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PERFORMANCES OF THE BETTER METALLIC ELECTRODES IN CESIUM THERMIONIC CONVERTERS

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IN CESIUM THERMIONIC CONVERTERS

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ABSTRACT

    This paper presents outputs for some
cesium diodes having primarily emitters of
highly oriented polycrystalline or single-
crystal 110 tungsten or 0001 rhenium. Power
densities at 10 A/cm^2 or 0.5 V appear as
functions of emitter temperatures and electrode
spacings.

PERHAPS THE MOST PERMISSIVE YEARS for thermionics were the early nineteen sixties. At that time enough research had been done to emphasize the potentials of the cesium diode. And too little product development had occurred to impose pragmatic limitations and system compromises. The thermionic converter had several obvious advantages: As a theoretic heat engine it was nearly peerless. It promised maximum source temperatures and minimum mechanical stresses. No moving parts, just heat in and electricity out. So in addition to nuclear thermionics for space, other applications like solar and fossil-fuel versions got much attention. The plane diode was a prime candidate for practical energy conversion as well as for research work. And its extremely hot single-crystal emitter, almost touching a collector aided by low but highly active concentrations of impurities, poured out power in great densities. In fact, advocated outputs for cesium diodes often rose well above those implied by the '62's on the figures of this paper.

But adaptations of thermionics to nuclear systems for space power demanded results not promises. Within those development programs detailed analyses and life testing soon revealed difficulties: Extreme environmental and operating conditions caused emitter vaporization, columnar growths and whisker extensions across the gap, thermal warping and ratcheting because of expansion differences and cold-working histories, insulator degradation and spalling, seal failures, and transport and reaction of nuclear-fuel components and other impurities. Reducing these phenomena and their fatal effects in cesium diodes meant lower emitter temperatures, wider electrode spacings -- and less power. Meanwhile large edge inefficiencies and a lack of geometric compatibility with compact cylindric heat-transfer systems precluded planar diodes for most applications. This in turn outmoded the ultimate metallic electrodes, single-crystal faces with greatest surface atom densities of refractory metals having the highest work functions. Also improving quality control reduced impurities at the expense of converter performances. And electric and thermal lead losses plus the penalty for conditioning thermionic outputs reduced the importance of power and efficiency maxima compared with increased voltages. Finally insurance against system instabilities like in-core thermal runaway required off-optimum operation. As a cumulative result conservative cesium-diode performances today fall near those of the '72's on the figures.

In the interim, though, questions have been answered, workable compromises have been found -- progress has been made. The plots themselves illustrate the resourcefulness that typifies the thermionic technology: They present outputs for cesium diodes having primarily emitters of highly oriented polycrystalline or single-crystal 110 tungsten or 0001 rhenium. As these results reveal, specially prepared poly-crystalline surfaces now allow practical cylindric converters to approach performance highs established by plane single-crystal electrodes. Contributions like this advance other areas of science and engineering as well as those centered on the cesium diode.

The data selected for the present paper indicate effects of electrode spacings and emitter temperatures on power densities at 10 A/cm^2 or 0.5 V. Related surveys appear in figures 1 of reference 80, 6 to 10 of 82, 4 of 97, 14 to 16 of 105, 4 or 8 of 121, and 10 and 11 of 123 -- all sources as tabulated in the single reference, the literature survey, for the present paper (1).[*] On the plots shown here the works cited also come from that reference, which is obtainable upon request. Perhaps the prose part of that report rationalizes this referential short cut:

Most cesium-diode performance studies reach the Thermionic Conversion Specialist Conferences eventually. If the work fails to appear in the proceedings originally, it often enters in subsequent comparisons. And the accompanying references generally include expansive current, voltage data in agency, contractor, or company publications. So the Thermionic Conversion Specialist Conferences provide extensive cesium-diode output information. To increase the accessibility of this technology the present report indexes and summarizes such contributions for the past decade.

Beginning with the 1963 conference an annotated, chronological tabulation indicates 129 papers containing thermionic-converter results. Lists of diode materials,

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[*]Number in parentheses designates Reference at the end of paper.

geometries, conditions, outputs, and lifetimes, if they were found, accompany the references. Then a simple chemical index for emitters, collectors, and additives directs the reader to appropriate selections. Because these chemical labels are guides not analyses, they lack the complexity of additive product permutations; they are easily recognized elemental or molecular forms. But they identify the materials involved.

With a set of the proceedings for the Thermionic Conversion Conferences and the present report, comprehensive literature surveys on cesium-diode performances are readily available.

This presentation exemplifies the last statement in a rather restricted way: The figures show limited results for some of the better-performing cesium diodes; that qualification explains the prominence of tungsten or rhenium emitters. For the selected converters the tabulations give electrode materials and emitter temperatures (K x 10^{-2} in figures 1 and 2) or electrode spacings (mm in figures 3 and 4). Occasionally temperatures of the collectors and the reservoirs also appear in that order after those of the emitters (T_E, T_C, T_R in K x 10^{-2}).

Either arbitrary criterion, 0.5-V or 10-A/cm^2, tends to obviate very low-voltages for practical outputs -- and generally precludes maxima for power and efficiency. Normally 0.5 V gives better high-temperature, close-spacing performances than 10 A/cm^2. Of course, the product of these two parameters is 5 W/cm^2; so all four figures focus on the region of conservative in-core outputs indicated by the '72's.

Performance curves for three tungsten emitters provide gauges for comparisons in figures 1 and 2; additional perspective comes from inclusions of some data for tantalum, a rather poor thermionic electrode. The plots in figure 3 conform approximately to

$$P \left(\frac{W}{cm^2}\right) = \left(\frac{T_E(K)}{56} - 25.7\right) (1 \pm 0.22).$$

And those in figure 4 diverge rapidly. The nonfaired curves merely tie related data points together.

In general fully optimized outputs form the upper boundaries of the groupings in

figures 3 and 4. As figures 1 and 2 reveal, electrode spacings for maximum power are usually much smaller than the conventional 0.254 mm, particularly for high emitter temperatures. The wider gaps with collector- and reservoir-temperature optima tend toward the lower performances in figures 3 and 4. But the previously mentioned off-optimum operation of in-core diodes reduces their outputs even more. This explains why the '62's fall in the middle of the referenced picture while the '72's are slightly out of it.

As stated before, the conservative performances indicated for contemporary nuclear thermionics are primarily system-dictated: In-core designs restrict electrode materials and collector and reservoir temperatures. In contrast, thermal optima and the improved emitter of reference 107 produce 0.5-V outputs twice as high as the designated '72 levels with the same emitter temperatures, the same electrode gap, and the same mediocre collector. Of course, performances of typical in-core diodes also improve considerably with optimum collector and reservoir temperatures. Incidentally the extensive current, voltage maps behind reference 107 and subsequent results for that same etched-rhenium, niobium diode detail among other things the variation of power densities with collector temperatures. In-core designs often neglect this important effect because of an established performance correlation that applies for essentially one collector temperature. Except for this one major difference these two representations of diode outputs are rather similar. So reference 107 and its follow-on data serve advantageously for zero-time in-core analyses. But for promising auxiliary space power systems the rhenium emitter with optimum cesium and collector temperatures -- and a high-performance collector -- would be allowable as well as desirable. Then cesium-diode outputs at 0.5 V would readily exceed twice those of the '72's on the plots.

If this paper emphasizes emitters, it does so because of the extreme doubt that must attend any evaluation of collectors. As source 123 of reference 1 implies, normally careful cesium-diode processing and operation allow a reasonable test of the emitter. But they in no way assure that the measured effects of the collector represent the true capability of its bulk material. Apparently characteristics of surface contaminants dominate in most collector

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appraisals. Therefore, while data for different
types of collectors appear on the power-density
plots, a generalization on the efficacies of
these electrodes seems premature at this time.

More concretely the figures indicate some
rather diverse performances where quite similar
outputs should be expected. This undoubtedly
is an effect caused by small quantities of
strongly influential impurities. For example,
cesium diodes made with the least oxygen con-
tamination generally give the worst results for
a given pair of metallic electrodes. Today
experts assemble thermionic converters with the
most exacting processes under the best conditions
available; yet impurity differences still creep
in. In a practical sense, any cesium cell is
an additive diode to some degree. Although the
problem causes quality-control difficulties now,
suitable harnessing of additives should lead to
practical thermionic gains in the near future.
This is particularly true for terrestrial and
oceanic nuclear thermionic applications: There
the low rejection temperatures necessary to
prevent excessive back emission from additive-
augmented collectors will not penalize the
systems with prohibitively large radiators as
in designs for space.

So additives pose complex problems in the
fabrication, control, performance, lifetimes,
and system interactions of cesium diodes. And
raising such questions appropriately signals the
end of this paper and the beginning of the
subsequent one by Firooz Rufeh.

REFERENCE

1. James F. Morris, "Cesium-Diode
Performances from the 1963-to-1971 Thermionic
Conversion Specialist Conferences." NASA
TM X-2589, 1972.

SYM/REF 1 NO/DESCRIPTION (Kx10^{-2})

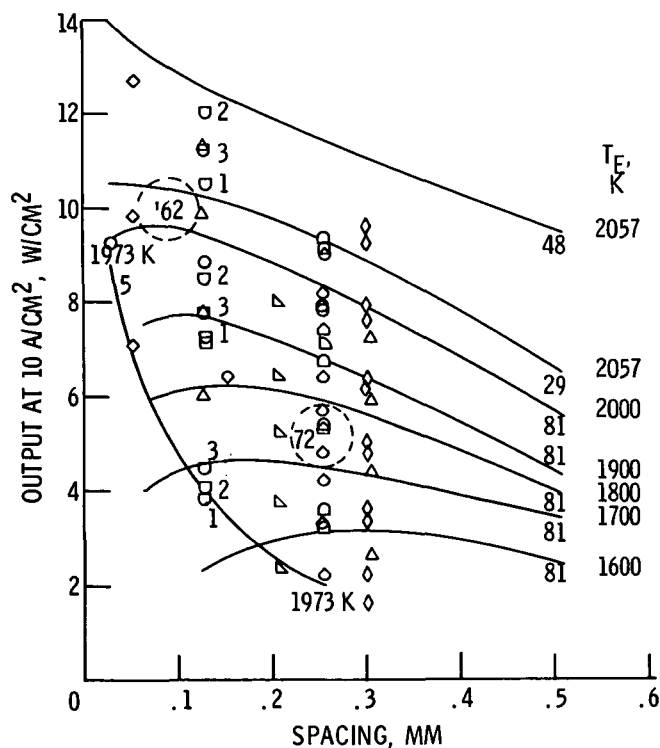| 5	5	Ta, Mo; 19.7, 11.2, Opt.
29	29	W, Nb; 20.6, 10.2, Opt.
48	48	Etched-F⁻W, Nb; 20.6, 9.2, Opt.
81	81	1-xtal-110W, Nb.
o	11	Ru, Ru; 18. Ir, Mo; 18.6.
□	49	Cl⁻W, Mo; 18.5, 8.7, Opt.
◇	58	Etched-Re, Re; 18, 19, 20.
△	65	Re; Re; 16, 17, 18, 19 at 0.305 MM
		18, 19, 20, 21 at 0.127 MM
◁	70	Ave 3 Cl⁻W, Nb; 16, 17, 18, 19, 20
▷	78	Ave 2 W, 25 Re; W; 25 Re at 20.
◁	79	0001 Re, Nb; 16, 17, 18, 19, 20.
◇	87	Cl Re, Cl⁻Re at 18.
◊	106	3 Etched-F⁻W, Nb; 15.7, 16.7, 17.7, 18.7, 19.7, 20.7.
◊	107	Etched Re, Nb; 16, 16.6, 17, 17.6, 18.1, 18.6, 19, 19.6, 20.
△	108	Cl⁻W, Mo; 16, 17, 18, 19.
◻	121	Cl⁻W; 1Nb, 2Ni, 3W at 16.7, 18.7, 20.6.

Figure 1. - Some electrode-gap effects on cesium diode power densities at 10 A/cm^2.

SYM/REF 1 NO/DESCRIPTION (Kx10^{-2})

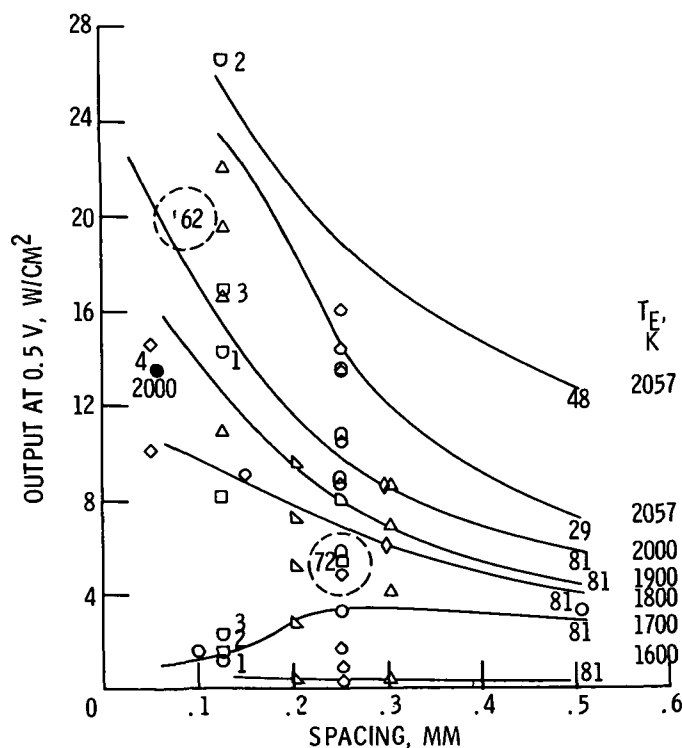| SYM	REF 1 NO	DESCRIPTION (Kx10^{-2})
4	4	Ta, Ta; 20, 9, Opt.
29	29	W, Nb; 20.6, 10.2 Opt.
48	48	Etched-F⁻W, Nb; 20.6, 9.2, Opt.
81	81	1-xtal-110W, Nb.
o	11	Ru, Ru; 1700 K
□	49	Cl⁻W, Mo; 18.5, 8.7, Opt.
◇	58	Etched-Re, Re; 18, 19.
△	65	Re, Re; 16, 17, 18, 19 at 0.305 MM
		18, 19, 20, 21 at 0.128 MM
▷	70	Ave 3 Cl⁻W, Nb; 16, 17, 18, 19, 20.
◁	78	Ave 2 W, 25 Re; W, 25 Re at 20.
◻	79	0001 Re, Nb; 17, 18, 19, 20.
◌	87	Cl⁻Re, Cl⁻Re at 18.
◊	106	3 Etched F⁻W, Nb; 18.2, 19.7.
○	107	Etched-Re, Nb; 16, 16.6, 17, 17.6, 18.1, 18.6, 18, 19.6, 20.
△	108	Cl⁻W, Mo; 17, Opt, opt.
◻	121	Cl⁻W; 1Nb, 2Ni, 3W at 16.7, 18.7.

Figure 2. - Some electrode-gap effects on cesium-diode
power densities at 0.5 V.

SYM/REF 1 NO/DESCRIPTION (GAP IN MM)

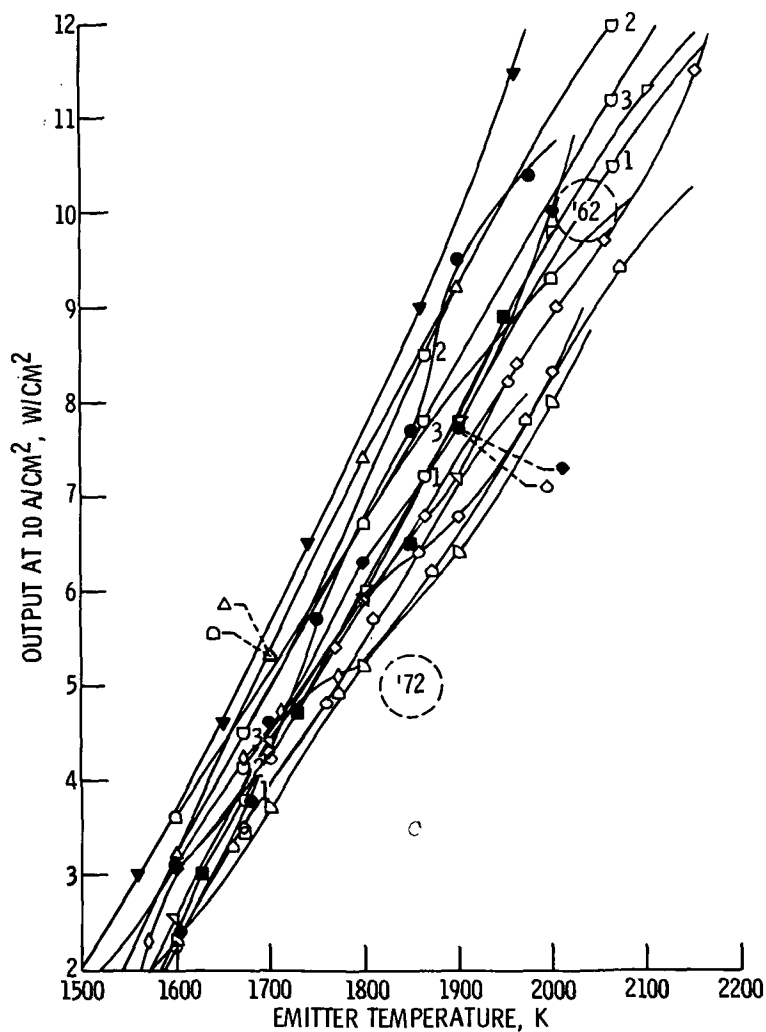| SYM	REF NO	DESCRIPTION (GAP IN MM)
●	22	Re, Mo; Fully opt.
■	22	W, Mo; Fully opt.
◇	29	W, Nb; 0.178, T's opt.
▼	31	Re, Mo; Fully opt.
▽	65	Re, Re; 0.127, T's opt.
◁	65	Re, Re; 0.305, T's opt.
◻	70	Ave polyxtal 110W, Nb; 0.203
⬠	79	0001 Re, Nb; 0.254.
⬤	81	1-xtal-110W, Nb; Fully opt.
○	81	1-xtal-110W, Nb; 0.254.
◊	101	Re, Nb; 0.762 (Hot)
⬠	106	Ave 3 etched-F⁻W, Nb; 0.30, T's opt.
◇	107	Etched-Re, Nb; 0.254
△	108	Cl⁻W, Mo; 0.254, T's opt.
⬠	121	Cl⁻W; 1Nb, 2Ni, 3W: 0.127.

Figure 3. - Some emitter-temperature effects on cesium-diode power densities at 10 A/cm^2

SYM/REF 1 NO/DESCRIPTION (GAP IN MM)

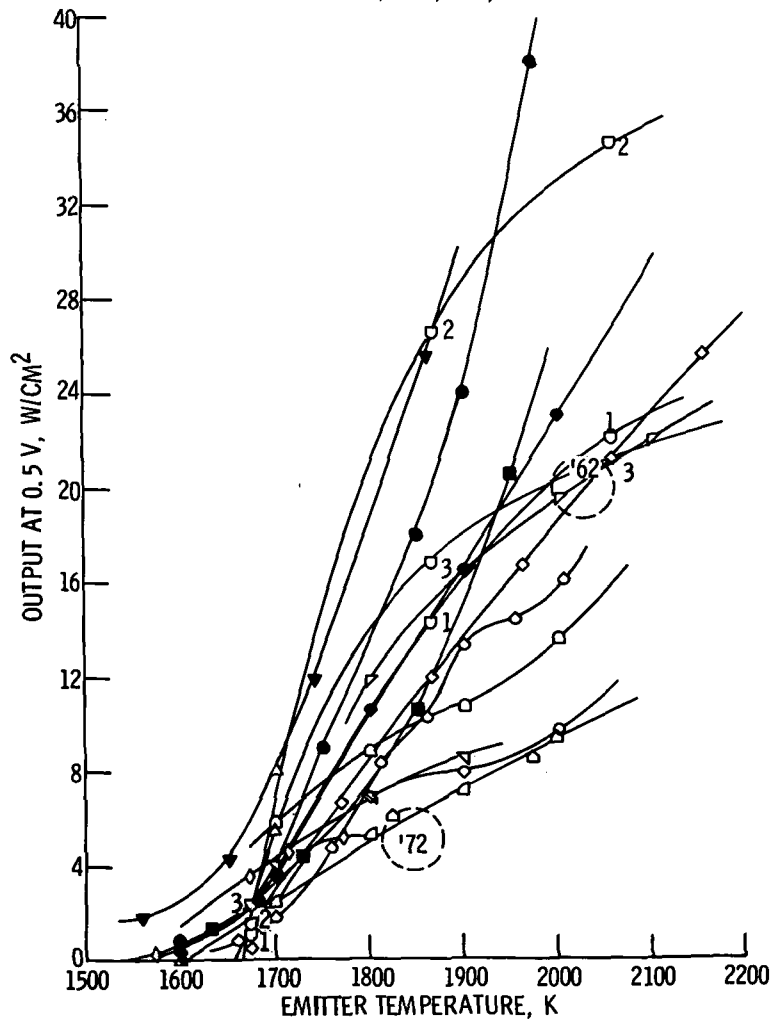|		
●	22	Re, Mo; Fully opt.
■	22	W, Mo; Fully opt.
◇	29	W, Nb; 0.178, T's opt.
▼	31	Re, Mo; Fully opt.
▽	65	Re, Re; 0.127, T's opt.
◁	65	Re, Re; 0.305, T's opt.
◱	70	Ave polyxtal 110W, Nb; 0.203.
◲	79	0001 Re, Nb; 0.254.
●	81	1-xtal-110W, Nb; Fully opt.
○	81	1-xtal-110W, Nb; 0.254.
◊	101	Re, Nb; 0.762 (Hot)
△	106	Ave 3 etched-F¯W, Nb; 0.30, T's opt.
○	107	Etched-Re, Nb; 0.254.
△	108	Cl¯W, Mo; 0.254, T's opt.
◻	121	Cl¯W; 1Nb, 2Ni, 3W: 0.127.

Figure 4. - Some emitter-temperature effects on cesium-diode power densities at 0.5 V.