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Abstract

The Ra tandem mirror fusion reactor concept features inherent safety, high net plant efficiency, low cost of electricity, low radioactive waste generation, low activation, highly efficient direct conversion, thin radiation shields, and axisymmetric magnets. The safety and environmental features are achieved through the use of D/He-3 fuel, while the high efficiency derives from a new operating mode. ICRF stabilization allows an axisymmetric magnet set.

Introduction

The objectives of the Ra D/He-3 tandem mirror reactor scoping study were to determine the benefits of operating a thermal barrier tandem mirror reactor using the D/He-3 fuel cycle and to examine the so-called "Ra mode" of operation [1]. The main effort concentrated on identifying and examining key systems and critical issues rather than stressing systems integration for the design. Nevertheless, sufficient design detail was accomplished to allow reasonable estimates of cost of electricity, net efficiency, and reactor parameters. The focus on D/He-3 was motivated by the anticipated attractiveness of this fuel cycle in tandem mirrors and by the recent discovery of a substantial He-3 resource on the lunar surface [2].

The Ra mode gives high efficiency by retaining only sufficient fusion product energy to sustain losses, while inducing nonadiabaticity and consequent prompt loss for the remaining fusion products. Most of the nonadiabatic loss will consist of protons centered at 14.7 MeV energy with an energy spread of 1.8 MeV. The high energy and small spread of the escaping protons allows very efficient direct conversion (~80% for high-transparency grids).

RF stabilization of MHD modes is used in Ra rather than end cell octupole coils as in MINIMARS [3] or quadrupole coils as in MARS [4]. This traded the cost of the octupole coils and hot electron "mantle" power for the cost of central cell ICRF power. This choice of MHD stabilization method allows Ra to have a totally axisymmetric magnet configuration.

The design guidelines for Ra were based on those of the most recent tandem mirror reactor study, MINIMARS [3]. That is, Ra was assumed to be a tenth-of-a-kind reactor of modular design with safety as a major consideration, and the costing algorithms were essentially those of the Fusion Engineering Design Center. Safety and environmental considerations were important in the reference design point choice, and they moved the reference case 2 mills/kWh from the lowest COE point.

Plasma Physics

The Ra reactor uses D/He-3 fuel, with most of the energy produced by the reaction D + He-3 → He-4(3.67 MeV) + p(14.68 MeV) but including the important neutron-producing side reactions D + D → He-3(0.82 MeV) + n(2.45 MeV), D + D → T(1.01 MeV) + p(3.02 MeV), and D + T → He-4(3.52 MeV) + n(14.07 MeV). The reference case He-3 to D density ratio of 3 and tritium burn fraction of 63% lead to a neutron power production of only 1.5% of the total fusion power. However, this density ratio and the relatively high plasma operating temperature give a large bremsstrahlung radiation fraction. Nevertheless, 35% of the fusion product protons were not required to sustain the plasma and were assumed to be lost promptly.

Nonadiabaticity may be induced by a sufficiently steep magnetic field ramp at the central cell ends. To make approximately one-half of the fusion-product protons nonadiabatic requires creating an axial magnetic field gradient of about 2 T/m at the end of the central cell [1]. Nonadiabaticity effectively enlarges the velocity-space loss region by greatly enhancing pitch-angle scattering of ions in a high energy region adjacent to the mirror loss cone.

MHD stabilization in Ra is provided by central cell ion cyclotron range of frequencies heating (ICRF). Experimental results are very encouraging [5] and good theoretical progress is being made [6]. However, a best-estimate value of 25 MW absorbed was legislated for Ra.

Fueling is a major issue for Ra, because incorporating He-3 into pellets is difficult and present theories indicate that pellet penetration at high electron temperatures will be difficult. This issue is treated in a separate paper in this conference [7]. An alternative fueling method of particular interest for Ra, because it would allow higher velocities and is no more difficult for He than for H, is the use of compact toroids [8].

Reference case axial profiles of magnetic field, electrostatic potential, and densities are shown in Figure 1. These are schematically drawn based on values calculated at the central cell, choke coil peak, thermal barrier bottom, ion-plugging potential peak and end coil peak.

Optimizing Systems Code and Parametric Variation

Using a methodology similar to that of MINIMARS [3], a D/He-3 tandem mirror optimizing systems code was developed for Ra. Plasma particle and power balance equations were solved along with a simplified plant power flow and optimization was done over a space of fourteen variables. Note that the COE values quoted do not include the He-3 fuel cost, which is obviously uncertain at this time and would add about 1 mill/kWh for each $90/g cost of He-3.

Although the COE minimum lay near a He-3 to D density ratio of 1, the dependence was weak as shown in Figure 2, so radioactivity and materials considerations drove the reference point toward a higher density ratio. The important dependence of COE on net power level is shown in Figure 3. Unlike MINIMARS, there is still a strong dependence for Ra at the 600 MWe level, and thus there remain major gains to be made by going to higher power levels. The nominal reference case parameters for Ra are given in Table 1.

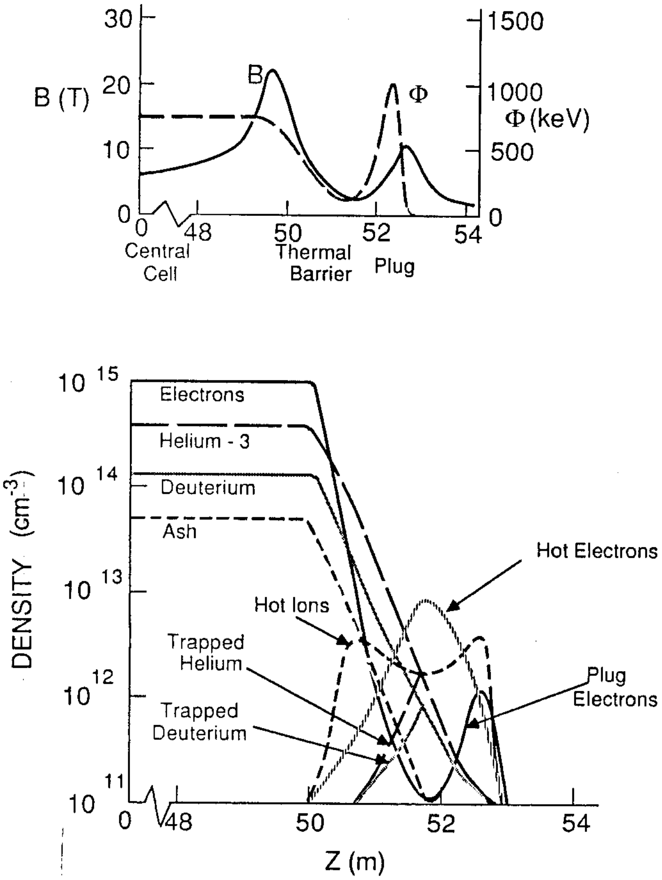

Fig. 1. Axial profiles of magnetic field, electrostatic potential, and densities for the Ra reference case.

Central Cell Shield

The primary objective of the shield is to protect the superconducting magnet against radiation. Satisfying the heating limit is the design driver for the shield. The minimum thickness shield was found to consist of two layers: a 53 cm thick B-SS layer, followed by a 3 cm thick B_4C layer. Throughout the shield, 10 vol% SS structure and 20 vol% H_2O coolant are used. Figure 4 shows schematically the radial build of the central cell. For a neutron wall loading of 0.05 MW/m^2, the peak nuclear heating in the coil is 0.1 MW/cm^3, the peak fast neutron fluence to the NbTi superconductor is 4×10^{18} n/cm^2, and the peak dose in the electric insulator is 3×10^{19} rads. These values are below the design limits adopted for this study. The neutron-induced damage in the first wall is low, implying that there is no need to replace the first wall during the 30 FPY reactor life due to radiation damage.

Magnets

The Ra magnet design is much simpler than that of MINIMARS, since the burden of MHD stabilization falls on central cell ICRF rather than on octupole coils and mantle electron cyclotron range of frequencies (ECRF) heating power. This configuration relieves the severe access problems of the octupole coil option. As in MINIMARS, an axisymmetric, 24 T choke coil consisting of 16 T from a superconducting coil and 8 T from a copper insert coil consuming 8 MW is used.

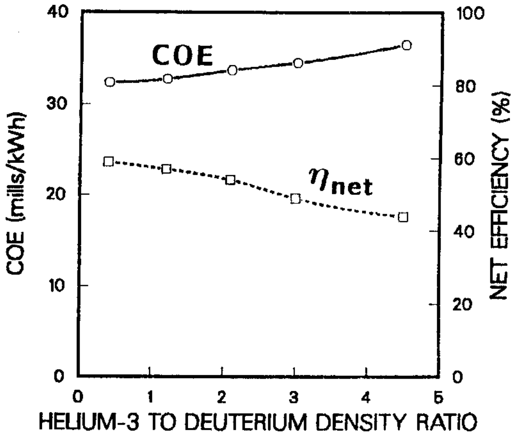

Fig. 2. Dependence of the Ra cost of electricity and net efficiency on the ratio of helium-3 to deuterium densities.

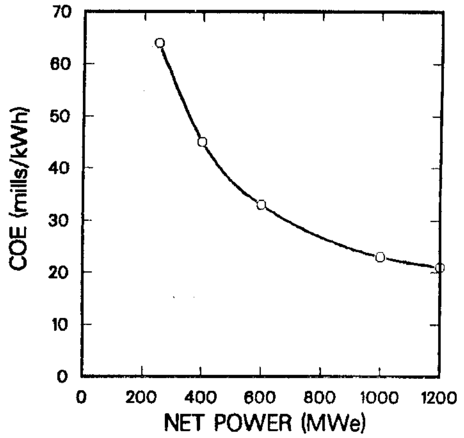

Fig. 3. Dependence of the Ra cost of electricity on the net power level.

Table 1. Ra Reactor Reference Case Parameters

Fusion Power, MW	1227
Net Electric Power, MWe	600
He-3:D Density Ratio	3:1
Neutron Wall Load, MW/m^2	0.05
Tritium Inventory, g	2
Central Cell B Field, T	6.5
Central Cell Length, m	100
First Wall Radius, m	0.59
Blanket and Shield Thickness, m	0.56
Blanket Coolant	H_2O
Recirculating Power Fraction, %	13
Thermal Cycle Efficiency, %	34
Direct Converter Efficiency, %	80
COE, mills/kWh	34*

*without He-3 cost; He-3 adds 1 mill/kWh per $90/g

Direct Converter

The Ra direct converter design consists of the series of grids and angled plates (venetian blinds) shown schematically in Figure 5. The ion reflector grid is a new concept and serves to turn the high current of thermalized ions back to the venetian blind so that these ions do not generate secondary electrons on the electron suppressor grid. The aggressive assumptions that the grid transparency is 0.99 and the venetian blind transparency is 0.95 are

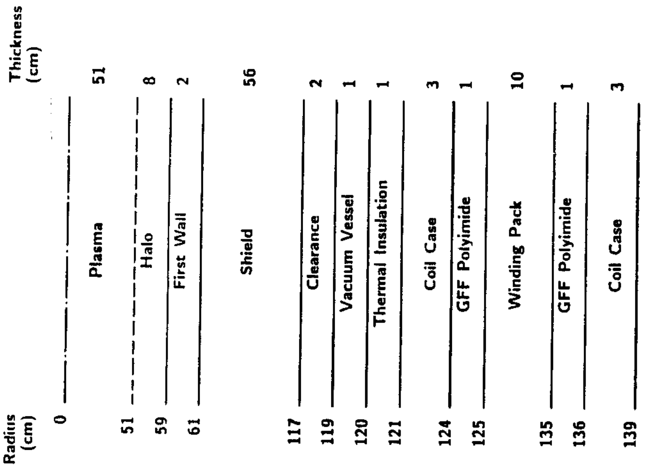

Fig. 4. Schematic of the Ra central cell shield and magnet.

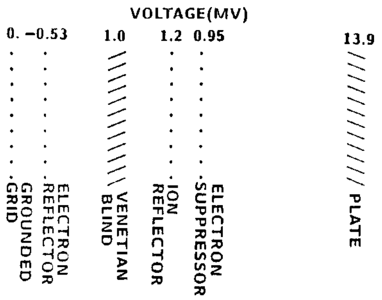

Fig. 5. Schematic of the Ra direct converter.

made. Relaxing those assumptions to 0.95 and 0.90 increases the reference case cost of electricity by 0.7 mills/kWh and decreases the direct converter efficiency to 67%. Table 3 gives direct converter parameters. Because 71% of the input power is in the form of a proton stream at 15.4 MeV with a 1.8 MeV energy spread, a net efficiency of 80% is achieved.

Table 3. Direct Converter Parameters

	Input Power	Input Current
14.7 MeV protons	356 MW	23 A
3.6 MeV alphas	11 MW	3 A
Thermalized ions	133 MW	112 A
Assumed secondary electron emission coefficient		3
Radiated power		100 MW
Output power		400 MWe
Efficiency		80%

Ra mode operation depends on designing the final direct converter plate to stand off 13.9 MV. Based on accelerator technology, this appears feasible, but resolution of the question will require experimental verification of the concept for high voltage and large dimensions.

Power Conditioning

The high direct conversion efficiency of Ra is predicated on our ability to switch high voltage dc electricity and convert it to lower voltage ac. We have considered using high power thyristors or motor generator sets to accomplish the high voltage (about 14 MV) conversion. However, present versions of these devices are limited to relatively low voltage (130 kV for thyristors, 2 kV for motors) and synchronizing the switching is difficult in the resultant long series of devices. There has been much work done in high power switching for various applications (ICF test facilities' power supplies, SDI-related work) at voltages up to 30 MV [9], where high voltages usually do not present as many problems as high currents. Ra has a relatively low current output (about 23 A).

One of the devices used for switching high voltages is a spark gap, where operating voltages range up to 5 MV. The losses are in the range of 2-10%. The lifetimes reported for typical high power operations are on the order of 10^8 shots [9]. However, with laser triggering, multi-stage switches can have lifetimes of 10^9 to 10^{10} shots [10] for high current (5 MA) and high voltage (30 MV) applications. Since high charge transfer is responsible for electrode erosion, and since Ra will have relatively low charge transfer, a virtually unlimited life of spark gap switches for this application can be postulated [11].

Transformers in the range of 3 MV to 6 MV have been tested, and energy transfer efficiency of over 90% has been demonstrated. Compromise has to be made between the transformer size (which decreases with pulse frequency) and the lifetime of spark gaps, capacitors, etc. which may have a limit on the number of shots and frequency of discharges. High voltage capacitors have lifetimes of 10^8 to 10^{12} discharges. However, keeping the electric field small (<100 kV/cm) should insure adequate lifetime [11].

Plant Power Cycle

A helium-cooled thermal cycle is more efficient than a water-cooled cycle in converting first wall surface heat and other thermal power to electricity. However, the lower cost of the water-cooled cycle and the reduction in shield thickness (because water can provide some neutron shielding) led to the choice of the relatively simple pressurized-water-reactor (PWR) cycle for converting thermal power in Ra. The estimated COE for either choice of thermal cycle was the same, so there was no incentive to choose the more difficult He-cooled technology. The calculated efficiencies are 34% for the thermal cycle and 80% for the direct converter, and the assumed injection power efficiency is 65%. Thus, the overall net plant power efficiency for Ra is 49%. This value rises to 61% at a He-3 to D density ratio of 1 due to the higher fusion power density at that fuel mixture.

Materials

A key point related to the use of the D/He-3 fuel cycle is that existing experimental data for neutron-induced damage to materials could be used in designing the device. Figure 6 shows that the Ra reference case falls well within the radiation damage data available, even after 30 full power years (FPY) of operation. For confident design of a typical D-T reactor, however, both a substantially increased materials testing program and multiple change-outs of vulnerable components would be required.

Radioactivity

Ra would have significantly lower activation levels than a D-T reactor. In particular, all components would satisfy Class C waste disposal requirements, so that near-surface burial of waste would suffice. Figure 7 shows the relative values of activation in terms of curies/kWe, waste disposal rating (WDR), and first wall afterheat density for

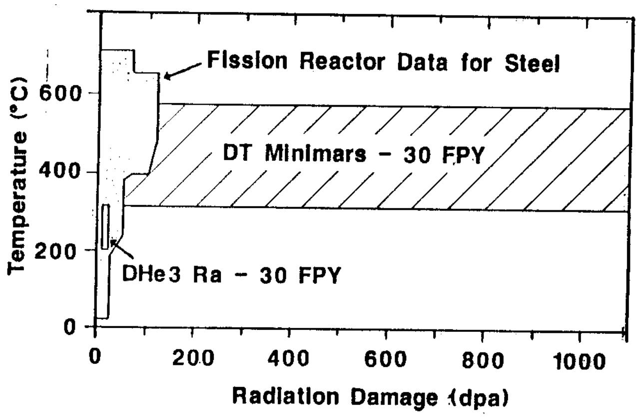

Fig. 6. Comparison of radiation damage data needs for D/He-3 and D-T fusion reactors with available fission reactor data.

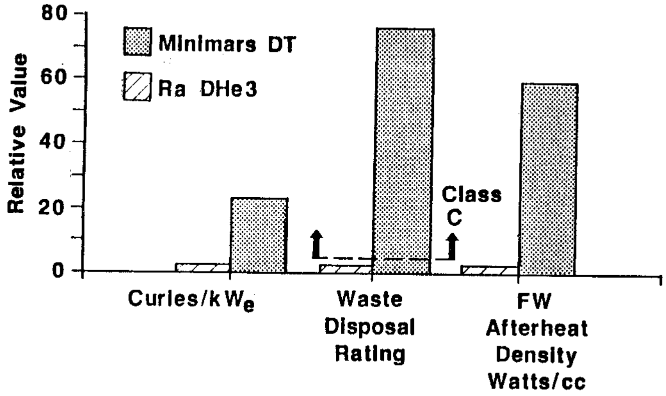

Fig. 7. Comparison of activation levels for Ra and MINIMARS.

both Ra and MINIMARS. A further consideration is that the volume of waste is greatly reduced.

Safety

Ra would be an inherently safe reactor. Even under the pessimistic assumption of adiabatic heatup of the shield in a loss of coolant accident (LOCA), the shield in the Ra reference case would warm up to less than 600 C after a month of shutdown and, therefore, would not even melt. Although adequate means for achieving inherent safety in MINIMARS, such as heat pipes to distribute the heat, are available, a D-^{3}He reactor has a clear advantage.

Safety is also greatly enhanced in Ra because of the reduced inventory of radioactive volatiles. The total tritium inventory in Ra is 2 g, a factor of 250 less than that of MINIMARS. Even the worst case of total release would only give an exposure of 0.1 Rem at the site boundary. Also, due to the low neutron production and because no tritium breeding blanket is present, other radioactive volatiles are not expected to pose a problem.

Conclusions

The Ra tandem mirror fusion reactor appears very attractive with respect to economic, safety, and environmental criteria. The Ra concept requires an economic source of He-3, such as the recently proposed lunar resource [2], and a modest physics extension of the requirements for a D-T tandem mirror reactor. The three critical technology areas for a Ra mode reactor are the high-energy neutral beams, fueling, and the high-voltage direct converter. The direct converter design difficulties could be mitigated by operating without the Ra mode prompt-proton loss at a much lower direct converter voltage but with slightly reduced performance. The high efficiency available from Ra mode operation makes the concept also attractive for specialized applications such as space power.

Acknowledgements

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