pass maxima if the electrodes reach high enough temperatures; cesium surface coverages shrink; net negative current densities entering the plasmas swell; and work functions approach a maximum of 4.59 volts for bare polycrystalline tungsten. In part, these findings reveal how electrodes, sheaths, and plasmas depend on each other in very complex ways.

INTRODUCTION

As references 1 to 5 state, electrode processes in cesium thermionic diodes react to changes in positive-ion sheaths. Surface potentials and particle emissions depend on the voltages and fields of these sheaths. In addition to cesium arrivals from the plasma the electrode receives emitted ions thrown back by the sheath. This higher arrival rate increases the cesium coverage and varies the work function below the value for the bare electrode. The fields of the positive-ion sheaths depress emission barriers and allow more electrons to escape the electrodes. In the present study the results of these effects appear as emitter, collector, and sheath characteristics of thermionic diodes with polycrystalline tungsten electrodes at or near equilibrium with cesium plasmas. Here the work functions of the polycrystalline tungsten surfaces depend on cesium adsorption. The theory relating this dependence and the positive-ion sheath model appears in reference 5.

References 1 to 7 detail the models, theories, and calculation methods for these plane collisionless sheaths between thermally ionized plasmas and emitting electrodes affected by the electric fields of the sheaths. More specifically the sheaths separate Saha plasmas (ref. 8) from Schottky emitters (ref. 9) of electrons (Richardson, Dushman; refs. 10 to 12), ions, and atoms (Saha, Langmuir; ref. 13). Descriptions of the interactions of cesium plasmas with polycrystalline tungsten appear in references 5 and 7. For this work, reference 14 correlates work functions and cesium coverages very well; reference 5 discusses the problems and advantages of reference 14. The good correlation and broader applicability of reference 15 make it basically better for predicting "physical properties of bimetallic adsorption systems," but the precision and ease of handling cesium and polycrystalline tungsten recommend reference 14 for the present studies.

For the present calculations the assigned temperatures fall between 1600 and 2400 K for systems with 10^{12} or 10^{13} electrons per cubic centimeter in the plasmas. Plasma electron, ion, and atom temperatures are identical and range above those of the collectors and below those of the emitters. With all of these variables assigned parametrically and with a bare work function of 4.59 volts, the computing process yields incremental and overall results like those of reference 1. But only sheath voltages, plasma potentials, net negative current densities, cesium arrival rates, surface coverages, and work functions appear in this report. Graphs and tables present these results and estimates of some internal diode characteristics. The latter come from matching net negative current densities from the emitters with those to the collectors.

Because references 1 to 4 treat the sheath model and reference 5 adapts the theory to the system of cesium and polycrystalline tungsten, the present report carries no theoretic section. References 5 and 7 give the calculation method used to obtain the results for this report.

DISCUSSION OF RESULTS

The physical model for this work requires conditions at or near equilibrium that produce essentially no collisions in the sheaths. In references 1 to 3 the implications of these restrictions receive much attention. Reference 5 discusses the limitations of the correlation for work functions and surface coverages of polycrystalline tungsten in cesium. These qualifications add to the property limits mentioned in the INTRODUCTION. Within these confines certain generalizations hold for the results presented in figures 1 to 5. This sequence evolves the sheath effect on the electrode in a manner indicated by the qualitative descriptions in table I. Properties for a 4.59-volt work function also given here typify the results for parametric work functions of references 1 to 3. When these solutions compare with those for work functions affected by adsorption, they reveal how and where cesium loses its influence on electrodes. All these characteristics depend on the positive-ion sheath model of references 1 to 7; therefore, the general correlations given in references 1 to 3 also apply here.

Because the theory remains unchanged, except the method of assigning the work function, the estimates for near-equilibrium thermionic diodes given in table II interpolate those presented in references 2 and 3. As the INTRODUCTION states, these cesium cells result from matching the net current leaving the emitter to that entering the collector. For a specified plasma, figure 5 yields the electrode temperatures. Then this set of plasma and electrode data allows the selection of additional information from the other graphs. Although the net currents balance in these diode approximations, the energy flows do not (ref. 2). But the near-equilibria prevent large energy discrepancies.

Among these findings the most striking effect appears in figure 2. As in the previous references for this model, the positive-ion sheath strongly influences the total cesium arrival rate. If the contribution of ion arrivals is most obvious in figure 2, it is no less important in the other figures. For example, a rather traditional method of analyzing thermionic data assumes that work functions vary only with electrode temperatures for a given cesium plasma. This error stems from the use of atomic instead of total arrivals to determine the electrode coverage; the atomic arrival rate is constant for a particular plasma while the total cesium arrival rate depends on the sheath and electrode properties. And the interdependence often causes great changes in the characteristics of the sheaths and electrodes. Figures 1 to 5 and table II present some conditions for thermionic diodes at or near equilibrium where effects of ionic cesium arrivals at the electrodes obviously demand attention.

The ranges of variables given here suffer limits imposed to maintain solid electrodes, essentially collisionless sheaths, and near-equilibria. Throughout this report and its precursive references, the need for using the sheath model at or near equilibrium recurs. Yet these net negative current densities extend past 10 percent of the random fluxes for plasma electrons. This is not a sanction. The present calculations serve to imply trends from equilibria and to allow comparisons with previous findings. Net current densities below 1 percent of their random plasma counterparts for each particle are more desirable. In fact, the smaller the net transport and the closer all temperatures approach one value, the better the theory applies. As the previous references indicate, departure of this model from equilibrium brings problems of energy conservation, electrode and plasma radiations, collisional randomization, beam interactions, plasma fields, ionization, plasma potentials, and particle distributions and transport. Although calculations show where some of these effects ruin a near-equilibrium estimate, other phenomena may destroy the approximation even more readily. Therefore, no definition attends the phrase "near-equilibrium"; the experimenter best defines this qualification for his conditions.

CONCLUDING REMARKS

The present results for cesium thermionic diodes at or near equilibrium approach actuality. In fact, the equilibria presented here represent an almost rigorous theoretic solution - almost because no sheath is truly without particle interactions. Only the vacuum-diode model comes this close to the reality of thermionic conversion. But practical thermionic converters operate at conditions far from either vacuum or equilibrium. Then what is the value of nearly correct theories for such impractical systems?

First, these models correspond to almost attainable operating points for well-defined, well-controlled diodes. This fact allows theoretic checks on the thermionic converter and its instrumentation. Such insurance is valuable because diode systems are very complex and deceptive compared with their disarmingly simple schematics. Their internal conditions and mechanisms defy measurement and definition. Next, these models hold reasonably well at states slightly removed from equilibria. This adaptability obviates the need and great complication of producing a fully instrumented thermionic converter to test diode data at true equilibrium with high temperatures. And finally, these models enable separation of sheath and plasma transport processes and identification of the onset of nonequilibrium phenomena at conditions near equilibrium. This approximation brings hope for finding the controlling mechanisms in a plasma gap too small for localized instrumentation.

Therefore, cornerstone theories like those for vacuum and equilibrium diodes are important and practical. Such models form bases for understanding and predicting the far more involved systems that produce intense power (ref. 16).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 6, 1968,
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TABLE I. - GENERAL TRENDS FOR ELECTRODE AND SHEATH CHARACTERISTICS IN SYSTEMS WITH CESIUM PLASMAS AND POLYCRYSTALLINE TUNGSTEN SURFACES

	As electrode temperatures T_E increase,	As plasma temperatures T_P increase,	As plasma electron concentrations $N_{e,P}$ increase,	Figure
Sheath voltages ΔV_s -	Increase but stay below 0.4 V plus 20 times the voltage equivalent of the electrode temperatures (K) minus 1600	Increase at low electrode temperatures and decrease at high electrode temperatures	Decrease at low electrode temperatures and increase at high electrode temperatures	1
Atomic cesium arrival rates μ_a -	Remain constant and well below ionic cesium arrival rates except at low electrode temperatures and small sheath voltages	Decrease	Increase	2
Total cesium (atom plus ion) arrival rates μ_{ai} -	Increase and apparently maximize at high electrode temperatures	Decrease	Increase	2
Electrode surface coverage by cesium θ -	Decrease almost exponentially, initially, then more rapidly	Decrease	Increase	3
Electrode work functions φ -	Increase and approach 4.59 V	Increase	Decrease	4
Net negative current densities from emitters J_E -	Increase - very abruptly near equilibrium	Decrease	Increase	5
Net negative current densities from collectors $-J_c$ -	Decrease - very abruptly near equilibrium	Increase as electrode temperatures approach plasma temperatures and decrease at low electrode temperatures	Decrease	5

TABLE II. - APPROXIMATIONS OF INTERNAL CHARACTERISTICS FOR CESIUM THERMIONIC DIODES

WITH POLYCRYSTALLINE TUNGSTEN ELECTRODES

Net negative current density, J, (A)(cm^{-2})	Plasma temperature, T_P, K	Plasma electrode number density, $N_{e,P}$, cm^{-3}	Emitter temperature, T_{EE}, K	Collector temperature, T_{EC}, K	Sheath drop, ΔV_s, V	Cesium atom arrival rate, μ_a, (cm^{-2})(sec^{-1})	Total cesium arrival rate, μ_{ai}, (cm^{-2})(sec^{-1})	Electrode coverage by cesium, θ	Electrode work function, φ, V
0	1700	10^{12}	1700	1700	0.27	2.7×10^{19}	2.7×10^{19}	0.19	3.16
	1800		1800	1800	.73	5.8×10^{18}	7.6×10^{18}	.093	3.82
	1900		1900	1900	.89	1.5	5.5	.049	4.17
	2000		2000	2000	.93	4.2×10^{17}	4.4	.022	4.40
	2000	10^{13}	2000	2000	.66	4.2×10^{19}	5.1×10^{19}	.10	3.74
0.01	1800	10^{12}	1880	----	0.89	5.8×10^{18}	9.8×10^{18}	0.076	3.95
	1800		----	1760	.63	5.8	6.9	.10	3.74
	1900		2015	----	1.03	1.5	8.7	.034	4.29
	1900		----	1795	.65	1.5	4.1	.063	4.04
	2000		2105	----	1.02	4.2×10^{17}	5.6	.013	4.47
	2000		----	1870	.79	4.2	2.7	.026	4.28
0.1	1700	10^{12}	1830	----	0.67	2.7×10^{19}	2.8×10^{19}	0.13	3.50
	1700		----	1675	.19	2.7	2.7	.20	3.09
	1800		2180	----	1.32	5.8×10^{18}	2.9	.036	4.28
	1800		----	1665	.36	5.8	5.9×10^{18}	.13	3.49
	1900		2275	----	1.29	1.5	1.6×10^{19}	.013	4.48
	1900		----	1630	.40	1.5	1.7×10^{18}	.10	3.75
	2000		2315	----	1.14	4.2×10^{17}	6.2	.041	4.56
	2000		----	1610	.40	4.2	7.1×10^{17}	.079	3.93
0.2	2000	10^{13}	2075	----	0.81	4.2×10^{19}	6.0×10^{19}	0.089	3.87
	2000	10^{13}	----	1955	.58	4.2	4.7	.11	3.65
0.5	2000	10^{13}	2205	----	1.00	4.2×10^{19}	8.7×10^{19}	0.065	4.03
	2000	10^{13}	----	1915	.47	4.2	4.5	.12	3.57
1.0	2000	10^{13}	2325	----	1.16	4.2×10^{19}	1.2×10^{20}	0.051	4.15
	2000	10^{13}	----	1880	.38	4.2	4.3×10^{19}	.13	3.49

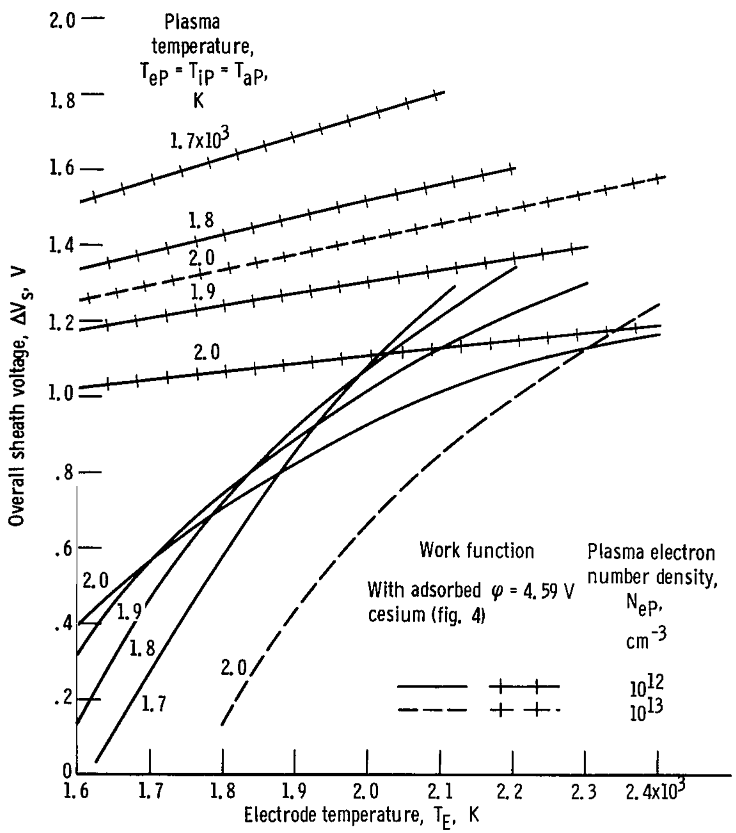


Figure 1. - Potential drops across positive-ion sheaths separating cesium plasmas (Saha, ref. 8) from plane polycrystalline tungsten surfaces (Richardson and Dushman, refs. 10 to 12; Saha and Langmuir, ref. 13; and Schottky, ref. 9).

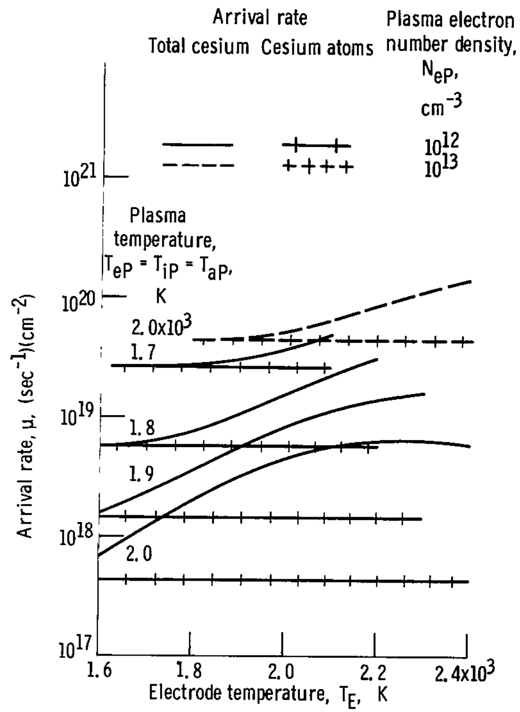


Figure 2. - Cesium arrival rates at polycrystalline tungsten surfaces (work function φ, 4.59 V; Richardson and Dushman, refs. 10 to 12; Saha and Langmuir, ref. 13; and Schottky, ref. 9) with plane positive-ion sheaths in cesium plasmas (Saha, ref. 8).

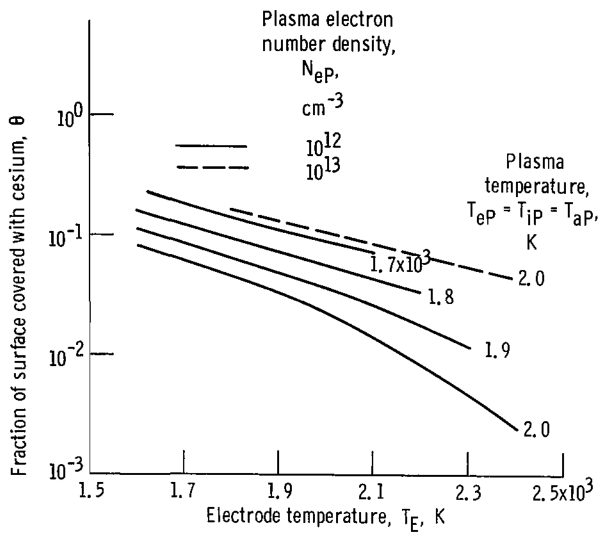


Figure 3. - Fractional coverages by cesium of polycrystalline tungsten surfaces (work function φ, 4.59 V; Richardson and Dushman, refs. 10 to 12; Saha and Langmuir, ref. 13; and Schottky, ref. 9) with plane positive-ion sheaths in cesium plasmas (Saha, ref. 8).

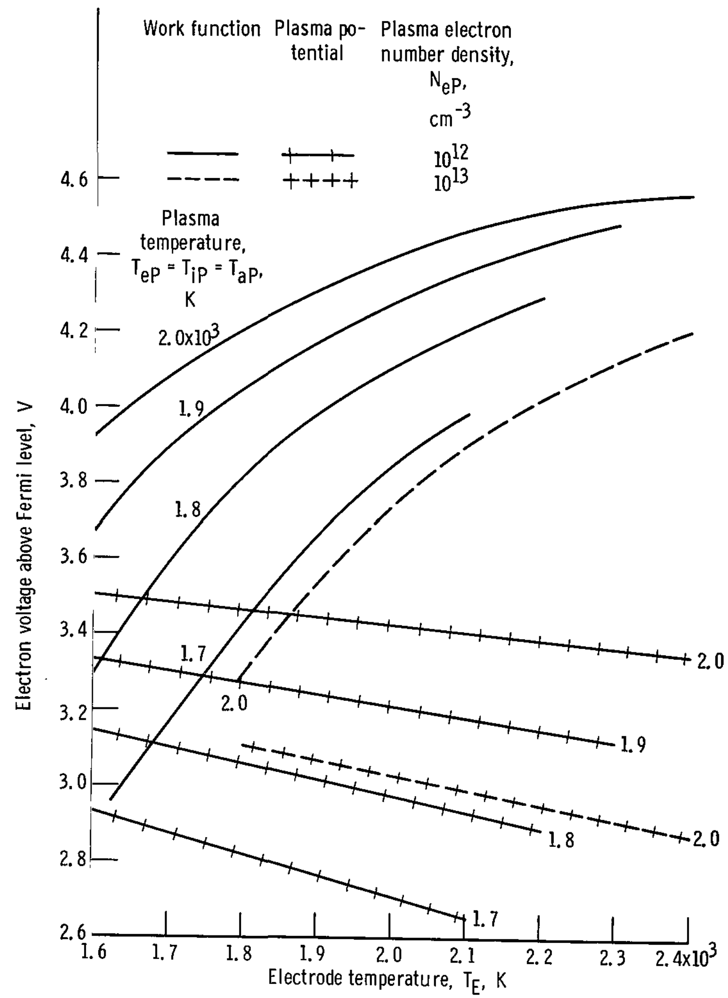
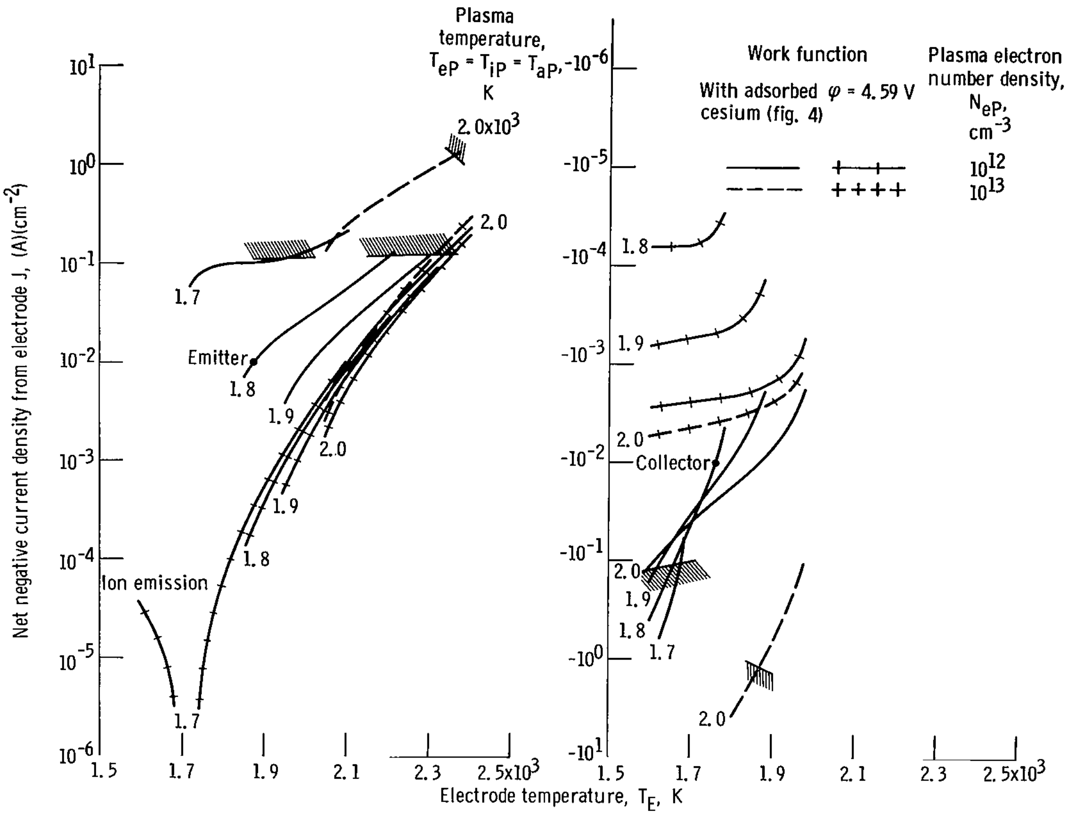


Figure 4. - Work functions and plasma electron potentials for polycrystalline tungsten surfaces (work function φ, 4.59 V; Richardson and Dushman, refs. 10 to 12; Saha and Langmuir, ref. 13; and Schottky, ref. 9) and cesium plasmas (Saha, ref. 8) separated by plane positive-ion sheaths.



(a) Emitters.

(b) Collectors.

Figure 5. - Net negative current densities from polycrystalline tungsten surfaces (work function φ, 4.59 V; Richardson and Dushman, refs. 10 to 12; Saha and Langmuir, ref. 13; and Schottky, ref. 9) and cesium plasmas (Saha, ref. 8) separated by plane positive-ion sheaths. Curves for variable work functions have net current densities greater than 11 percent of random plasma electron current densities on shaded sides of straight lines; for diode, read electrode temperatures for equal absolute values of current densities from positive and negative curves for same plasma conditions.

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