Critical Issues for SOAR: The Space Orbiting Advanced Fusion Power Reactor

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ABSTRACT

A conceptual design has been developed for a Space Orbiting Advanced Fusion Power Reactor (SOAR) which would achieve a specific power of approximately 2 kWe/kg at an electric power level of 1000 MWe. The SOAR configuration would be a tandem mirror reactor burning deuterium/helium-3 fuel. This paper summarizes the design and examines considerations of scaling with output power of the reactor. Critical issues identified in the first phase of this study are discussed. Key plasma physics issues include ion end-plugging, thermal barrier operation, magnetohydrodynamic stability, and the maintenance of non-equilibrium end-cell plasmas. Some necessary technologies also remain to be proved, including high temperature plasma fueling and high-voltage direct converter operation. Experimental and theoretical progress on these issues is assessed, and tentative design solutions are presented. The radioactivity levels present after operation of SOAR have been calculated and found to be low.

INTRODUCTION

This paper focuses on the critical issues for the conceptual tandem mirror fusion reactor SOAR (Space Orbiting Advanced Fusion Power Reactor). SOAR is a space-based, burst-mode power system which would provide 1000 MWe for 600 s at specific power levels of about 2 kWe/kg. Although the initial SOAR design aimed at 1000 MWe (Santarius et al. 1988), the concept should perform well even at lower power levels, and scaling with net power level is discussed. After briefly reviewing the initial SOAR reference case, the critical issues are addressed.

The good performance of the SOAR concept stems from the use of the D/He-3 fusion fuel cycle, which produces less than 5% of its power in neutrons. A large fraction of the fusion power is therefore available as charged particles, which may be converted directly to electricity by efficient (>80% for direct converter) electrostatic means. Consequently, heat rejection mass can be greatly reduced, as can neutron shielding for the superconducting magnets.

The main critical issues for SOAR are in the areas of plasma physics, fueling, high voltage direct converter design, and the operational impact of low radioactivity. Although SOAR utilizes plasma physics models that are very similar to those of standard conceptual D/T tandem mirror reactors (Logan et al. 1986), considerable experimental effort in improving and verifying those models remains. Fueling of SOAR requires new ideas for incorporating He-3 into useful pellets, and a plasma gun approach also looks promising. A feasible direct electrostatic converter has been designed, but more information on high-voltage breakdown in space is required. SOAR is very attractive from the perspective of radioactivity, because no radioactivity would be present at launch and, even after operation, radiation levels would be relatively low.

OVERVIEW OF THE 1000-MWe SOAR DESIGN

SOAR would deliver 1000 MWe for 600 s from a D/He-3 plasma. A more detailed discussion of the design is given in Santarius et al. (1988). About 96% of the fusion energy is in charged particles, and much of this energy is electrostatically converted directly into electricity at high efficiency (>80% for direct converter). The basic reactor configuration is shown in Figure 1. Advanced materials and shielding techniques would allow SOAR to deliver approximately two watts of electricity for every gram of material orbited. The SOAR reactor would allow rapid startup and shutdown and, although the initial thrust of the study was to design a single-shot system, moderate design modifications would allow a multiple-shot capability. A key feature of the present design is that all of the rejected heat generated during the 600 s operating time is absorbed adiabatically in the LiH shield, and no thermal cycle is used. For steady-state operation, we envision utilizing some of the existing structure to add a thermal cycle, with a goal of increasing the net electric power and reducing the necessary radiator mass. The lack of radioactivity on launch and the low radioactive inventory after operation make the SOAR concept attractive from both safety and environmental perspectives. The symbiosis of burst mode requirements, D/He-3 tandem mirror fusion reactor characteristics, and the space environment lead to a flexible high-performance design concept, whose main parameters are shown in Table 1.

The total mass of the central cell magnets, shield, and cryoplant may be treated and minimized as a single system. For SOAR, an optimized shield of LiH has been chosen (El-Guebaly 1988), and the shielding thickness for minimum mass is approximately 40 cm. The peak power density in the magnet windings is 10 mW/cm^3. Waste heat generated during the 600-s operation time is adiabatically absorbed in the shield. This requires a small pump to circulate helium

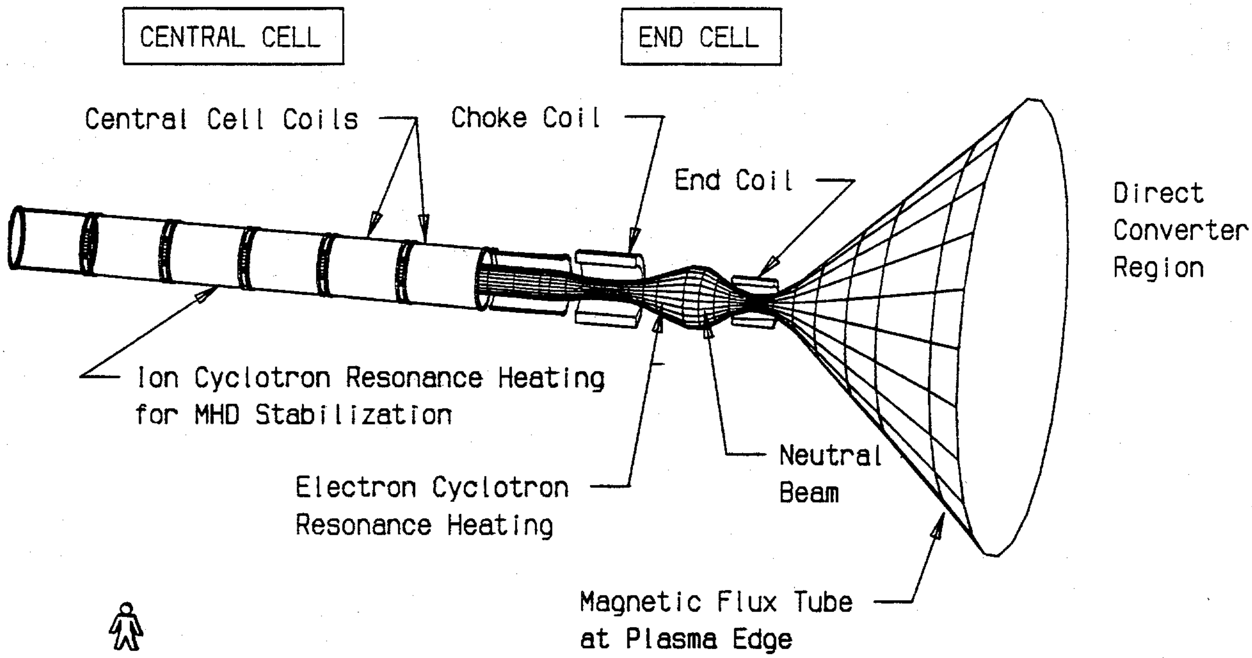

Figure 1. SOAR reactor configuration.

Table 1 Machine and Power Parameters.

Parameter	Value
Specific power (kWe/kg)	2.2
Fusion power (MW)	1960
Net power (MWe)	1000
Net efficiency (%)	51
Direct converter efficiency (%)	84
Recirculating power (%)	12
Total mass (tonnes)	450
Central cell first wall radius (m)	0.41
Central cell length (m)	93
He-3 to D density ratio	1
End cell lengths (m)	8
First wall surface heat load (MW/m^2)	1.6
Neutron wall load (MW/m^2)	0.17
Shield thickness (m)	0.32
Central cell magnetic field (T)	6.4
Choke coil magnetic field (T)	24[a]

[a]8 T from copper insert coil

in order to evenly distribute the heat over the shield volume and avoid hot spots.

The direct converter for SOAR consists of conducting grids and thin plates tethered at the ends of the tandem mirror reactor. Because the direct converter could be tethered at any reasonable distance, heat loads and voltages are kept to manageable values. With the design flexibility inherent in the space environment, an efficiency of 84% is predicted for the direct converter. This high efficiency derives from the narrow energy spread compared to the peak energy of the charged particle flux escaping axially from the plasma. The net efficiency for SOAR as a whole is considerably less because no conversion system is included for the thermal power.

SOAR could be regularly tested with little impact on fuel or coolant inventories. Typically, a 90-s test run would suffice to check all systems at full power, while consuming only 5% of the helium coolant inventory. Furthermore, the standby power source could be used to cool the helium back to its original temperature. Thus, by providing a few grams of excess fuel, SOAR could be periodically tested for reliability without adversely affecting system performance. Because the response time of the electrostatic direct converter is extremely fast, fusion power in the form of charged particle end loss from the core plasma can be used to bootstrap startup. For example, based on plasma energy content the power required to bring the plasma to a density of 5×10^{19} m^{-3} and a temperature of 55 keV in 10 s is about 9 MW, and the plasma would then be producing 34 MW of fusion power. Thus, we anticipate the need for a startup power source, e.g. capacitors, providing about 100 MJ of energy.

SCALING WITH OUTPUT POWER LEVEL

The first phase of SOAR was designed for burst-mode power at 1000 MWe. Two low-power options are also of interest:

1. The basic SOAR design could be optimized for a lower power level and smaller size, and
2. A 1000 MWe SOAR device could be operated steady-state at low density with minimal modifications to provide housekeeping or alert-mode power.

The first option is useful in that the flexibility inherent in the SOAR concept allows it to match overall systems requirements with few changes in the basic design. The second option would allow a single device to fulfill multiple roles without compromising performance.

SOAR remains reasonably attractive for burst-mode power down to at least 200 MWe. Figure 2 shows the dependence of the net power to mass ratio on net power level for optimized SOAR configurations. Even at 200 MWe, SOAR would achieve about 0.7 kWe/kg. Because tandem mirror reactors require almost the same end cell size and input power regardless of the central cell length, the main design change in going to lower powers is to shorten the central cell. End cell parameters change slightly, because the recirculating power fraction changes and the designs optimize at somewhat different points.

For low-power, steady-state operation, the rejected heat presently absorbed in the LiH shield must be radiated to space, and a small refrigerator would be needed to keep the superconducting magnets cold. The magnets would probably be designed for continuous rather than the present "blow-through" cooling. These changes would raise the total mass of the system for a given power level, but the increased flexibility appears to favor such a trade. We are presently considering options for utilizing some of the existing structure in a thermal cycle to reduce the radiator mass and increase the net power.

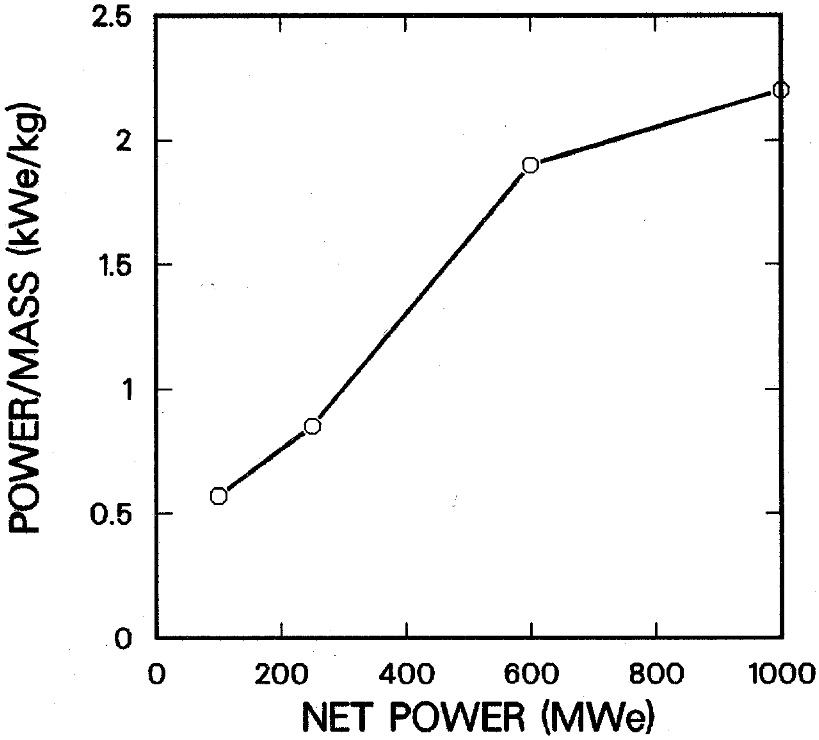

Figure 2. Dependence of net power to mass ratio on net power level for optimized SOAR configurations.

PLASMA PHYSICS ISSUES

The critical issues for D/He-3 tandem mirror operation are related to verifying the theoretical plasma physics models at high density and temperature. The key issues are:

1. Providing plasma ion end-plugging,
2. Operating the thermal barrier region which thermally insulates the end cell electrons from the central cell electrons,
3. Maintaining magnetohydrodynamic (MHD) stability of an axisymmetric tandem mirror, and
4. Maintaining a non-Maxwellian (non-thermal) hot electron population in the end cells.

Experimental progress is being made at relatively low density for all of these issues both in the U.S. and in Japan. A good, recent review is by Post (1987).

Ion end-plugging depends on maintaining a complicated mix of magnetically and electrostatically trapped plasma populations in the end cells. These, in turn, create the electrostatic potential peak that controls the central cell ion end loss. A key element of the theory is the prediction that ion end-plugging will scale exponentially with the ratio of potential peak to central cell ion temperature (Pastukhov 1974 and Cohen et al. 1978). This relation has been verified (Inutake et al. 1985).

Tandem mirrors require thermal barriers to efficiently create the electrostatic potential needed for axial ion plugging. The existence of a thermal barrier potential dip has been verified (Cho et al. 1986). The existence of electron populations with different temperatures on opposite sides of the thermal barrier has also been shown. However, a clear demonstration of a causal connection between the thermal barrier and thermal insulation between species has not yet occurred.

Totally axisymmetric operation of tandem mirror experiments using radio frequency (RF) stabilization has been demonstrated at relatively low density and temperature (Ferron et al. 1983 and Breun et al. 1986). Considerable theoretical progress has also been made in understanding the physics of this stabilization mechanism (D'Ippolito and Myra 1986). Nevertheless, the power requirements for RF stabilization are still very uncertain, and the 25-MW absorbed power for SOAR is an assumed value. However, the effect of RF stabilization power on the net power to mass ratio is weak in SOAR, as shown in Figure 3.

Hot electron populations with profiles similar to those used in modelling SOAR have been shown to exist in the Gamma-10 experiment (Kiwamoto et al. 1986). The thermal barrier region in that machine is axisymmetric, as is the case in SOAR. Devices which have quadrupolar magnetic fields at one or both ends of the thermal barrier have had much more difficulty maintaining hot plasma populations above a given density threshhold (Simonen et al. 1987). Those difficulties are possibly related to the creation of asymmetric azimuthal potentials caused by electron cyclotron resonance heating in the quadrupolar magnetic field configuration.

In general, considerable extrapolation remains between the parameters of SOAR and existing tandem mirror experiments. The U.S. Department of Energy fusion program is not likely to address these in the near future. Thus, a dedicated set of experiments would be necessary to test the SOAR concept. However, the basic physics of SOAR could be tested on relatively short devices due to the effective decoupling of central cell and end cell operation. Also,

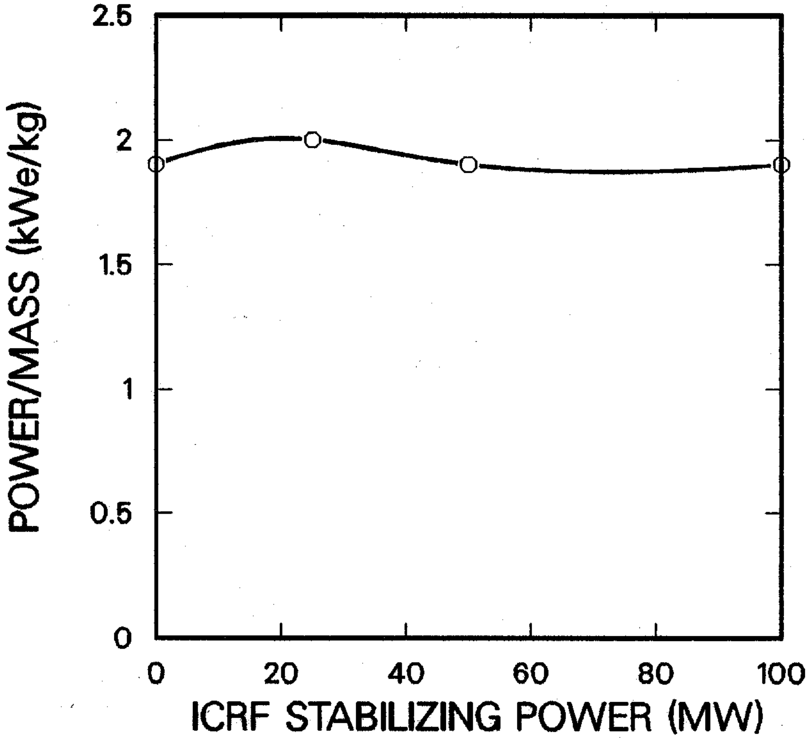

Figure 3. Dependence of net power to mass ratio on RF power applied to provide MHD stability in SOAR.

much of the end cell physics could be tested utilizing a driven central cell, and ignition would only be required in a demonstration device.

HIGH VOLTAGE DIRECT CONVERTER DESIGN

The present SOAR reference design requires a direct electrostatic converter operating at about 1 MV with respect to the potential of the rest of the device. The first-phase SOAR design was based on a mode in which 14.7 MeV fusion-product protons are efficiently converted to electrical energy through the use of the so-called "Ra" mode with an electrostatic direct converter operating at about 14 MV (Santarius 1987). The various grids, plates, and voltages for both configurations are shown in Figure 4. Although a direct converter design at the 14-MV level appears to be feasible, a parametric study, using the reactor optimizing computer code discussed in Santarius et al. (1988) with an improved direct converter module, indicates that the performance of SOAR in the standard mode, where the maximum direct converter voltage is about 1 MV, gives essentially the same performance, as shown in Figure 5. The overall size of the direct converter in the standard mode is a factor of three to four less than the size of a Ra-mode direct converter.

The critical question in both modes is that of high voltage breakdown in space, which is poorly characterized at present. Very few experiments have been run even at modest voltages in the space environment. Therefore, the SOAR direct converter design is based on guidelines from terrestrial experiments, space shuttle experience, and theory. Much of the basic analysis follows the pioneering direct converter work at Lawrence Livermore National Laboratory (LLNL) (Moir and Barr 1973 and Barr and Moir 1983). The key issues and the design solutions chosen are summarized in Table 2.

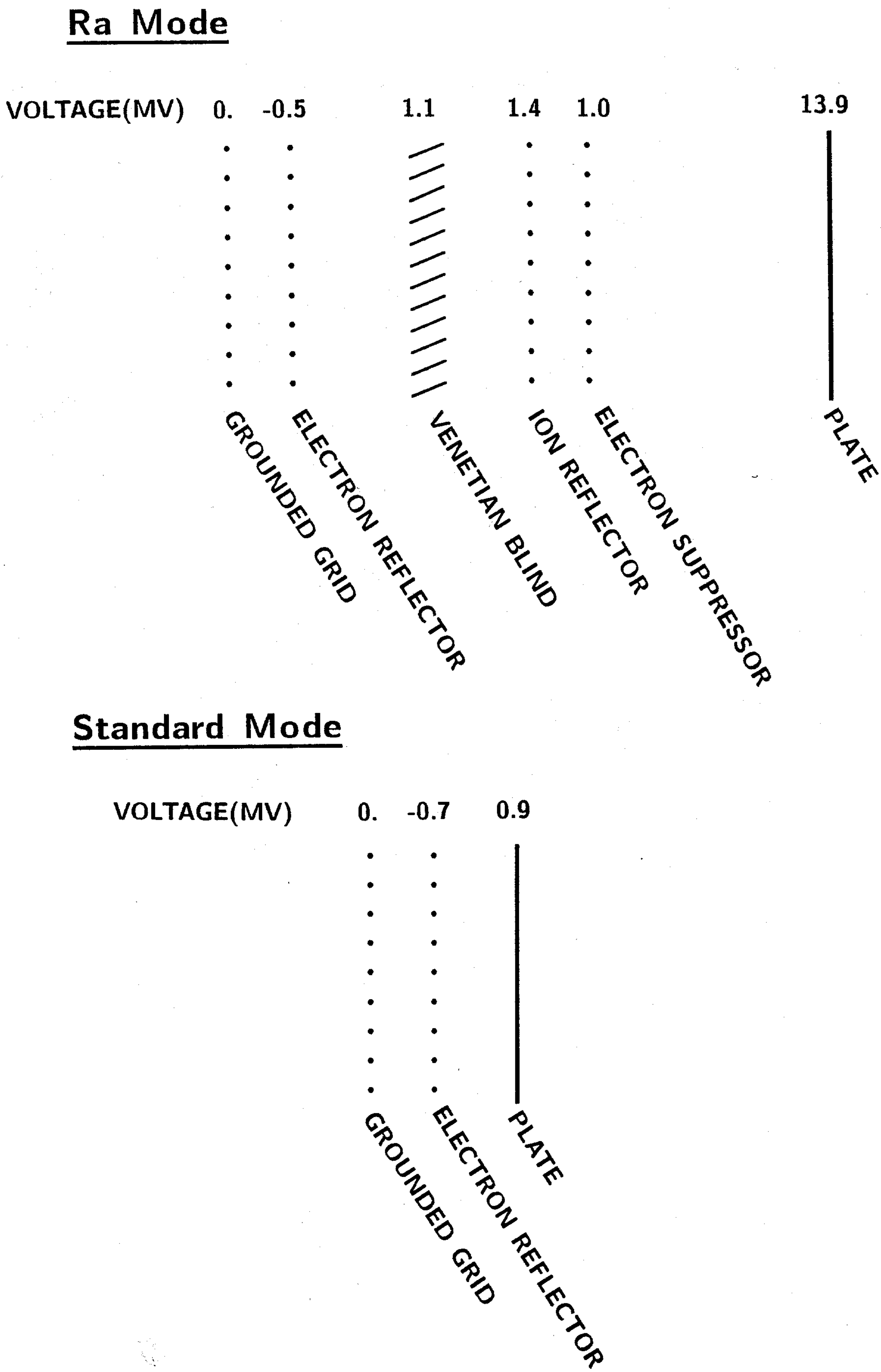

Figure 4. SOAR direct converter grids and plates for standard and high-voltage configurations.

Table 2 Tentative Solutions for Direct Converter Design Problems.

Issues	Solution
Thermionic electron emission	Upper temperature limit for surfaces
Secondary electron emission	Self-consistent design
Space charge effects	Maximum allowed grid spacing
Sheath extent	Faraday cage
High voltage breakdown Reduced neutral gas density Reduced plasma density	Controlled voltage gradients

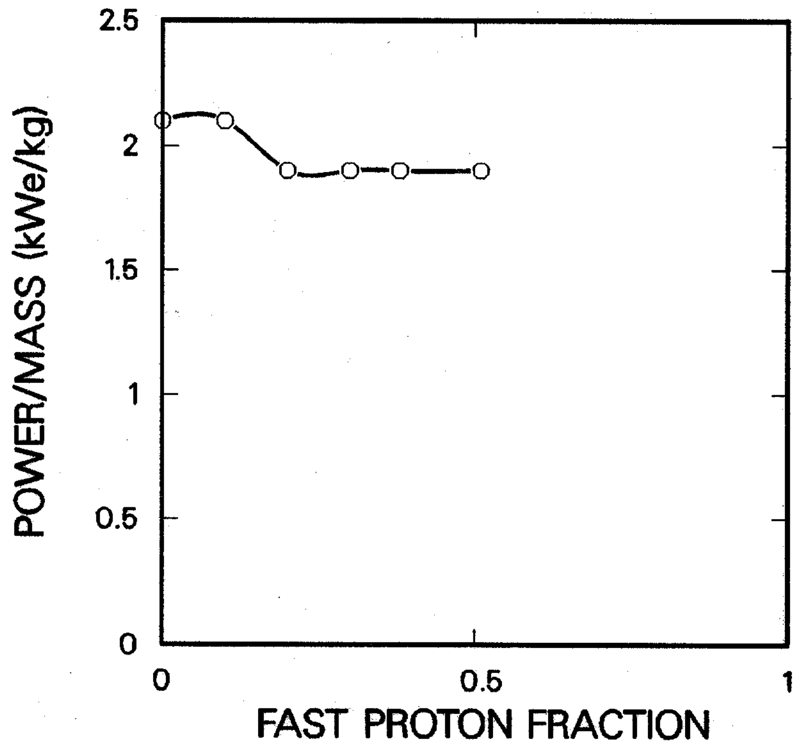

Figure 5. Dependence of net power to mass ratio on fraction of high energy proton power converter directly to electricity for SOAR. The 1-MV standard case converts only the energy of standard end-loss ions and corresponds to a high energy proton conversion fraction of zero.

To keep thermionic electron emission low, the entrance (reference potential) grid of the direct converter is placed sufficiently far from the end of the central cell to keep the temperature of the grid wires below 1600 K. To allow adequate radiative cooling of the wires, their aspect ratio is 4, and the surface heat flux is limited to 4 MW/m^2. Secondary electron emission is self-consistently included for the calculated currents present in the direct converter using a secondary electron emission coefficient of 3. The space charge analysis follows the Child-Langmuir law. An important feature of SOAR is that a Faraday cage (radius=25 m but mass < 1 tonne) surrounds the direct converter. The Faraday cage keeps the extent of the electrostatic sheath relatively small. We conjecture that the Faraday cage will protect the direct converter from an electromotive pulse (EMP), but we have not yet addressed this question. The SOAR direct converter configuration is shown in Figure 6.

Based on LLNL experience (Barr and Moir 1983), the direct converter grid wires were designed with an average surface electric field of < 2 MV/m. This required a modest increase in grid spacing and the use of larger radius wires than would be needed from structural considerations. The resulting grid transparency for the reference case was 97.5%. The ambient neutral gas and plasma environment must also be carefully controlled. However, based on Space Shuttle experience, the SOAR direct converter could be operated in the wake of a shield of relatively small mass (about 1 tonne). The resulting environment would be adequate to maintain direct converter voltage standoff.

A further question regards power conditioning, partly because the requirements for end-use voltages are not presently well-defined. Spark-gaps have been tentatively identified as the best solution for high-voltage switching in SOAR. Losses are typically 2% to 10%. Electrode erosion does not appear to be a problem for SOAR due to the relatively low current and

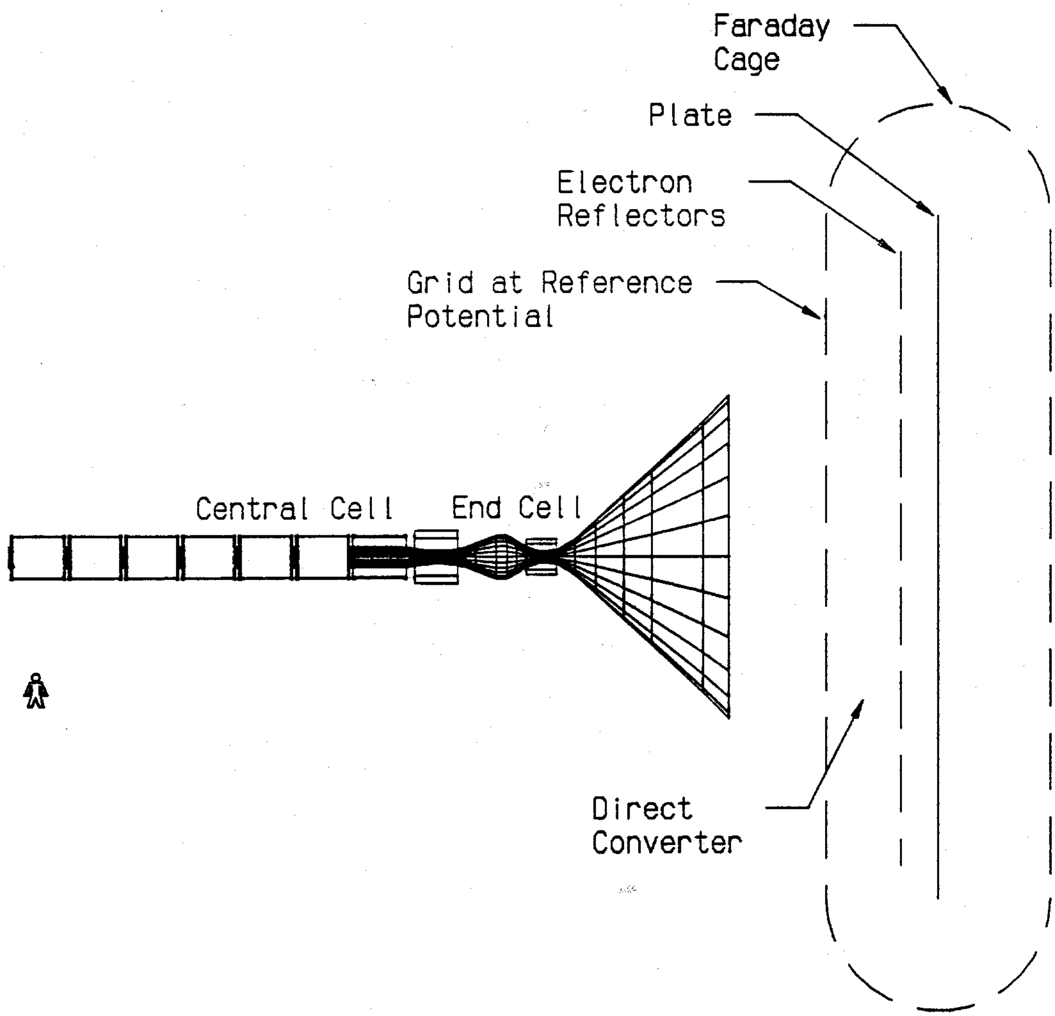

Figure 6. SOAR direct converter configuration for the 1-MV reference case.

short operating time. The total power-conditioning mass for SOAR at the 1000-MWe level is estimated to be less than 50 tonnes.

FUELING

The D/He-3 plasma in SOAR will be a hostile environment for materials, and fuel-pellet velocities must be very high, >10 km/s, even for shallow penetration. Furthermore, helium remains liquid except at high pressures, so that "ice" pellets, as used for D/T fusion reactors, will not work. Concepts have been formulated for fabricating He-3 pellets using thin plastic or low-Z metal shells (Wittenberg 1987). Pellets incorporating He-3 would be made by diffusing He-3 gas into a pellet, cooling the pellet to liquify the He-3, coating with D_2 ice, and keeping the pellet cold until injection.

An alternate fueling mode, using plasma toroids created by plasma guns, appears promising and has been demonstrated experimentally with hydrogen at low density (Leonard et al. 1987). This concept should work equally well with He-3, D, or T. However, a detailed analysis of this fueling method for the SOAR design has not yet been done.

IMPACT OF LOW RADIOACTIVITY

SOAR is very attractive from the perspective of radioactivity, because no radioactivity would be present at launch and, even after operation, radiation levels would be relatively low. However, despite the low neutron flux generated by SOAR, some operational radioactivity will be present. The radiation fields in the vicinity of the reactor have been mapped as a function of time in order to assess their impact on nearby objects. The results are shown in Figure 7.

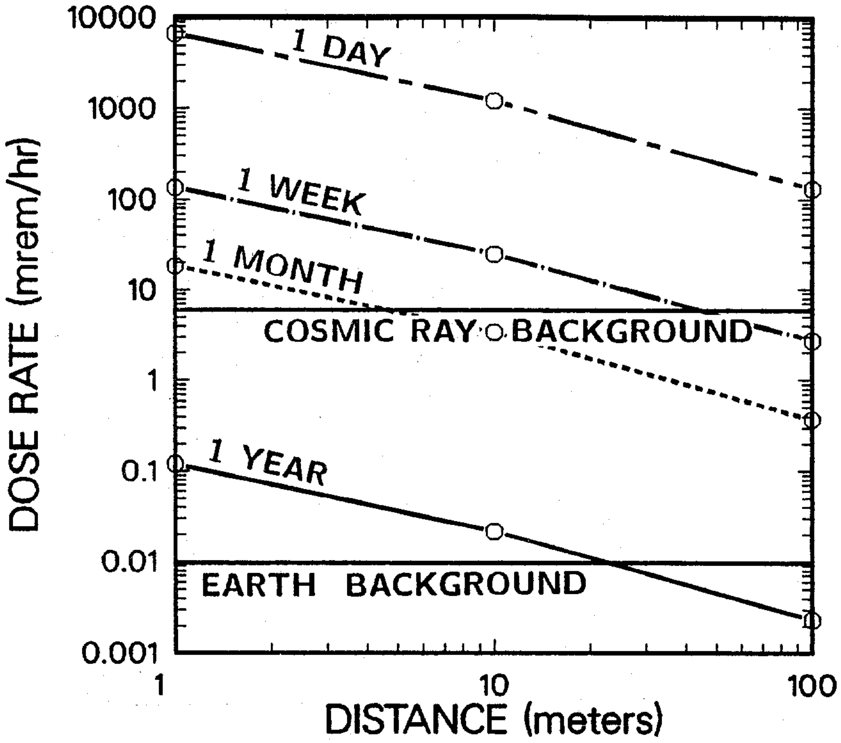

Figure 7. Radiation fields in the vicinity of SOAR after 600 s operation. No radioactivity exists in SOAR until after its operation.

CONCLUSIONS

The SOAR concept applies to a variety of missions at diverse power and operating time levels--including housekeeping, alert-mode, burst-mode, and steady-state power. Essentially the same device, in different operating modes, could be used for those missions. SOAR will require a substantial development program, but the critical issues have been identified and tentative solutions suggested. An experimental approach to resolving these issues definitively in a relevant time frame appears to be feasible.

ACKNOWLEDGMENTS

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REFERENCES

Barr, W.L. and R.W. Moir (1983) "Test Results on Plasma Direct Converters," Nucl. Technol./Fusion 3: 98-111.

Breun, R.A. et al. (1986) "Stabilization of MHD Modes in an Axisymmetric Magnetic Mirror by Applied RF Waves and Initial Results of Phaedrus-B," in Plasma Physics and Controlled Nuclear Fusion Research 1986, Vol. 2, International Atomic Energy Agency, Vienna, p. 263-271.

Cohen, R.H. et al. (1978) "Collisional Loss of Electrostatically Confined Species in a Magnetic Mirror," Nucl. Fusion 18: 1229-1243.

D'Ippolito, D.A. and J.R. Myra (1986) "Stabilization of Magnetohydrodynamic Modes by Applied Radio-Frequency Waves," Phys. Fluids 29: 2594-2604.

El-Guebaly, L.A. (1988) "Magnet Shielding Analysis for SOAR--A Space Reactor," in Space Nuclear Power Systems 1987, M.S. El-Genk and M.D. Hoover, eds., Orbit Book Co., Malabar, FL.

Ferron, J.R. et al. (1983) "RF Stabilization of an Axisymmetric Tandem Mirror," Phys. Rev. Lett. 51: 1955-1958.

Inutake, M. et al. (1985) "Thermal Barrier Formation and Plasma Confinement in the Axisymmetrized Tandem Mirror GAMMA 10," Phys. Rev. Lett. 55: 939-942.

Kiwamoto, Y. et al. (1986) "Production of Hot Electrons for Axisymmetric Thermal Barrier Formation in a Tandem Mirror," Phys. Fluids 29: 2781-2784.

Leonard, A.W., R.N. Dexter, and J.C. Sprott (1987) "Trapping of Gun-Injected Plasma by a Tokamak," Phys. Fluids, 30: 2877-2884.

Logan, B.G. et al. (1986) "MINIMARS Conceptual Design: Final Report Vols. 1 and 2," Report UCID-20773, Lawrence Livermore National Laboratory, Livermore, CA.

Moir, R.W. and W.L. Barr (1973) "'Venetian-Blind' Direct Energy Converter for Fusion Reactors," Nucl. Fusion 13: 35-45.

Pastukhov, V.P. (1974) "Collisional Losses of Electrons from an Adiabatic Trap in a Plasma with a Positive Potential," Nucl. Fusion 14: 3-6.

Post, R.F. (1987) "The Magnetic Mirror Approach to Fusion," Nucl. Fusion 27: 1579-1739.

Santarius, J.F. et al. (1988) "SOAR: Space Orbiting Advanced Fusion Power Reactor," in Space Nuclear Power Systems 1987, M.S. El-Genk and M.D. Hoover, eds., Orbit Book Co., Malabar, FL.

Santarius, J.F. (1987) "Very High Efficiency Fusion Reactor Concept," Nucl. Fusion 27: 167-171.

Simonen T.C. et al. (1986) "TMX-U Tandem Mirror Thermal Barrier Experiments," in Plasma Physics and Controlled Nuclear Fusion Research 1986, Vol. 2, International Atomic Energy Agency, Vienna, p. 231-241.

Wittenberg, L.J. (1987) "Helium-3 Fueling Concepts for Magnetically Confined Fusion," in Proceedings of the 12th Symposium on Fusion Engineering, held in Monterey, CA, 12-16 October 1987.