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ADVANCED-FUELED FUSION REACTORS SUITABLE FOR DIRECT ENERGY CONVERSION

Fourth Quarterly Progress Report: October 1976 through December 1976
First Quarterly Progress Report: January 1977 through March 1977

Scientific Editor: A. S. Blum

September 9, 1977

Performed for the Electric Power Research Institute under contract No. RP645-2.

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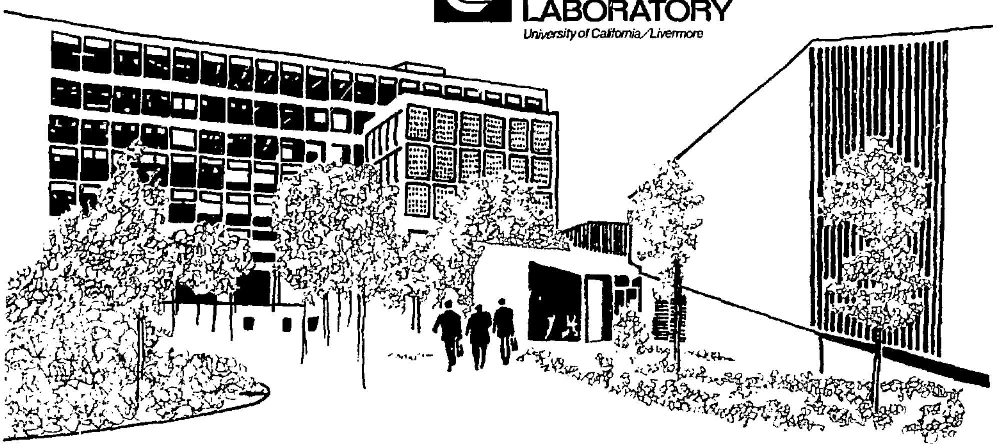
LAWRENCE LIVERMORE LABORATORY
University of California/Livermore



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Foreword

This report describes research performed by the Lawrence Livermore Laboratory under the sponsorship of the Electric Power Research Institute contract No. RP645-2. Work under this contract is directed toward the realization of practical, advanced-fueled, fusion reactors utilizing direct energy conversion to produce electrical power.

Contents

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ABSTRACT

The direct energy conversion efficiencies calculated for Cat-D and D-^{3}He fueled Tokamak reactors are summarized over a range of reactor designs, collector configurations, assumed T_e/T_i ratios, and power densities. We also discuss the performance of a system of superconducting coils that produce those fields required to guide escaping plasma along the path between the bundle divertor coils and the direct converter.

TECHNICAL DISCUSSION

Summary

We are reporting only the highlights of our efforts during the fourth quarter of 1976; work performed during the first quarter of 1977 is reported in greater detail. A more detailed summary of the work performed during the first of these periods will appear in the Annual Report. The major achievements are:

- The direct converter model has been generalized to allow T_e/T_i ratios in addition to one, and results for the direct conversion of plasmas escaping from the two Cat-D and three D-^{3}He reactor designs have been calculated. A multistage Venetian blind collector analysis has been added.
- Magnetic coils for guiding plasma from the diverter to the direct convertor have been studied; a promising solution for this problem has been developed.
- An experimental He cryotrapping program has been initiated.

Direct Energy Converter Modeling

We have extended and altered the direct conversion model in three respects:

- T_e/T_i values other than one are allowed.

- An ambipolar potential of $4.5\ kT_e/e$ has been assumed.
- We have added an estimate of the efficiency improvement resulting from the use of a multistage Venetian Blind Collector.

With respect to direct conversion, the ratio T_e/T_i is important because it affects the ion velocity spread and the ambipolar potential. The logic is as follows. The divertor coil field is intense enough to partially mirror-confine the escaping plasma. The plasma in the region beyond the separatrix (the separatrix associated with the bundle divertor) is weakly trapped within the reactor by these "mirrors." We associate ion and electron temperatures T_i and T_e with the partially trapped plasma in this region. If the ratio of these temperatures is known, then T_e and T_i can be calculated by assuming an ambipolar potential of $4.5\ kT_e/e$ and by using the power balance equation:*

Charged particle power =

$$\sum_{\substack{\text{All ion}\\ \text{currents}}} \frac{k\,T_i}{Z_j\,e}\left(\frac{3}{2} + 4.5\,\frac{T_e}{T_i}\,Z_j\right) I_j + \frac{k\,T_e}{e}\,(1.085) \sum_{\substack{\text{All ion}\\ \text{currents}}} I_j \quad (1)$$

where I_j as the ion current of the j^{th} ion specie and Z_j is its ionic charge number. A University of Illinois fuel cycle study provides values of the total charged-particle power escaping from the plasma and values of the ion current associated with each ion species.

Just before leaving the divertor the plasma is mirror-confined (along field lines between the separatrix and the wall). In this region one would expect a T_e/T_i value less than one as well as a positive ambipolar potential. The T_e/T_i ratio is important, and allows direct determination of the ion and electron temperatures from Eq. 1. However, because the physics is too involved for our purposes, the T_e/T_i ratio has been left as a parameter to be varied. Conversion efficiencies have been plotted for values of $T_e/T_i = 1$, 0.5, and 0.25. The ambipolar potential is immediately estimable from T_e and the ion velocity spread can be computed from T_i.

Although the direct conversion efficiencies are not included in this report (they will appear in the Annual Report), they are generally lower than we calculated for mirror machine plasmas. These reduced

*If a Boltzmann distribution of electron energies is assumed, the mean (remaining) kinetic energy of the population tail that escapes over a $4.5\ kT_e/e$ barrier is $1.085\ kT_e/e$. As the barrier is further increased, this mean energy approaches kT_e/e.

efficiencies are caused by the following:

- The electrons escaping from the Tokamak carry a larger proportion of the energy, and the resulting heat loading requires a larger diameter, grounded grid to accommodate the required coolant flow. Increased grid diameter decreases efficiency by intercepting more ions.
- The lower mean ion energy of the Tokamak plasma increases the charge-exchange neutralization losses.

It should also be noted that the direct conversion efficiency decreases as the charged-particle power density incident on the direct converter increases. This occurs because the smaller tank structure corresponding to this higher power density has a smaller vacuum pump surface and pumps the resulting neutral gas away more slowly (consequently charge-exchange losses increase). In addition, the grounded grid diameter must be increased to accommodate the increased power density. Above 150 W/cm^2, thermionic emission from the negative grid also decreases efficiency.

Figure 1 summarizes the range of efficiencies calculated for the low- and high-β, catalyzed-D reactor designs. Our inclusion of both designs and the full range of assumed T_e/T_i values causes the spread in results. With the addition of a 40%-efficient thermal bottoming cycle, charged particle energy is converted to electrical energy with the efficiencies denoted in Fig. 1 as "plant electrical efficiency." Figure 2 presents similar results for the D-^{3}He designs.

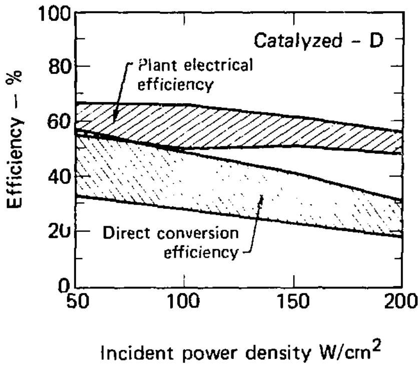

Fig. 1. Efficiencies of direct converters attached to high- and low-β catalyzed-D reactor designs. Direct conversion efficiency can take on a range of values depending on reactor design, assumed T_e/T_i, and power density. The plant electrical efficiency is shown over the same range of conditions.

Guiding the Plasma into the Direct Converter

We have considered the feasibility of providing a set of superconducting, current-carrying rings and bars that would provide a magnetic field suitable for guiding the escaping plasma from the reactor interior, through

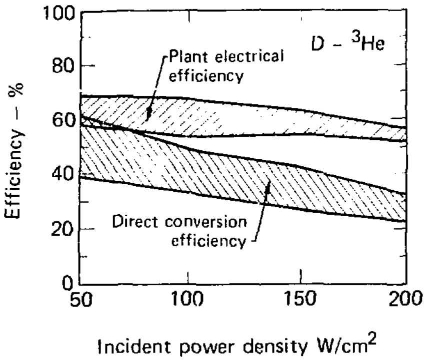

Fig. 2. Results similar to those in Fig. 1 are shown for D-^{3}He designs.

the bundle divertor coil, radially outward through the toroidal field, and into the expander. A radial field must be created and the existing toroidal field must be canceled over the plasma path. We have studied a coaxial series of ring coils to provide the radial field (Fig. 3); the first (smallest) ring coil is the usual bundle divertor coil. The toroidal field, which would otherwise traverse the expander and deflect the escaping plasma into the wall, is canceled by the coil arrangement shown in Fig. 4. The resulting magnetic field was studied only in the horizontal mid-plane (plan view) of the reactor. Figure 5 shows a detailed view of the field lines near the divertor.

The results are summarized as follows:

- The computed fields approximate the desired result and suggest that such a coil configuration can, with some modifications, solve the problem of guiding the plasma into the direct converter.
- The field is known, from the midplane plot, to be excessive near the divertor coil where it reaches 18 T (see Fig. 5). In addition, it would be desirable to displace the separatrix about 10 cm further out from the vertical midplane between expanders; for this design, such a displacement will slightly increase the already excessive field at the divertor coil. Forces were not computed but are known to be large. The field should also be examined in other view planes.
- Other divertor configurations such as pairs of rectangular or D shaped coils should be considered.

HE Pumping

Advanced fueled D-D and D-^{3}He reactors will handle large through puts of ^{3}He and ^{4}He gas. Because this gas cannot be pumped by conventional cryogenic pumps, and because of the high cost and large space requirements of diffusion pumps, we have begun experiments on the cryotrapping of ^{3}He and ^{4}He.

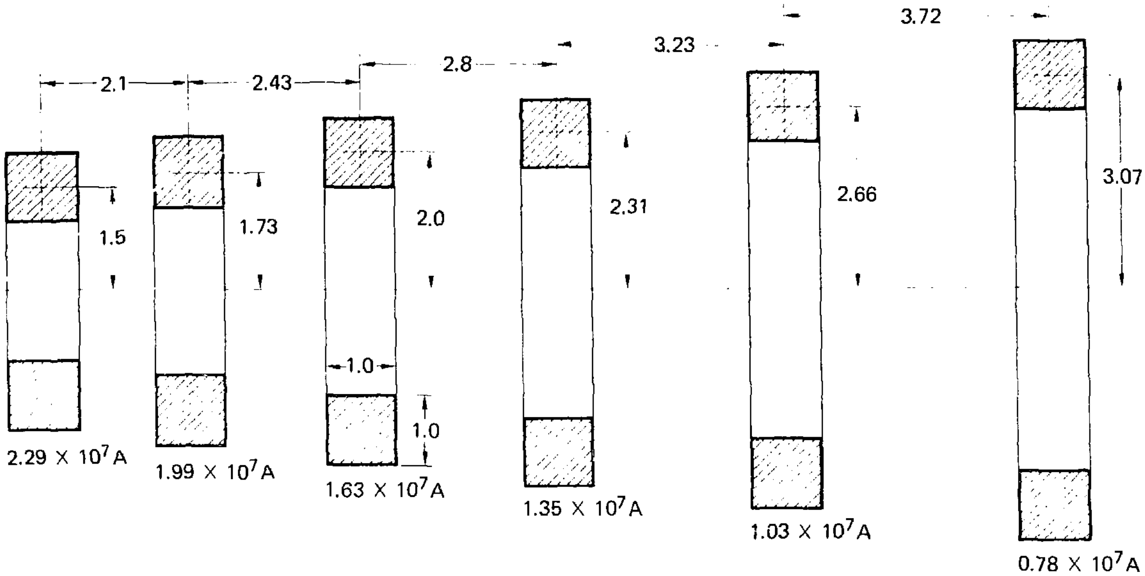

Fig. 3. A section through first six coils. All dimensions are in meters.

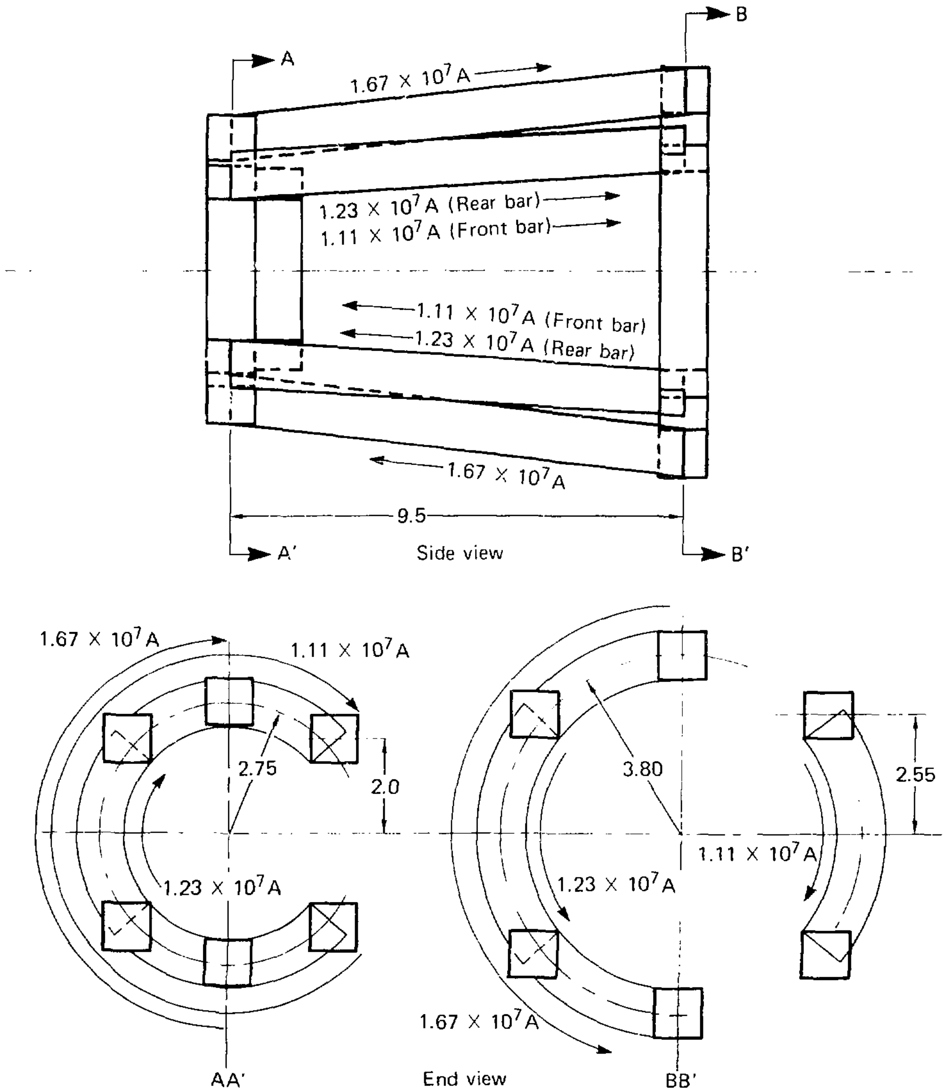

Fig. 4. Side and end views of the bar and arc arrangement used to model the toroidal field nulling coil. A mirror image of this arrangement is used on the adjacent expander. All bars and arcs have a 1m × 1m cross section.

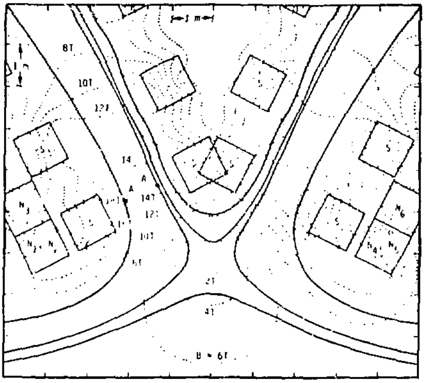

Fig. 5. The magnetic field lines (solid) are shown in the region of the expander entrance. S denotes ring coil cross sections, N_i denotes the toroidal field nulling coil elements, and A and A' denote openings in the shield through which the plasma passes.

PLANNED EFFORT FOR NEXT QUARTER

It is anticipated that the next quarter will be occupied with the following:

- An evaluation of ^3He cryo-trapping.
- An examination of the ^3He neutral beam injection problem.
- The editing of material for the 1976 Annual Report.