COMMERCIAL REACTORS WITH RESISTIVE MAGNETS

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Abstract

A cost-based systems model is used to re-examine resistive-coil tokamak power reactors and to examine physics, engineering, and operational tradeoffs needed to project an economically competitive system. The developmental, technological, costs, and operational issues of copper-coil reactors are revisited in light of recent engineering innovations and new developments in physics. The critical issues of engineering innovation (neutronics related) are discussed.

1 Introduction

Interest in normal conducting tokamak reactors is justified because of substantial advantages offered over superconducting magnets.1,3 Some of these advantages include ease of maintenance, minimization of the shield-thickness requirements, and a reduced developmental path (in the engineering issues) for fusion commercialization.

The technological and operational advantages of using resistive (copper alloy) magnets to generate the toroidal field in a commercial fusion power station must be balanced against the increased costs associated with a more massive fusion power core and the added power needed to supply ohmic dissipation in the magnets. After detailing the technological and operation features and advantages of copper-coil fusion reactors in Section 2 and the neutronic characteristics of the system in Section 3, the tradeoffs are quantitatively evaluated using the cost-based systems model described in Section 4; parametric results are also given in Section 4. A summary and conclusions are given in Section 5. The primary goal of this study is not to generate an optimized design, but rather to identify fertile areas and future directions for improved tokamak power reactors.

2 Engineering Issues

In this section, design issues of resistive tokamak reactors previously addressed are summarized, and innovative engineering features are described. A novel method of increasing the lifetime of the magnet, the self-shielded coil, is analyzed.

Resistive magnets have many advantages over superconducting magnets. The one disadvantage that they have is the resistive power. The power dissipated results in an increased power recirculating fraction for the plant. It can be easily shown3 that the dissipated power in the toroidal field coil is minimized (at constant weight) by making the cross-section of the coil uniform (i.e., constant current density in the magnet). Under these conditions the dissipated power in a magnet can be estimated by

\[ P_{TF} = \frac{\rho \sigma \sigma}{\gamma} \]

where \( \rho \) is the resistivity of the conductor, \( \sigma \) is the average minor radius of the toroidal field coil, \( \sigma \) are the stresses in the throat, and \( \gamma \) is the conductor filling fraction. In order to decrease the recirculated power, the magnet should have low stresses, resulting in large cross-section and low current density. High conductor filling fraction \( f \) is also desirable. One consequence of minimizing the dissipated power in the magnet is that problems associated with static or fatigue loads are reduced drastically, an important consideration for pulsed test reactors.

The design approach follows closely the C-MOD tokamak experimental test reactor. The coils are manufactured of simple, jointed sections. Figure 1 shows an elevation view of the toroidal field coil system for a commercial reactor using resistive coils.2 The main difference between this design and Alcator C-MOD is in the presence of cooling channels in the toroidal field coil, plus the use of a structure through the center of the machine to react the vertical loads. The plates are thick enough to carry the bending created by the vertical Lorentz load, which is reacted by the structure both outside of the bore and in the outer perimeter of the magnet. The structure through the bore of the machine and the use of thick horizontal plates that can carry most of the in-plane bending minimize the required superstructure on the top and the bottom of the reactor.

The simple sections required, coupled with the low stresses in the toroidal field coil, decreases the unit cost of the toroidal field coil. Thick plates of soft copper (does not require work hardening) can be used. Machining operations can be kept at a minimum, with only polishing and grinding operations required. This result in unit costs for the toroidal field coil that should be comparable to those of the shield. The only exception to the simple machining operation are the cooling channels and the joints. The cooling channels have to be machined (or possibly etched) and then covered. The manifolding can be done inside the plates, minimizing pipe-jointing operations (one inlet and outlet per plate). Figure 2 shows a cross-section of a coil section. The tolerance requirements for the joints can be minimized by utilizing spring-backed contacts, such as used in Alcator C-MOD. Estimates for the unit cost for the toroidal field magnet are $30-40/kg, which is a factor of 3-4 less than for superconductor magnets, but comparable to the cost of the copper in the superconducting magnets.

Resistive magnets need to be cooled in order to remove the dissipated power and the neutron heating. In order to minimize the power, the temperature of the magnet should be kept low. Due to the low heating power densities, gas cooling of the toroidal field coil can be envisioned. In order to minimize possible interaction between the coolant and the breeding material, helium is a good candidate. Organic coolants could also be considered. Radiolytic decomposition of the gaseous or liquid coolant would not be a major problem for this application, due to the reduced neutron flux at the location of the toroidal field coils. Magnet lifetime limitations due to interaction with radicules produced by radiolysis are therefore eliminated. The reliability of gas cooled, resistive magnets should be high.

Plate magnets also have the advantage of using planar insulation. It is expected that due to the nature of the loading (mostly under compression, with very little shear across the insulation) and the planar nature of the insulation, the choice of materials that can be used for insulation is substantially increased. Inorganic insulations, with much improved neutron irradiation survivability, could be used. Ceramic coolings are regularly manufactured on materials that are of interest for the magnet conductor (aluminum, through the process of anodizing, and on copper). The process is inexpensive.

The shielding required for the magnet can be further minimized by the self-shielded magnet. Since the toroidal field coils are relatively thick and the stresses are small, it is possible to thin the copper conductor in the region close to the plasma,