TOKAMAK FUSION POWER REACTORS

REACTORS

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The major parameters and corresponding economic characteristics of a representative class of commercial tokamak fusion power reactors are examined as a function of four major design parameters: plasma β_t, toroidal magnetic field strength, first-wall lifetime, and power output. It is shown that for $\beta_t \geqslant 0.06$, the minimum cost of energy is obtained for toroidal field strengths of ~8 to 9 T. Tokamak power plants exhibit an economy of scaling with a lower cost of energy for larger power reactors. Representative design parameters, costs, schedule, and technology advances are presented for a sequence of three reactors that could lead to the demonstration of commercial feasibility of this class of tokamak fusion power reactors near the turn of the century.

INTRODUCTION

The first generation of designs for commercial[1-3] and experimental power reactor[4-7] (EPR) tokamak fusion power reactors served to elucidate many of the technological problems of fusion reactors and to identify possible solutions. Because these studies were based, by and large, on conservative assumptions regarding the plasma physics and the extrapolation of technology, the reactor designs were large and expensive. Moreover, the conservative first-cut solutions to engineering design problems sometimes led to somewhat complex designs. While these first-generation designs were a valuable and necessary first step in defining the characteristics of tokamak fusion power reactors, they created an overly pessimistic impression of tokamak reactors as large, complex, and expensive devices. They also stimulated a search for better design solutions and a reexamination of the plasma physics bases of the design.

Presently, second-generation designs for commercial,[8] precommercial demonstration[9-11] (DEMO), and experimental[12] reactors are evolving. In addition, codes are becoming available that allow a parametric analysis[13] of a wide range of design parameters. This second generation of designs is generally smaller because of a higher power density, simpler because of better design solutions, and potentially less expensive than the first generation of designs. The higher power densities are postulated on the basis of shaping the plasma cross section to allow confinement of the plasma at higher pressure (i.e., higher β_t), a favorable reevaluation of previously supposed magnetohydrodynamic (MHD) limits on the maximum β_t that could be confined and/or the use of higher magnetic fields to confine higher density plasmas.

In addition to the power reactor design activities, there are two substantial design efforts, one at General Atomic Company and Argonne National Laboratory (ANL), the other at Oak Ridge National Laboratory and Westinghouse Electric Company, for plasma ignition experiments, which are currently envisioned as the next step (TNS) in the tokamak program after the Tokamak Fusion Test Reactor (TFTR). Design solutions that are being developed in the TNS designs are, in some instances, extrapolatable to power reactors.

Thus, the perception of a tokamak power reactor that is emerging from ongoing work is more encouraging than the earlier perception based on the first-generation design studies.

The purposes of this paper are

1. to identify the size and economic characteristics of one particular class of commercial tokamak fusion reactors and to assess the sensitivity of these characteristics to four important parameters: plasma β_t, toroidal magnetic field strength, first-wall lifetime, and power output. A single geometric configuration has

been chosen to limit the scope of the study; an extensive parametric study is in progress and will be reported elsewhere.[13]

2. to describe a plausible path along which tokamak power reactors could evolve toward a commercial reactor.

COMMERCIAL TOKAMAK POWER REACTORS

One of the principal lessons learned from the first-generation design studies was that it was necessary to increase the fusion power density in the plasma to reduce the size, and hence the cost, of the reactor. The power density in a β_t-limited tokamak can be written as

$$P \propto \beta_t^2 B_t^4 (1 + \kappa^2)^2 \quad , \tag{1}$$

where

β_t = plasma kinetic-to-magnetic pressure ratio

B_t = toroidal field strength at the center of the plasma

κ = plasma height-to-width ratio or elongation.

Plasmas with D-shaped cross sections and elongations in the range $1 \leqslant \kappa \leqslant 2$ and plasmas with connected double-teardrop, or Doublet, shaped cross sections and elongations in the vicinity of $\kappa = 3$ have been the most extensively studied. In this paper, a single D-shaped plasma with $\kappa = 1.65$ is considered.

The magnetic field, B_t, depends on the maximum magnetic field, B_{TFC}, at the coil and on the geometry according to

$$B_t = B_{\mathrm{TFC}} \left(1 - \frac{1}{A} - \frac{\Delta_{BS} + \Delta_V}{R} \right) \quad , \tag{2}$$

where

$A \equiv R/a$ = aspect ratio

R = major radius of the plasma torus

a = plasma minor radius

Δ_{BS} = thickness of the blanket and shield on the inside of the torus

Δ_V = thickness of the scrape-off region between the plasma and chamber wall.

In this paper, a single set of geometric parameters ($A = 3$, $\Delta_{BS} = 1$ m, $\Delta_V = 0.2$ m) is considered. The 1-m blanket/shield thickness has been found to be economically optimum.[13] Toroidal field strengths $B_{\mathrm{TFC}} \lesssim 9$ T are believed to be achievable with a NbTi superconductor, which allows magnets to be designed to a strain level of 0.2%. At fields $B_{\mathrm{TFC}} \gtrsim 9$ T, Nb_3Sn superconductors would be required, and the magnets probably must be designed to a much lower strain level; 0.1% is used in this paper, although a smaller strain level may well be necessary. The limits on β_t will be determined by MHD stability constraints. These limits have not yet been established, so a plausible range of β_t values is considered.

This part of the study will examine the range of possibilities for a tokamak reactor that would produce a thermal power of 3000 MW(th); this roughly corresponds to an electrical power of 1000 MW(e). The size of such a reactor is indicated in Fig. 1 as a function of B_{TFC} and β_t. Based on this range of parameter space, parametric studies were performed to evaluate the economic characteristics of reactors. Lithium-cooled reactors with an intermediate sodium coolant and thermal energy storage loop and a conventional steam cycle were considered. Superconducting magnets and advanced electromagnetic energy storage and transfer systems were assumed. Costs were estimated for the entire reactor facility, including the nuclear island, balance of plant, and facilities. The plasma physics, reactor systems, and cost algorithms employed in developing the data displayed in Fig. 1 and in assessing its reactor implications are discussed in Ref. 13.

The capital cost per unit electric power of 3000-MW(th) tokamak reactors is displayed in Figs. 2 and 3, as a function of B_{TFC} and β_t; the corresponding size can be determined from Fig. 1. The capital cost includes direct cost plus indirect costs. The indirect cost is assumed to be ~50% of the direct cost to cover the cost of construction facilities, engineering services, interest during construction, and other owner costs. No allowance was made for contingency.

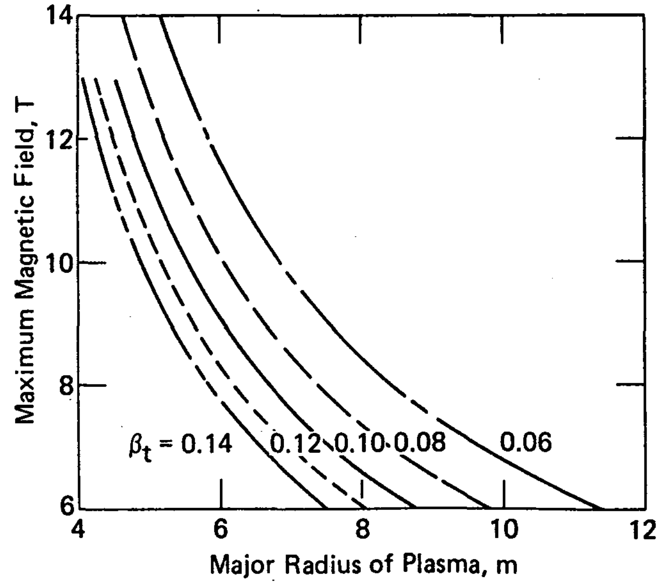

Fig. 1. Effect of toroidal magnetic field strength and plasma β_t on the size of a tokamak reactor for a fixed thermal power output of 3000 MW(th). (Aspect ratio = 3, plasma D elongation = 1.65, plasma safety factor = 3, inner blanket/shield thickness = 1 m.)

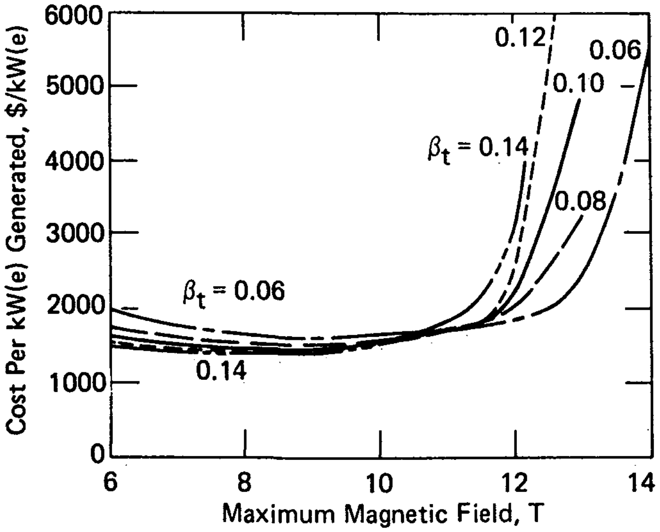

Fig. 2. Effect of toroidal magnetic field strength and plasma β_t on the capital cost per unit power for a fixed thermal power output of 3000 MW(th) in a lithium-cooled tokamak reactor with stainless-steel structural material. [Aspect ratio = 3, plasma D elongation = 1.65, plasma safety factor = 3, inner blanket/shield thickness = 1 m, maximum structure temperature = 500°C, electrical power output ≈ 940 MW(e).]

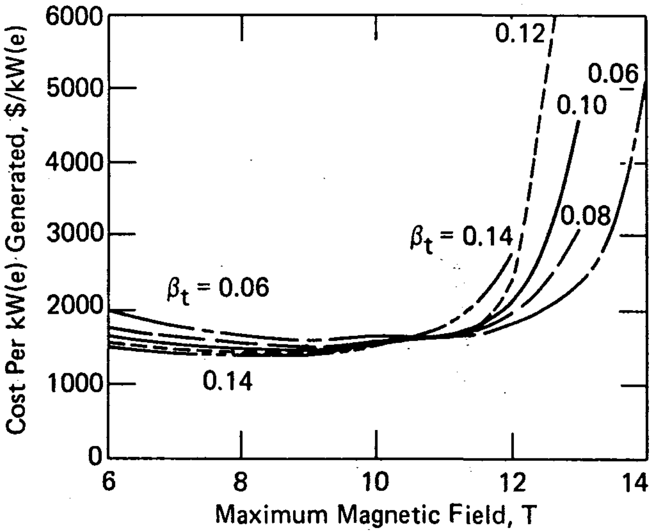

Fig. 3. Effect of toroidal magnetic field strength and plasma β_t on the capital cost per unit power for a fixed thermal power output of 3000 MW(th) in a lithium-cooled tokamak reactor with vanadium-alloy structural material. [Aspect ratio = 3, plasma D elongation = 1.65, plasma safety factor = 3, inner blanket/shield thickness = 1 m, maximum structural temperature = 650°C, electrical power output ≈ 1060 MW(e).]

Several interesting trends are evident in Figs. 2 and 3. At low magnetic fields, the cost is quite sensitive to β_t; increasing β_t from 6 to 14% for B_{TFC} = 6 T reduces the major radius of the reactor from 11.4 to 7.5 m, and the cost is reduced by ~30%. However, at higher magnetic fields, the economic incentive of increasing β_t diminishes, and at sufficiently high fields there is an economic penalty associated with increasing β_t. For any given value of β_t, the minimum costs are obtained for toroidal field strengths in the range 8 T $\leqslant B_{TFC} \leqslant$ 9 T, which is achievable with a NbTi superconductor. The advantages of higher temperature operation, and hence higher thermal conversion efficiency, associated with an advanced structural alloy relative to an austenitic stainless steel are offset by increased costs, with the result that there is very little difference in the capital cost per unit power between the two systems.

The rather dramatic increase in costs at high field is primarily due to power supply costs for the pulsed ohmic heating (OH) coils. These costs roughly scale as the transferred energy, which is proportional to the field squared.[a] In the conventional reactor design concept considered in these studies, with a solenoid OH coil located inside the central core formed by the inner leg of the toroidal field coils (see Fig. 4), the field in the OH coil increases as the central flux core decreases; the magnetic flux is the product of the field and the flux core area. An increase in toroidal field strength reduces the flux core area in two ways: (a) the major radius decreases and (b) the thickness of the toroidal field coils increases. This problem is exacerbated by the necessity of reducing the strain level for the higher field (B_{TFC} > 9 T in this study) magnets that use a Nb_3Sn superconductor. Other design concepts for the OH system, which would ameliorate this particular problem with high-field tokamak reactors, have been suggested. However, the present studies indicate that costs tend to increase at high field even when power supply costs are factored out, albeit not so dramatically as shown in these figures.

The incentive for an advanced structural alloy is better illustrated by considering cost of energy production: the ratio of the annual cost to the annual energy production. The annual cost is computed as 15% of the capital cost as an annual return on capital, plus the operation and maintenance cost, plus the prorated first-wall/blanket replacement cost, plus a trivial fuel cost. The annual energy production computation allows for a 28-day miscellaneous outage time and a prorated share of an 80-day first-wall and blanket rebuilding time. The cost of energy production with an austenitic (Type 316) stainless steel and an advanced vanadium alloy structure is shown in

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[a] No technological limit has been imposed on the field in the OH coil. Imposing such a limit would eliminate some of the high-field, high-β_t cases and/or would limit the burn time, and hence duty cycle, increasingly as β_t and B_{TFC} increase. The net effect is the same as shown here; the cost increases dramatically at high field, particularly with high β_t.

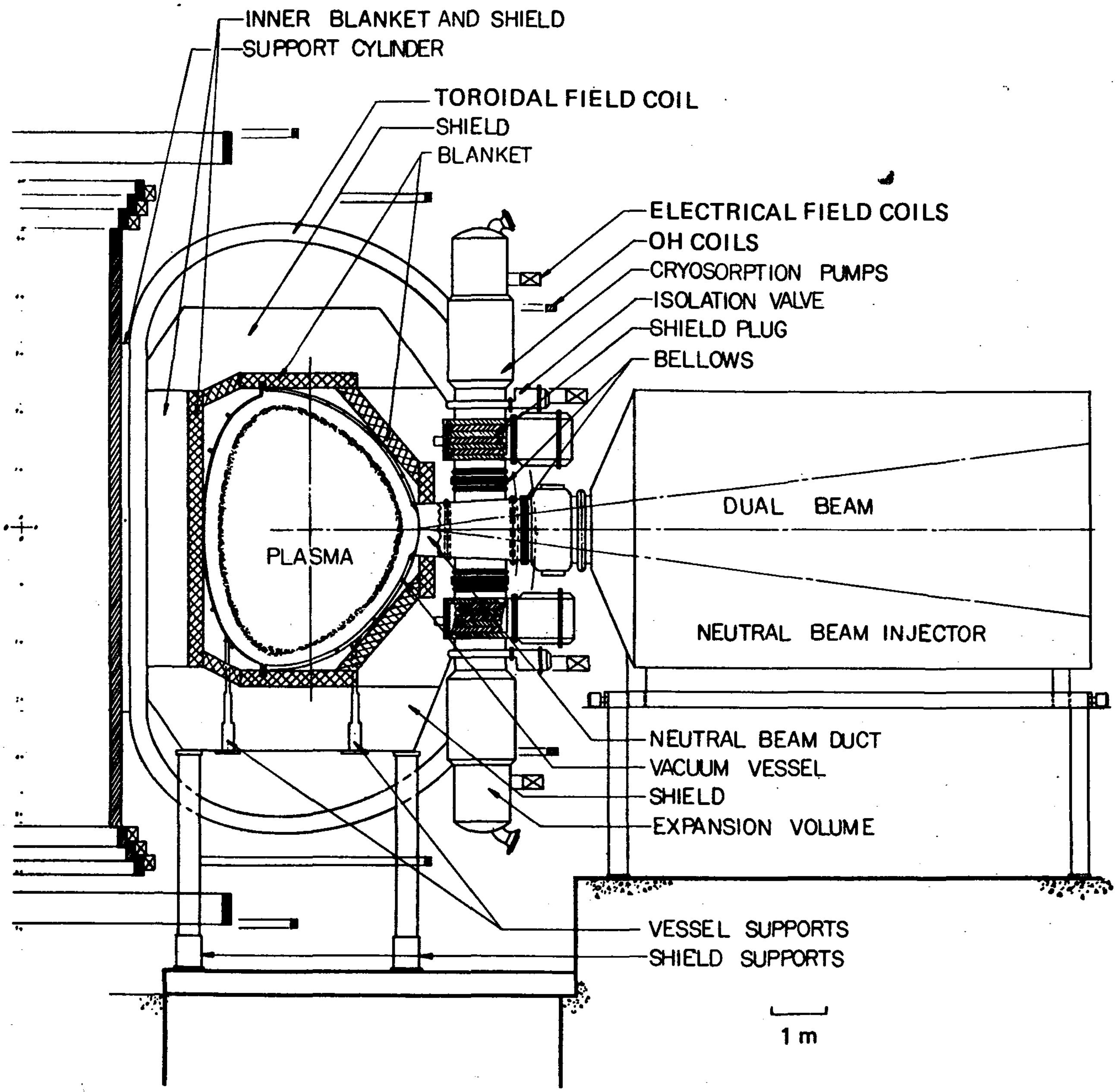

Fig. 4. Cross section of a tokamak EPR.

Figs. 5 and 6. The structural material lifetimes are computed from the best current estimates of materials data.[14] The end-of-life criteria used for the structural materials are 8% void swelling, 1% uniform elongation ductility, and 2% creep elongation. Stress levels of 48.26 and 82.74 MPa (7000 and 12 000 psi) were used for stainless steel and vanadium alloys, respectively. For the design temperatures considered in this paper, violation of the void swelling criterion was the lifetime limiting factor. The materials data base for stainless steel[14] is considerably more complete than for a vanadium alloy, of course, and Fig. 6 should be viewed as illustrating the economic incentive of using an advanced structural material rather than as the prediction for a specific material. This incentive is emphasized in Fig. 7, where cost of energy production is displayed as a function of wall lifetime. Clearly, there is a strong economic incentive to develop structural alloys with lifetimes in the range from 10 to 20 MW · yr/m^2.

Up to this point, the study has compared reactors with a fixed thermal power output. The "economy of scale" in going to reactors with larger power outputs is illustrated in Fig. 8. Greater benefits of increasing the reactor power output are realized in reactors with an advanced structural alloy than in reactors with

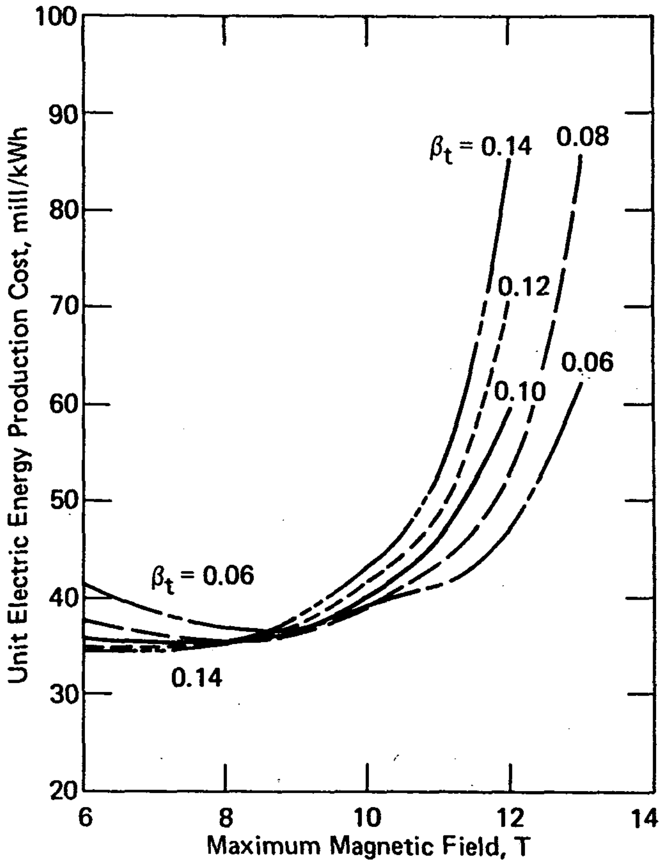

Fig. 5. Effect of toroidal magnetic field strength and plasma β_t on the cost of energy production for a fixed thermal power output of 3000 MW(th) in a lithium-cooled tokamak reactor with stainless-steel structural material. [Aspect ratio = 3, plasma D elongation = 1.65, plasma safety factor = 3, inner blanket/shield thickness = 1 m, maximum structural temperature = 500°C, first-wall lifetime = 3.1 MW·yr/m^2, electrical power output ≈ 940 MW(e).]

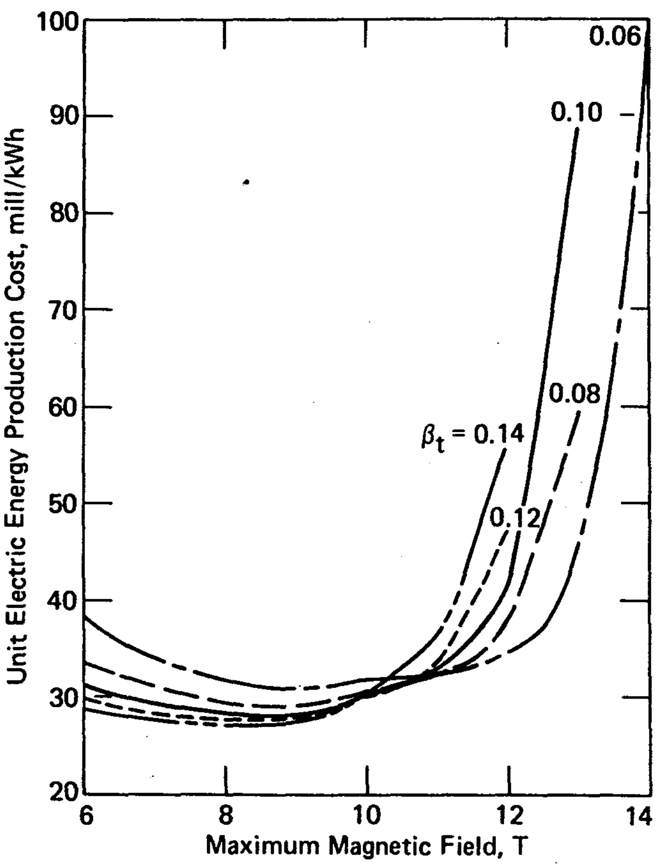

Fig. 6. Effect of toroidal magnetic field strength and plasma β_t on the cost of energy production for a fixed thermal power output of 3000 MW(th) in a lithium-cooled tokamak reactor with vanadium-alloy structural material. [Aspect ratio = 3, plasma D elongation = 1.65, plasma safety factor = 3, inner blanket/shield thickness = 1 m, maximum structural temperature = 650°C, first-wall lifetime = 34 MW·yr/m^2, electrical power output ≈ 1060 MW(e).]

Type 316 stainless steel because of the more frequent wall replacement associated with the latter.

The basis for the cost estimate is detailed in Ref. 13. Table I shows the cost breakdown for two of the design points shown in both Figs. 2 and 5. The maximum toroidal magnetic field is 8 T for one design point and 12 T for the other design. The two designs have the common parameters P_{th} = 3000 MW(th), A = 3, κ = 1.65, Δ_{BS} = 1 m, β_t = 0.08, and stainless-steel structure with maximum temperature of 500°C. This cost breakdown should be useful in identifying the major cost items in tokamak power plants.

PATH TO COMMERCIAL TOKAMAK FUSION POWER REACTORS

Many, if not all, of the presently outstanding plasma physics questions about transport and energy confinement, limits on β_t, plasma shape optimization, impurity control, heating, and fueling should be resolved by existing and planned experiments—PLT, ISX, Alcator-C, Doublet-III, PDX, and TFTR—over the period between now and 1982 to 1983. It is conceivable that one of these experiments, or perhaps an upgrade, could demonstrate ignition and a relatively long, controlled deuterium-tritium (D-T) burn pulse, thereby definitively establishing the plasma physics feasibility of fusion. However, this is not generally anticipated, and it is likely that an ignition test reactor (ITR) is needed to fully demonstrate the plasma physics feasibility before proceeding to an EPR.

A possible schedule for the development of commercial tokamak reactors is given in Fig. 9. This schedule is similar to the Logic III Reference Option in the U.S. Energy Research and Development Administration (ERDA) Program Plan.[15] Several years

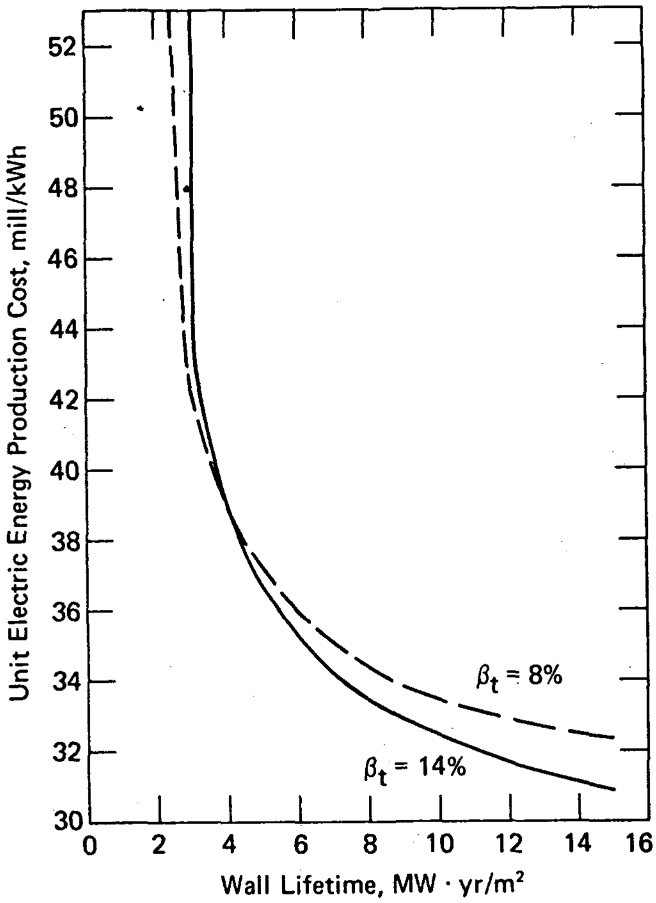

Fig. 7. Effect of first-wall lifetime on the cost of energy production for a fixed thermal power output of 3000 MW(th) in a lithium-cooled tokamak reactor. (Aspect ratio = 3, plasma *D* elongation = 1.65, plasma safety factor = 3, inner blanket/shield thickness = 1 m, maximum toroidal field strength = 9 T.)

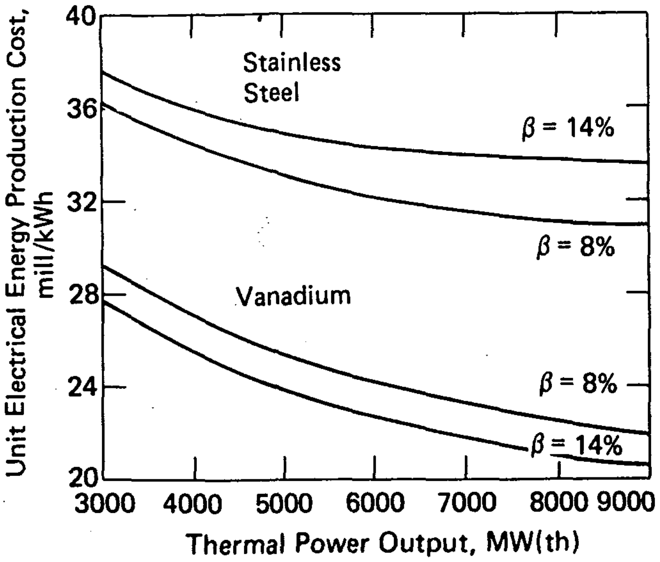

Fig. 8. Effect of plant thermal power output on the cost of energy production in a lithium-cooled tokamak reactor. (Aspect ratio = 3, plasma *D* elongation = 1.65, plasma safety factor = 3, inner blanket/shield thickness = 1 m, maximum structural temperature = 500°C for stainless steel and 650°C for vanadium alloy, first-wall lifetime = 3.1 MW·yr/m² for stainless steel and 34 MW·yr/m² for vanadium alloy, maximum toroidal field strength = 9 T).

of scoping and preliminary design are assumed to have taken place prior to the initiation of detailed design, which latter is shown in Fig. 9. The objectives of the three reactors are defined in Table II. This schedule allows for the plasma physics feasibility to be demonstrated with an ITR before the design of an EPR is frozen. Approximately 5 yr of EPR operation is allowed before the DEMO design must be frozen, providing time for the accumulation of some materials radiation damage data and the testing of DEMO blanket modules. Ten-year minimum operation times are prescribed for both the EPR and the DEMO, so that these reactors can provide adequate materials radiation damage data.

There are a number of ways in which the schedule shown in Fig. 9 could be accelerated. If an ITR is not required, by virtue of unusually favorable results from predecessor experiments or upgrades thereof, then the EPR schedule could be pushed ahead 2 or 3 yr. Alternatively, the functions of an ITR and an EPR could be combined in a single device, perhaps by staging the construction and operation of the device to proceed to EPR-type operation only after ITR-type objectives have been met, with the net result of pushing the EPR operation date ahead by 2 to 4 yr. The DEMO schedule could be pushed ahead relative to the EPR operating date by a couple of years if the DEMO design could proceed without the high-fluence radiation damage data that would be provided by several years of high-duty factor EPR operation; this would be more feasible if the DEMO design was based on stainless steel rather than an advanced structural alloy.

Estimated costs of the three reactors are given in Table III. These cost estimates are based on a low-duty cycle ITR ~4 m in major radius and an EPR and a DEMO, as is subsequently discussed.

The two ongoing TNS designs are considering a range of options varying from an ITR up to a reactor with characteristics approaching those of the EPR. Hence, the designs and research and development requirements of an ITR should be reasonably well defined in the near future.

The first-generation EPR designs[4-7] have been reviewed in detail, and a revised design has recently been defined.[12] Major parameters that characterize one of the revised EPR design options are given in Table IV, and a cross-section view was shown in

TABLE I

Cost Breakdown (in millions of dollars) for Two of the Design Points Shown in Figs. 2 and 5

[P_{th} = 3000 MW(th), A = 3, κ = 1.65, Δ_{BS} = 1 m, β_t = 0.08, and stainless-steel structural material with maximum temperature = 500°C]

Maximum Toroidal Magnetic Field	8 T	12 T
Reactor		
First wall/blanket/shield	76	48
Poloidal coils and power supplies	131	464
Toroidal magnets	62	101
Tritium and vacuum systems	53	39
Auxiliary heating system	14	11
Remote maintenance equipment	26	19
Instrumentation	15	15
Rest of plant (includes buildings, heat transfer and transport system, electric and turbine plant equipment)	597	573
Total direct cost	974	1270
Total indirect cost	486	640
Total capital cost	1460	1910
Capital cost, \$/kW(e)	1540	2030
Return on capital, \$/yr	219	286
Operations and maintenance cost, \$/yr	4	4
Prorated wall replacement cost, \$/yr	10	12
Cost of electricity, mill/kWh	35.5	52.7

Fig. 4. The EPR requires a number of advanced technologies, as indicated in Table V, but does not require advanced structural alloys or coolant technology. This particular EPR design could be upgraded somewhat to obtain a more adequate materials radiation facility; this question is being examined in the continuing EPR design activity.

The integration in a power reactor of all of the advanced technologies that are required for commercial tokamak fusion reactors must be accomplished in the DEMO. A range of possible DEMO parameters is shown in Fig. 10 for a geometric configuration and for plasma conditions that are consistent with those of the EPR and the commercial reactors discussed in this paper. The discontinuity at 9 T is a result of switching from NbTi to Nb_3Sn as a superconductor. Representative parameters for both Type 316 stainless steel and advanced vanadium alloy designs are given in Table VI. A stress level [103.42 MPa (15 000 psi)] higher than the actual design stress [82.74 MPa (12 000 psi)] and a stringent requirement on creep not to exceed 1% were assumed in predicting a conservative limit on the lifetime of the vanadium-base alloys shown in Table VI. This avoids having to base the DEMO design on an uncomfortable extrapolation beyond the radiation damage data and blanket engineering information that could be provided by EPR. However, extrapolation of present data for the actual design and operating conditions of the DEMO shows that the lifetime for the vanadium alloys will be considerably longer than that shown in Table VI.

The principal technology advances required for the development of commercial fusion power are indicated in Table V. The general features of these technology requirements have been identified in the previously cited design studies in several documents devoted to the subject[16-18] and in correspondence that has not appeared in the literature. In those cases in which it is not clear whether a technology is required for a reactor, a question mark is included in Table V. In some cases (e.g., neutral beams), substantial and progressive advances in technology are required at more than one reactor stage.

Superconducting magnets are almost certainly necessary for fusion power reactors because of the large power losses that would be associated with nonsuperconducting magnets, although some studies have indicated that these power losses may be tolerable under certain conditions. Even if the power losses with nonsuperconducting magnets were tolerable, a substantial advance in technology would be needed to produce nonsuperconducting magnets on the scale required. A substantial basis of experience with large NbTi superconducting magnets exists by virtue of work in the fields of high-energy physics and MHD. Many studies, including those summarized in this paper, indicate that the fields thought to be obtainable with the NbTi superconductor are adequate. However, the high-field, high-density concept[11] would require the development of more advanced high-field superconductors such as Nb_3Sn.

The most immediate materials problem is contamination of the plasma by radiation-induced erosion of the first-wall surface. Surface modifications (e.g., lining with a low-atomic-number material to minimize radiation losses from the contaminated plasma) may suffice to achieve short burn pulses, but additional technologies for impurity control (e.g., a magnetic divertor) may be required to achieve longer burn pulses. Electrical insulators for the magnets and blanket, which can withstand the radiation environment, must be developed. Although Type 316 stainless steel may be adequate for TNS and EPR, there is a clear economic incentive to develop an advanced structural alloy to achieve first-wall lifetimes of at least 10 to 20 MW · yr/m^2.

Neutral beams have been demonstrated to be effective in heating plasmas, but the increasing plasma size and/or density in the progression of reactors shown in Fig. 9 requires increasing technology for the ion source and the energy transfer and recovery systems at each stage. Radio-frequency wave heating of the plasma may be less demanding technologically and lead to more attractive designs, but the plasma physics feasibility has yet to be definitely established.

If gas injected into the vacuum chamber is drawn into the plasma core, as appears to be the case in

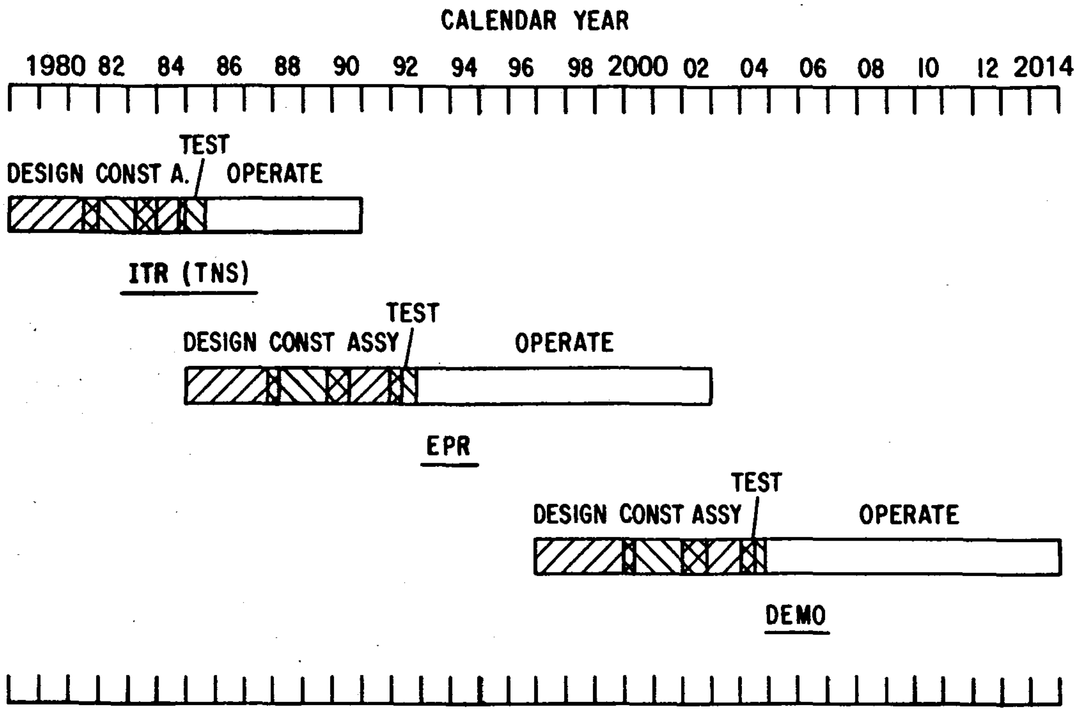

Fig. 9. Possible schedule for the achievement of commercial tokamak fusion power reactors.

TABLE II

Tokamak Reactors on Path to Commercial Fusion Power Reactor Development

Ignition Test Reactor (ITR)	Primary:	Demonstrate plasma physics feasibility of fusion power.
	Secondary:	Demonstrate those fusion technologies required to achieve primary objective.
Experimental Power Reactor (EPR)	Primary:	Produce electrical power from fusion and demonstrate the technological feasibility of fusion power reactors. Physics and technology systems integration.
	Secondary:	Demonstrate fusion technologies and serve as an engineering/materials test reactor.
Demonstration Power Reactor (DEMO)	Primary:	Demonstrate the commercial feasibility of electrical power production from fusion.
	Secondary:	Serve as a test reactor for advanced fusion technologies.

some experiments, then refueling is trivial. Otherwise, technology for injecting fresh fuel into the plasma core (e.g., as high-speed pellets) must be developed.

The large, pulsed energy transfer in and out of the poloidal coil system and into the plasma heating system during startup and shutdown requires the development of advanced technologies for storing, transferring, switching, and recovering energy. Although some of these functions could be met with existing technologies, there appears to be a substantial economic incentive to develop new energy storage and transfer technologies.

The problems of radiation shielding, primary energy conversion into heat, and heat removal are similar to those encountered in fission reactors, so a substantial technology base exists on which to build. However, there are some unique new problems arising from the geometry and the interaction of the magnetic field with the structural material and a flowing liquid-metal coolant. Although there are other possible coolants (e.g., helium, molten salt), liquid lithium appears to offer significant advantages.

Experience in the weapons program provides a

TABLE III

Tokamak Reactor Cost Estimates

	ITR	EPR	DEMO
Total capital costs,[a] $M	400	600	1050
Annual operating costs,[b] $M	4.1	5.4	5.8

[a] Does not include supporting research and development or unusual expenses associated with the development of first-of-type manufacturing capability.

[b] Does not include cost of materials and engineering testing.

TABLE IV

Representative Tokamak EPR Parameters

Major radius, m	4.7
Aspect ratio (A)	3.5
Plasma D elongation (κ)	1.65
Maximum toroidal field, T	9.0
Superconductor	NbTi
Average plasma β_t, %	8
Plasma safety factor (q)	3
Thermal power, MW(th)	270
Electric power, MW(e)	67
Net electric power, MW(e)	39
Plasma current, MA	7.6
Maximum OH field, T	4.0
Coolant	H_2O
Structural material	Stainless steel
Maximum structural temperature, °C	500
Wall lifetime, yr	8
Direct capital cost, $M	420
Total capital cost,[a] $M	600

[a] Including contingency and engineering.

TABLE V

Advanced Technology Requirements for the Development of Commercial Fusion Power

Advanced Technology	Reactor for Which Technology Must Be Available
Superconducting magnets	
Steady-state toroidal field coils	ITR
Pulsed poloidal field coils	ITR?, EPR
Impurity control	
Short burn pulse (~1 min)	TFTR?, ITR
Long burn pulse (≫1 min)	DEMO
Materials	
Insulators	ITR?, EPR
Advanced structural alloy	DEMO[a]
Heating and fueling	
Neutral beams	TFTR, ITR
Radiofrequency	(backup)
Fueling	ITR
Energy storage and transfer	
Pulsed coil energy transfer	EPR
Central energy storage	EPR
Storage, switching, recovery for neutral beams	ITR?, EPR
Blanket/shield	
Radiation shielding	TFTR, ITR
High-temperature operation	EPR[a]
Lithium (or alternative) coolant	DEMO[a]
Tritium	
Fuel cycle and containment	ITR
Breeding and blanket extraction	DEMO[a]
Vacuum	TFTR, ITR
Engineering	
Assembly and disassembly	TFTR, ITR
Remote maintenance	TFTR, ITR

[a] Could be tested in earlier reactors.

basis on which the technology for the tritium fuel cycle can be developed. Chemical processing technology of a different type will be required to extract the tritium bred in fusion reactor blankets from the lithium-containing breeding medium.

Advances in high-vacuum technology will be required because of the large volumes involved, although a substantial basis exists on which to build, particularly in the aerospace industry. The low-aspect-ratio toroidal geometry of a tokamak calls for the development of innovative engineering designs, procedures for assembling and disassembling the reactor, and remote maintenance technology.

SUMMARY

The major parameters and corresponding economic characteristics of a representative class of commercial tokamak fusion power reactors have been examined as a function of four major design parameters: the plasma β_t, the toroidal magnetic field strength, the first-wall lifetime, and the power output. An economically optimum value of the toroidal field strength was found. This optimum value was in the range of $6\ \mathrm{T} \leqslant B_{\mathrm{TFC}} \leqslant 9\ \mathrm{T}$, depending on the value of β_t and the first-wall lifetime. The costs of electrical energy production were found to decrease rapidly with first-wall lifetime up to ~10 to 20 $\mathrm{MW \cdot yr/m^2}$ and more gradually beyond this range. An economy of scale was found. Reactors with a large thermal power output [6000 to 9000 MW(th)] and based on an advanced structural alloy design were predicted to have electrical energy production costs in the range from 20 to 24 mill/kWh.

A possible sequence of three reactors—an ignition test reactor to establish plasma physics feasibility, an experimental power reactor to establish technological feasibility, and a demonstration power

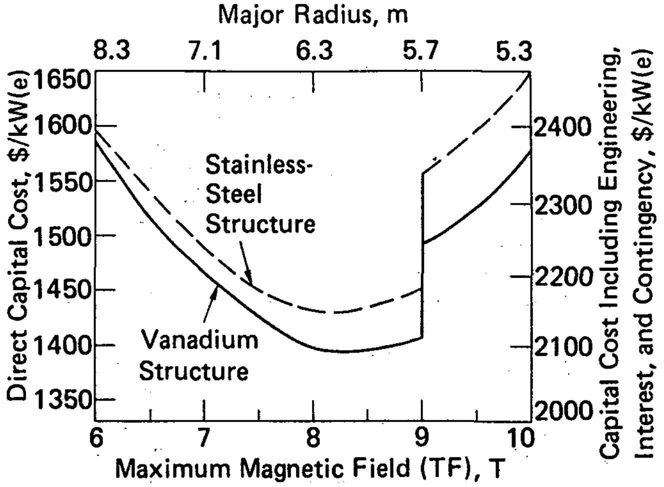

Fig. 10. Effect of toroidal magnetic field strength and structural material on the capital cost per unit power for a fixed thermal power output of 1500 MW(th) of a lithium-cooled tokamak demonstration reactor. [Aspect ratio = 3, plasma D elongation = 1.65, plasma safety factor = 3, plasma β_t = 8%, inner blanket/shield thickness = 1 m, maximum structural temperature = 500°C for stainless steel and 650°C for vanadium alloy, electrical power output = 403 MW(e) with stainless steel and 460 MW(e) with vanadium alloy.]

reactor to establish commercial feasibility—was outlined that could lead to a demonstration of fusion power in the last decade of this century and to a demonstration of commercial feasibility near the turn of the century. Representative design parameters and costs were presented for such a sequence of reactors that would lead to the class of commercial reactors discussed in this paper. The principal technological advances that would be required to support this sequence of reactors were discussed.

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TABLE VI

Representative Tokamak Demonstration Plant Parameters

Major radius, m	6.01	
Aspect ratio (A)	3.0	
Plasma D elongation (κ)	1.65	
Maximum toroidal field, T	8.5	
Superconductor	NbTi	
Average plasma β_t, %	8	
Plasma safety factor, q	3	
Thermal power, MW	1500	
Plasma current (I_p), MA	13.3	
Maximum OH field, T	5.5	
Coolant	Lithium	
Structural material	Vanadium Alloy	Stainless Steel
Electric power, MW	460	403
Maximum structural temperature, °C	650	500
Plant availability factor, %	86	81
Wall lifetime, yr	3.3	1.7
Direct capital cost, $M	650	580
Total capital cost,[a] $M	1040	930
Direct cost of power, $/kW(e)	1390	1440

[a] Including contingency, engineering, and interest.

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