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SURFACE REQUIREMENTS FOR ELECTROSTATIC DIRECT ENERGY CONVERTERS

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SURFACE REQUIREMENTS FOR ELECTROSTATIC DIRECT ENERGY CONVERTERS*

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Abstract

There are two major electrostatic direct energy converter concepts which will be discussed from the point of view of the surfaces. One is the Venetian blind concept and the other is the periodic electrostatic focusing concept. They are both of the direct collector type. Fluxes of D^+ , T^+ , He^{++} , electrons, and x-rays are given. Design consideration due to thermionic emission, secondary electron emission, and radiation cooling are discussed. A detailed discussion is devoted to breakdown physics, the voltages and electric field strengths that can be employed, and how surface deterioration may affect voltage holding due to He^{++} bombardment blistering.

Introduction

Studies of conceptual mirror reactors based on present understanding of the plasma physics of magnetic mirror confinement show that in the best of circumstances (no instability enhanced losses) the overall power plant efficiency would be uneconomically low if the energy produced was converted to electricity by thermal conversion alone (1,2). However, by using the technique of electrostatic direct energy conversion of the plasma

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energy, Post has shown that reasonable overall plant efficiencies can be obtained (3). For a particular case, Werner et al. (4) and Lee (5) have shown that for a direct conversion efficiency of 70% with a thermal bottoming cycle to the direct converter, the overall efficiency is 27%.

Two quite different direct conversion concepts have been developed. One called the Venetian blind (VB) converter (6), see Fig. 1, can operate with a 150 keV D-T plasma with an efficiency of about 60% under conditions (7) that are not necessarily inconsistent with economics (\$109 per kW handled). The upper limit appears to be about 70% for the VB concept, ignoring economic limitations. The other concept called periodic electrostatic focusing (3) (PEF), see Fig. 2, can operate with a 600 keV D-T plasma with an efficiency of about 66% under conditions (8) that are not necessarily inconsistent with economics (\$176 per kW handled). The upper limit appears to be about 90% for the PEF concept, ignoring economic limitations. It would appear highly desirable to reduce the cost of both these direct converters to make them more practical.

This paper is devoted to a discussion of the expected environment which the surfaces will be exposed to for the VB and PEF direct conversion concepts. For a discussion of how the converters work and why the designs are as they are, the reader can look at Refs. 4-8.

Fluxes on the Surfaces of the Venetian Blind Direct Energy Converter

The collector structure of the VB unit is shown in Fig. 3 and described in Refs. 6 and 7 along with the energy distribution entering the direct converter. For an optimized two-stage VB converter matched to a 150 keV injection energy, D-T, 10 to 1 mirror ratio reactor, the fluxes will be 4×10^{13} , 2×10^{13} , and 6×10^{11} particles $\text{cm}^{-2}\text{-sec}^{-1}$ of D^+ , T^+ , and He^{++} respectively on the first collector and 2×10^{13} , 1×10^{13} , and 3×10^{11} particles $\text{cm}^{-2}\text{-sec}^{-1}$ on the second. The wires of the grounded grid and negative grid intercept the sum of the above fluxes. The suppressor grid wires intercept the same flux as the ribbons. The average kinetic energy per charge of the ions striking the electrodes is 22 keV for the first collector and 41 keV for the second. The approximate energy distribution is given in Fig. 4. At 150 keV, the average total ion current is $100 \mu\text{A}/\text{cm}^2$ on the plane of the first collector ($40 \mu\text{A}/\text{cm}^2$ to the ribbon surfaces), and $50 \mu\text{A}/\text{cm}^2$ at the second collector.

Of the $100 \mu\text{A}/\text{cm}^2$ to the first collector, about $1 \mu\text{A}/\text{cm}^2$ of grid plane surface area is intercepted by the secondary electron suppressor grid. The average ion energy at impact with a grid wire is 32 keV, resulting in $\gamma \approx 2$ for the secondary electron emission coefficient. Therefore, about $2 \mu\text{A}/\text{cm}^2$ of electron current will flow from the 80 kV grid to the 180 kV plate. The effect of the x-rays produced by these 100 keV electrons needs further study.

Fluxes on the Surfaces of the Periodic Electrostatic Focusing Direct Energy Converter

Some typical collectors are shown in Fig. 5 for the PEF converter. The energy distribution of the ions as they strike the collector surfaces in the PEF converter is nearly independent of the incident energy distribution because of the good energy resolution of the many stages. However, the mean energy at impact is directly proportional to the mean incident energy. At a mean energy of 600 keV, the mean impact energy is 80 keV per charge when the power level is 3 MW per meter of circumference. The average ion flux at the collector surfaces is $2.3 \times 10^{13} \text{ D}^+$, $1.4 \times 10^{13} \text{ T}^+$, and $3.2 \times 10^{11} \text{ He}^{++}$ per $\text{cm}^2\text{-sec}$, giving $0.5 \text{ W}/\text{cm}^2$ of heating. The energy distribution is given in Fig. 6.

At the grids, the current density is $25 \mu\text{A}/\text{cm}^2$ and the mean energy is 300 keV. The beam power density is $7.5 \text{ W}/\text{cm}^2$ striking the grid wires. Grids will intercept about 3% of the ions, resulting in about $1.5 \mu\text{A}$ of secondary electron current per cm^2 of channel wall. Depending on the point of origin, these electrons can fall through a wide range of potential difference. The average energy gained by a secondary electron is about 600 keV. The effect of the x-rays produced by this $1.5 \mu\text{A}/\text{cm}^2$ of 600 keV electrons needs further study.

Secondary Electron Emission Due to Ion Impact

Secondary electron emission poses problems for direct energy conversion and can be one of the biggest loss mechanisms (see the sections on fluxes on the surfaces). Both the VB and the PEF are designed to minimize this loss. The literature was searched for secondary emission data relevant to our case. The surfaces are expected to be quite clean due to the high temperature operation and continuous sputtering. Perhaps there will be

a few monolayers of deuterium and tritium, however. We are interested in tungsten for grid wires and other refractory metals for the hot collectors. Figure 7 summarizes some of the relevant data found. We note that fairly large discrepancies exist, especially around 100 keV, and therefore we would like to see more data for relevant conditions appropriate to direct energy converters.

Thermionic Emission

In both the VB and the PEF direct converter, the grids will be cooled only by radiation and will therefore run rather hot. They must not be allowed to get so hot that thermionic emission of electrons degrades the efficiency. This is one consideration that sets an upper limit on the power density that can be handled by a converter. In the VB converter it might be feasible to use ribbons instead of wires in the grids to increase the cooling area without increasing the interception of the beam. Emission can be reduced by choosing grid material with a high work function, such as tungsten or rhenium (which also have high melting points), and by increasing the emissivity for better radiant cooling.

In Ref. 6 it is calculated that the grounded grid in the VB converter would run at 1520°C. If tungsten wires are used, thermionic emission current would be about 1 μA per cm of wire (0.2 μA per cm^2 of grid-plane area).

Because of the lower beam power at the grids in the PEF converter, thermionic emission is not a problem there. The grid wires will run at about 1000°C. This is too hot to allow stainless steel wires (stainless melts at 1450°C).

Radiation Cooling of Collector Surfaces

The designs call for operation of the surfaces at high temperatures in order to recover the not-directly converted power in a thermal cycle. Some of the electrodes are so small (grid wires 0.6 mm diameter) that direct cooling with liquids or gases seemed impractical, so we employed radiation cooling. These designs take into account view factors when hot surfaces are facing both hot and colder surfaces and making the radiation surface broad while keeping the surface that intercepts the beam small, thus leading to finned grid designs. Once the geometry is fixed the heat transfer is proportional to

ϵT^4 . For black bodies ϵ is 1.0, but for a clean tungsten, at 1500°C for example, ϵ is 0.23. It would be quite advantageous to find practical ways of raising ϵ . The material choice for the ribbons was niobium; however, much more work is needed on the cooling of ribbons, including choice of materials.

Pumping Considerations

In order to minimize losses due to charge exchange and ionization, the neutral gas density must be kept quite low. For direct converters operating below 200 keV, pumping is a major design problem (6,7). In the energy range below about 150 keV, diffusion pumps become impractical and some other technique should be developed. One thinks of surface pumping by cryogenic means or sublimation of material which traps deuterium and tritium. One of the best techniques might be to never allow the directed high energy particles to thermalize, but rather to bury into metal collectors and diffuse on into special pumping ducts, or for the metal collectors to physically be removed for outgassing. One can visualize the problem by the following example: A beam of 150 keV D^+ carrying 25 W/cm² gives a gas throughput of 1.5×10^{-5} Torr-l/sec per cm² of beam. At this energy, the pressure must be maintained below 2×10^{-6} Torr to keep ion loss by charge exchange on cool gas less than 3%. Therefore, the required pumping speed is 150 l/sec per kW of beam. If diffusion pumps are used, the cost and the power consumption of the pumps are both uncomfortably large. Diffusion pumps cost at least \$0.10 per l/sec, leading to \$15 per kW, and they consume 0.25 W per l/sec, leading to 40 W per kW of beam.

Breakdown Physics

Before the effects of bombardment on voltage holding can be evaluated, it is necessary to understand normal vacuum breakdown for realistic collector configurations. This in itself is not trivial since voltage breakdown involves complex mechanisms that are quite sensitive to surface conditions. Furthermore, the geometry and high-temperature surfaces involved pose some unique problems (8-11). Thus the experiments described in Ref. 9 were undertaken to develop suitable breakdown criteria in the absence of bombardment. Breakdown limits were measured using 1- to 7-mil-diam tungsten wires

centered in a 2-in.-i.d. stainless-steel anode. Several important observations were reported from this work:

- (a) Breakdown limits increase significantly with prior heat-treatment under vacuum, and three breakdown regimes can be identified depending on the length of treatment: initial, field-emission, and ultimate. In the initial regime the breakdown process involves absorbed gases or actual loose clumps of material on the surfaces. After vacuum baking at 800°C for 1/2 hr, the surfaces are partly cleaned and breakdown appears to be initiated by field-emission currents originating from whisker sites* on the surface. Yet higher voltages can be achieved by baking overnight (ultimate regime), in which case prebreakdown currents drop many orders of magnitude, suggesting that the whisker projections have partly melted or evaporated.
- (b) High-temperature operation (at least to 1400°C), including thermionic emission, does not adversely affect breakdown. Due to the large current-density involved ($\sim 10^8$ A/cm²), field-emission from whisker sites can initiate breakdown; however, thermionic emission is more uniformly distributed over the surface. Even if the total thermionic current exceeds the total field-emission current, the current density of the former ($\sim 10^{-2}$ A/cm² at these temperatures) remains too low to initiate breakdown.

* Whiskers are microscopic projections that occur on most surfaces, even after fairly extensive cleaning (see Fig. 8). There is some evidence that additional whiskers can be drawn out from surfaces in large electric fields. Strong electric fields may occur near the whisker tips, resulting in large emission currents which can initiate breakdown.

A proposed breakdown correlation based on these experiments plus some data from accelerator operation is shown in Fig. 9. Since the accelerator data is taken from operational observations where surface conditions were not accurately controlled, the scatter in this data is not surprising. Thus the correlation shown represents a fit of a Cranberg-type clump-model (12) to the tungsten-wire data without directly incorporating the accelerator data. For reference, points corresponding to limiting fields encountered in typical conceptual reactor-scale designs for both VB and PEF collectors are included (compare Ref. 9; the geometries involved cause some ambiguity in the location of these points, and the values plotted represent "worse" case estimates). It is observed that both designs involve "equivalent" field strengths of the order of 10^5 V/cm and both design points fall somewhere in the field-emission regime. Thus, depending on the results of future studies, it may be necessary to reduce the design fields somewhat to fall below the initial-regime breakdown limit. The decision to do this largely rests on three factors: (a) whether or not further experiments at large spacings bear out the correlation of Fig. 9; (b) whether or not techniques can be developed to insure that all voltage surfaces are well conditioned prior to operation, including restarts after plant shutdowns; (c) the effect of ion bombardment on surface conditions and the success of methods developed to handle potential problems such as blistering and spalling.

Bombardment and Blistering Effects

To date there have been no voltage-holding experiments with sufficient ion fluxes to allow a study of bombardment effects. However, it is postulated that three different phenomena may be involved:

- (a) dynamic changes in microstructure,
- (b) clump formation via collection of sputtered material, and
- (c) ultimate damage culminating in helium-blister rupture.

A rough threshold for helium blistering is 10^{18} cm⁻² dose of He⁺⁺. Since, as shown in earlier sections, this threshold is reached in a matter of 40-80 hr in typical designs, it seems certain that blister damage will be encountered. However, it might first be asked whether or not the large ion fluxes envisioned might cause instantaneous breakdown

or result in short term effects leading to breakdown. Two potentially serious mechanisms can be envisioned. First, as the ions strike the surface, they may disrupt the structure, creating new whisker-like projections which could serve as field-emission sites and subsequently initiate breakdown. This needs to be investigated; but present thinking is that shapes of any projections created in this manner will not lead to large field enhancements. As pointed out in Ref. 9, enhancement depends strongly on the diameter of the projection. With their small size ($\sim 1 \mu\text{m}$ diam), normal whiskers can result in enhanced electric fields that are several orders of magnitude larger than the average surface value. Ion bombardment would not generally create such sites, although there is always the danger that certain combinations of temperature and electric field could result in unique eruptions. Two general observations tend to support this contention. Some of the accelerator data of Fig. 9 includes runs where the ion beam intercepted parts of the deflector surfaces, and no deleterious effects were noted. Also, low-energy ion bombardment created by increasing gap pressures to $\sim 10^{-4}$ Torr appears to erode existing whiskers rather than create new sites (9).

Another consequence of ion bombardment, namely sputtering of the collector electrodes, could lead to serious problems due to the build-up of eroded material on other surfaces. Sputtered neutrals will be line-of-sight redeposited on surrounding electrodes and surfaces, while sputtered ions or charged clumps may be selectively channeled in the electrostatic fields.

In the PEF design, for example, it has been estimated that over 80% of the sputtered material will be redeposited in this fashion (10). This could have two serious consequences: (a) a coating of conducting material on insulators would lead to surface arcs and leakage currents; and (b) such a coating on electrode surfaces could initiate clump breakdown. Clearly, the collector design must be such that insulator surfaces are suitably shielded from sputtered material, and while this is not a trivial task, we will assume that it can be accomplished. The possibility of clump initiation is, however, more serious. This involves clumps of material that tear loose from one electrode and strike the opposite one with sufficient energy to initiate an arc (frequently called

Cranberg's clump theory (13)). Such a mechanism is thought to occur in the initial regime of Fig. 9 before the surfaces are conditioned, and this could also account for breakdown in the ultimate regime. In fact, clump breakdown could well dominate the field-emission regime if the surfaces are not carefully conditioned, e.g., it is generally agreed (13) that with untreated surfaces clump breakdown dominates for electrode spacings greater than 0.1 cm. There is no direct experimental data available concerning the possibility that sputtered material might create clumps; however, Brodie (14) has reported a marked decrease in breakdown strength when minute quantities of material were transferred from a dispenser-type thermionic cathode to high-voltage electrodes.

With the particle fluxes indicated in earlier sections and using approximate sputtering yields of 10^{-3} and 5×10^{-2} for D^+ (or T^+) and He^+ , respectively, on niobium, a gross sputtering rate of $\sim 1/3$ μm per year is indicated. (Since much of this material is redeposited, the net rate of erosion is much smaller.) At any given moment, a thin coating of sputtered material will exist over the electrode surfaces. The key question then is the nature of this film. Will it be uniformly distributed with good adhesive properties, or will sites of loose clumps form that can initiate breakdown? That the sputtering rates are sufficient to cause a problem can be appreciated by noting that clumps of the size of 10^{14} to 10^{15} atoms have been observed in some breakdown experiments (15). Thus with the ion fluxes considered here, sufficient material would be sputtered in about 1 min to form one such clump per cm^2 . Such problems would be avoided if uniform deposition were maintained (on the contrary, a smoother surface might develop); however, any channeling of material into select sites could quickly form clumps of sufficient size to initiate breakdown.

We now turn to helium blistering effects. Since refractory metals are prime candidates for the hot electrodes, blistering data from niobium studies is probably representative of what should be expected (e.g., see Refs. 16-20). Since the normal threshold for blistering is reached in a matter of 40-80 hr with the ion fluxes anticipated, the only alternatives seem to be to attempt operation while blistering

proceeds or, alternatively, to attempt to design around the problem. We will briefly consider the former possibility first.

The rough surface structure caused by blistering could, in itself, affect voltage holding. Perhaps more serious are two potential consequences of blister rupture: (a) the spalled platelets may trap substantial amounts of tritium, making its recovery difficult (10), and (b) breakdown could be initiated, either via a clump-type initiation involving the loose material formed upon rupture or via field enhancement due to the jagged structure remaining after rupture. (Note that electrode dimensions and structural requirements are such that erosion per se via blistering is not as critical as it might be for the first wall of a reactor.) As Werner points out (10), even without considering tritium hold-up, the spalled material must be periodically removed for reprocessing, and techniques to do this could incorporate tritium recovery. Thus, this resolves into a design problem which is again far from trivial, but which appears to be solvable.

The effect on voltage holding will depend critically on the details of blister shapes and sizes, the kinetics of rupture, and postrupture structure. Information about blistering is yet too fragmentary to allow any firm conclusions, but several points might be noted. The operating temperatures envisioned ($\sim 1100^\circ\text{C}$ for electrodes and up to 1500°C for tungsten grid wires) are higher than those covered in present blistering experiments (16-20). However, extrapolation of current data to higher temperatures appears to be favorable. This is clearly seen from the photographs in Fig. 10, reproduced from recent He^+ -Nb bombardment studies by W. Baures of Sandia Laboratories in Livermore, California. Smaller blisters, lower erosion rates, and perhaps most important, relatively smooth postrupture structure may be expected. Thus, it is concluded in Ref. 9 that the blister shapes expected (before and after rupture) lead to lower field-enhancement factors than those associated with normal whisker structure. (A schematic comparison of the two is shown in Fig. 10.) If true, this suggests that the main problem with blistering relative to voltage breakdown could be clump formation rather than field enhancement. These problems are quite similar to those already discussed relative to sputtering; however, several different mechanisms potentially exist now for forming

clumps. Blister rupture could deposit foreign material on surrounding electrodes; loose parts of the ruptured blister could tear off in "clump fashion"; or fragments of material released during rupture could, by virtue of their initial velocity and charge, gain sufficient energy to cause breakdown in the same fashion as postulated for clumps.

If it turns out that voltage holding is seriously degraded by blistering, at least three design alternatives are available (7,10): (a) moving plates and grids, (b) liquid-metal collectors, or (c) special coatings with sufficient sputtering rates to provide "self-cleaning" surfaces (21). These approaches introduce new problems, and a careful evaluation of them has yet to be done. Thus only a few comments will be offered here. Moving plates and grids, while feasible, introduce a mechanical complexity that is undesirable if simpler approaches can be found. Liquid-metal collectors also introduce added complexity, and problems associated with vapor pressure, sputtering (sputtering rates rapidly increase as the melting point is approached, indicating large yields for liquid metals (10)), and maintenance of vacuum conditions could be critical. Finally, a "self-cleaning" surface might be devised by using materials that would sputter away so rapidly that blisters cannot form. To achieve this, Werner (21) estimates that a sputtering coefficient greater than 6×10^{-2} atoms/ion would be required. This exceeds values for refractory metals for the ion energies involved, but Werner notes that copper could meet this requirement. Thus copper-plated steel electrodes might be considered. While simple from a mechanical point of view, this approach has the disadvantage of requiring lower electrode temperatures, i.e., reducing the efficiency for recovery of thermal energy generated in the collector. Also, if clump formation via sputtering turns out to be a problem, the large sputtering rates involved might be prohibitive.

In conclusion, it is clear that a number of experimental studies are necessary before a final collector design is possible. As suggested by the preceding discussion, an orderly progression of experiments in the following areas should clarify the situation:

- (a) verification of the breakdown correlation of Fig. 9 for large electrode spacings,
- (b) study of the dynamic effect of bombardment on voltage holding via
 - (i) changes in electrode surface microstructure and
 - (ii) clump formation associated with sputtering,
- (c) study of the effect of blisters, both prior to and after rupture, on voltage breakdown.

Fortunately, it appears that ion fluxes available from accelerators are adequate to study such effects. Initial experiments might be done on samples that are irradiated and subsequently used in high voltage tests. Ultimately, however, in situ breakdown irradiation studies appear to be necessary.

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FIG 1

Conceptual design of direct energy converter: conical shaped expander and Venetian blind collectors.

FIG 2

Conceptual direct energy converter: fan shaped expander and periodic focusing collector.

Collector and grid array for the Venetian blind converter. The pair of wire grids at the left reflects the electrons and allow ions to pass on through the Venetian blind appears transparent to the incoming ions but opaque to the ions reflected by the second collector.

FIG 4

Energy distribution of particles hitting the first collector (ribbon) and the second collector.

FIG 5

Collectors of the periodic electrostatic focusing converter.

FIG 6

Energy distribution of particles hitting the collector surface of the periodic electrostatic focusing converter.

FIG 7

Secondary electron emission coefficient vs ion energy.

FIG 8

Schematic comparison of typical whisker and blister shapes. The shapes of these projections vary considerably with conditions, so this comparison must only be viewed as illustrative.

FIG 9

Proposed breakdown correlation for direct converter design. The grid cylinder data of Ref. 9 is well fit by a correlation where the breakdown voltage V_b is proportional to the square root of the equivalent spacing y

100μ
400°C 4 X 10¹⁸

10μ
1000°C 4 X 10¹⁸

100μ
600°C 4 X 10¹⁸

10μ
1200°C 2 X 10¹⁸

FIG 10

Scanning electron micrographs of implanted surfaces of niobium. The temperature, fluence, and magnification are indicated in each case. These photographs are taken from Fig. 6 of Ref. 19.