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THE ELMO BUMPY TORUS (EBT) REACTOR*

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ABSTRACT

The ELMO Bumpy Torus (EBT) concept has many encouraging and attractive features as a fusion reactor system. These include a high beta, magnetohydrodynamically stable equilibrium; absence of parallel currents; a large aspect ratio; the modular nature of individual sectors; no interlinking coils; ease of maintenance; steady-state operation; and economic potential. The first EBT reactor study was initiated in 1976 and provided the required starting point for continued assessment of the validity of the concept. Major refinements in plasma physics and design engineering have now resulted in a revised system description. A new design based on the present physics, practical design, and present and near-term technologies has been established. This paper discusses the details of key design elements and critical scientific and technological factors which are substantially different from other fusion reactor approaches. The paper also provides a useful summary of where the EBT program is, where it is going, and why these efforts are, in fact, self-consistent, with a motivation toward potential reactor application of EBT's.

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I. BACKGROUND

The goal of the ELMO Bumpy Torus (EBT) Reactor Study [1] is the evaluation of the EBT confinement concept [2] as the basis for development of a commercial fusion power reactor. The EBT is an attractive alternative to other mainline confinement systems and has potential advantages in the reactor physics and technology areas.

The main emphasis in current fusion research is on the tokamak approach toward providing a plasma with sufficiently high temperature (T), density (n), and confinement time (τ). As the most studied configuration, with a dozen or so experimental devices, tokamaks have achieved the most promising results to date with $n\tau \sim 2 \times 10^{13}$ and $T_i \sim 2$ keV using reactor-relevant technology. Although one can regard the tokamak as a prototype device for gaining operational experience with a confined plasma undergoing thermonuclear burn, commercial fusion reactors will not necessarily have to be built on the tokamak principle.

The magnetic mirror systems are also widely studied. As a pure fusion reactor, a mirror device would have to operate as a power amplifier (nonignited). The main advantages of a mirror reactor are the possibility of steady-state operation; high beta (the ratio of plasma pressure to magnetic field pressure), which is a figure of merit often used in discussing the efficiency of magnetic field confinement; and automatic divertor action (impurity control) by the end loss of plasma. However, the fusion power gain, Q (fusion power output divided by the power injected into the plasma), even with "Reversed Field Mirror" or "Tandem Mirror" concepts [3], is very low (<5), necessitating large recirculating power, very efficient energy recovery, and high heating efficiency in order for a mirror reactor to produce net power. The capital cost might therefore be prohibitive.

The EBT experiment [2] at Oak Ridge National Laboratory (ORNL) was designed to combine the attractive features of both mirrors and tokamaks. The feasibility of this combined system has been demonstrated successfully in the EBT-I experiment and is discussed at greater length in Ref. 2. Because EBT is basically a toroidal device without the end loss problems of mirror devices, the reactor performance estimates give significant power gain values, Q > 10 [1]. Also, EBT regarded as a toroidal system is free from many of the physical and engineering problems of axisymmetric toroidal systems--it is a truly steady-state system with no toroidal current; it has MHD stability at high beta (as high as 50% [4]); it is a self-cleaning system with no tendency to accumulate high Z material on axis [5]; it has a natural bundle divertor; it is a large aspect ratio torus permitting good access and reduced engineering problems; and its containment properties do not

scale as radius [6-8], so that feasibility can be demonstrated in a relatively small plasma cross section.

Requirements for operation of an EBT system are a toroidal bumpy (or corrugated) magnetic field structure and an electron-cyclotron resonance (ECR) heated, hot electron "annulus" contained in each bump of the field. The purpose of the annuli is to provide a modification not otherwise possible of the magnetic fields, so that broad scale instabilities do not form to disrupt the plasma confinement. High power millimeter microwave power supplies furnish the energy to form and maintain the hot electron annuli. The same sources are adequately effective in the formation and heating of the toroidal plasma in which the fusion reaction is to occur. Additional and/or alternative heating techniques (e.g., neutral beam injection heating) can also be used as an option.

Although the present EBT, EBT-I, is a first-generation device and also the first device of its kind, the existing experimental and theoretical evidence indicates that the EBT approach can be extended to confine steady-state, high beta plasmas. If this extension can be demonstrated, then EBT may, in the long run, become the most desirable system.

II. THE PRESENT AND NEAR-FUTURE EBT EXPERIMENTS

In the present experiment, EBT-I [2], the plasma is produced in a bumpy torus with a major radius of 1.5 m and a minor radius of 0.1-0.15 m by microwave heating [electron-cyclotron heating (ECH)] of electrons that in turn transfer heat to the ions by Coulomb collisions. It employs a toroidal array of 24 mirror coils which have magnetic fields of 1.0 T at their throats and 0.5 T at the mirror midplanes. Two microwave power supplies effectively give independent control of the hot electron annuli and the toroidal plasma. On either side of each mirror midplane electrons are heated by 60 kW of microwave power at a frequency of 18 GHz, which is equal to the electron gyrofrequency. The location of these resonant zones provides heating of the toroidal plasma at all the minor radii and is called "bulk heating." In addition, 30 kW of 10.6-GHz microwaves resonantly heat the electrons in off-axis annular regions near the mirror midplanes and produce the stabilizing, high beta ($\beta_A \geq 40\%$), hot electron annulus. The 10.6-GHz "profile heating" supply tailors the radial profile of the hot electron annuli and also provides parallel heating of toroidal plasma electrons. The toroidal plasma has ion and electron temperatures in the range of 100-400 eV and a beta value ($\beta_{toroidal}$) of 5×10^{-3}. When the 10.6-GHz power is turned off, the decay time of the bulk plasma is about 50 ms.

Present understanding of equilibrium, stability, and transport in EBT suggests a sequence of research and development activities aimed at a full-scale

reactor. The sequence depends on demonstration of favorable scaling of plasma confinement into the collisionless regime (collision time, ν^{-1}, longer than precession time, Ω^{-1}) and on the development of microwave power sources, with high specific power levels, at millimeter wavelengths. The EBT program includes an aggressive development effort for high power millimeter continuous wave (cw) microwave sources based on the Cyclotron Resonant Maser (CRM) principle. Varian Associates, Palo Alto, California, has developed a 28-GHz, 200-kW cw gyroklystron, which is a scale version of the 120-GHz device required for heating an EBT fusion reactor.

A new experiment, EBT-S, is presently under way, scheduled to begin operation in November 1977, which will provide an important addition to the EBT data base. EBT-S is a modified version of the existing EBT-I facility, with an increased magnetic field and increased microwave power (60 and 200 kW) and frequencies (18 and 28 GHz) and is designed to be a more definitive test of the transport scaling in EBT. These changes are intended to increase the plasma parameters (T_e, T_i, n_e) significantly relative to those presently accessible. This technological step will also provide important operating experience with the 28-GHz power supplies. By adding relatively low current field shaping coils to the EBT-S structure, EBT-SA, substantial improvement to the confinement could be possible by an increase in the effective aspect ratio through symmetrizing effects without increasing the mechanical aspect ratio (or volume) of the device. These are called aspect ratio enhancement (ARE) coils [9] and the details of the different classes of ARE coils will be discussed elsewhere.

The Nagoya Bumpy Torus of the Institute of Plasma Physics at Nagoya University in Japan will start its operation in the spring of 1978. The scale and power level of this device are similar to those of EBT-S.

A detailed design is also under way of a higher field, larger aspect ratio device, EBT-II. EBT-II will use superconducting coils to provide the required dc cyclotron resonant magnetic field of 4.3 T. This is consistent with the use of microwaves at 70 and 120 GHz and would allow operation at plasma parameters that approach reactor conditions. This device will also act as a forcing function for the development of high power, high frequency microwave technology; the prognosis for success in this area is very good. The operation of such a system will be a scale demonstration of much of the EBT reactor technology as well. This experimental facility, EBT-II, could come into operation in the early 1980's.

III. EXPERIMENTAL RESULTS

In the previous sections, many of the details of the operation of EBT were outlined. In this section, a brief discussion of several of the diagnostics which have contributed to the understanding of the plasma behavior is given.

As indicated, EBT is a toroidal magnetic confinement system in which plasma is produced and heated through interaction between plasma electrons and applied microwave power. A toroidal array of mirror coils (24 in EBT-I) provides steady-state confinement of toroidal (passing) particles and of particles trapped in the mirror sectors. The magnetic field along the minor toroidal axis varies periodically, with a 2:1 mirror ratio. The plasma stability results from the modification of the vacuum magnetic field by an annular, high energy, mirror-trapped electron population.

As mentioned earlier, there are two principal plasma components: mirror-trapped, high energy annuli and a higher density, lower energy toroidal plasma. The parameters characterizing these components vary widely with operating conditions. Control of the plasma properties is maintained through control of the ambient neutral hydrogen density and the applied microwave power. After the plasma is created, as the neutral density is lowered, three distinct regimes of operation are identifiable in terms of macroscopic plasma behavior: the C-, T-, and M-modes. The C-mode occurs at low power or high neutral density. In this mode, very few energetic (annular) electrons are observed and no gross instabilities are seen, but low amplitude fluctuations in density are observable in the frequency ranges of drift wave phenomena. The ions and electrons are relatively cold, a few tens of electron volts.

At lower pressures, as the power level is increased, the stored energy in the energetic annuli increases significantly, the fluctuation amplitude drops to very low values, and a transition takes place to the quiet T-mode. The annular beta ($\beta_A \sim 8\%$) at which this transition occurs experimentally agrees with theoretical estimates of the beta value required to produce a local minimum in the magnetic field [4]. Both the toroidal and annular plasma components are free from gross instabilities, and the toroidal core electron and ion temperatures rise by more than an order of magnitude. Low level density fluctuations occur mostly in the surface plasma and the level of impurities in the well developed toroidal plasma is very low. This quiet regime of operation is consistent with theoretical neoclassical transport models. At still lower pressure, the density drops rapidly and only the energetic electron annuli remain, fluctuating macroscopically, in the M-mode. It is very difficult to measure plasma properties in this regime.

Because of the relatively long lifetimes and low fluctuation levels in the

T-mode, the major thrust of the diagnostic development has been directed at a determination of the plasma properties in this stable, well confined mode of operation. The toroidal core plasma which has been identified in the T-mode would be the reactive region in the EBT reactor.

Outside the hot electron annulus, the plasma is dilute, cold, and unstable. Therefore, the density profile in the T-mode is sharply increased near the hot electron annulus and rather flat inside the minor cross section. This is confirmed by the existence of localized drift waves on the surface of the plasma column as well as the distribution of the H-line intensity detected by scanning a mirror across the plasma cross section. The electron line density, measured by a microwave interferometer, is $\langle n\ell \rangle \sim 4 \times 10^{13}$ cm^{-2} resulting in an average $n_e \sim 1\text{-}3 \times 10^{12}$ cm^{-3}. Soft x-ray measurements indicate electron temperatures of 100-400 eV with a nearly Maxwellian energy distribution. The ion energy distribution consists of two components: a thermal (Maxwellian) distribution with an average temperature in the range of 30-100 eV (depending on pressure: ~30 eV in C-mode, ~70-100 eV in T-mode) and a high energy tail which is also Maxwellian. Typically, 10% of the ions are in the higher energy group with an average energy in the range of 80-500 eV.

The parameters characterizing the hot electron annulus are n_e(annulus) $\sim 1\text{-}4 \times 10^{11}$ cm^{-3}, T_e(annulus) $\sim$ 100 keV, and $0.1 \leq \beta_A \leq 0.5$. The annulus is observed to form a narrow belt in the midplane; its radial location is roughly determined by the location of the fundamental of the profile heating frequency (10.6-GHz) and the second cyclotron harmonic of the bulk heating resonance frequency (18 GHz).

Spatially resolved measurements of the ambipolar electric field have been carried out with a heavy ion beam system [10]. The potential may be either positive or negative relative to the wall in the plasma core, but it always shows a large positive peak (~200 V) at a position near the annulus. This space potential in EBT serves to improve the confinement properties of most ions and electrons and to reduce the influx of impurities from the plasma exterior [5].

The toroidal core plasma is surrounded by a region of magnetic drift surfaces which intersect the wall. Observations from spectroscopic measurements show that the electron density and temperature in this region are appreciably lower than in the core plasma ($n_e \sim 10^{11}$ cm^{-3}, $T_e \sim 30$ eV). The impurity lifetimes are in the neighborhood of 300 μsec. The dominant impurities are the lower charge states of aluminum, nitrogen, oxygen, and carbon. The characteristic CV (carbon V) radiation was unobservable, leading to the estimate that $n(CV)/n_e < 6 \times 10^{-5}$ in the toroidal core plasma. The short lifetime of impurities, coupled with the requirement that they gain sufficient energy to overcome the potential

barrier at the surface of the core plasma, provides a reasonable explanation of the apparent "divertor" efficiency of the surface plasma.

The plasma stability in EBT is examined by measuring plasma fluctuations as one or more external parameters are varied [2]. Recent studies involve the measurement of fluctuations using the field error as an external parameter [11]. Magnetic field errors can give rise to a parallel (toroidal) current and in turn to instabilities in EBT. The field error effect becomes important when it exceeds a critical value of $(\delta B/B)_{cr} \approx \sqrt{3/2}(\rho/R)$, where ρ and R are the particle gyroradius and major radius of the torus, respectively [11]. This value is about 10^{-3} for ions in EBT (field error in EBT-I is $\sim 10^{-4}$). The effects of field error on EBT plasma behavior were studied by simultaneously measuring various parameters as externally induced field errors were varied. Within the range of field error $(\delta B/B) < (\delta B/B)_{cr}$, the plasma is highly stable and relatively dense, and the potential profiles are symmetric, therefore excluding the possibility of convective cell formation. For $(\delta B/B) > (\delta B/B)_{cr}$, low frequency modes appear to be destabilized so that density fluctuations increase. Field errors obtainable with superconducting coils are in the range of 10^{-6} to 10^{-7} so that this effect does not pose a problem for future devices.

IV. THEORETICAL CONSIDERATIONS

Several of the key aspects of EBT operation, such as confinement, equilibrium, ring formation, stability, transport, etc., have been modeled theoretically. In the area of particle confinement and equilibrium, codes have been developed to demonstrate the existence of full three-dimensional (3-D) equilibria in EBT with finite aspect ratio and with diamagnetic currents carried by hot electron annuli. These codes are used to determine sensitivity of particle trajectories and confinement to the parameters of the annuli, the external field shaping currents, and to the ambipolar (radial) electric potentials that are observed in the experiments.

An ideal bumpy torus provides absolute confinement of single particles [12]. In realistic cases, the guiding center drift motion leads some particles directly to the chamber wall. Thus, the confinement properties of an EBT are influenced significantly by the guiding center drift orbits of the individual plasma particles. Plasma confinement in EBT depends on the modification of the toroidal vertical drift by the poloidal gradient B and E × B drifts (produced by bumpiness in the toroidal field and by the ambipolar electric field). The particle orbits are approximately circular with the center of the orbit displaced from the minor axis amount δ which is the ratio of toroidal to poloidal drift velocities,

$$\delta = \frac{V_T}{\Omega} \tag{1}$$

with

$$V_T = \frac{mV^2}{2eBR_T}\left(1 + \frac{V_{\parallel}^2}{V^2}\right) \tag{2}$$

$$r\Omega = \frac{mV^2}{2eBR_c}\left(1 + \frac{V_{\parallel}^2}{V^2}\right) + \frac{E_r}{B} \tag{3}$$

where R_T and R_c are the toroidal and mirror radii of curvature and E_r is the radial electric field. One can expect better confinement for large aspect ratios and large electric fields. This displacement δ acts as the basic step size for diffusion of particles and energy. This drift orbit diffusion is called "neoclassical" and is the minimum diffusion one can hope for in a toroidal device.

From the linearized kinetic equation, the diffusion coefficients were first calculated by Kovrizhnykh [6] in the limit of large radial electric fields, given as

$$D \approx \frac{V_T^2}{24}\frac{\nu}{\nu^2 + \Omega^2} \tag{4}$$

where ν is the effective collision frequency. The plasma confinement time is then given by

$$\tau \sim \begin{cases} \left(\frac{a}{V_T}\right)^2 \nu & \text{for } \nu \gg \Omega \text{ (collisional)} \\ \left(\frac{R_T}{R_c}\right) \nu^{-1} & \text{for } \nu \ll \Omega \text{ (collisionless)} \end{cases} \tag{5}$$

where a is the plasma radius and $R_c \approx a$, leading to aspect ratio squared scaling for the confinement time in the collisionless case.

The work of Kovrizhnykh [6] is extended by Spong et al. [8] to include arbitrary values of the ambipolar electric field which represent realistic modeling of the EBT plasma. Additional dependence upon the electric field is found. The results are used as input to the transport calculations described next.

Procedures and codes at three levels of sophistication are now available for analyzing the transport properties of the EBT system. These are a so-called "point model" [7], a radially resolved "fluid model" [13], and a "kinetic model" [13]. The point model is used to study global questions such as scaling to, and

optimization of, systems where the details of spatial profiles are not considered critical. Analytical expressions for toroidal plasma densities and temperatures are derived from the zero-dimensional point model using Kovrizhnykh coefficients [7]. Results are in reasonable agreement with the EBT-I experiment.

In the radial fluid model simulation, coupled equations for plasma density, neutral density, electron and ion temperatures, and ambipolar electric field are developed along with appropriate numerical solution techniques. As pointed out in Ref. 13, several phenomena are still omitted which can influence the shape of the ambipolar potential. For example, microwave heating of electrons can provide additional scattering and increase the effective collisionality of the electrons by an amount that has not yet been calculated. This one-dimensional code is used for detailed study of profiles and compared with EBT-I experimental data. It is found that the transport properties of EBT-I are consistent with neoclassical predictions.

A more detailed "kinetic model" [13] is used for detailed studies of such areas as the hot electron annuli enhanced collisionality due to microwave scattering, and the radial electric field. These problems are partially circumvented in the fluid transport codes. The drift kinetic equations are solved directly in a multidimensional phase space (including radius) using Fokker-Planck collision terms. This model has not yet reached the same level of sophistication as the simpler "fluid model."

EBT-I has demonstrated a regime of macroscopically stable operation [2], as indicated earlier. All the potential instabilities for EBT can be broadly classed as drift waves or drift waves coupled to other waves.

In EBT, the stability of the toroidal plasma component depends on the diamagnetism of the hot electron annulus which transforms the bumpy torus into an average minimum-B configuration. Without such an effect, the toroidal core would be subject to simple interchange modes, as shown by Kadomtsev [14] for a scalar pressure closed-line torus with monotonically increasing $\int d\ell/B$. However, calculations in the guiding center fluid model [4] have shown that the hot electron annulus can provide the requisite stabilization of the toroidal core plasma by a very interesting mechanism. The hot electron diamagnetic currents act as "invisible coils" colocated with the bulk plasma and create a magnetic well when the beta value of the annulus (β_A) exceeds a minimum value in which $\int d\ell/B$ decreases, thus satisfying Kadomtsev's criterion for stability. The theoretical prediction for this critical value of beta in the annulus is about 8% and this is the experimentally observed value for the transition from the C-mode to the quiet T-mode. Once a magnetic well has been established by the annuli at $\beta_A \sim 8\%$, a beta of the toroidal core plasma comparable to the beta of

the annuli can be achieved which is stable to all modes encompassed by guiding center or ideal MHD theories [4]. This is a very encouraging result from the reactor application point of view. The modes, which limit toroidal beta, are pressure-driven ballooning interchanges.

The stability of the hot electron rings requires a Vlasov treatment because the characteristic drift frequencies exceed the ion-cyclotron frequency. Analysis of the Vlasov-Maxwell equations shows that the hot electron drift waves are stabilized by interference between the responses of the fast drifting electrons and the slowly drifting ions [15]. The recent calculations of Dominquez and Berk [16] indicate that the rings are stable provided the ratio of cold to hot electron density is sufficiently high [e.g., $\sim$10]. These slab model calculations are presently restricted to stability of the hot electron rings, since the ion temperature was set equal to zero. A similar Vlasov model, including ion temperature has also been used by Nelson et al. [4].

One can draw the following conclusions from the stability result to date. Apparently there is a coupled relationship between the toroidal core plasma and the hot electron rings: the toroidal core plasma provides the cooler electrons to stabilize the rings, while the hot electron rings provide the minimum-B necessary to stabilize the toroidal core plasma.

V. EBT REACTOR DESIGN

The experimental results from EBT have motivated a consideration of the EBT concept as the basis for a potential reactor [1]. The first EBT reactor (EBTR) study was initiated in 1976 and provided the required starting point for continued assessment of the validity of the concept. Major refinements in plasma physics and design engineering have now given a revised system description [1] which incorporates increased understanding from recent plasma research activities.

A power-producing EBT reactor system is especially attractive because of its steady-state operation at high plasma pressure. EBT is a large aspect ratio device, so the accessibility problems are virtually eliminated, remote maintenance difficulties are eased, and relatively uniform structural loadings (due to weak curvature) alleviate engineering design problems. No pulsed fields are required for EBT operation; therefore, it is less likely to be subject to thermal and mechanical fatigue than reactors with large pulsed fields and short bursts of fusion power.

A summary of an integrated reference design is presented here. This design is based on the present physics understanding discussed in Sections III and IV, practical design approaches, and technologies that are consistent with present and near-term development programs. The design should be viewed as a representative

system, not an optimum one, since there is no unique solution to the overall design problem. The "optimum design" is strongly dependent on the weight given to the constraints in each area. For EBT-based systems, a small number of design choices is sufficient to indicate the major aspects of the final design: the choice of wall loading, mirror ratio, and limiting plasma pressure determines the size of a standard module of the system and, given total plant power output, the number of modules in the system.

The following set of design parameters is specified in order to select a reference design for discussion: from the utilities point of view, power output is limited to 2000-6000 MW(th); neutron wall loading is taken to be in the range of 1-2 MW/m^2 from wall lifetime considerations; mirror ratio required for annulus formation is typically 2:1 [2]; the limiting plasma (toroidal core) pressure is in the range of 25-50% [4]; and the device should be capable of ignition and should use, if possible, 150-keV Tokamak Fusion Test Reactor (TFTR) neutral beams or 120-GHz EBT-II microwave heating sources for the toroidal plasma and 70-GHz EBT-II microwave sources for the sustaining of annuli. Within these specifications, the self-consistent set of plasma parameters and a range of machine characteristics in Table I are obtained.

Steady-state plasma performance parameters are obtained from a consistent solution of the equilibrium and the plasma particle and power balance equations [17]. A simple model which retains the essential physics of the phenomena has been developed [17] to assess the energy balance in an EBTR plasma. In this model, the toroidal plasma is characterized by energy and particle containment times with appropriate density and temperature scaling. The reactor plasma simulated in this model is consistent with the physics model discussed in previous sections: a toroidal core in the quiet T-mode with nearly uniform density and temperature within the plasma cross section, which is determined by the stabilizing hot electron annuli. The effects of different scaling assumptions on EBTR performance and operating point have been analyzed in Ref. 17. The selected scaling parameters for EBTR are shown to be flexible enough to accommodate enhanced losses above those given by the present neoclassical theory [6, 7], i.e., the reference EBTR can accommodate anomalous losses one to two orders of magnitude greater than the neoclassical losses at the operating point.

A comparison of the parameters of EBT-I and those projected for EBT-S/SA, EBT-II, ..., EBTR yields an interesting result. Virtually all the dimensionless parameters which influence stability are roughly the same in EBT-I, EBT-II, and in the projected EBTR. Thus, the following dimensionless parameters are either the same or in the direction of increased stability: annular beta; ratio of

gyroradii to various scale lengths; field errors; aspect ratio; ratio of cold to hot electron density; ratio of electron to ion temperature; ratio of electron plasma frequency to cyclotron frequency; and ratio of ambipolar potential to temperature. The beta of the toroidal core plasma, and, to a lesser extent, the collisionality are factors which change appreciably. The approximate constancy of these dimensionless parameters which are known to influence stability is very encouraging, and the extrapolation of EBT-I results to EBTR is feasible. The first test of toroidal beta limitations on stability/instability will be demonstrated in EBT-II where the toroidal core beta will be about 10%. Collisionality, ν/Ω, differs from EBT-I to EBTR only by factors of 2 and 10 for electrons and ions, respectively.

For a high beta, steady-state system, the plasma equilibrium, particle orbits, ambipolar electric field, and transport phenomena are closely coupled to one another. From these interrelations, specifically from equilibrium requirements and to provide efficient use of the magnetic field, a displaced aperture/inner wall design has been adopted this year. Figure 1 shows the mod-B contours and field lines for one sector of EBTR for the straight cylindrical wall design (original wall design from last year's study) and for the displaced aperture flux following wall design (without finite beta effects). In the latter case, the plasma is shifted about 25 cm from the coil axis toward the major axis. This change leads to a usable volume of about 100% [1], compared to about 50% for the straight cylindrical case.

The magnetic field in the EBTR is produced by 24 (48) 6-m-bore NbTi superconducting coils with a maximum field of about 7.8 T at the coil. The magnetic fields at the magnet throats and at the midplanes (confining magnetic field) are 4.5 T and 2.5 T, respectively, giving a mirror ratio of 1.8. As long as the ratio of reactor major radius to the number of coils is constant, the axial field strength produced is not sensitive to the size of the reactor. Thus, an important advantage of an EBTR is that the same module-magnet design can be used in reactors of different sizes and power outputs. Also, EBT has a large aspect ratio so that the magnetic field strength is reasonably uniform around the coil perimeters; thus the magnetic forces are nearly symmetrical. Circular coils are used. Natural convection pool boiling is employed as the cooling method. Advanced conductor designs are not required because EBT has no pulsed fields. Details of the EBTR magnets are discussed elsewhere [1, 18].

Conceptual designs of EBT reactors based on the modular concept are studied for a wide range of sizes [1]. Each module consists of one superconducting magnet coil, a shield of articulated cylindrical units, and multiple blanket modules (conforming roughly to the plasma shape) as well as vacuum pumping and

microwave injection ports. The blanket is divided into segments both poloidally and toroidally. The blanket segments consist of "buckets" arranged in a circular frame. These buckets are filled with lithium for neutron absorption and tritium production. The back section of each bucket has stainless steel spheres mixed with lithium for gamma absorption. Double wall cooling tubes are coiled in the buckets. Helium gas at a pressure of 70 atm is circulated through the blanket to remove the heat for steam generation. The shield sections are made of stainless steel containers (tanks) filled with stainless steel spheres around which borated water is circulated for heat removal. These tanks are divided into appropriate shapes and sizes to permit access to the blanket with relative ease.

The torus is assembled in a concrete moat which is evacuated to provide a secondary vacuum enclosure for the machine. This vacuum environment greatly simplifies the assembly procedure and eases the remote maintenance problem since it is not necessary to provide a vacuum-tight primary enclosure for the plasma. Thus, the individual blanket segments are not required to be welded together. Also, the numerous penetrations through the blanket need not be welded to the blanket wall. All assembly and remote maintenance operations are performed from above the moat. Two gantry cranes, capable of rotating completely around the moat, are mounted on a continuous circular track. A general plan view of the entire EBTR plant is shown in Fig. 2.

The coils are installed in a concrete "picture frame." The gravity load and the magnetic centering forces are transmitted to the picture frame through laminated load bearing pads of insulating material and a liquid nitrogen cooled buffer zone. A plan view of the components of the torus is shown in Fig. 3.

The plasma region is maintained at a lower pressure than the moat by two vacuum pumping ports between each toroidal field (TF) coil. Microwave injection is made through these same vacuum ports. The vacuum system for the plasma region is located in tunnels running radially under the moat. The large area encircled by the moat is used for microwave generators and power supplies, cryogenic refrigerators, primary heat exchangers, and other equipment. This central location minimizes the lengths of lines running to these auxiliaries.

Neutronic analysis of the EBTR lithium blanket assembly has been performed in a one-dimensional cylindrical geometry [19]. The reactor blanket modeled includes a 60-cm-thick assembly consisting of lithium in a 316 stainless steel structure which is cooled with high pressure helium. The shield is 55 cm thick, separated from the blanket by a 30-cm-thick maintenance void, and is composed of 65% 316 stainless steel, 35% water and is supported by a stainless steel structure. Surrounding the blanket and shield is a magnet assembly consisting of NbTi/Cu

coil which is supported by a stainless steel structure. The blanket assembly recovers 96% of the neutron and secondary gamma energy in the form of heat. Approximately 4% of the energy is deposited in the shield and the remainder, $\sim 10^{-4}$%, is deposited in the magnet assembly. The tritium breeding ratio is 1.3 tritium nuclei per incident neutron.

In order to establish the economic potential of the EBT reactor, two independent system costing models have been developed [20]. The first model relies on an explicit model of EBTR, discussed in this paper, to compute the cost of the reactor itself and on the United Engineers and Constructors 1972 plant cost estimate developed for the Liquid Metal Fast Breeder Reactor (LMFBR) [21] (suitably inflated for 1977 dollars) to compute the costs of the balance of the plant. The sensitivity of the reactor cost (nuclear island cost) to the design is then examined by parametric variations. To relate the results for comparison with the tokamak system, a second cost estimate was made using the model developed for the tokamak system [22]. The results of the two models, which are discussed in detail in Ref. 20, are in general agreement and predict capital costs of approximately $300-400/kW(th). Figure 4 shows capital costs as a function of aspect ratio, wall loading, beta, and power output for fixed plasma radius and magnetic field. Since the efficiency of the power conversion system varies and has yet to be demonstrated, cost estimates are given on the basis of dollars per kilowatt thermal instead of dollars per kilowatt electric.

In comparing the EBTR cost to the tokamak reactor cost [22], cost savings of the EBTR over the tokamak system are realized by the lack of poloidal coil and driving systems and of the economic penalty of a duty factor associated with pulsed operation. These costs include neither the expected increased maintenance cost associated with the much more complex tokamak system and operating cycle nor the advantages of favorable EBTR geometry for ease of maintenance. In comparison, therefore, the EBT concept appears competitive both among fusion reactor concepts and among different power plants.

VI. CONCLUSIONS

The present status of the EBT research activities at ORNL is described briefly in order to provide a basis for the reactor study. The EBT-I has experimentally demonstrated stable confinement in true steady-state operation, and theoretically, it can be projected that the system can scale to satisfy net fusion power conditions. Engineering design studies also demonstrated that with an inherently steady-state, modular system, the technological requirements are also relatively straightforward. To be sure, such projections are highly speculative since there are, of course, uncertainties in extrapolating the present plasma physics knowledge (which is

not fully understood and demonstrated) to predict the behavior of future devices. Nevertheless, these projections are a part of fusion research and are necessary to determine the best steps in the program and to lend credibility to a system.

The EBT reactor described here is based on specific present and near-term technologies, practical design approaches, and flexible plasma characteristics. It is noted that the design should be viewed as a representative system, not an optimum one. If the physics extension can be demonstrated from near-future planned experiments, the reactor system will operate at high beta and high power density, and in steady state. The large aspect ratio, reduced forces, and lack of pulsed magnetic fields make the EBTR very attractive from the engineering point of view.

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TABLE I

EBT Reactor Parameters

Plasma radius (m)	1.0
Mirror ratio (-)	1.8
Magnetic field (midplane/mirror) (T)	2.5/4.5
Aspect ratio (-)	30-60
Number of sectors	24-48
Particle density (m^{-3})	1.4×10^{20}
Ion/Electron temperature (keV)	15
Toroidal plasma beta (%)	27
Neutron wall loading (average) (MW/m^2)	1.47
Total fusion power [MW(e)]	1000-2000
Cold zone (m)	0.2
Blanket thickness (m)	0.6
Shield thickness (m)	0.55
Coil inner radius (m)	3.0
Coil outer radius (m)	3.7
Coil half axial length (m)	1.05
Current density (A/cm^2)	1525
Neutral beam energy (keV)	150[a]
Neutral beam power (MW)	50-200[a]
Microwave frequency (GHz)	
Toroidal plasma	120[a]
Hot electron annuli	70
Microwave power (MW)	
Toroidal plasma	50-200[a]
Hot electron annuli	5-10

[a]A toroidal plasma will be heated to ignition conditions using either microwaves or neutral beam injection. Power required for ignition is in the range of 50 to 200 MW (total) depending on the startup procedures.

FIGURE CAPTIONS

Figure 1. Mod-B contours (solid lines) and field lines (dashed lines) in the equatorial plane for one sector of EBTR for straight cylindrical (upper curve) and displaced aperture (lower curve) inner wall design. In the upper curve, the boundary is the inner wall (and the coil planes). In the lower curve, the aperture has been moved toward the major axis about 25 cm so that its projection along field lines into the midplane lies on mod-B contours.

Figure 2. EBTR plan view.

Figure 3. A plan and section elevation view.

Figure 4. The capital cost per kilowatt thermal vs aspect ratio for several values of neutron wall loading and fusion power output for fixed plasma radius, coil size, and magnetic field strength. (Note that total thermal power is 22.4/17.6 times fusion power.)

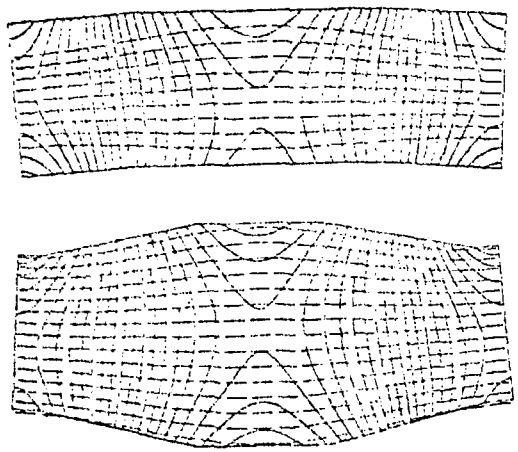

Figure 1

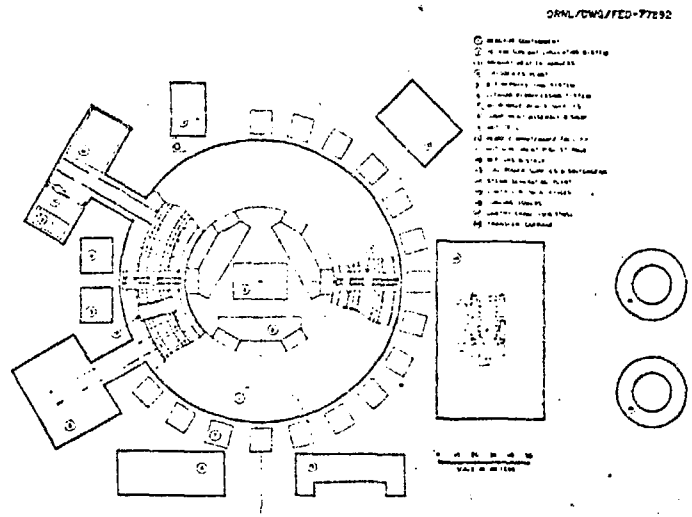

Figure 2

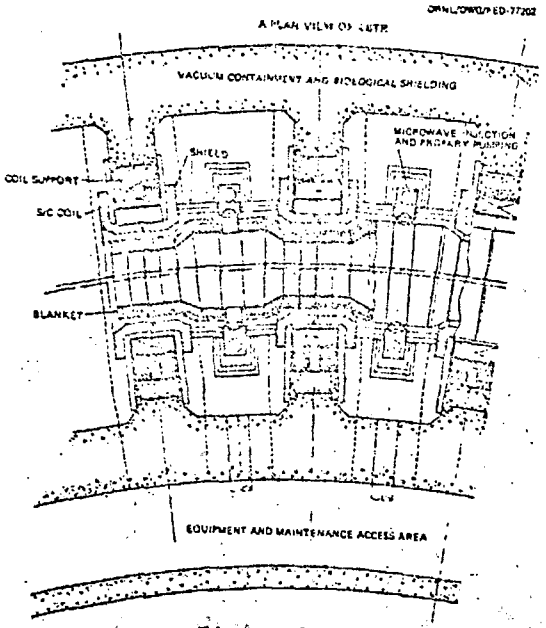

Figure 3

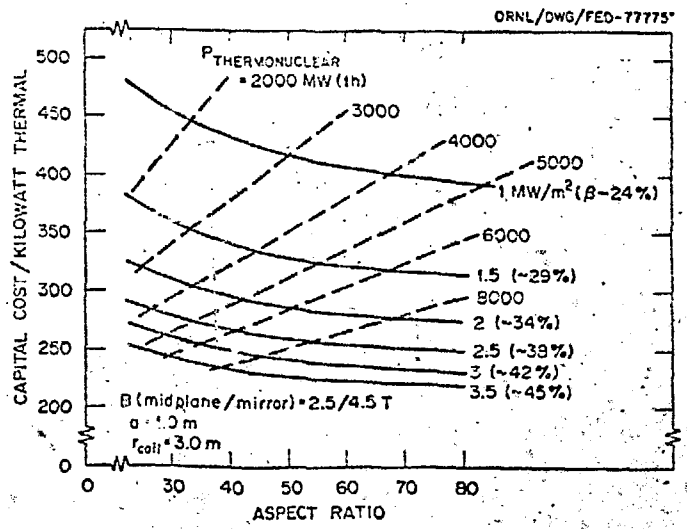

Figure 4