PFC/RR-78-14

HELIUM COOLED EBT REACTOR DESIGN STUDY

FOR EPRI-BECHTEL

Alternative Fusion Concepts Study

(EPRI RP 547-3)

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1. INTRODUCTION

The description of the ELMO BUMPY TORUS reactor contained in this report differs in several respects from the description given in the TASK I and TASK II reports. Helium has been selected as the coolant in order to provide a common base of comparison for other alternative fusion concepts. This does not represent an optimized design for the EBT concept.

The primary changes are substitutions of helium as the primary coolant instead of a molten salt, increasing the wall loading from 1.1 to 2 MW_n/m^2 and reducing the number of magnets from 36 to 24.

The blanket design is an adaptation of a design developed jointly by Westinghouse and Oak Ridge National Laboratory for a Tokamak type reactor operating at 4 MW/m^2. By reducing the wall loading to $2MWn/m^2$ for an EBT type reactor, with a major radius of 30m and a wall radius of 1.2m, the net electrical output will be on the order of 1000MWe which is the desired level.

The plasma physics, and general mechanical design remains as described in ORNL/TM-5669[1] for an EBT-24 configuration. This document will present a summary of the material contained in that reference plus a description of the blanket design concept. The appendices referred to in this report will be the appendices of that document.

2. EBTR Reference Design Parameters

An EBTR reference design has been developed. Preliminary power balance calculations suggest that the toroidal plasma should be heated to ignition conditions using neutral beam injection and that the stabilizing relativistic electron rings should be sustained by microwaves. Figure 1 is a plan view of the first configuration considered for the EBTR using 48 coils and including 4 divertors. The current reference design uses 24 coils with half the major radius (30 m.).

The reactor is fueled by deuterium and tritium and operates in the ignited mode. It produces 3660 MW thermal including blanket
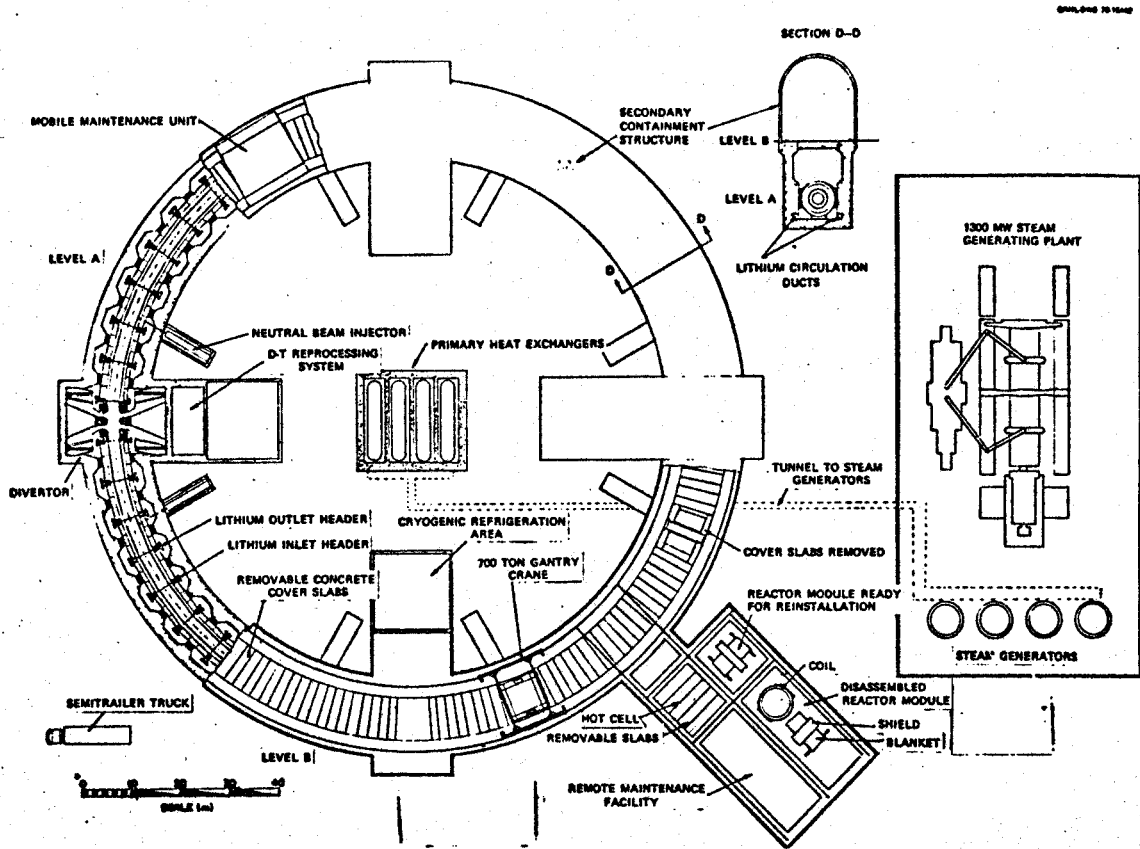
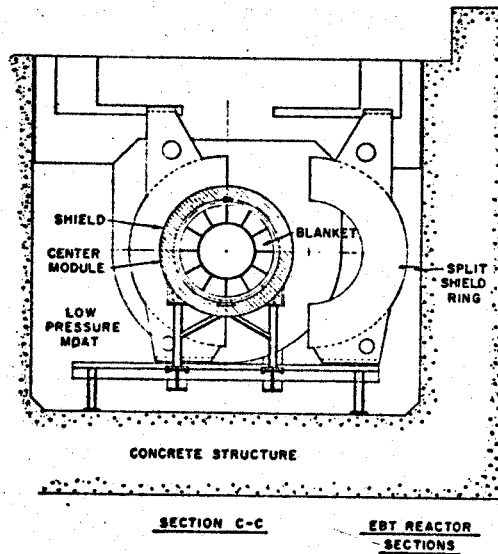Fig. 1. EBTR plan view

(48 Magnet Configuration)

Fig. 2. Cross section view of the torus and moat.

multiplications. This is consistent with a 2 MW_n/m^2 neutron wall loading, 18.7 Mev per fusion deposited in the blanket and shild and the plasma parameters given in the following table.

EBTR REACTOR REFERENCE PARAMETERS

Plasma radius, a(m)	1.0
Aspect ratio, A	30.
Major radius, R_o(m)	30
Mirror ratio, M	1.78
Ion temperature (kev)	15
Ion density, $N_i \times 10^{-20}$ m^{-3}	1.77
Beta, β (%)	34
Magnetic Field on axis, B_T(T)	2.5-4.5
Number of Coils, N	24
Power P_t (MW)	3666
Neutron Wall Loading (MW/m^2)	2
Cold zone, σ (m)	.2
Blanket and shield thickness, t_{sb}(m)	1.75
Coil inner radius, v_c(m)	2.95
Current density, J_c(A/cm^2)	1500
Coil radial thickness, t_c(m)	0.71
Coil half thickness, L/2 (m)	1.3

The entire torus is enclosed in a concrete moat which provides
a structural foundation for the reactor components and remote main-
tenance equipment, and a biological shield. Figure 2 shows a cross
section of the torus and moat at an early stage of dissembly.

The blanket is constructed from 20% cold worked 316 stainless
steel with natural lithium as the breeding material. The coolant
is helium at 54.4 atmospheres. The module design to be presented
here is an adaptation from a recent design developed in a study con-
ducted by Westinghouse and Oak Ridge National Laboratory for a
tokamak reactor operating at a 4 MW/m^2 neutron wall loading.[2]
As part of that study two design criteria applicable to steady state
operation were identified:

1. From a reliability standpoint the blanket module
   should be capable of withstanding coolant pres-
   sure since it is judged that a coolant leak can-
   not be precluded.

2. Integrally cooled walls are required to assure ab-
   ility of the blanket to remove the large heat
   fluxes without excessive structural temperatures.

A consideration in requiring integrally cooled walls was the pos-
sibility of helium generated in the lithium forming pockets within
a module. If the first wall receives a large surface heat flux and
conduction through lithium to a coolant tube is required, a void
in this region could lead to burnout of the first wall.

A cylindrical blanket module design as shown schematically
in Figure 3 was evolved which satisfied all design criteria.
Natural lithium and a stainless steel shield are contained within
an inner cylinder. A cylindrical baffle is between this cylinder
and the outer container wall. Helium coolant enters at the base,
flows towards the first wall between the outer wall and baffle,
goes through a hole in the baffle and reverses direction to flow
back between the lithium containing cylinder and the baffle. The
baffle itself is doubled walled with stagnant helium between the
walls to provide thermal insulation between the hot and cold legs.

FIRST WALL

Li CONTAINER

FLOW BAFFLE

STAINLESS STEEL SHIELD
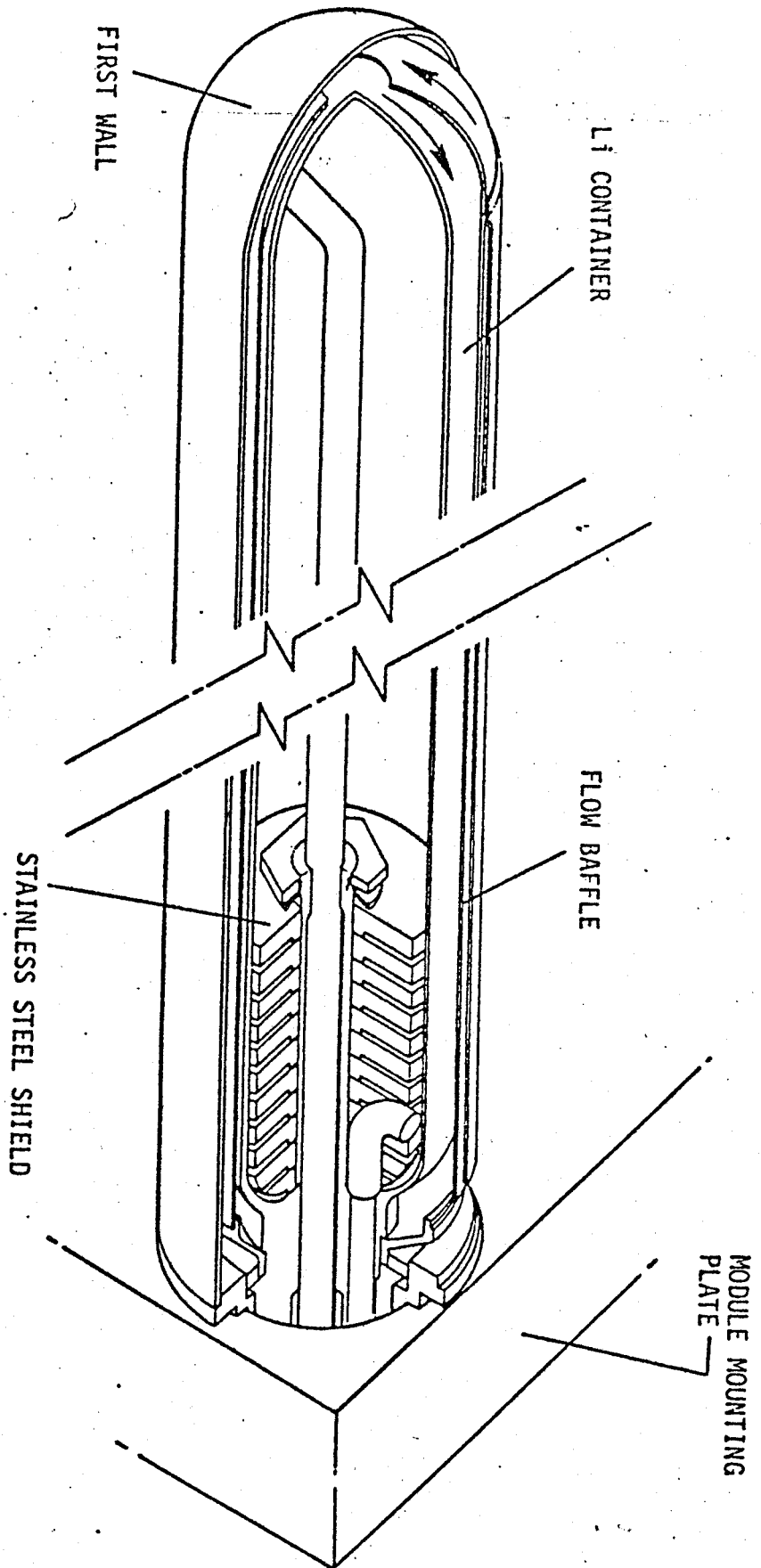
MODULE MOUNTING PLATE

Figure 3.   Cylindrical Blanket Module

The modules are welded to a backing plate and close packed on a triangular pitch. An extensive thermal hydraulic and structural analysis was carried out for modules with a 10.16 cm outside diameter at a 4 MW/m^2 neutron wall loading and the pulsed cycle of a tokamak. For EBTR, modules with double the radius and half the wall loading are proposed. The same coolant flow rates could be used for the same bulk coolant temperature rise. With double the wall thickness the hoop stress would be the same and the through thickness ΔT due to the surface heat flux at the first wall the same.

To limit the effect of radiation damage the first wall temperature was kept at or below 450°C. The peak structural temperature is approximately 500°C and occurs on the inner cyclinder where the hemisphere joins the cylinder.

For EBTR it is proposed to form 48 assemblies of modules. Each assembly would contain approximately 900 modules and their associated header system and piping for helium and lithium. Each assembly would be installed or removed as a single unit. One type assembly would fit under a magnet and another between magnets. The magnets would be fixed and one would be removed only if it fails.

A short summary of the cylindrical module parameters is given in Table 2. A more complete description of the Westinghouse-O.R.N.L. design will be available after publication of the final report on the Tokamak Blanket Design Program.

3. Plasma Engineering

Plasma engineering uses the results from applied physics analyses to design fusion systems. The design process in EBTR is difficult since some of the critical aspects of the system and its behavior are not well understood at present. It is necessary to make plausible estimates of the parameters and to retain flexibility so the design can accommodate new results from theoretical and experimental programs. This approach generates design criteria which define the appropriate directions for engineering and technology development efforts.

TABLE 2

CYLINDRICAL MODULE PARAMETERS

Length (cm)	75
Outside Diameter (cm)	20.32
Outer Wall Thickness	3.2 mm
Coolant Pressure	5.5 MPa
Maximum First Wall Temperature (°C)	450
Coolant Inlet Temp. (°C)	200
Coolant Exit Temp. (°C)	250
Pumping Power[a] (%)	2.2

[a] Pumping Power to heat removal ratio assuming 70% efficient pumps.

The fundamental plasma and device characteristics, system economics, and technology considerations for a commercial reactor of about 4000 MW(th), exclusive of blanket multiplication have been studied (see Appendix A). The neutron wall loading has been restricted to values near 1 MW/m². Although modest increases in wall loading improve system economics, loadings about 3 or 4 MW-m² will almost certainly be uneconomical due to the reliability and pumping penalties.

The plasma size is determined by specifying power output, power density, and neutron wall loading. Plasma dynamics simulations, equilibrium, and drift orbit calculations show that a plasma radius of about 1 m is adequate to attain ignition, assuming neoclassical and/or classical scaling. However, no definitive basis for the size required for the reactor plasma has been developed. As in the other system studies, size and plasma parameters are determined self-consistently from theoretical models, but the ultimate values will be determined by experimental results which validate the assumptions used or provide the basis for changing them.

3.1 System Characteristics

The first material boundary surrounding the plasma is assumed to be capable of tolerating a neutron wall loading, L_w, on the order of 1 to 3 MW/m². This boundary exists at a distance from the plasma center equal to the average plasma radius, a, plus the cold zone, δ. The total fusion thermal power output (exclusive of blanket multiplication), P_{th}, produced in the plasma is

$$P_{th} \cong \frac{17.6}{14.1} L_w (2\pi)^2 Aa^2 (1 + \delta/a)$$ (1)

where A is the plasma aspect ratio.

The wall loading is coupled to the thermal power density, which in turn will dictate the desirable characteristics for the plasma.

For example,

$$\frac{P_{th}/L_w}{V_p} \approx \frac{17.6}{14.1} \frac{2}{a} (1 + \delta/a), \tag{2}$$

where V_p is the plasma volume. Note that for an assumed wall loading, the thermal power density is independent of A and depends only on δ and a.

The plasma power density required to attain a particular wall loading in a given size device has been determined, and dicatates the range of plasma densities and temperatures required to produce the power density. That is,

$$P_{th}/V_p \approx 2.8 \times 10^{-18} \frac{N_i^2 <\sigma v>}{4}, \tag{3}$$

where $<\sigma v>$ is the fusion reaction rate probability and $N_d \approx N_t \approx N_i/2$ has been assumed. The power density can be written in terms of beta (β), the ratio of plasma pressure to magnetic energy density, and B, the magnetic field strength:

$$P_{th}/V_p \approx 2.8 \times 10^{-18} \frac{<\sigma v>}{4T^2} \frac{\beta^2 B^4}{(4\mu)^2}. \tag{4}$$

The trade-offs between β and B must be considered. High-β, low-B operation is desirable. The practical minimum magnetic field in this work is taken to be $B \approx 2.5$ T.

In addition to the magnetic and plasma physics constraints des-

cribed above, the required microwave frequencies must be determined. A magnetic field of $\sim$ 4.0-4.5 T exists near the magnet throat, where the resonant frequency is $\sim$ 120 GHz, suitable for background plasma heating. Because of the decreased density and field strength in the region of the stabilizing annuli, microwave frequencies less than this by a factor of 2 may be acceptable to sustain the annuli. A final decision on the means of heating the EBTR plasma should not be made now but the frequency requirements, if microwaves are used, are compatible with those of components under development. It is more likely, in view of cost, complexity, and efficiency criteria, that an optimized system will utilize microwaves to sustain the annuli but use neutral beam injection to heat the plasma to ignition. To test the plausibility of beam heating, a plasma point kinetic model (see Appendix D) was used in a computer study of various start-up scenarios. For the particular case studied in Appendix D, it was determined that 200 MW of neutral beam power (150 keV) would be sufficient to heat EBTR-48 to ignition in about 3 sec. The value of 200 MW is probably an overestimate since longer start-up times may require smaller amounts of input power. Full penetration calculations have not been completed. The estimates in Appendix D serve to demonstrate feasibility, but are not sufficiently detailed for optimization studies.

4. Plasma Physics

The plasma physics areas which determine the EBTR operating characteristics are: (1) particle orbits and their effects on efficient use of the plasma chamber colume, (2) plasma stability and equilibrium, and (3) scaling, transport and modeling, which are described at length in Appendixes B-D.

For a high beta, steady state system, the plasma equilibrium, particle orbits, ambipolar electric field, and transport phenomena are closely coupled to one another, and an adequate treatment of any

one requires consideration of the others. The interrelations are:
(1) equilibrium magnetic fields depend on the plasma pressure pro-
file, (2) guiding-center drift orbits depend on the equilibrium
magnetic field and the ambipolar electric fields, and (3) transport
rates, which together with energy sources and sinks determine the
profile, depend on the guiding center drift orbits. A self-
consistent treatment of this coupled set of problems for a large-
scale EBTR, while being vigorously pursued, is not yet available.
Intermediate and/or partial answers have been used to proceed into
the full self-consistent treatment.

4.1 Equilibrium and Drift Surfaces

The requirement for efficient use of the volume within the
vacuum chamber of the reactor proved to be very important to the de-
sign. The shield and blanket which surround the plasma chamber in
the reactor make efficient field usage more difficult than in the
present experimental device (EBT-1).[3]

Finite beta and ambipolar electric fields make considerable dif-
ferences in the particle orbits. For the EBTR-48, a detailed cal-
culation was carried out for a sample equilibrium, guided by the ex-
perimental observation that the ambipolar electric field is
strongest in the vicinity of the annuli. The spatial position
of the hot electron annuli is critical to obtaining efficient utiliza-
tion of the volume within the vacuum chamger. Macroscopic stability
demands that the toroidal core plasma pressure be relatively con-
stant near the minor axis and fall rather rapidly in the region of
the annuli, so the annuli form a set of "guard rings" which surround
the toroidal core. Experimental observation and numerical computa-
tion show that the annuli form near contours of constant $|\vec{B}_{vacuum}|$
in the midplane of the device. Toroidal effects cause these con-
tours to be shifted inward toward the major axis. To the lowest
order, the plasma follows the field lines, and for a fixed inner

wall radius some of the field lines which pass through the coil aperture intersect the lateral wall of the chamber. This problem can be solved by "bulging" the inner wall near the midplane (as in EBT-I) and using a nonuniform shield and blanket thickness within the coil throat. Consideration is also being given to the use of supplementary coils for the proposed 24 coil design.

There are three features which are relatively independent of the details of the inner wall design and the magnetic equilibrium and ambipolar electric fields: (1) low energy particles are well confined, (2) mirror trapped particles are well confined, and (3) high energy particles with $v_{||}/v \sim 1$ are not well confined. The use of supplementary coils can improve the confinement of this last class of particles.

4.2 Macroscopic Stability

The viability of EBT as a reactor requires the stable confinement of a plasma with a density of about 10^{20} m^{-3} and a temperature on the order of 10-15 keV. A relativistic hot electron population (annuli) with $T_e \sim 100$ keV is crucial to the stability of the EBT plasma. The annulus density, however, is only about 10^{18} m^{-3}, a small fraction of the total electron density. The hot electron population is immune to the macroscopic flute-like drift instabilities because of the fast drift velocities and large Larmor radii of its particles. By modifying the magnetic field, the annuli also provide stability for the rest of the plasma, which is composed of warm ions and electrons. Thus the simplest model for discussing the stability of the EBT plasma is one with three components: hot electron annuli, warm electrons, and warm ions. One can treat first the instabilities of the hot electrons, and then the instabilities of the warm species. The effort to date has been concentrated on macroscopic instabilities those which produce large particle transport and would be fatal to a reactor.

Stability of the Hot Electron Annuli

The requirement for stability is that the temperature of the hot electrons be high enough and the magnetic field gradient produced by diamagnetism be large enough to achieve a ∇B drift frequency which exceeds the ion cyclotron frequency. When this condition is satisfied, the Vlasov-Maxwell equations show that hot electron drift waves are stabilized, apparently by interference between the responses of the fast drifting electrons and the slowly drifting ions.[5] As the hot electron density or temperature is reduced, these waves become unstable, and at still lower temperature, where the magnetohydrodynamic (MHD) and guiding center theories are applicable, they become the unstable flutes and ballooning interchanges predicted by these theories. Thus, stable operation of a reactor will require that the hot electrons achieve a temperature comparable to that in the present device (EBT-I) and a pressure profile of sufficient steepness to produce large ∇B drifts. Near the outer edge of the annuli, the hot electron temperature is not high enough to stabilize drift waves. However, the outer edge of the plasma can be line-tied, which effectively stabilizes these modes. Present theory does not allow a definitive answer on how large the line-tied region must be, nor how line tying will be affected by the addition of a divertor system.

Stability and Beta Limitations of the Bulk Plasma

In the vacuum field of EBT, the bulk plasma is likewise subject to unstable drift and MHD modes at frequencies characteristic of their ∇B and diamagnetic drifts. The hot electron diamagnetic currents act as "invisible coils" colocated with the bulk plasma to create a region of minimum average B in which $\oint d\ell/B$ decreases with radius. In this region a stable bulk plasma can be established and then stably extended to the magnetic axis, even though the minimum average B region does not extend to the magnetic axis. Figure 4 shows the location of the hot electron plasma, the region of decreasing $\oint d\ell/B$ and the stably confined bulk plasma. The bulk plasma β can approach that of the annuli before instabilities occur.
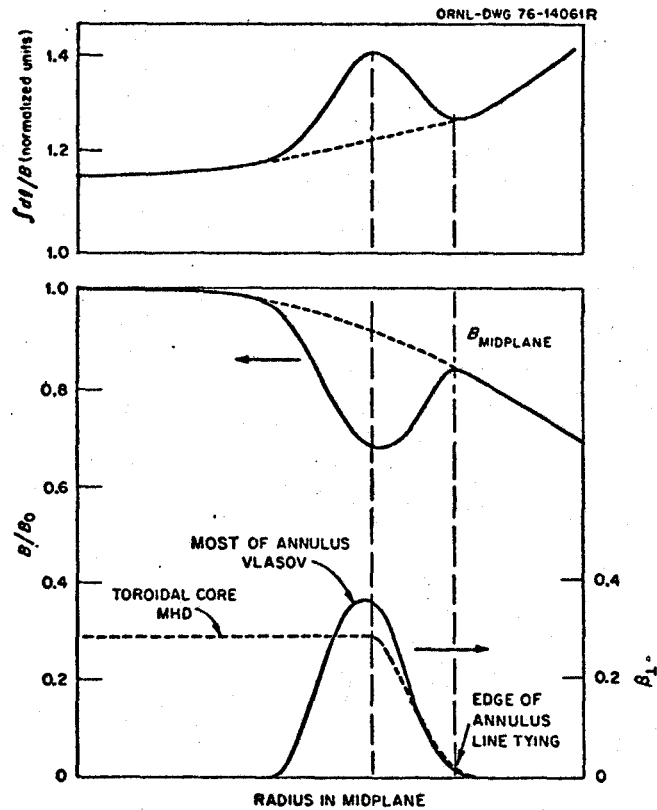
Figure 4. $\oint d\ell/B$, magnetic field, and pressure vs. distance from the minor axis in the midplane for the vacuum field (dashed) and the finite β field (solid).

Once a magnetic well has been established by the annuli (at annuli $\beta \sim$ 5-15%), a β of the bulk plasma comparable to, or even somewhat higher than the β of the annuli can be achieved which is stable to all modes encompassed by guiding center or ideal MHD theories. The modes, which limit bulk β, are pressure-diven ballooning interchanges.

Experimental confirmation of these optimistic β predictions is not possible in the present device because there β is limited by heating and transport considerations. However, the lower threshold for stable confinement at annuli $\beta \sim$ 8% is observed, where it marks the boundary between the C- and T-modes.[6]

4.3 Scaling, Transport, and Modeling

The design of EBT fusion reactors must be based on scaling laws which have not been fully verified by experiments. However, in the observed macrostable regime of operation in EBT-I[6] there is a reasonable agreement between experiment and a simplified neoclassical point model. The EBT-S and EBT-II[3] devices are designed to allow further study of transport ans caling properties, especially in the collisionless regime (of interest to reactor operation). Theoretical work in support of these experiments will refine the existing transport theories.

In view of the uncertainties in the theoretical coefficients and the present lack of experimental evidence in this area, the plasma energy balance was modeled using both neoclassical and classical theory with appropriate density and temperature scale lengths (see Appendix D). The reactor plasma model is consistent with the theoretical physics model: a toroidal core with nearly uniform density and temperature within the plasma radius, which is determined by the stabilizing annuli. Flexibility was retained in the simulation models to permit updated data to be incorporated as they become available.

5. Toroidal Magnet System Design and Scaling

The EBTR magnet system designs are determined by considerations of scaling, conductor design, coil design, cryogenics, and protection. Aside from the plasma constraints, the main goal was the design of coils which could be built with existing technology or with technology which is the immediate goal of existing development programs.

A description of an alternate magnet design is also given. This design is based on the high current density, forced-flow, bundled conductor concept. This approach holds great promise for the future. Main features of both designs are discussed in detail in Appendix E.

5.1 Magnet Scaling

Independent of plasma physics considerations, the number of coils, mirror ratio, coil radius, and the reactor major radius can all be related by the geometry of the vacuum magnetic fields. Plasma physics considerations further relate the allowable mirror ratios to the aspect ratio, electron ring beta, stable plasma volume, magnetic axis shift, and similar quantities.

5.2   Conductor Design

It is generally agreed that superconducting magnets are required for an economical fusion reactor. Reactor application also demands high reliability, requiring a fully cryostabilized conductor design. Multifilamentary Nb_3Sn is at an early stage of development, so presently available monolithic composites of multifilamentary NbTi in Cu matrix are used in the reference reactor study. The average current density in the windings is 1500 A/cm^2, which gives a peak field strength in the winding of 7.3 T. The alternative design uses $NbTi-Nb_3Sn$ composite superconducting coils, yielding peak fields in the Nb_3Sn and NbTi windings of 10 T and 5.2 T and corresponding average current densities of 2000 and 4000 A/cm^2.

Cryostability is achieved by soldering the composite to formed copper strips with punched slots. There are sufficient cooling surfaces to transfer up to six times the Joule heating produced if all

the current were to flow in the copper.

5.3 Magnet Design

In contrast to the tokamak, the EBT has a high aspect ratio, so the magnetic field and loading are nearly symmetrical and there is no need to use D-or oval-shaped coils to minimize the bending moments. Circular coils are used in EBTR-48 and EBTR-24. For this reference design 24 of the EBTR-48 type of magnet are employed.

The coils are faily long compared with their radial thickness, and their axis is horizontal. Pancake-wound construction with spaces between pancakes is chosen for its high voltage capability and short cooling channels.

Natural convection pool boiling is chosen as the cooling method for the reference design, while the alternative design option operates under forced-flow conditions. Coolant can pass along the conductor through the copper strip fins or through the slots, resulting in a flow in both radial and azimuthal directions. This allows flow mixing and aids helium bubbles to reach the top of the coil, an important feature for a coil with a horizontal axis.

An interesting possibility is that the magnets may be made modular and used in reactors of different sizes. As long as the ratio of major radius to the number of coils is fixed, the field strengths produced by modular magnets of the same size are not sensitive to the size of the reactor. The mirror ratio and coil bore fixes the length of the blanket and shield modules which are located between adjacent magnets. These parameters are fixed by plasma physics and blanket-shield engineering requirements. Furthermore, for given neutron wall loading, the plasma radius is relatively insensitive to changes in the major radius of the machine. The various components of the reactor system can be modular and standardized and still serve in reactors of different major radii and power outputs.

5.4 Cryogenics

The toroidal magnets in the EBTR will be cooled by liquid helium under pool boiling conditions for the reference case and by supercritical helium under forced-flow conditions for the alternate case. Individual dewars and vacuum vessels are used for each coil. To avoid interference with the remote assembly of the blanket, helium will be supplied to the magnets in the radial direction from the cold box.

The EBT reactor is expected to operate in steady state. Accordingly, there will be no heat load requirement due to pulsed fields. The heat loads that must be removed by the liquid helium (or supercritical helium) cryogenic system include the radiation heat absorbed from the magnet dewar surface, the loads due to conduction through the support and instrument leads, and the radiation energy absorbed from incident neutrons and gamma rays.

5.5 Protection

High operating current (25 kA) is used to reduce terminal voltage during discharge, and four conductors (each carrying 6.25 kA) are connected in parallel to supply the total current. To ensure even distribution of current, a spiral winding technique is adopted.

Voltage taps are used on each coil as the main quench detection device. Pick-up coils on the current leads of the power supplies can be used to compensate for the inductive voltage. External dump resistors are used as heat sinks.

6. Divertors

Divertors may be required in fusion reactors to provide for the removal of plasma reaction products, to act as conduits for steady state removal of diffusing plasma, to serve as access for initial pumpdown, and to keep atoms sputtered from the system boundaries from

diffusing deeply into the plasma. The high aspect ratio and relatively low magnetc field of EBT make it possible to design a relatively simple "classical toroidal divertor" (See Appendix F). The present module design, however, conservatively assumes the full surface heat flux on a module.

7. Mechanical Design

The EBT reactor study has considered the mechanical design of the following: (1) the first wall, (2) the nuclear blanket, (3) the radiation shield to protect the coils, (4) the superconducting coil support, and (5) the concrete enclosure and biological shield. The design was carried to sufficient detail (see Appendix G) to demonstrate fabrication and remote maintenance. The stresses will be within acceptable limits and the required heat removal will be possible.

Since the EBTR has a high aspect ratio and relatively wide magnet spacing, it is possible to design modules that can be used in machines of various sizes. In the reference case of a reactor with a 30-m major radius, 48 modules are required, together with 24 magnets and 96 shield sections. The number of modules in a larger device increases in proportion to the major radius so that the spacing of the magnets remains constant. This concept of standardized modules is extremely favorable in the context of a fusion reactor economy.

A standard module is located under each coil and a module is located between each pair of adjacent coils. Removal of the spacer modules (between coils) permits the less accessible modules to be rolled axially into position for vertical removal from the machine. This procedure permits maintenance to be performed with the coils in place and at $4.2°K$.

Each large module is an assembly of approximately 900 of the cylindrical modules as discussed previously.

The superconducting coils must be shielded from the radiation produced in the plasma and blanket. The proposed shield is 53.5 cm thick and is composed of concentric cylinders; the annular spaces are filled with stainless steel spheres, and borated water.

The borated water is circulated to cool the shield. It enters at 20°C and exits at 32°C. The shield is divided into 96 modules, 2 per blanket module assembly. The fixed magnets use cables to support the gravity loads and the centering forces, so the dewars can completely enclose the magnets except that bellows seals are used where the cables penetrate the dewar wall. The cables give a uniform stress on the coil bobbin and maintain a uniform load distribution during magnet cooldown.

A concrete moat with articulated roof slabs encloses the torus. The moat is about 15 m wide and 18 m high with a wall thickness of 3 m. Concrete abutments are located on the inner side of the walls adjacent to each coil. These are used to restrain laterial movement of the coils in case of a quench. The roof slabs over the coils are used to support the coil and module gravity loads. Modules between the coils are supported from the moat floor.

8. Neutronics

Preliminary neutron analysis for several EBTR designs have been carried out using the one-dimensional discrete ordinates code ANISN.[7] For the cylindrical nodules analyzed by Westinghouse the breeding ratio was 1.1 with a 60 cm breeding zone of lithium followed by a 15 cm stainless steel gamma-ray shield. This was slightly less than the values attained by previous designs at ORNL due to the increased amounts of structure and void required to make each module a pressure vessel. This breeding ratio is probably adequate but could improve by increasing the length of the breeding zone.

9. Conclusions

An EBTR reference design has been developed. If the present understanding of the physics extends to the reactor regime, the system will operate at high beta and high power density, and in steady state. Problems of accessibility, structural design, and remote maintenance are eased considerably because of the high aspect ratio in the EBTR and the fact that there are no pulsed magnetc fields.

REFERENCES:

1. D. McAlees, et al, "The ELMO Bumpy Torus Reactor (EBTR)
        Reference Design", ORNL-TM-5669, Nov. 1976.

2. J.S. Karbowski, "Tokamak Blanket Design Program Final
        Report", WFPS-TME-102 (ORNL Number Not Available)
        to be published.

3. R.A. Dandl, et al, The ELMO Bumpy Torus Program, ORNL/TM-5451,
        Oak Ridge (April 1976).

4. C.L. Hedrick, et al, "Transport and Scaling in the ELMO Bumpy
        Torus (EBT)", Paper CN-35/D7, 6th   Conf. on
        Plasma Phys. and Cont. Nucl. Fus. Res., Berchtesgaden,
        Germany, FRG, Oct. 6-13, 1976.

5. G.E. Guest, C.L. Hedrick, and D.B. Nelson, Phys. Fluids 18,
        871 (1975).

6. R.A. Dandl, et al, Research Program for Plasma Confinement and
        Heating in ELMO Bumpy Torus Devices, ORNL/TM-4941,
        Oak Ridge (June 1975).

ALTERNATE FUSION CONCEPTS INFORMATION SHEET

	UNIT	LINUS	FLR	RFPR	LTPR	LASER SOLN'D.	EBHSR	SHWCR	EBT
1. POWER OUTPUT									
*1.1 THERMAL POWER TO POWER CYCLE (TIME AVERAGE)	MWt								3666
*1.2 DIRECT ENERGY CONVERSION (TIME AVERAGE)	MWe								N/A
*1.3 PLASMA CHAMBER POWER DENSITY	MWt/m^3								4.3
1.4 PLANT GROSS ELECTRICAL OUTPUT	MWe								
1.5 PLANT NET ELECTRICAL OUTPUT	MWe								
2 REACTOR COOLANT SYSTEM									
*2.1 BLANKET COOLANT TYPE									Helium
*2.2 BLANKET OUTLET TEMP. (HOT LEG)	°C.								450
*2.3 BLANKET INLET TEMP. (COLDL LEG)	°C.								200
*2.4 BLANKET OUTLET PRESSURE	MPa								5.42
*2.5 BLANKET INLET PRESSURE	MPa								5.51
*2.6 BLANKET COOLANT FLOW RATE	Kg/s								2820
2.7 BLANKET COOLANT PIPE MATERIAL									
*2.8 FIRST WALL COOLANT TYPE									See Attachment
*2.9 FIRST WALL OUTLET TEMP.	°C.								
*2.10 FIRST WALL INLET TEMP.	°C.								
*2.11 FIRST WALL OUTLET PRESS.	MPa								
*2.12 FIRST WALL INLET PRESS.	MPa								

*INFORMATION ON ITEMS WITH ASTERISK TO BESUPPLIED BY REACTOR CONCEPT DESIGNERS.

2 REACTOR COOLANT SYSTEM (CONT'D.)

	UNIT	LINUS	FLR	RFPR	LTPR	LASER SOLN'D.	EBHSR	SHWCR	EBT
*2.13 FIRST WALL COOLANT FLOW RATE	Kg/S								N/A
2.14 TOTAL NUMBER OF BLANKET COOLANT LOOPS									
2.15 TYPE OF BLANKET COOLANT CIRCULATOR									
2.16 POWER INPUT TO EACH CIRCULATOR	MWe								
*2.17 PEAK BLANKET TEMP. IN CASE OF LOSS OF COOLANT FLOW	°C.								
3 INTERMEDIATE COOLANT SYSTEM									
*3.1 COOLANT TYPE									HITEC
*3.2 IHX OUTLET TEMP. (HOT LEG)	°C.								430
*3.3 IHX INLET TEMP. (COLD LEG)	°C.								187
*3.4 IHX OUTLET PRESSURE	MPa								.35
*3.5 IHX INLET PRESSURE	MPa								.35
*3.6 COOLANT FLOW RATE	Kg/S								8060
3.7 COOLANT PIPE MATERIAL									
3.8 TOTAL NUMBER OF COOLANT LOOPS									
3.9 TYPE OF COOLANT CIRCULATOR									
3.10 POWER INPUT TO EACH CIRCULATOR	MWe								
3.11 NUMBER OF IHX PER LOOP									
3.12 IHX MATERIAL - SHELL/TUBE									

4. STEAM GENERATION SYSTEM UNIT

	UNIT	LINUS	FLR	RFPR	LTPR	LASER SOLN'D.	EBHSR	SHWCR	EBT
4.1 STEAM OUTLET TEMPERATURE	°C. (°F)								
4.2 STEAM OUTLET PRESSURE	MPa(PSIA)								
4.3 STEAM FLOW RATE	Kg/S(LB/HR)								
4.4 FEEDWATER TEMPERATURE	°C (°F)								
4.5 NUMBER OF STEAM GENERATORS PER LOOP									
4.6 NUMBER OF MODULES PER SG									
4.7 SG MATERIALS, SHELL/TUBE									
5. SHIELD COOLANT SYSTEM									
*5.1 TOTAL ENERGY DEPOSITED IN THE SHIELD	MW$_t$								114
*5.2 SHIELD COOLANT TYPE									H_2Oa
*5.3 SHIELD OUTLET TEMP.	°C								.32
*5.4 SHIELD INLET TEMP.	°C								20
*5.5 COOLANT OUTLET PRESSURE	MPa								.152
*5.6 COOLANT INLET PRESSURE	MPa								.203
*5.7 COOLANT FLOW RATE	Kg/S								2233

a   Borated water.

6. REACTOR AUXILIARY SYSTEMS

	UNITS	LINUS	FLR	RFPR	LTPR	LASER SOLN'D.	EBHSR	SHWCR	EBT
6.1 VACCUM PUMPING SYSTEM									
• PLASMA CHAMBER PRESSURE	TORR								7.6×10^{-5}
• PLASMA CHAMBER VOLUME	M^3								853
• NUMBER OF CRYO-PUMPS									8
• CAPACITY OF EACH CRYO-PUMP	TORR–LITRE/SEC								80
6.2 MAGNET COOLING SYSTEM									
• COOLING LOAD	WATT								1250[a]
6.3 PLASMA HEATING SYSTEM	WATT								13.1[b] MW
• COOLING LOAD									
6.4 TRITIUM PROCESSING AND RECOVERY SYSTEM									
• TOTAL TRITIUM INVENTORY	Kg								≤ 14

a See Table E-5 for EBTR-48 Coils.

b Assumes -25% efficiency for microwave generation.

7. REACTOR COMPONENTS

7.1 BLANKET/FIRST WALL

	UNIT	LINUS	FLR	RFPR	LTPR	LASER SOLN'D.	EBHSR	SHWCR	EBT
*MATERIAL									20%CW 316 ss
*NUMBER OF MODULES									48
*WEIGHT OF EACH MODULE	TONNES								100
*WEIGHT OF LARGEST SINGLE COMPONENT	TONNES								100
*DIMENSIONS OF THE LARGEST COMPONENT	MXMXM								4.2x4.26 x4.26
7.2 SHIELDING									
*MATERIAL									65%316SS 35%H_2O^a
*NUMBER OF MODULES									96
*WEIGHT OF EACH MODULE	TONNES								106
*WEIGHT OF LARGEST SINGLE COMPONENT	TONNES								106
*DIMENSIONS OF THE LARGEST COMPONENT	MXMXM								5.43x4.28 x2.71
7.3 MAGNET									
*COIL FORCES TRANSMITTED TO BUILDING	NEWTON								
7.4 REACTOR ASSEMBLY									
*TOTAL WEIGHT OF REACTOR ASSEMBLY	TONNES								2.5×10^4
8. BUILDINGS									
8.1 CONTAINMENT BUILDING									
*MINIMUM WALL THICKNESS FOR SHIELDING	M								3
*INTERNAL PRESSURE, NORMAL/ACCIDENT	MPa								10^{-3}torr .27 MPa
*CONTAINMENT ATMOSPHERE									air
8.2 ELECTRICAL ENERGY STORAGE BUILDING									
*WALL THICKNESS FOR SHIELDING	M								
*INTERNAL PRESSURE, NORMAL/ACCIDENT	MPa								
*SAFETY RELATED OR NOT	YES/NO								N/A

a) Borated Water

ELECTRICAL POWER REQUIREMENTS

	UNIT	LINUS	FLR	RFPR	LTPR	LASER SOLN'D.	EBHSR	SHWCR	EBT
*COLD START POWER FROM GRID	MWe VS. SEC								6-13 hr 400-5 Sec
AUXILIARY POWER REQUIREMENT(NORMAL OPERATION)	MWe								
*ELECTRICAL ENERGY STORAGE									
*MAGNET POWER SUPPLY (OTHER THAN ENERGY STORAGE)									
BLANKET CIRCULATORS									
FIRST WALL COOLANT CIRCULATORS									
SHIELD COOLANT CIRCULATORS									
*REFRIGERATION SYSTEM									6.3
*VACUUM SYSTEM									0.5
*PLASMA HEATING SYSTEM (Microwaves)									17.5
*MISCELLANEOUS REACTOR PLANT AUXILIARIES									
FEED PUMP SYSTEM									
CONDENSING SYSTEM									
HEAT REJECTION SYSTEM									
MISC. BOP AUXILIARIES									

REACTOR MAINTENANCE

	UNIT
10.1 BLANKET/FIRST WALL REPLACEMENT	TONNES/YR
10.2 RADIOACTIVE MATERIAL STORAGE REQUIREMENT; YEARS/VOLUME	YR/M³
10.3 DESCRIPTION AND SKETCHES OF REPLACEMENT CONCEPT	

REACTOR ASSEMBLY

*DETAILED DIMENSIONAL DRAWINGS OF REACTOR ASSEMBLY