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Introduction

An Engineering Scoping Study of a Field-Reversed Configuration (FRC) burning D-T fuel is being performed by the Universities of Wisconsin, Washington, and Illinois. The research has begun only recently, so the information contained in this paper should be considered preliminary. The effort concentrates on tritium-breeding blanket design, shielding, radiation damage, activation, safety, environment, plasma modeling, current drive, plasma-surface interactions, economics, and systems integration. A systems analysis code serves as the key tool in defining a reference point for detailed physics and engineering calculations plus parametric variations. Advantages of the cylindrical geometry and high β (plasma pressure/magnetic-field pressure) are already emerging.

With regard to fusion development, the FRC provides a good balance between physics uncertainty and engineering attractiveness. In particular, the trade-offs among physics, engineering, safety, and environmental considerations have only recently gained prominence—partly due to the difficulties encountered when the fusion community realistically faced engineering issues in designing ITER. While the physics obstacles on the FRC development path should not be underestimated, excellent progress is being made by the very small worldwide FRC research community [3]. The key physics issues include operation at large s (average number of radial gyroradii), startup with reasonable power, and sustainment. From an engineering standpoint, an FRC burning D-T fuel appears capable of being built with near-term technology to a large extent. The main exceptions are the materials used for the first wall, blanket, and shield, which will be subject to high neutron fluences with consequent radiation damage and activation. If the more difficult physics requirements of D-^{3}He fuel can be achieved, essentially all necessary FRC technology appears to be in hand, benefits would be gained from direct conversion, and environmental and safety characteristics would be substantially improved [4].

Objective and Tasks

The objective of the D-T FRC engineering issues scoping study is to investigate the critical engineering issues for D-T FRC electric power plants. The main tasks involved in this research and the institutions with primary responsibility are:

- *University of Wisconsin*
  - ☐ Coordination
  - ☐ Systems analysis and economics
  - ☐ Tritium-breeding blanket design
  - ☐ Radiation shielding and damage
  - ☐ Activation, safety, and environment
- *University of Washington*
  - ☐ Plasma modeling
  - ☐ Current drive
- *University of Illinois*
  - ☐ Plasma-surface interactions
  - ☐ Plasma exhaust handling

If time and resources permit, other areas will be investigated. Those with the potential for having an important positive or negative impact on the design include maintenance, high-T_c superconducting magnets, energy conversion, liquid-metal first walls, and systems integration.

Status

The status of the study as of March, 1998, which is about six months into the two-year project, is as follows:

- The U. Wisc. D-T/D-^{3}He tokamak systems code is being modified to include FRC physics, engineering, and economics based on U. Wash. physics models and U. Wisc. engineering and economics models.
- U. Wisc. is developing an innovative tritium breeding blanket concept and evaluating the possible use of previously published blanket designs.
- U. Wisc. is assessing options for radiation shielding.
- U. Wash. is generating current-drive models.
- U. Ill. is investigating plasma-surface interaction and plasma exhaust handling issues.

The systems code contains plasma physics, engineering, and economics models, and its power flow model is illustrated in Fig. 1. Viable FRC startup and sustainment methods with reasonable input powers are being sought. The requirements for two promising methods, rotating-magnetic-field (RMF) current drive and merging spheromaks, are being determined and modeled. Plasma-surface interactions are being studied in both the fusion core and end tanks. Most transport losses are along the magnetic field lines to an end tank or direct energy converter. There, flux tubes can be expanded to reduce heat fluxes and particle erosion of surfaces. Thus, while plasma exhaust issues are similar to those encountered in a tokamak divertor, in an FRC the ability to employ larger surface areas significantly alleviates design difficulties. Trade-offs among various reactor design options are being assessed.

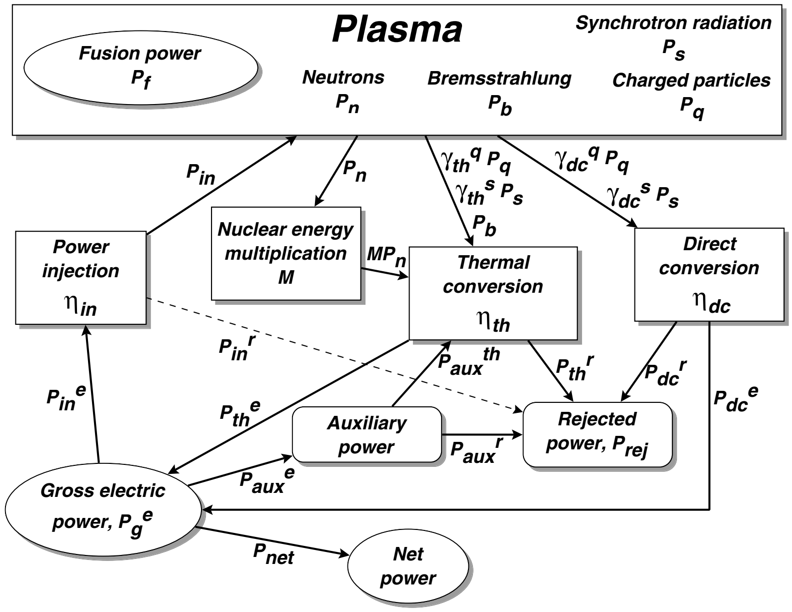

Figure 1: *FRC plasma and plant power flow.*

A tritium-breeding blanket for an FRC is in many ways simpler than for a tokamak. The extremely high tokamak magnetic fields lead to large toroidal field coils which, along with the toroidal geometry, reduce maintenance access and usually require splitting blanket modules into several submodules and translating them toroidally for removal. In an FRC, the cylindrical geometry and low magnetic field allow removal of *single* modules containing the first wall, blanket, shield, and magnets. If liquid-metal coolants are used, the MHD pressure drop will also be substantially reduced by the low magnetic field and short flow paths. A key question is whether it will be necessary to use exotic materials, such as SiC or V, or nearly off-the-shelf materials, such as low-activation ferritic and austenitic steels.

We are pursuing parallel courses for scoping tritium-breeding blanket designs: (1) evaluate new ideas and (2) assess established concepts. Figure 2 shows the initial blanket concept, which uses Li_2O breeder, austenitic or ferritic steel structure, and helium coolant. Stainless steel structure and water coolant would be used for the shield. Another possibility is use of the Mirror Advanced Reactor Study (MARS) [1] blanket, shown in Fig. 3, with key parameters given in Table 1. This approach would take advantage of the geometrical similarity of FRC and tandem-mirror core regions.

An important advantage of FRC power plants is that they are not subject to the type of disruption experienced by a tokamak, where the energy from the thermal quench gets deposited inside the fusion core chamber on divertor plates or the first wall. Analogous MHD instabilities in FRC's will cause the plasma to flow along the magnetic flux tube and deposit in an end tank, where the flux tube can be expanded to mitigate the effect and space exists for a more robust design. This avoids the tokamak's extremely difficult divertor design problem and also helps keep material ablated by a disruption from coating the fusion chamber in unpredictable locations.

The steady-state heat flux on an FRC first wall results mainly from bremsstrahlung radiation, because almost all charged particles will follow magnetic flux tubes to the end tanks. Although

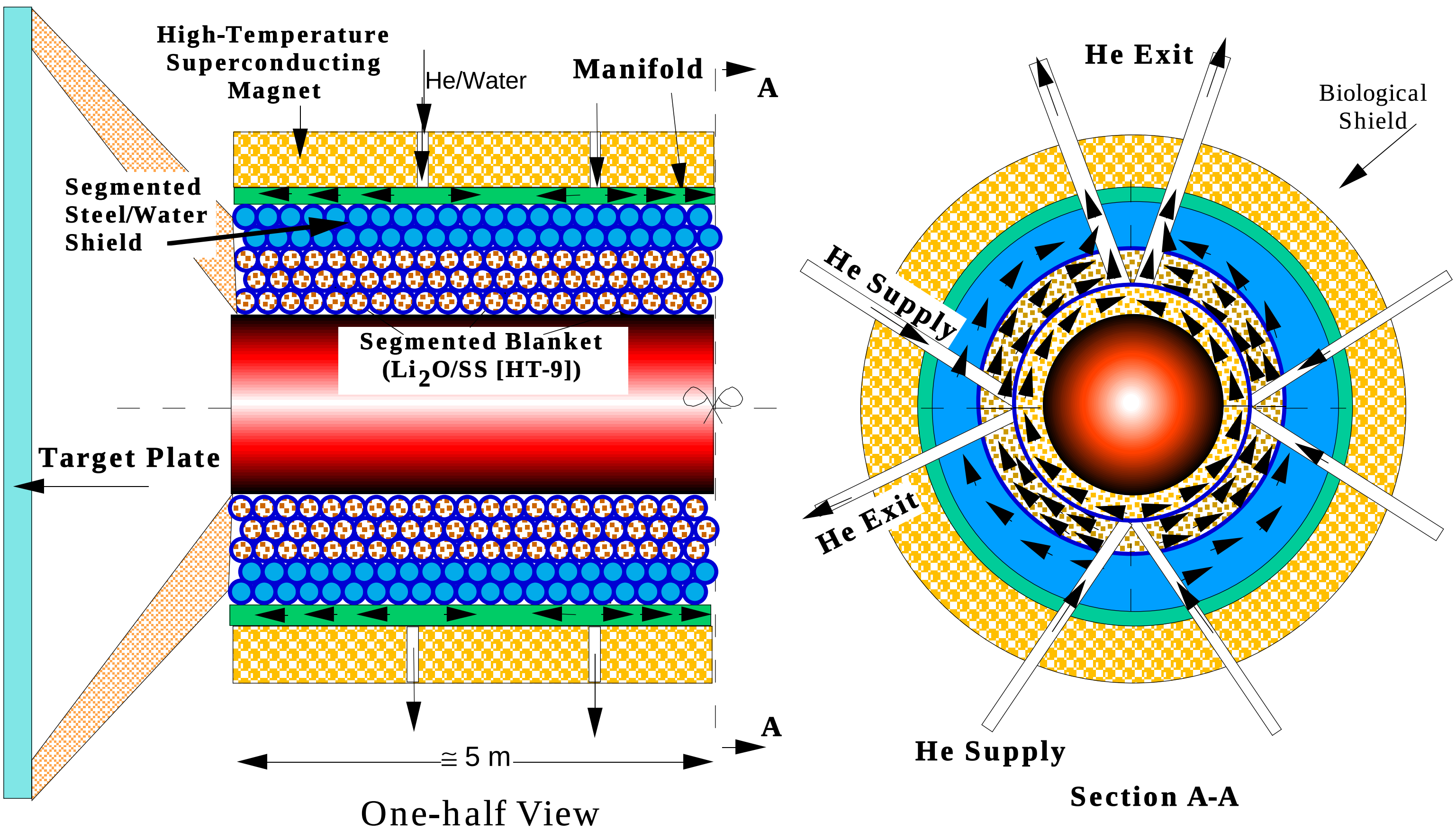

Figure 2: *One-half view and cross section of a preliminary concept for the tritium-breeding blanket.*

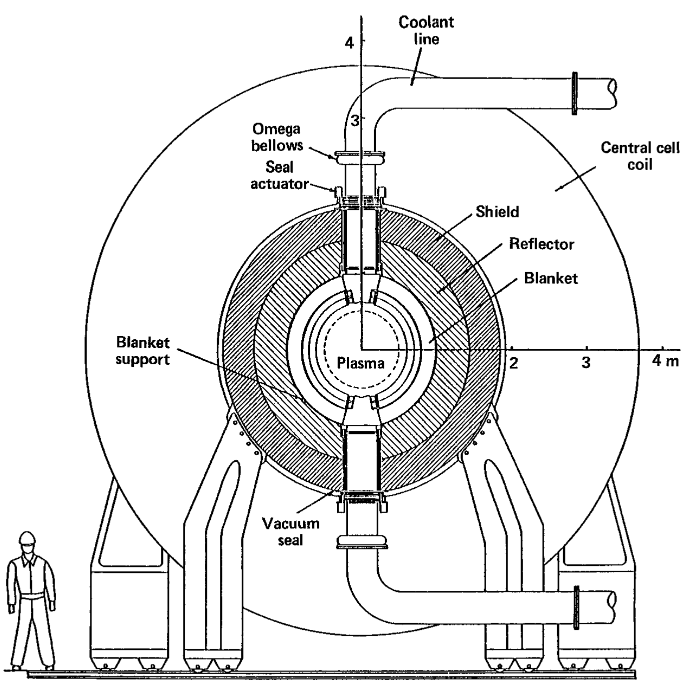

Figure 3: *Cross section of the MARS tritium-breeding blanket.*

Table 1: *Parameters for the MARS blanket.*

Structure	HT-9 Steel
Coolant	Li17 Pb83
Breeder	Li17 Pb83
r_w	0.6 m
Γ_n	4.3 MW/m^2
M	1.36
TBR	1.15
η_{th}	42%

the first wall surface heat loads resulting from the radiation will be $\sim$1 MW/m^2, the heat flux will be fairly uniform, and the FRC should not experience the steady-state and much higher peak and average surface heat fluxes of the tokamak divertor.

Several neutronics and safety advantages exist for a D-T FRC:

- The FRC geometry allows a high coverage fraction for tritium breeding and hence allows efficient breeding using a solid breeder with possibly no need for a beryllium multiplier.
- Eliminating the beryllium multiplier would allow the use of water inside the vacuum vessel while maintaining good safety by eliminating the risk of severe hydrogen production caused by the beryllium-water interaction.
- An FRC has no analogue to tokamak disruptions, thus providing a significant safety advantage by lowering the vulnerability to an accidental release of radioactivity.

For the FRC magnets, the MINIMARS [2] central-cell magnets, which were radially thin coils that covered the tandem mirror central cell nearly uniformly, would be suitable for the present design. Parameters for the MINIMARS central-cell magnets are given in Table 2. Even more leverage would be gained by the use of high-temperature superconductors, which should be more robust against quenching, require less shielding and, therefore, allow larger internal heat deposition by radiation.

Table 2: *MINIMARS central cell parameters.*

Number of modules	24	Peak B field	3.1 T
Module length	2.8 m	Current density	37 MA/m^2
Module radius	1.75 m	Current	30 kA
Magnet thickness	0.06 m		

Fusion Development Perspective

Field-Reversed Configurations appear capable of satisfying the key requirements of an attractive electricity-producing power plant, listed in Table 3. A mixture of deuterium and helium-3 (D-^{3}He) will most likely be the fuel of choice for the most attractive FRC power plants, and the required technology for these appears to be essentially in hand [4]. An important aspect of this is that the engineering-driven development path required for an FRC should be less time consuming and expensive than the physics-driven path being followed by the tokamak. This stems from the generally longer time required for developing engineering systems compared to investigating physics issues. These paths are contrasted in Fig. 4.

Using ^{3}He fuel, however, does require ‘thinking outside the box,’ for it probably necessitates acquiring ^{3}He from the Moon [5, 6] or breeding ^{3}He using a driven, deuterium-fueled reactor [7]. Briefly summarizing the ^{3}He resource situation, there are:

- $\sim$400 kg ^{3}He accessible on Earth ($\sim$8 GW-yr fusion energy) for R&D.
- $\sim 10^9$ kg ^{3}He on the lunar surface for the 21st century.
- $\sim 10^{23}$ kg ^{3}He in gas-giant planets for the indefinite future.

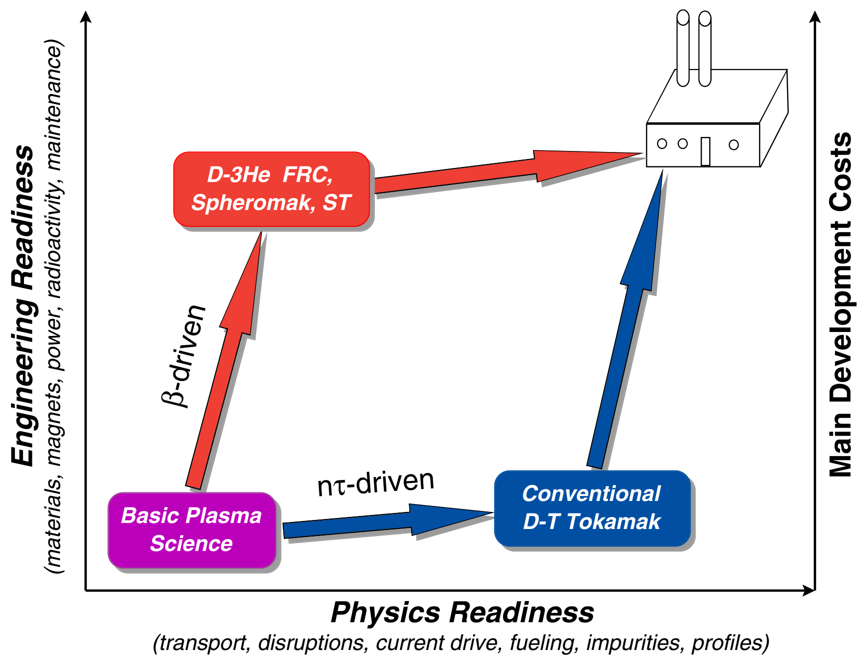

Figure 4: *D-^{3}He and High β will lower fusion development costs.*

Fortunately, lunar ^{3}He mining needs only straightforward extrapolations of terrestrial mining technologies: bucket wheel excavators, conveyor belts, and process heat [5, 6]. The main leverage areas for the cost of ^{3}He are Earth-launch costs or use of in-situ materials to construct lunar ^{3}He miners.

One of the most intriguing aspects of D-^{3}He power plant design is that they should not contribute to nuclear proliferation. The thickness of radiation shields for superconducting magnets in D-^{3}He fusion cores are typically a factor of two less than required for D-T fuel. Thus, burning D-T in such reactors would both overheat and damage the superconducting magnets to unacceptable levels.

Table 3: *Key requirements for an attractive electricity-producing power plant.*

- *Low cost*
  - $\Longrightarrow$ High engineering power density
  - $\Longrightarrow$ Low unit costs for materials
  - $\Longrightarrow$ Efficient energy conversion
  - $\Longrightarrow$ Low recirculating power
- *Safety*
  - $\Longrightarrow$ Low radioactivity
  - $\Longrightarrow$ Low chemical toxicity
  - $\Longrightarrow$ Minimal sources of free energy
- *Protected environment*
  - $\Longrightarrow$ Low long-lived radioactive inventory
  - $\Longrightarrow$ Minimal pollutant release
  - $\Longrightarrow$ Environmentally benign construction

Summary

The high power density and cylindrical geometry of D-T FRC's should allow them to overcome the major engineering obstacles facing D-T tokamaks. On the fusion energy development path, FRC's occupy the important position of leading the β-driven, engineering route. FRC's match D-^{3}He fuel well and the combination potentially could outperform D-T power plants.

Acknowledgement

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