A Primary Energy Conversion System and Design Analysis of a Tokamak Experimental Fusion Reactor

Jay V. Kalinani
Nuclear Science and Engineering, SRM University, Katankullathur, Chennai, TN – 603202, India
Email: jayvijayk@yahoo.com

***Abstract*—Major efforts are underway to define the objectives of a Tokamak Experimental Fusion Reactor (TEFR). A tokamak is a toroidal chamber that uses a strong toroidal magnetic field to contain high temperature plasma within the torus. Charged particles cannot easily move across strong magnetic fields, and if the fields are closed into nested surface, then deuterium and tritium ions trapped in this way and colliding with sufficient energy to overcome their repulsive Coulomb potential, will fuse and liberate energy. The ultimate goal of this study is to establish the scientific and engineering basis for a detailed reactor design. This paper will concentrate on the TEFR primary energy conversion system (PECS). The PECS includes all the components that lie between the plasma and the toroidal field coil.**

***Index Terms*—tokamak, fusion, toroidal, plasma, chamber**

I. Introduction

A major purpose of this study is to focus and refine the objectives of a scientifically and technologically feasible device. Such a device should represent the logical next step beyond the Tokamak Fusion Test Reactor (TFTR) in the achievement of D-T plasma confinement adequate for power reactors. The TEFR should be a major step in the demonstration of engineering feasibility of Tokamak power reactors. It should provide experience with and demonstrate the technologies needed to synthesize a power reactor, thereby serving as a focal point for the technology development program.

The TEFR should be the logical step along the path to achievement of plasma confinement that is adequate for a power reactor. Achievement of sufficient pulse length and pulse repetition rate so that the cycle- averaged thermonuclear power, if converted to electrical power, would be in the desired range is a major goal. Conversion of this energy into sensible heat in an energy-conversion blanket is a second major goal. If these two goals could be achieved, conversion of the thermal energy in the primary coolant into electrical energy in a secondary system could be accomplished straightforwardly.

II. Basic Design and Working

The toroidal field coils, equilibrium field coils (also called poloidal field coils, which produce the vertical field and shaping field), ohmic heating coils (primary windings of the current transformer), and vacuum vessel form the base of the design. Sometimes the term 'poloidal field coils' means both the equilibrium field coils and the ohmic heating coils. By raising the current of the primary windings of the current transformer (ohmic heating coils), a current is induced in the plasma, which acts as the secondary winding.

The vacuum vessel is usually made of thin stainless steel or in-conel so that it has enough electric resistance in the toroidal direction. Therefore the voltage induced by the primary windings can penetrate it. The thin vacuum vessel is called the liner. Before starting an experiment, the liner is out gassed by baking at a temperature of 150–400◦C for a long time under high vacuum. Furthermore, before running an experiment, a plasma is run with a weak toroidal field in order to discharge-clean the wall of the liner. Inside the liner there is a diaphragm made of tungsten, molybdenum, or graphite that limits the plasma size and minimizes the interaction of the plasma with the wall. This diaphragm is called a limiter. Recently, a divertor configuration was introduced instead of the limiter. In this case the magnetic surface, including the separatrix point, determines the plasma boundary. A conducting shell surrounds the plasma outside the liner and is used to maintain the positional equilibrium or to stabilize MHD instabilities during the skin time scale. The magnitude of the vertical field is feedback-controlled to keep the plasma at the center of the liner at all times.

Many improvements have been made in tokamak devices over the years. The accuracy of the magnetic field is also important to improve the plasma performance in tokamak and other toroidal devices. Measurements by magnetic probes surrounding the plasma are a simple and useful way to monitor plasma behavior. As the magnetic probes detect MHD fluctuations, they are indispensable in the study of MHD instabilities. These small magnetic coils are called Mirnov coils. The loop voltage V_L and the plasma current I_p can be measured by the magnetic loop and Rogowsky coil, respectively.

III. PECS Design Summary

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The PECS is designed (1) to generate and remove a certain amount of sensible heat, (2) adequately protect the magnet system from radiation damage-and activation and excessive nuclear-energy deposition, (3) allow for continuous operation of reactor-level plasmas at a plant duty factor of 30-50 percent and (4) demonstrate all operational aspects of a Tokamak fusion power reactor except tritium breeding and breeder-blanket performance. The materials selected for designing the PECS were included on the basis that they:

(1) Satisfy the nuclear requirements for deposition of energy and radiation attenuation, (2) prove to be economical permitting PECS construction, operation and maintenance with regards to the current advancement in existing technology, and (3) provide a reasonable point for extrapolation to a demonstration scale of the TEFR.

A. First Wall Design Consideration

The first wall (treated as a subsystem of the PECS) includes the vacuum vessel that surrounds the plasma region and other associated components, i.e. a low-2 liner, a plasma-aperture limiter, a flux breaker, and the vacuum and neutral beam wall penetrations. The principal requirements of the TEFR first wall are: (1) to protect the plasma region from excessive atmospheric contamination, (2) to prevent excessive plasma contamination by products of plasma- wall interactions, and (3) to maintain its structural integrity for sufficient times under the severe irradiation, thermal, and stress conditions imposed by an operating fusion reactor environment.

The first-wall system design options that can be considered for the TEFR include: (1) a bare- metal first wall, (2) a first wall fabricated from sintered metal-metal oxide product, (3) a composite consisting of a metal vacuum wall with a protective low-2 coating, and (4) a metal vacuum wall protected from the plasma by a separate liner. The bare metal wall is the most attractive of the four options on the basis of fabricability; but recent studies show that due to the relatively high atomic number of the atoms puttered from the typical structural metal surfaces like stainless steel, prevents the attainment of the satisfactory plasma performance and efficiency. For the present design effort emphasis is placed on the use of graphite, silicon-carbide, or beryllium either as a coating on the vacuum vessel inside-wall or, in the case of graphite and silicon carbide, as a separate radiatively-cooled liner. The coating option has several attractive features, the major one being simpler fabrication; the coating could be put on after the vacuum wall is assembled and replaced remotely after extended reactor operation.

B. Blanket/Shield Design Considerations

The blanket region for the TEFR can designed to convert the kinetic energies of the neutrons and associated gamma rays into sensible heat. Other important functions of the combined blanket/shield region are: (1) to reduce radiation damage in the toroidal- field coils to acceptable levels from the standpoint of induced electrical resistivity in the copper stabilizer, and super-insulation deterioration; (2) to reduce nuclear heating in the toroidal-field coil system to tolerable levels; and (3) to minimize the induced activation and biological dose in the magnet structure such that magnet maintenance can be tarried out in place with a minimal degree of radiation protection after reasonably short cool down periods (i.e., a few weeks). All of these functions have to be performed with materials that: (1) are mutually compatible; (2) can withstand radiation damage for reasonable operating lifetimes; and (3) can be fabricated and/or implemented with existing or near-term technology.

Nuclear performance characteristics of a variety of plausible material compositions, which might meet the design requirements for the TEFR blanket/shield region, were studied and investigated. Options employing stainless steel (SS) seem viable because of the excellent radiation- attenuation characteristics of SS, and because it is a construction material for which a substantial technology base exists. Options employing tungsten (W) and tantalum (Ta) were considered on the basis of their superiority to SS in attenuating neutron and gamma radiation. Vanadium was considered because of the favorable compatibility of vanadium-base alloys with liquid lithium, and because of its reasonably good nuclear performance characteristics. Options containing graphite (C), boron carbide (B_4C), lead (Pb) and aluminum (Al) were studied because they lend themselves to the development of a minimum activation blanket/shield assembly for a TEFR.

Implications of the study on the above mentioned materials with different compositions may be summarized as follows: (1) Mixtures of stainless steel (SS) and boron carbide (B_4C) can be considered as superior to all material compositions studied, except for mixtures of tungsten (or tantalum) and B_4C, from the standpoint of nuclear energy deposition in the magnet. (2) Studies of the induced radioactivity generated in the blanket/shield indicate that remote handling and maintenance would be required for the options employing stainless steel, tungsten (and tantalum), and to a lesser degree vanadium; even after a year of cool-down whereas graphite and/or aluminum-containing compositions appear to be accessible with a minimal degree of radiation protection. (3) Designs employing W-B_4C and SS-B_4C mixtures offer the best prospects for achieving magnet-protection objectives with the smallest blanket/shield thickness. In light of these findings, the materials option employing optimized compositions of SS and B_4C is suggested for the preliminary blanket/shield design for the TEFR.

C. Thermal Fluid Analysis for the Preliminary PECS Design

Both pressurized helium and pressurized water can be considered for the primary blanket coolant in the reference PECS design. While helium appears to have greater long- range potential as a fusion reactor' coolant, the advantages of reduced coolant-channel volume fraction and lower pumping power afforded by water

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could help to ameliorate several of the design complications for PECS.

The shield region, which backs up the blanket, is simply an extension of the blanket insofar as materials composition is concerned, but it is operated at or near ambient temperature and is cooled with a low-temperature coolant circuit (probably borated water) that is separate and distinct from the primary coolant circuit. The substitution of tantalum or tungsten alloys, for the stainless steel zones in the inner blanket and shield will require that the respective coolants be channeled through stainless steel ductwork or that the tantalum (or tungsten) be canned in stainless steel since both helium and water are incompatible with the refractory metals.

D. Remote Maintenance & Repair

All aspects of maintenance, repair or modification can be done with remote handling equipment due to the residual radioactivity from fusion neutrons. Thus all components of the PECS and the reactor need be designed for remote handling, a very impressive task considering the size, weight, and geometric complexities encountered.

1) 1st wall vacuum chamber

The first wall is an independently supported structure that can be cooled using a separate circuit from the blanket. Both helium and water are under consideration. Water-cooling has more apparent advantages, including smaller coolant channels, simple routing, lower temperature operation (620 F) away from the creep range, low, pumping power, and ease of locating and repairing leaks. Disadvantages are thermal gradient problems associated with placement and attachment of coolant tubing, high-pressure requirements to 2000 psi, tritium buildup-in the eater system, and radioactivity buildup in the water system.

Present design effort favors a thick wall with ring and spar reinforcement cooled on the interior surface with separately stacked panel sections. The design includes a standoff liner that may have an initial low Z coating. The liner has provisions for cooling if necessary.

2) Blanket

The present blanket design effort for the TEFR segments the blanket annulus into contoured blocks. Each of these contoured blocks contains- coolant piping and lead connections, standoff insulation and support to the companion shield; torque limiters, and handling fittings. Cooling systems designs using all helium and all water are being carried.

3) Shield

The geometrical arrangement of the shield is similar to that of the blanket. The major shield design problems are found in trying to minimize fabrication costs of the large volume of materials.

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REFERENCES

[1] D. C. Robinson, "Fusion energy and plasma physics," presented at First Energy Independence Conference, 1988.

[2] G. O. Ludwig, A. Montes and P. H. Sakanaka, "Preliminary design of a small aspect ratio tokamak," in *Research Using Small Tokamaks*, Vienna, 1989.

[3] P. M. Bellan, *Fundamentals of Plasma Physics*, Cambridge: Cambridge University Press, 2006.

[4] J. R. Lamarsh and A. J. Baratta, *Introduction to Nuclear Engineering*, 1975

[5] K. Niu, *Nuclear Fusion*, Cambridge: Cambridge University Press, 2009.

[6] M. J. Hole, G. V. Nessi, M. Fitzgerald, K. G. McClements, and J. Svensson, "Identifying the impact of rotation, anisotropy, and energetic particle physics in tokamaks," in *Plasma Physics and Controlled Fusion*, 2011.

[7] C. C. Baker *et al.*, "Experimental power reactor conceptual design study," General Atomic Co., Report GA-A13534, July 1975.

[8] M. Roberts *et al.*, "Oak Ridge Tokamak experimental power reactor study-reference design," Oak Ridge National Laboratory Report, August 1975.

[9] S. Dean, "The Tokamak fusion reactor research and development plan," in *Proc. Annual Meeting of the American Nuclear Society*, New Orleans, La., June 8-13, 1975

[10] M. Abdou, "Nuclear design of the blanket/shield system for a tokamak experimental power reactor," in *Nuclear Technology*, April 1976.

[11] E. Hameiri, "The equilibrium and stability of rotating plasmas," in *Physics of Fluids*, 1983.

[12] L. Appel, G. Huysmans, L. Lao, P. McCarthy, D. Muir, E. Solano, J. Storrs, D. Taylor, and W. Zwingmann, "An unified approach to equilibrium reconstruction," in *Proceedings 33rd EPS Conference*, Rome, 2006, no. 6.

[13] H. Grad, H. Rubin, in *Proceedings second United Nations International Conference on the Peaceful Uses of Atomic Energy, Nuclear Physics*, 1958.

[14] R. Akers, L. Appel, P. Carolan, N. Conway, G. Counsell, M. Cox, S. Gee, M. Gryaznevich, R. Martin, A. Morris, M. Nightingale, A. Sykes, M. Mironov, and M. Walsh, "Neutral beam heating in the START spherical Tokamak," *Nuclear Fusion*.

[15] M. Cox, "The mega amp spherical Tokamak," in *Fusion Engineering and Design*, 1999.

[16] R. Hawryluk, "An empirical approach to tokamak transport," in: *Physics of Plasmas Close to Thermonuclear Conditions*, CEC, Varenna, Italy, 1979.

[17] A. Fasoli, C. Gormenzano, H. Berk, B. Breizman, S. Briguglio, D. Darrow, N. Gorelenkov, W. Heidbrink, A. Jaun, and S. Konovalov, "Physics of energetic ions," *Nuclear Fusion*, 2007, ch. 5.

[18] J. Goedbloed, R. Keppens, and S. Poedts, "Advanced magnetohydrodynamics: with applications to laboratory and astrophysical plasmas," Cambridge Univ. Press, 2010.

Jay V. Kalinani was born in Mumbai, India on 29th June 1991. Kalinani has done his high schooling from Westview High School, San Diego, California and Anand Vidya Vihar, Vadodara, Gujarat. He is currently pursuing his Bachelors of Technology degree in Nuclear Science and Engineering from SRM University, Chennai, India and is currently in his 4th year of college. He is interested to do his Masters in Theoretical Physics, and his area of interest includes particle physics, plasma physics and cosmology.

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