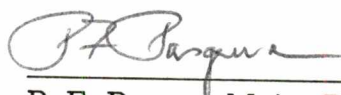


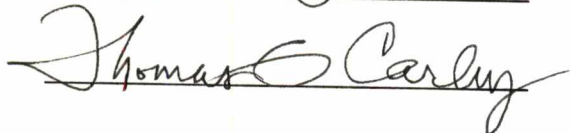
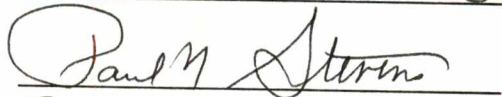
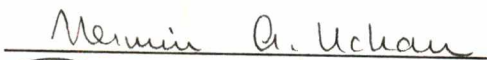
To the Graduate Council:

I am submitting herewith a dissertation written by Thomas E. Shannon entitled "Design and Cost Evaluation of a Generic Magnetic Fusion Reactor Using the D-D Fuel Cycle." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Engineering Science.



P. F. Pasqua, Major Professor

We have read this thesis
and recommend its acceptance:



Accepted for the Council:



Vice Provost
and Dean of The Graduate School

**DESIGN AND COST EVALUATION OF A GENERIC
MAGNETIC FUSION REACTOR USING THE
D-D FUEL CYCLE**

**A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville**

**Thomas E. Shannon
December 1988**

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ABSTRACT

A fusion reactor systems code has been developed to evaluate the economic potential of power generation from a toroidal magnetic fusion reactor using deuterium-deuterium (D-D) fuel. A method similar to that developed by J. Sheffield¹ for deuterium-tritium (D-T) fuel was used to model the generic aspects of magnetic fusion reactors. The results of the systems study and cost evaluation show that the cost of electricity produced by a D-D reactor is two times higher than that produced by an equivalent D-T reactor design.

The significant finding of the study is that the cost ratio between the D-D and D-T systems can potentially be reduced to 1.5 by improved engineering design and even lower by better physics performance. The absolute costs for both systems at this level are close to the costs for nuclear fission and fossil fuel plants.

A design for a magnet reinforced with advanced composite materials is presented as an example of an engineering improvement that could reduce the cost of electricity produced by both reactors. However, since the magnets in the D-D reactor are much larger than in the D-T reactor, the cost ratio of the two systems is significantly reduced.

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INTRODUCTION

Nuclear fusion holds the promise of providing almost unlimited power for future generations. It is also an environmentally attractive energy source since the impact of the overall process appears to be much less severe than that of fossil fuels and nuclear fission. Solar energy is the only other source that could provide such a clean fuel cycle; however, much of the world's populated areas do not have enough sunlight to generate the large-scale power needed for heating or industrial applications. Fusion energy is therefore of great importance for the future.

Although a number of different atomic nuclei can combine to release net energy from fusion, the D-T is the fundamental basis of planning for the first generation of fusion reactors. This choice is based on considerations of reactor economy. The D-T reaction occurs at the lowest temperature, has the highest cross section, and therefore provides the greatest output of power per unit of cost. The disadvantages of D-T as a fusion fuel are twofold. Tritium does not occur naturally in nature and must therefore be bred in the fusion reactor or elsewhere. Secondly, tritium is a radioactive isotope of hydrogen with a relatively long half-life of 12.3 years. Since it can readily combine with air and water, it is considered a major nuclear hazard when handled in the quantities required for a fusion reactor.

The purpose of this dissertation is to show that the D-D fuel cycle can be a viable alternative to D-T. In this case, the fuel supply is essentially unlimited since deuterium is abundantly available in water. The problem of radioactivity is decreased substantially since only a small amount of tritium is handled in the fuel cycle.

The research was carried out in two phases. In the first phase, a systems study and cost evaluation were conducted for both systems. In the second phase,

a concept for a superconducting magnet reinforced with advanced composite materials was developed that has the potential to significantly reduce the difference in cost of electricity (CoE) between D-T and D-D reactors.

Two unique contributions have resulted from this dissertation. First, the D-D computer code is the first to model the generic features of D-D reactor systems. By comparing those results with the results obtained for a D-T system, using the same model, the sensitivity of physics and engineering parameters could be compared on an equal basis. The second contribution is a new design for a high-strength and potentially low-cost superconducting magnet which uses a carbon/epoxy composite as the structural material.

This document is organized to describe the technical work in four major chapters. Chapter I provides background information on the need and justification for the D-D fuel cycle, including an explanation of the approach used for the analysis and subsequent design work.

Chapter II describes the development of the computer model with an illustration of typical data output. The results of the systems analysis are given in Chapter III. Sensitivity studies are presented to show the primary design and cost drivers necessary to optimize the D-D reactor. Comparisons are made to the D-T reactor, indicating that both physics and engineering improvements could significantly narrow the difference in CoE.

A design for a high-strength and potentially low-cost magnet is presented in Chapter IV. The design is an example of an engineering improvement, based on existing composite materials technology, that could reduce the ratio of the CoE between the D-D and D-T systems. A D-D reactor producing electricity at the reduced cost level is close to estimates for future nuclear fission and fossil fuel plants.

The overall conclusions of the work are given in Chapter V.

CHAPTER I

BACKGROUND

A benchmark used for this study was Wildcat,² the most comprehensive D-D fusion reactor design available. The work was carried out by the same group at the Argonne National Laboratory that earlier produced the widely referenced D-T reactor design Starfire.³ The estimated cost of electricity (CoE) for the D-D reactor was found to be 1.8 to 2.1 times that of the D-T reactor. The two designs were not directly comparable, however, because improved performance parameters derived for the D-D system were not applied to the earlier D-T system design. A recent study by the Massachusetts Institute of Technology⁴ reported costs for D-T and D-D reactors, based on the tokamak, that are similar to the findings of this generic-based study.

Because of the many advantages of the D-D fuel cycle, including the potential of an essentially unlimited fuel supply, there is considerable incentive to seek ways in which the cost difference may be further reduced. A generic model was used for this study to determine the performance requirements for an attractive reactor design. Using a generic model, rather than specific fusion confinement concepts, also avoids a premature judgment of which concept will ultimately prove most satisfactory.

The generic model covers a general class of fusion devices that includes the tokamak, the stellarator, and reversed-field pinch, the three most actively studied in the U.S. research program. These and other magnetic fusion reactor designs are made up of similar systems and components such as blanket and shielding, magnets, plasma heating systems, heat exchangers, and electrical power generation equipment. The major systems including the plasma are represented by algorithms that cover design, performance, and cost relationships.

The model intentionally avoids empirically derived limits on parameters from present confinement experiments. Limits are based only on fundamental principles of physics and engineering. By using this approach, design parameters can be identified that lead to the most cost-effective reactor.

The code was developed for an IBM personal computer by using the spreadsheet Lotus 1-2-3.⁵ For this application, the spreadsheet proved to be an ideal program, both for formation of the code and for running the many sensitivity and trade studies required. Lotus 1-2-3 also has a good graphics package, which was essential for evaluation of the data.

A unique feature of the code development and subsequent systems studies is that the D-T and D-D systems were evaluated and compared on an equal basis. The same modeling methods were used, and the systems studies assumed equivalent physics and engineering constraints. The spreadsheet format was arranged with an option to list side-by-side the input and output for both D-T and D-D systems.

Development of the model starts with the basic plasma power balance equation coupled with conventional nuclear reaction rate equations and other definitions used in plasma physics. Configuration assumptions for a toroidal fusion device, along with assumed engineering design constraints, provide a basis for dimensional analysis. Cost models provide a basis for estimating capital cost and CoE.

The most significant engineering finding of this study was that the electricity cost ratio between the two systems can potentially be reduced to ~ 1.5 by the use of improved structural materials in the toroidal magnet systems. This finding resulted from the fact that the large magnet systems in the D-D reactor dominate the capital cost of the plant (45%), whereas the magnet system in the D-T reactor accounts for a much smaller fraction of the total cost (20%). A design concept for a magnet reinforced with advanced composite materials is presented

as an example that has the potential to provide the required strength and cost reduction.

Finally, the ultimate solution to the development of fusion energy lies in the understanding and solution of scientific problems related to magnetic confinement of the fusion plasma. It was found that, by increasing the plasma beta, a measure of the effectiveness of the magnet field in containing the high-pressure plasma, the D-D reactor costs can be reduced at a much faster rate than costs for D-T systems. If a magnetic confinement concept can be developed with a beta value of 20-30% (more than three times the present experimental level for tokamaks), the CoE for the D-T and D-D systems becomes almost equal.

This chapter reviews the fusion fuels that are available as potential options for long-range power reactor applications. The justification for emphasis on the D-D fuel cycle is discussed, leading to an introduction to the reactor evaluation and design study.

A. Magnetic Fusion Reactor Description

A schematic diagram of a magnetic fusion reactor plant is shown in Fig. 1. At the core of the fusion reactor is an ultra-hot plasma with a temperature exceeding 100 million °C. The plasma, which is the fusion fuel, consists of charged particles that are confined by a magnetic field. The coils that provide the magnetic field are made from superconductors cooled by liquid helium to minimize the power required to sustain the field.

The fusion energy produced in the plasma is released as high-energy charged particles and neutrons. The first wall, blanket, and shield structures, shown in Fig. 1, intercept the particles and transfer their energy in the form of heat to a coolant. Once the heat is transferred to the coolant, a conventional steam generator and turbine system is used to generate electricity. Other

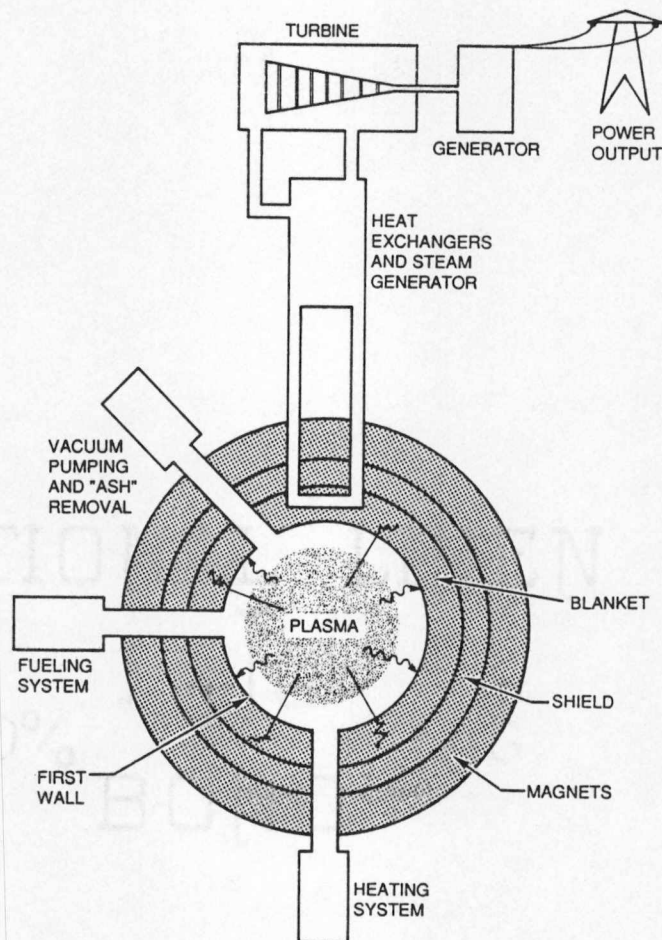


Fig. 1. A schematic diagram of a magnetic fusion reactor power plant.

auxiliary systems such as fuel injection, plasma heating, and vacuum pumping are indicated on the diagram.

Many different designs for the magnetic field and plasma configuration have been tested in the past 30-40 years,⁶ with the goal of finding a cost-effective system. The tokamak, the most successful device thus far, has become the major focus of the worldwide fusion program. A tokamak fusion reactor design, Starfire, is shown in Fig. 2.

B. Justification for the D-D Fuel Cycle

A deuterium-fueled fusion reactor has the attractive feature of not requiring a breeding blanket, a major technology and engineering feasibility issue for D-T fueling. Other advantages include a reduction in tritium inventory by two orders of magnitude,² reduced tritium handling, and the elimination of lithium in the blanket; significant safety issues for D-T reactors. Reductions in neutron activation and material damage will further simplify the blanket and shield design and increase the lifetime and reliability.

The major disadvantage of the fuel cycle is the small reaction cross section, and hence a smaller reaction rate parameter, $\langle\sigma v\rangle$, than that of the D-T reaction at equal burn temperatures. Since the fusion power density is directly proportional to the reaction rate, which is a function of temperature, the optimum D-D reactor requires more stringent operating parameters. The average plasma temperature for a D-T reactor is around 100 million °C, while the D-D reactor requires 300 million °C.

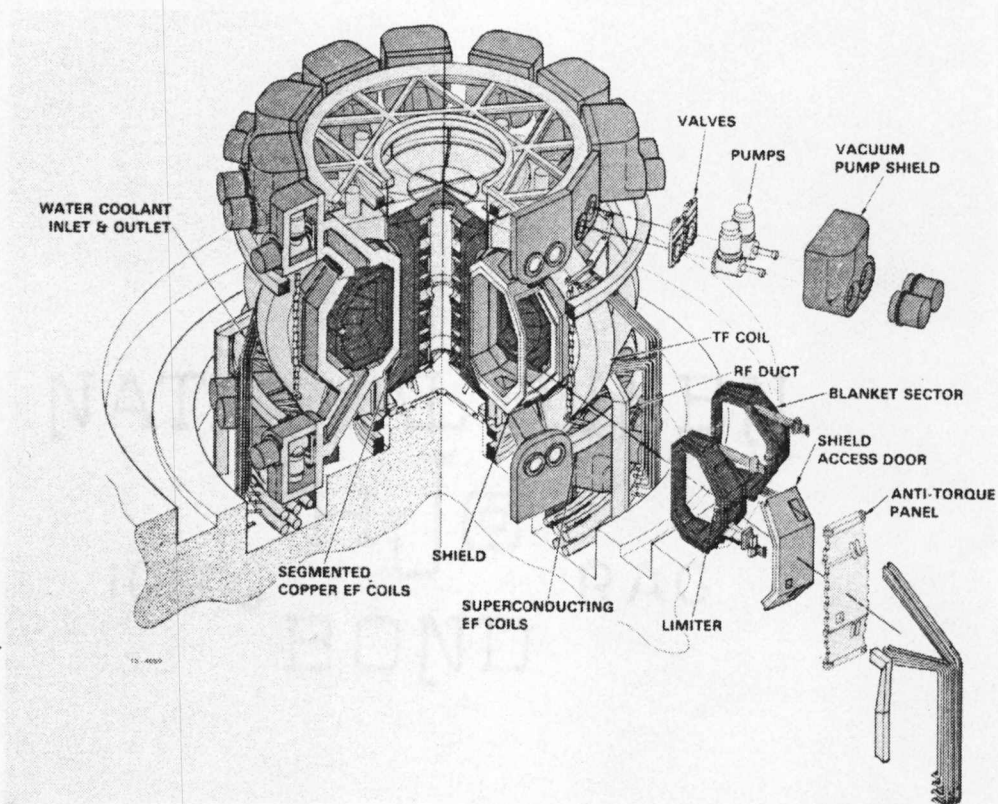
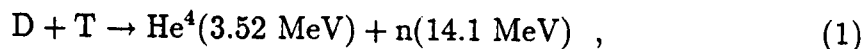


Fig. 2. Elevation view of Starfire, a commercial tokamak fusion reactor design.

1. Comparison of Alternate Fusion Fuels

The process of nuclear fusion involves the joining of two light nuclei to form a heavier nucleus and a lighter one. To overcome the long-range Coulomb forces that repel the positively charged nuclei, they must be forced close enough for the short-range nuclear force to "fuse" them together. Only the reactions involving isotopes of hydrogen are of interest for fusion because of the small fusion reaction cross section of larger ions.

The reaction of deuterium and tritium (D-T), the two heavy isotopes of hydrogen,



is the primary focus of fusion power research. The reaction products are a helium ion (alpha particle) and a neutron. The numbers in parentheses are the fusion energy levels associated with the release of each particle in units of millions of electron-volts ($1 \text{ MeV} = 1.6021 \times 10^{-13} \text{ joule}$).

The fusion power density produced by the reaction of two nuclei is given by⁷

$$P_f = \gamma \frac{n_i n_j \langle \sigma \nu \rangle_{ij}}{2} E_{ij} (1.6021 \times 10^{-13}) , \quad (2)$$

where P_f is the fusion power density (W/m^3), n_i and n_j are the ion densities of the two fusion ions (m^{-3}), $\langle \sigma \nu \rangle_{ij}$ is the reaction rate parameter (m^3/s), E_{ij} is the total energy released (17.6 MeV for D-T), and γ is a coefficient equal to 1 for fusion of like ions and 2 for unlike ions.

The D-T reaction is of particular interest because it has the highest value of the reaction rate parameter at lower energy than any of the other reactions involving isotopes of hydrogen. Figure 3 shows the variation in reaction rate parameter with temperature for the three fusion reactions to be discussed. Here temperature is given in units of keV, a common practice in fusion

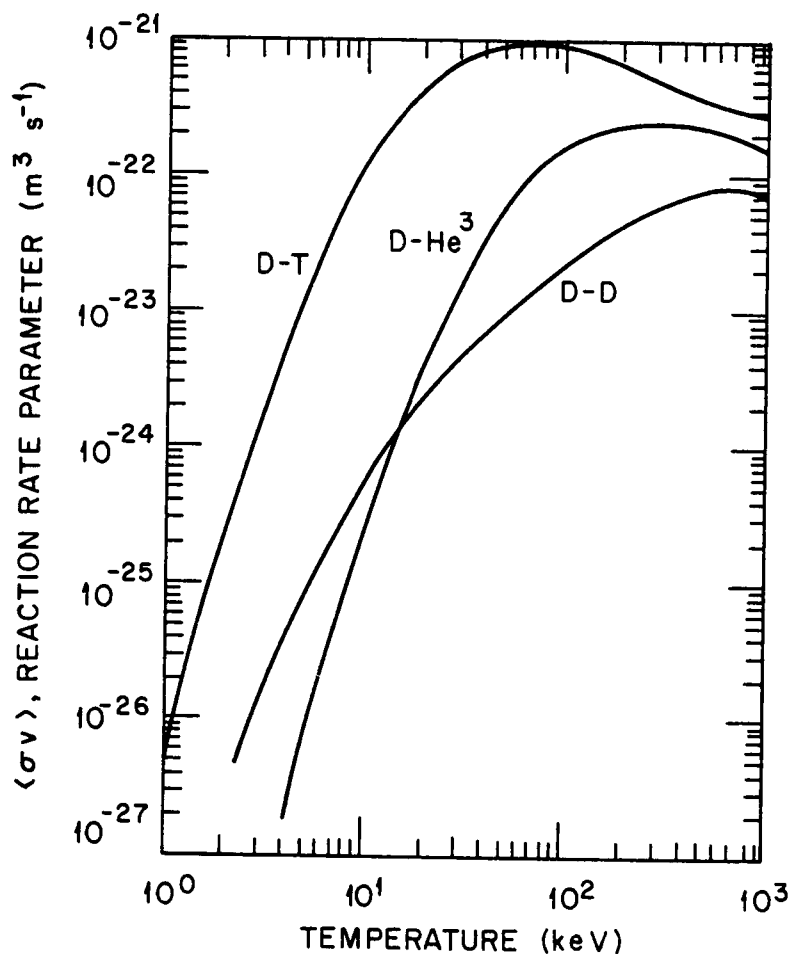


Fig. 3. Reaction rate parameters for the three most promising fusion fuels: D-T, D-D, and D-He³. [Ref. 8, Dolan, T. J., *Fusion Research*, Pergamon Press, Inc., New York, 1982 (p. 29).]

literature, normally indicating a Maxwellian particle velocity distribution (1 keV corresponds to 1.16×10^7 K).

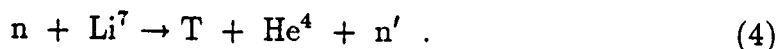
At a temperature of 10 keV and an equal density of D and T ions of $2 \times 10^{20}/\text{m}^3$, Eq. (2) results in

$$P_f = (2) \frac{(2 \times 10^{20})^2 (0.109 \times 10^{-21})}{2} (17.6) (1.6021 \times 10^{-13})$$

$$\simeq 12,000 \text{ kW/m}^3 = 12 \text{ W/cm}^3 .$$

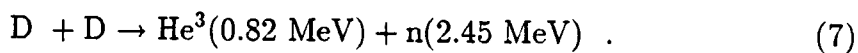
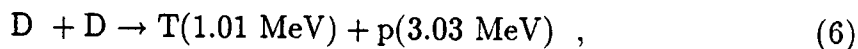
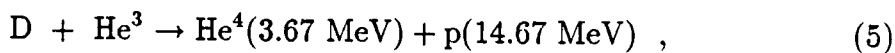
Even though the given parameters are typical of those presently projected for fusion power reactors, the power density is quite low, not much different from the density for an ordinary light bulb. Fusion reactor designs are therefore large, resulting in high capital costs for large power plant applications.

As mentioned previously, a D-T reactor requires breeding of tritium in blanket modules containing Li^7 and Li^6 :



The first reaction is more probable with thermal (slow) neutrons, while the second is more probable with fast neutrons.

The reactions of deuterium with He^3 (D- He^3) and deuterium and deuterium (D-D) are the other two shown in Fig. 3 that are potential candidates for fusion power reactors:



Note that there are two possible outcomes of the D-D reaction that have about equal probability of occurring. One produces tritium and a proton, and the other produces He^3 and a neutron. The reaction rate parameter is almost identical for each reaction. Only the first [Eq. (6)] is shown in Fig. 3.

The D- He^3 reaction is second to the D-T reaction in high reactivity at modest temperature. The problem, however, is that He^3 is thinly dispersed in the atmosphere and the earth's mantle as a small fraction of He^4 . The He^3/He^4 isotopic ratio is less than 20 appm.⁹ Man-made He^3 resources from the radiolytic decay of tritium, obtained from the U.S. Department of Energy resources and other fission reactors such as the Canadian CANDU reactors, could sustain a limited number of fusion reactors for only 10–20 years. The discovery of He^3 in large quantities on the lunar surface, however, may lead to a future possibility of D- He^3 reactors being fueled by He^3 mined on the moon and returned to earth.

The D-D reaction is the only one of the three involving isotopes of hydrogen in which the source of fuel is cheap, readily available, and almost limitless. The hydrogen in water is 0.015% deuterium.¹⁰

Another important application for the D-D reactor is the fusion-fission hybrid. A catalyzed D-D reactor of this type has been shown to be an attractive source for breeding fuel for fission reactors.¹¹

2. The Catalyzed D-D Fuel Cycle

A D-D fusion reactor obviously requires a major increase in one of the parameters of Eq. (2) to obtain a power level approaching that of a D-T reactor. The most straightforward improvement can be obtained by the so-called catalyzed D-D (CAT-D) process. In this process, the tritium and He^3 produced in the two branches of the D-D reaction are recycled and used along with the deuterium as fuel. The primary reactions of the CAT-D reactor are

$$D + D \rightarrow p(3.03) + T(1.01) , \quad (8)$$

$$D + D \rightarrow n(2.45) + He^3(0.82) , \quad (9)$$

$$D + T \rightarrow n(14.06) + He^4(3.52) , \quad (10)$$

$$D + He^3 \rightarrow p(14.67) + He^4(3.67) , \quad (11)$$

$$6D \rightarrow 2P + 2n + 2He^4 + 43.23 \text{ MeV} . \quad (12)$$

Note that the 14-MeV neutron from the D-T reaction contributes 33% of the fusion energy, assuming that all of the tritium and He^3 is reinjected and reacts. The 14-MeV neutron, on the other hand, accounts for 80% of the fusion energy in the D-T reactor.

An additional process called tritium-catalyzed deuterium (TCD)¹² further increases the fusion power density by converting the He^3 from the D-D reaction into tritium by a special blanket converter.¹³ This tritium is then reinjected into the D-D reactor in place of the He^3 . The reduction in electron density from He^3 permits an increase in ion density and a net increase in power density.

3. Relative Comparison of D-T and D-D Reactors

The relative fusion power density for the D-T, CAT-D, and TCD reactions is shown in Fig. 4. Note that the difference between the maximum power densities of the CAT-D and D-T reactions is almost two orders of magnitude. As shown in Chapter II, this difference is reduced to less than one order of magnitude for reactor designs having equal power output. The larger reactor size and reduced blanket and shielding thickness in the D-D reactor result in a higher fraction of the maximum magnetic field in the plasma. It will be shown in Chapter II that

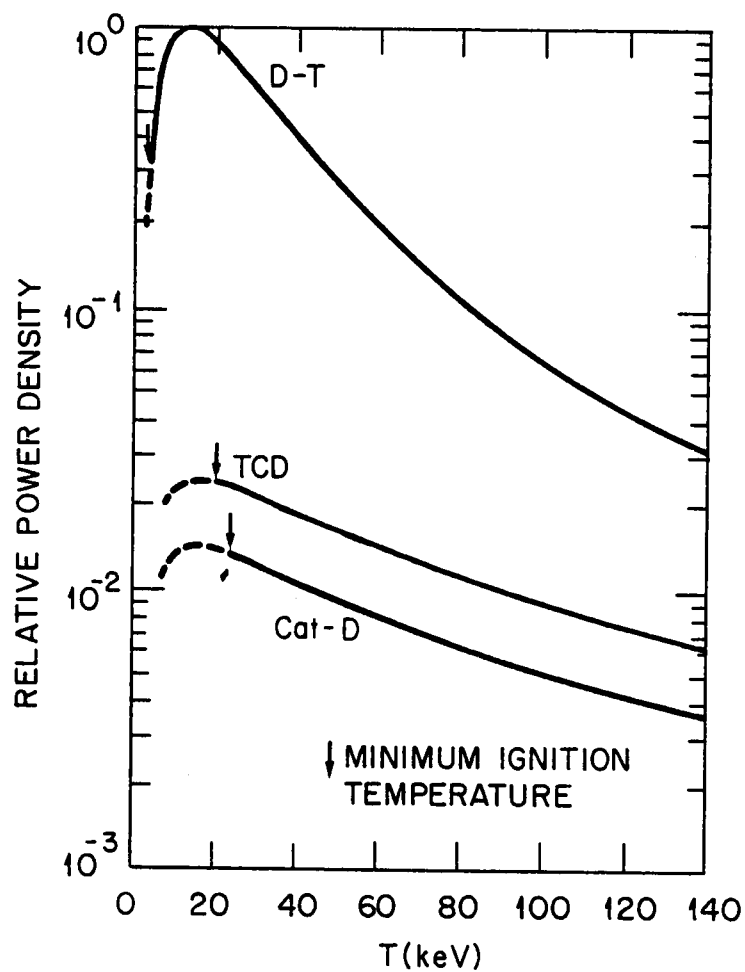


Fig. 4. Relative power density of the catalyzed deuterium fuels, CAT-D and TCD, compared with D-T. [Ref. 12, Greenspan, E., and Miley, G. H., "Partially Catalyzed Deuterium and Tritium-Assisted Plasma Characteristics," *Nuclear Technology/Fusion*, ANS, Vol. 2, October 1982.]

the fusion power is proportional to the fourth power of the magnetic field in the plasma.

An important property of plasma is its ability to maintain a balance between the energy released by the fusion reaction in the form of charged particles and the energy lost due to conduction and radiation. An expression for the thermal diffusivity needed to maintain the energy balance will be derived for a general set of plasma parameters.

The differential equation for energy balance in the plasma is given by⁷

$$\frac{\partial W}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} [r(q + W\Gamma)] + S , \quad (13)$$

where W is the thermal energy density, q is the conduction heat flux, Γ is the particle flux (convection), and S includes other source terms such as radiation and charged particle power density.

The heat and particle flux terms may be combined into a single heat transfer quantity:

$$q + W\Gamma = -n\chi_E \frac{\partial T}{\partial r} ,$$

where χ_E is the thermal diffusivity. The additional source terms can be combined as

$$S = p_{cp} - p_{rad} = p_h ,$$

where p_h is the net heating power density. At steady state conditions,

$$\frac{\partial W}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \left(n\chi_E \frac{\partial T}{\partial r} \right) \right] + p_h = 0 . \quad (14)$$

By assuming a uniform "flat" density profile and a parabolic temperature profile such as

$$T = T_o \left(1 - \frac{r^2}{\bar{a}^2} \right) ,$$

the solution to Eq. (14) becomes

$$\frac{4n\chi_E T_o}{\bar{a}^2} - p_h = 0 .$$

For a noncircular plasma, $\bar{a}$ is the average plasma radius. For the assumed plasma profiles, the needed thermal diffusivity is therefore

$$\chi_E = \frac{p_h \bar{a}^2}{6nT} . \quad (15)$$

For D-T and D-D reactors having equal power output, values for the plasma size, $\bar{a}$, and the total density, n , can be calculated for different values of average plasma temperature, T . The temperature must be above the minimum ignition value, shown on Fig. 4, and is optimum near the maximum value of the reaction rate parameter. As seen in the figure, this is around 10 keV for D-T reactors and 30 keV for D-D reactors. Typical values of the parameters from Eq. (15) are given in Table 1.

Table 1. Key Parameters Leading to the Needed Thermal Diffusivity in D-T and D-D Reactors

	D-T	D-D
Average radius, $\bar{a}$ (m)	1.00	2.40
Total density (m^{-3})	1.47×10^{21}	1.0×10^{21}
Average temperature (keV)	10	30
Charged particle power density, p_{cp} (MW/ m^3)	8.28	1.64
Radiation power density, p_{rad} (MW/ m^3)	0.92	1.24
Net heating power, p_h (MW/ m^3)	7.36	0.40
Thermal diffusivity, χ_E (m^2/s)	0.52	0.08

The higher heating power density and lower temperature of the D-T reactor more than compensate for the impact of the larger size of the D-D reactor, resulting in a thermal diffusivity a factor of 6 higher. If the needed low value of

0.08 m²/s for the D-D reactor cannot be obtained in future experimental devices, the plasma size and/or power density would have to be increased.

C. Generic Reactor Approach

A recent study by J. Sheffield et al.¹ has determined the conditions necessary to obtain economical power generation from a toroidal magnetic fusion reactor using D-T fuel. The unique feature of the study is that it models the generic aspects of magnetic fusion reactors rather than specific concepts, thereby avoiding a premature judgment of which system will ultimately prove to perform satisfactorily. The method used in the study has received widespread interest in the U.S. Fusion Program and in the past year has been further expanded by Krakowski and Delene¹⁴ to study the connections between physics and economics for tokamak power plants.

1. Definition of the Generic Reactor Concept

A magnetically confined fusion plasma can be characterized by a relatively simple set of equations derived from power balance considerations. The generic reactor model adds physical and engineering characteristics of toroidal systems, which can be described in a way that is common to most confinement concepts. The Balance of Plant (BoP), all systems except the reactor itself, is very similar to nuclear fission plants. The design cost data are well documented for both present and desirable future fission reactor plants.¹⁵

Figure 5, a schematic diagram of a generic fusion power plant, shows the features of the reactor and the BoP. The reactor model starts with a general plasma configuration that can be circular or elongated in cross section. The plasma is next enclosed in a blanket and shield structure, which may vary in

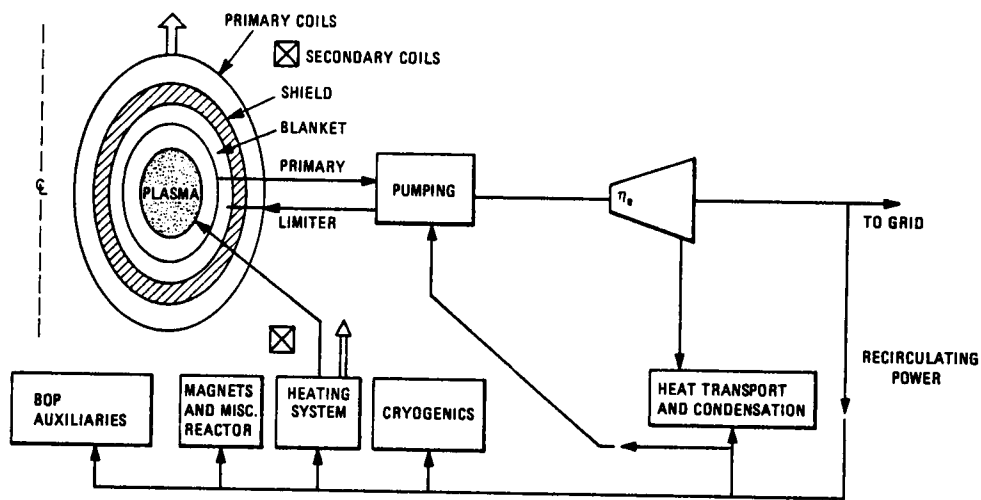


Fig. 5. Schematic diagram of the generic fusion reactor model as proposed by Sheffield. [Ref. 1, Sheffield, J., et al., *Cost Assessment of a Generic Magnetic Fusion Reactor*, ORNL/TM-9311, Oak Ridge National Laboratory, March 1986.]

thickness from inside to outside. Gaps are allowed for plasma control, assembly, and maintenance. Primary coils, normally called toroidal field (TF) coils, then enclose the blanket and shield. These are modeled as discrete magnets, the number of which may be varied. A secondary coil set is also included to account for the poloidal field magnets required for all toroidal systems. The fusion-specific auxiliary systems—plasma heating, fueling, cryogenics, and special power supplies—along with the more conventional BoP facilities are modeled based on scaling relationships derived from the Starfire reactor design.³ The Starfire study is the most comprehensive fusion reactor design study available, representing an excellent source of design and cost data.

By using the power balance equations, reactor systems models, and power reactor plant scaling, it is relatively easy to develop a computer model to perform parametric analysis and cost trade-off studies.

2. Findings of a Generic D-T Reactor Study

In the D-T generic study by Sheffield, an optimized reactor concept was developed based on projected physics and technology improvements. The goal was to define the requirements necessary to compete with equivalent CoE projections of fission and fossil fuel power plants of 45–60 mills/kWh(e) based on 1983 dollars.

An example of the findings of the Sheffield study is shown in Table 2. The generic reactor is compared to the Starfire design using the same model. The reduced CoE of the generic reactor resulted primarily from requiring a higher plasma pressure, smaller and higher-performance magnets, and reduced plasma heating and recirculating power while using greater conservatism in costing, redundancy, and availability. The estimated CoE of 49 mills/kWh(e) is well within the goal described above.

Table 2. Comparison of Starfire and an Optimized D-T Generic Reactor

	Starfire	Generic Reactor
Fusion power, MW(t)	4,000	3,750
Maximum auxiliary power, MW(e)	150	50
Thermal-electric efficiency	0.36	0.36
Net electric power, MW(e)	1,200	1,230
Neutron flux, MW/m ²	3.6	5.1
Aspect ratio, R/a	3.6	6.0
Ellipticity, b/a	1.6	2.0
Scrapeoff layer, a_w/a	1.1	1.2
Beta $\langle\beta\rangle(\langle\beta_i\rangle)$, %	6.7 (2.3)	10.0 (4.6)
Maximum coil field, B_m (T)	11.1	9.0
Thermal diffusivity, χ_E (m ² /s)	0.55	0.48
Fusion island weight, M_{FI} (t)	24,000	10,200
CoE, mill/kWh	~75	49

3. Justification for a Generic D-D Reactor Study

The most detailed assessment of a D-D reactor design published to date is "WILDCAT: A Catalyzed D-D Tokamak Reactor."² The tokamak was chosen as the basis for the study because it has been studied more extensively than other concepts and hence presents a good basis of comparison of D-D with D-T reactors. The study evaluated the design, operating space, and selected plasma parameters and then developed a conceptual design and cost estimate. Results of the study were then compared to the Starfire and D-T tokamak, the two designs being developed by the same group at the Argonne National Laboratory. A schematic comparison of the two designs is shown in Fig. 6. The study concluded that, in spite of the attractive features of the CAT-D system, the estimated increase in the CoE of a factor of two would strongly favor the choice of the D-T system if both were available.

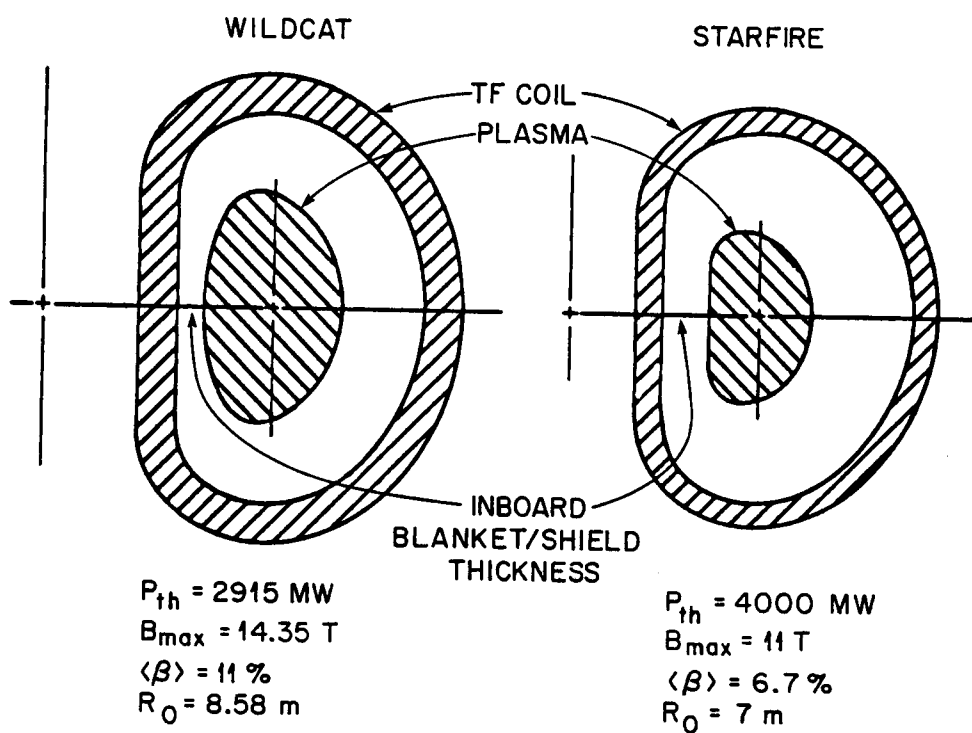


Fig. 6. Elevation view of the Wildcat and Starfire reactor plasma and TF coil designs by the Argonne National Laboratory. [Ref. 2, Evans, K., et al., *WILDCAT: A Catalyzed D-D Tokamak Reactor*, ANL/FPP/TM-150, Argonne National Laboratory, November 1981.]

A key justification for a reevaluation of the D-D reactor can be seen in the comparison of parameters shown in Fig. 6. Three important design parameters having significant impact on the CoE—total thermal power, maximum magnetic field, and beta—are all quite different. Projected improvements in technology and tokamak performance well beyond that assumed for Starfire were considered essential to reduce the size and cost of the D-D system. In the generic reactor study, D-T and D-D systems were evaluated “side by side” to get equivalent comparisons.

4. Limitations of the Generic Study Approach

Since the generic reactor model attempts to represent design and operating features of several toroidal magnetic confinement concepts, the level of detail which defines a particular concept is necessarily limited. In comparing the stellarator and tokamak concepts, for example, it is necessary to invoke additional auxiliary power necessary to drive current in the tokamak, whereas the stellarator does not require plasma current for steady-state operation. In spite of differences of this type, Sheffield¹ points out that those features common to all systems are more numerous than those that are different. The primary motivation for the approach is to identify general physics and technology requirements for a competitive fusion power reactor. Detailed systems analysis and design codes are available for specific confinement concepts such as the TETRA¹⁶ tokamak code.

CHAPTER II

DEVELOPMENT OF THE CATALYZED D-D REACTOR MODEL

The catalyzed D-D reactor computer model consists of a set of independent equations relating reactor power balance, plasma performance parameters, and engineering design constraints. A derivation of the model and an illustrative output of the spreadsheet program are included in this chapter.

A. Power Balance

The fusion power generated in the catalyzed D-D reaction is the sum of the power fraction from the fusion of each pair of ions existing in the plasma (deuterium, tritium, and He^3). From Eq. (2), the total power density is

$$\begin{aligned}
 P_f = & n_D n_T \langle \sigma v \rangle_{DT} E_{DT} + \frac{n_D^2 \langle \sigma v \rangle_{DD,n}}{2} E_{DD,n} \\
 & + \frac{n_D^2 \langle \sigma v \rangle_{DD,p}}{2} E_{DD,p} \\
 & + n_D n_{\text{He}^3} \langle \sigma v \rangle_{D\text{He}^3} E_{D\text{He}^3} ,
 \end{aligned} \tag{16}$$

where the energies for each reaction, E_{ij} , are as shown in Eqs. (8)–(11).

The other possible reactions involving T-T, T- He^3 , and He^3 - He^3 are not included since they have a small reaction probability¹⁷ relative to the reactions shown.

A steady-state burn condition may be derived¹⁸ by assuming that the T and He^3 are burned at the same rate that they are produced in the D-D reactions:

$$\text{TRITIUM BURN RATE} = \text{TRITIUM PRODUCTION RATE} ,$$

$$n_D n_T \langle \sigma \nu \rangle_{DT} = \frac{n_D^2 \langle \sigma \nu \rangle_{DD,p}}{2} , \quad (17)$$

He³ BURN RATE = He³ PRODUCTION RATE ,

$$n_D n_{He^3} \langle \sigma \nu \rangle_{DHe^3} = \frac{n_D^2 \langle \sigma \nu \rangle_{DD,n}}{2} . \quad (18)$$

Equations (17) and (18) can be solved explicitly for n_T and n_{He^3} and substituted into Eq. (16) to yield

$$P_f = \frac{n_D^2}{2} [\langle \sigma \nu \rangle_{DD,p} (E_{DD,p} + E_{DT}) + \langle \sigma \nu \rangle_{DD,n} (E_{DD,n} + E_{DHe^3})] .$$

By substituting the energy values from Eqs. (8)-(11),

$$\begin{aligned} E_{DD,p} + E_{DT} &= E_{DD,n} + E_{DHe^3} = 21.6 \text{ MeV} , \\ P_f &= \frac{n_D^2}{2} \langle \sigma \nu \rangle_{DD} E_{DD} (1.6021 \times 10^{-13}) , \end{aligned} \quad (19)$$

where

$$\langle \sigma \nu \rangle_{DD} = \langle \sigma \nu \rangle_{DD,p} + \langle \sigma \nu \rangle_{DD,n}$$

and

$$E_{DD} = 21.6 \text{ MeV} .$$

Unless otherwise noted, all units are in the rationalized mks system.

When the geometry of an elongated toroidal plasma is introduced, the expression for the total fusion power becomes

$$P_F = P_f V_p = 2\pi^2 R a b P_f . \quad (20)$$

An elliptical plasma cross section is assumed, where V_p is the plasma volume, R is the major radius of the plasma, a is the half-width or minor radius, and b is the half-height. The minor radius is related to the plasma height by the definition of plasma elongation, σ , where

$$\sigma = \frac{b}{a} . \quad (21)$$

For simplicity, the model assumes a uniform distribution of density and temperature throughout the plasma cross section. Jassby has shown that significant gains in fusion power density are possible through optimization of the plasma profiles.¹⁹ However, since for similar profiles these gains are essentially equal for D-T and D-D fuels, the assumption of uniform "flat" profiles will not change the relative comparison of one to the other.

B. Plasma Performance

A relationship among plasma density, temperature, and magnetic field is given by the definition of ion beta:

$$\beta_i = \frac{\text{Plasma ion pressure}}{\text{Magnetic pressure}} ,$$

where

$$\text{Plasma ion pressure} = \sum n_i T_i ,$$

n_i and T_i are the ion densities and temperatures for each species, and

$$\text{Magnetic pressure} = \frac{B_o^2}{2\mu_o} .$$

Therefore,

$$\beta_i = \frac{2\mu_o \sum n_i T_i}{B_o^2} . \quad (22)$$

T_i is the average plasma kinetic temperature in keV, B_o the magnetic field at the center of the plasma, and μ_o the magnetic permeability of a vacuum.

The ion beta, neglecting impurity ions for the CAT-D fuel, is

$$\begin{aligned} \beta_i &= \beta_D + \beta_T + \beta_{He^3} \\ &= \frac{2\mu_o}{B_o^2} (n_D + n_T + n_{He^3}) T_i . \end{aligned}$$

From Eqs. (17) and (18), n_T and n_{He^3} can be expressed as

$$\begin{aligned} n_T &= \frac{n_D \langle \sigma \nu \rangle_{DD,p}}{2 \langle \sigma \nu \rangle_{DT}} , \\ n_{He^3} &= \frac{n_D \langle \sigma \nu \rangle_{DD,n}}{2 \langle \sigma \nu \rangle_{DHe^3}} , \end{aligned}$$

and the expression for β_i becomes

$$\beta_i = \frac{2\mu_o n_D}{B_o^2} \left(1 + \frac{\langle \sigma \nu \rangle_{DD,p}}{2 \langle \sigma \nu \rangle_{DT}} + \frac{\langle \sigma \nu \rangle_{DD,n}}{2 \langle \sigma \nu \rangle_{DHe^3}} \right) T_i . \quad (23)$$

Solving Eq. (23) for n_D^2 and substituting into Eqs. (19) and (20) yields

$$\begin{aligned} P_F &= \frac{\pi^2 \beta_i^2 B_o^4}{4\mu_o^2 T_i^2} \left(\frac{1}{1 + \frac{\langle \sigma \nu \rangle_{DD,p}}{2 \langle \sigma \nu \rangle_{DT}} + \frac{\langle \sigma \nu \rangle_{DD,n}}{2 \langle \sigma \nu \rangle_{DHe^3}}} \right)^2 \langle \sigma \nu \rangle_{DD} E_{DD} R_{ab} \\ &= \frac{\pi^2 \beta_i^2 B_o^4}{4\mu_o^2 T_i^2} K_1^2 \langle \sigma \nu \rangle_{DD} E_{DD} R_{ab} , \end{aligned} \quad (24)$$

where

$$K_1 = \left(\frac{1}{1 + \frac{\langle \sigma \nu \rangle_{DD,p}}{2\langle \sigma \nu \rangle_{DT}} + \frac{\langle \sigma \nu \rangle_{DD,n}}{2\langle \sigma \nu \rangle_{DHe^3}}} \right)$$

or

$$P_F = \frac{\pi^2 \beta_i^2 B_o^4 K_1^2 \langle \sigma \nu \rangle_{DD} E_{DD}}{4\mu_o^2 T_i^2} \left(\frac{R}{a} \right) \left(\frac{b}{a} \right) a^3, \quad (25)$$

where R/a is the plasma aspect ratio and b/a is the elongation.

The fusion power for the TCD fuel cycle can similarly be derived by assuming that the He^3 is converted into tritium as described in Chapter I. The He^3 production rate given in Eq. (18) then becomes a source for additional tritium:

$$\text{ADDITIONAL TRITIUM BLANKET PRODUCTION} = \frac{n_D^2 \langle \sigma \nu \rangle_{DD,n}}{2}.$$

By substituting this term in place of the He^3 term in Eq. (16) and using Eqs. (17) and (18), the expression for power density becomes

$$P_f^{TCD} = \frac{n_D^2}{2} [\langle \sigma \nu \rangle_{DD,p} (E_{DD,p} + E_{DT}) + \langle \sigma \nu \rangle_{DD,n} (E_{DD,n} + E_{DT})] . \quad (26)$$

By continuing as with the CAT-D, the deuterium density term can be replaced with the expression for ion beta in the TCD cycle:

$$\beta_i^{TCD} = \beta_D + \beta_T ,$$

$$\beta_i^{TCD} = \frac{2\mu_o}{B_o^2} (n_D + n_T) T_i .$$

In this case, the tritium density is increased by the additional He^3 blanket production:

$$\begin{aligned} \beta_i^{TCD} &= \frac{2\mu_o n_D}{B_o^2} \left(1 + \frac{\langle \sigma \nu \rangle_{DD,p}}{2\langle \sigma \nu \rangle_{DT}} + \frac{\langle \sigma \nu \rangle_{DD,n}}{2\langle \sigma \nu \rangle_{DT}} \right) \\ &= \frac{2\mu_o n_D}{B_o^2} \left(1 + \frac{\langle \sigma \nu \rangle_{DD}}{\langle \sigma \nu \rangle_{DT}} \right) . \end{aligned} \quad (27)$$

The expression for total fusion power becomes

$$P_F^{TCD} = \frac{\pi^2 \beta_i^2 B_o^4 K_2^2}{4\mu_o^2 T_i^2} \left(\frac{R}{a}\right) \left(\frac{b}{a}\right) a^3 , \quad (28)$$

where

$$K_2^2 = \frac{[\langle \sigma \nu \rangle_{DD,p}(E_{DD,p} + E_{DT}) + \langle \sigma \nu \rangle_{DD,n}(E_{DD,n} + E_{DT})]}{\left(1 + \frac{\langle \sigma \nu \rangle_{DD}}{\langle \sigma \nu \rangle_{DT}}\right)^2} .$$

C. Engineering Constraints

Additional geometric and engineering constraints are introduced by relating the magnetic field on axis, B_o , to the maximum field at the magnet, B_m

$$B_o = B_m \left[\frac{R - a_w - (db_1 + dg_1 + ds_1) + dd}{R} \right] , \quad (29)$$

where a_w is the minor radius of the first wall of the plasma chamber. Refer to Fig. 7 for definitions of the radial build symbols; the subscript 1 refers to the inboard thicknesses.

When assumed values for fusion power, blanket and shield radial build thicknesses, maximum magnetic field, plasma elongation, aspect ratio, beta, and temperature are used, Eqs. (25) and (26) can be solved for the field on axis and for the plasma radius. From these so-called "zero-dimensional" parameters, a generic reactor system can be characterized. A complete listing of the spreadsheet equations is given in the Appendix.

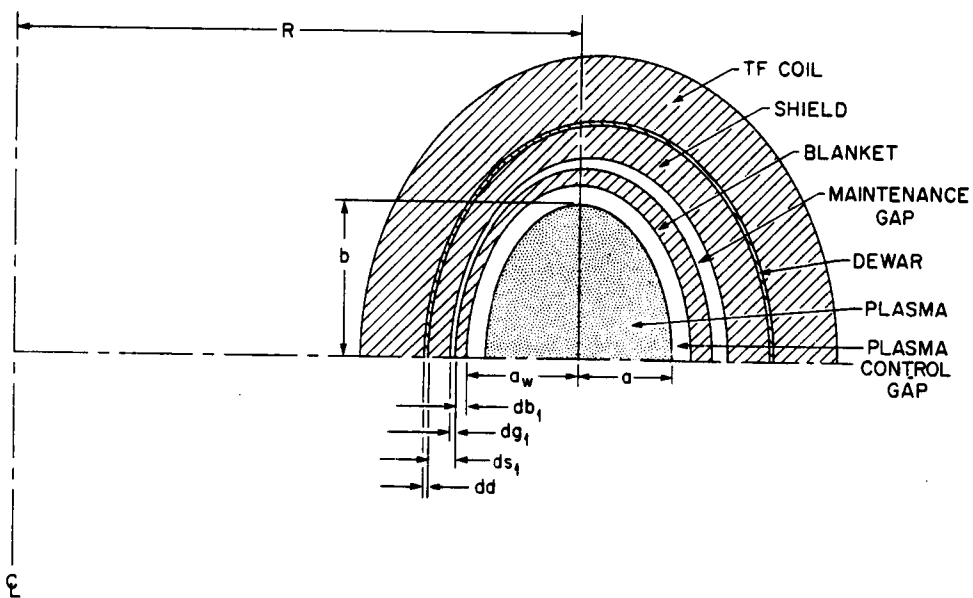


Fig. 7. Outline of the D-D generic reactor model.

D. Illustrative Run

Results for a typical solution to the zero-dimensional equations are shown in Table 3. The assumed input parameters are listed first, followed by a typical set of reactor parameters that can be calculated. The CAT-D, TCD, and D-T systems are shown for comparison. Each produces a net electric power of ~ 1150 MW.

E. Cost Model

To permit a comparison with the previous work by Sheffield, the capital cost modeling uses the same approach. Since a direct comparison is made between the two fuel cycles, a more simplified model was used to derive the CoE. The cost estimates provide a good basis for comparison of the two systems and for design optimization and trade studies. However, because of limited data on the cost of fusion reactor systems, the absolute values of capital cost and CoE are not as reliable.

1. Capital Costs

The capital costs of the fusion reactor and the associated power plant equipment are calculated based on essentially the same data used by Sheffield.¹ The costs of the reactor components are based on the calculated mass of material times a unit cost value derived from Starfire and other related studies. Table 4 lists the primary reactor components and the assumed unit cost values.

Table 3. Typical Results of the Generic Model

	CAT-D	TCD	D-T
Total fusion power, P_f (MW)	3,500	3,500	4,000
Plasma ion temperature, T_i (eV)	30,000	30,000	10,000
Reaction rate DT, $\langle\sigma\nu\rangle$ (m ³ /s)	6.65E-22	6.65E-22	1.09E-22
Reaction rate DDp, $\langle\sigma\nu\rangle$ (m ³ /s)	4.76E-24	4.76E-24	
Reaction rate DDn, $\langle\sigma\nu\rangle$ (m ³ /s)	5.41E-24	5.41E-24	
Reaction rate DDp+DDn, $\langle\sigma\nu\rangle$ (m ³ /s)	1.02E-23	1.02E-23	
Reaction rate parameter DHe ³ , $\langle\sigma\nu\rangle$ (m ³ /s)	1.45E-23	1.45E-23	
Tritium concentration, n_T/n_D	0.0036	0.0076	1.0
He ³ concentration, n_{He^3}/n_D	0.1866		
Deuterium/ion fraction, n_D/n_i	0.8402	0.9924	0.5
Deuterium/electron fraction, n_D/n_e	0.7264	0.9924	0.5
Deuterium fraction, $n_D/(n_e + n_i)$	0.3896	0.4962	0.25
Tritium fraction, $n_T/(n_e + n_i)$	0.0014	0.0038	0.25
He ³ fraction, $n_{He^3}/(n_e + n_i)$	0.0727		
Electron fraction, $n_e/(n_e + n_i)$	0.5363	0.5	0.5
Total beta, $\langle\beta\rangle$	0.11	0.11	0.11
Electron beta, $\langle\beta\rangle_e$	0.06	0.06	0.06
Deuterium beta, $\langle\beta\rangle_D$	0.04	0.05	0.03
Auxiliary heating power, P_a (MW)	100	100	100
Thermal/electric conversion efficiency, N_e	0.36	0.36	0.36
Recirculating power fraction, f_{re}	0.04	0.04	0.04
Maximum field at coil, B_m (T)	14.35	14.35	14.35
Total beta, $\langle\beta\rangle$	0.11	0.11	0.11
Fuel ion beta, $\langle\beta\rangle_F$	0.04	0.05	0.06
Aspect ratio, R/a	6	6	6
Plasma elongation, b/a	1.6	1.6	1.6
Blanket energy gain for DDn, g_1	3.43	3.43	1.93
Blanket energy gain for DTn, g_2	0.54	0.54	0.24
Overall thickness, $dbgs_1$ (m)	0.73	0.73	1.3
Dewar thickness, dd (m)	0.08	0.08	0.08
Ratio of wall/plasma radius, a_w/a	1.2	1.2	1.2
Wall reflectivity	0.95	0.95	0.95

Table 3. Typical Results of the Generic Model — cont'd.

	CAT-D	TCD	D-T
Results			
Plasma minor radius, a (m)	1.90	1.66	0.80
Field on axis, B_o (T)	10.46	10.31	7.33
Plasma major radius, R (m)	11.40	9.95	4.77
Plasma minor radius, large, b (m)	3.04	2.65	1.27
Plasma volume, V_p (m ³)	1,300.91	864.74	95.43
Plasma power density, P_f (MW/m ³)	2.69	4.05	41.91
First wall area, A_w (m ²)	1,298.73	989.18	227.50
Deuterium density, n_D (m ⁻³)	3.88E+20	4.81E+20	3.67E+20
Tritium density, n_T (m ⁻³)	1.39E+18	3.67E+18	3.67E+20
Helium density, n_{He} (m ⁻³)	7.24E+19		
Total ion density, n_i (m ⁻³)	4.62E+20	4.84E+20	7.34E+20
Electron density, n_e (m ⁻³)	5.34E+20	4.84E+20	7.34E+20
Impurity concentration, Z_{eff}	1.27	1	1
DT power, P_{DT} (MW)	1,314.69	2,860.38	3,950.01
DDn power, P_{DDn} (MW)	277.84	282.93	
DDp power, P_{DDp} (MW)	302.02	307.56	
DHe power, P_{DHe} (MW)	1,558.28		
Charged particle power, P_{cp} (MW)	2,132.10	873.48	789.96
Charged particle power density, p_{cp} (MW/m ³)	1.64	1.01	8.28
Neutron power, P_n (MW)	1,260.13	2,500.50	3,160.05
Neutron wall loading, p_{wn} (MW/m ²)	0.97	2.53	13.88
Total thermal power, P_t (MW)	4,784.04	4,870.78	4,758.42
Total electric power, P_{eg} (MWe)	1,205.58	1,227.44	1,199.12
Net electric power, P_e (MWe)	1,155.68	1,176.64	1,150.80
Bremsstrahlung power density, p_b (MW/m ³)	1.06	0.68	0.91
Synchrotron power density, p_s (MW/m ³)	0.17	0.17	0.01
Total radiation power loss, p_{rad} (MW/m ³)	1.24	0.85	0.92
Radiation power fraction, f_{rad}	0.46	0.21	0.02
Conduction power loss, p_{con} (MW/m ³)	0.40	0.16	7.36
Power fraction for conduction, f_{cp}	0.54	0.79	0.98
Thermal diffusivity, χ_E (m ² /s)	0.08	0.03	0.53

Table 4. Assumed Reactor Unit Cost Values

Reactor System	Unit Cost
Magnets	80 \$/kg
Blanket	70 \$/kg
Shield	22 \$/kg
Structure	23 \$/kg
Auxiliary Heating	2 \$/kg

The cost of the remaining plant systems including the steam generators, reactor building, power supplies, cryogenic systems, turbines, and other general BoP buildings and equipment are scaled based on the electric power output.

2. Cost of Electricity

The CoE is dominated by the capital cost of the fusion reactor and the associated power plant equipment. A total direct capital cost is determined as the sum of the three major plant components plus a contingency of 15%,

$$C_D = 1.15(C_{FI} + \text{Reactor Buildings} + \text{BOP}) ,$$

where C_{FI} is the cost of the fusion island and BOP is the cost of the Balance of Plant. The cost of reactor buildings and the BOP are based on scaling the Starfire values with the volume of the material in the fusion island and the thermal power, respectively. The expression for the direct capital cost then becomes

$$C_D = 1.15 \left[C_{FI} + 685 \left(\frac{P_t}{4150} \right)^{0.6} + 319 \left(\frac{V_{FI}}{5100} \right)^{0.67} \right] ,$$

where P_t is the thermal power and V_{FI} is the volume of the fusion reactor including the plasma chamber, blanket, shielding, structure and magnets.

Indirect costs are estimated as 35% of the direct cost to include engineering, management and construction facilities. An additional contingency of 20% of the fusion island cost is included to yield the constructed cost

$$C_c = 1.35C_D + 0.20C_{FI} \quad .$$

The CoE is calculated in constant dollars based on a fixed rate of 10% of the constructed cost including 11% interest during construction. The resulting CoE is

$$\text{CoE} = \frac{0.10(C_c + 0.11 C_c) + A_{oc}}{8760P_e * C_F} \quad ,$$

where P_e is the net electric power output, 8760 is the number of hours in a year, and C_F is the plant capacity factor generally assumed to be 0.75. The annual operating cost, A_{oc} is scaled as

$$A_{oc} = 49 \left(\frac{P_{eg}}{1100} \right)^{0.7} \quad ,$$

where P_{eg} is the gross electrical power.

An output listing all of the calculated costs is given in Table 5. A complete listing of the cost equations is given in the appendix.

Table 5. Cost Model

	CAT-D	TCD	D-T
Radial Build			
Plasma major radius, R (m)	11.40	9.95	4.77
Plasma minor radius, a (m)	1.90	1.66	0.80
Wall minor radius, a_w (m)	2.28	1.99	0.95
Blanket thickness, inboard, db_1 (m)	0.21	0.31	0.45
Blanket thickness, outboard, db_2 (m)	0.41	0.51	0.90
Maintenance gap, inboard, dg_1 (m)	0.10	0.10	0.10
Maintenance gap, outboard, dg_2 (m)	0.30	0.30	0.30
Shield thickness, inboard, ds_1 (m)	0.42	0.52	0.75
Shield thickness, outboard, ds_2 (m)	0.80	0.80	0.80
Coil dewar thickness, dd (m)	0.08	0.08	0.08
Blanket			
Bore minor radius (m)	2.28	1.99	0.95
Minimum volume, V_{bm} (m ³)	100.20	116.09	44.45
Maximum volume, V_{bmz} (m ³)	408.28	400.38	212.02
Total volume, V_b (m ³)	508.48	516.48	256.47
Density, r_b (kg/m ³)	6,400.00	6,400.00	6,400.00
Unit cost, $\$b$ (\$/kg)	70.00	70.00	70.00
Blanket cost, C_b (M\$)	227.80	231.38	114.90
Shield			
Bore minor radius (m)	2.59	2.40	1.50
Minimum volume, V_{sm} (m ³)	235.27	241.48	118.04
Maximum volume, V_{smz} (m ³)	958.50	783.29	255.55
Total volume, V_s (m ³)	1,193.77	1,024.77	373.59
Density, r_s (kg/m ³)	6,400.00	6,400.00	6,400.00
Unit cost, $\$s$ (\$/kg)	22.00	22.00	22.00
Shield cost, C_s (M\$)	168.08	144.29	52.60
Coils			
Maximum field, B_m (T)	14.35	14.35	14.35
Number of TF coils	20	20	20
Current per coil, I_c (MA)	29.82	25.66	8.75
Winding current density, J_p (MA/m ²)	28.39	28.39	28.39
Winding area (m ²)	1.05	0.90	0.31
Radius of coil inside bore, r_1 (m)	8.31	6.95	2.44
Radius of coil outside, bore, r_2 (m)	15.27	13.63	7.81
Coil free bore width (m)	6.96	6.68	5.37
Coil tension, T (lb)	1.216E+08	9.417E+07	2.003E+07
Allowable coil membrane stress, S (psi)	40,000	40,000	40,000
Coil structural area, A_{cs} (m ²)	1.96	1.52	0.32
Total coil area, A_{tc} (m ²)	3.01	2.42	0.63
Coil area, all coils (m ²)	60.25	48.45	12.63

Table 5. Cost Model — cont'd.

	CAT-D	TCD	D-T
Coils — cont'd.			
Maximum available space, coil area (m^2)	217.09	151.82	18.69
Coil current density, J_m (MA/m^2)	9.90	10.59	13.86
Coil thickness, d_{if} (m)	1.25	1.22	1.05
Coil average radius (m)	4.10	3.95	3.21
Average coil perimeter (m)	34.40	33.10	26.91
Coil magnetic pressure (psi)	11,884	11,884	11,884
Primary coil volume, V_{cp} (m^3)	2,072.90	1,603.72	339.70
Total coil volume, V_{ct} (m^3)	2,591.13	2,004.65	424.63
Density, r_c (kg/m^3)	8,000	8,000	8,000
Unit cost, $\$c$ ($\$/\text{kg}$)	80	80	80
Coil cost, C_c (M\$)	1,989.98	1,539.57	326.11
Structure			
Volume, V_{st} (m^3)	1,554.68	1,202.79	254.78
Density, r_{st} (kg/m^3)	6,000	6,000	6,000
Unit cost, $\$st$ ($\$/\text{kg}$)	23	23	23
Structure cost, C_{st} (M\$)	214.55	165.98	35.16
Auxiliary Power			
Unit cost, $\$a$ ($\$/\text{W}$)	2	2	2
Auxiliary power cost, C_{ap} (M\$)	150.00	150.00	150.00
Steam Generators			
Steam generator cost, C_{sg} (M\$)	91.48	92.47	91.19
Total fusion island cost, C_{FI} (M\$)	2,841.89	2,323.69	769.96
Balance of Plant (M\$)	746.00	754.09	743.60
Reactor buildings (M\$)	310.12	269.51	110.92
Direct capital cost, C_D (M\$)	4,482.71	3,849.38	1,868.15
COST OF ELECTRICITY			
Indirect cost, I_C (M\$)	1,568.95	1,347.28	653.85
Contingency, $CONT$ (M\$)	568.38	464.74	153.99
Constructed cost, C_C (M\$)	6,620.04	5,661.40	2,676.00
Interest rate, %	0.11	0.11	0.11
Interest during construction, I_{DC} (M\$)	728.20	622.75	294.36
Total capital cost, T_{CC} (M\$)	7,348.25	6,284.16	2,970.36
Annual operating cost, A_{OC} (M\$)	52.25	52.91	52.05
Fixed charge rate, F_{CR} (%)	0.10	0.10	0.10
Capacity factor, C_F	0.75	0.75	0.75
Cost of Electricity, CoE (mills/kWh)	104	88	46

CHAPTER III

OPTIMIZATION OF THE D-D REACTOR SYSTEM

The CAT-D was selected over the TCD system for the optimization study. The CAT-D system, hereafter called D-D, has been studied extensively, is simpler than the TCD, and is thus a more credible reactor option at this time. The first step in the evaluation of the D-D reactor system was to examine the sensitivity of the reactor parameters to variations in the assumed input to the model. The Wildcat study was used to select the basic parameters for the blanket and shield system. Values for auxiliary heating power, recirculating power fraction, electric conversion efficiency, and several other radial build assumptions were taken from Sheffield's study. The remaining parameters varied in the sensitivity analysis were total fusion power, ion temperature and beta, maximum magnetic field, and plasma aspect ratio and elongation.

The CoE was used as the primary figure of merit in the evaluation. As explained previously, there is an unreliability in the absolute value of the CoE; however, it does provide an excellent overall measure of the total reactor system design. Results of the analysis are discussed in the following sections.

A. Sensitivity Studies

1. Total Power and Reactor Size

The CoE for variation in total fusion power in the plasma is shown in Fig. 8. The other variables listed in the figure were selected after considerable evaluation and optimization studies.

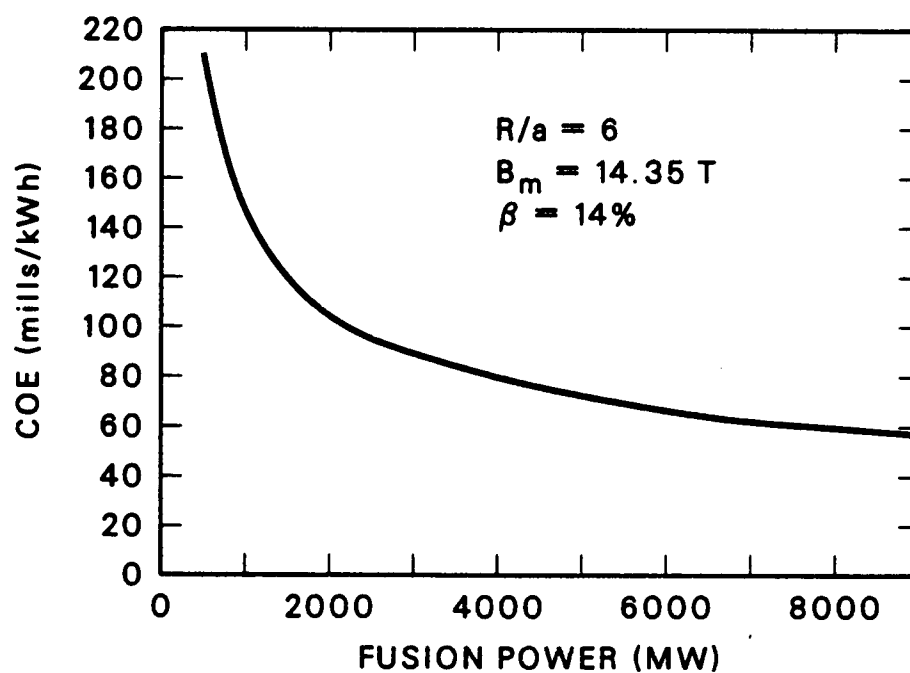


Fig. 8. Variation in cost of electricity with fusion power, illustrating the economy of scale.

The economy of scale, which is well known for nuclear fission reactor systems, is also evident for the D-D reactor. A 4000-MW system, somewhat in the knee of the curve, was selected for the remainder of the study to be compatible with the Starfire D-T study. Capital cost and reactor size are also important considerations in the design and planning of power plant facilities. Figure 9 shows the relationship between total capital cost and the net electric output, almost a linear relationship. The capital cost variation with major machine radius is shown in Fig. 10 and also exhibits a nearly linear relationship.

2. Plasma Ion Temperature

As shown in Fig. 11, the CoE is not strongly influenced by the plasma ion temperature above the minimum ignition value. Plasma physics considerations such as impurity concentrations, confinement time, and ignition requirements must be taken into account in selecting the best value for the ion temperature. The Wildcat study, which included a rather detailed assessment of the plasma physics, proposed an ion temperature of ~ 30 keV. This is the value chosen for the remainder of the trade studies.

3. Maximum Magnetic Field

The CoE for variation in maximum magnetic field at the coil is shown in Fig. 12. Although the minimum is fairly broad from 12 to 17 T, the optimum field turns out to be the same as that selected for the Wildcat design, 14.35 T. This value is considered to be a reasonable extrapolation of present superconducting magnet technology. The assumed current density in the magnet conductor, an important factor in determining the overall cost, is assumed to vary as shown in Fig. 13.

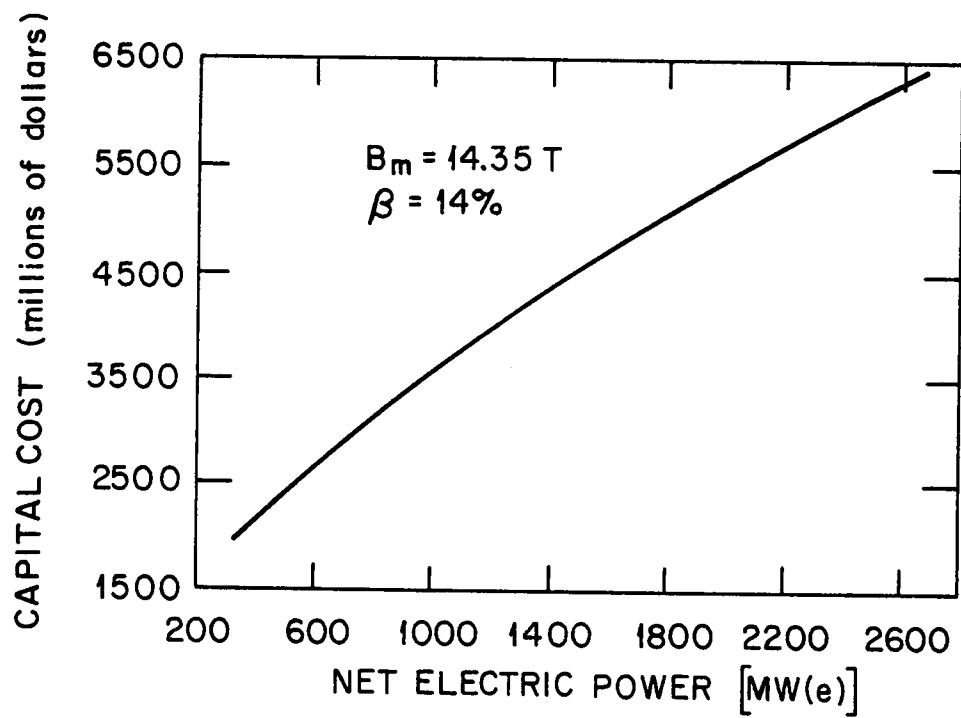


Fig. 9. Variation in plant capital cost with net electric power.

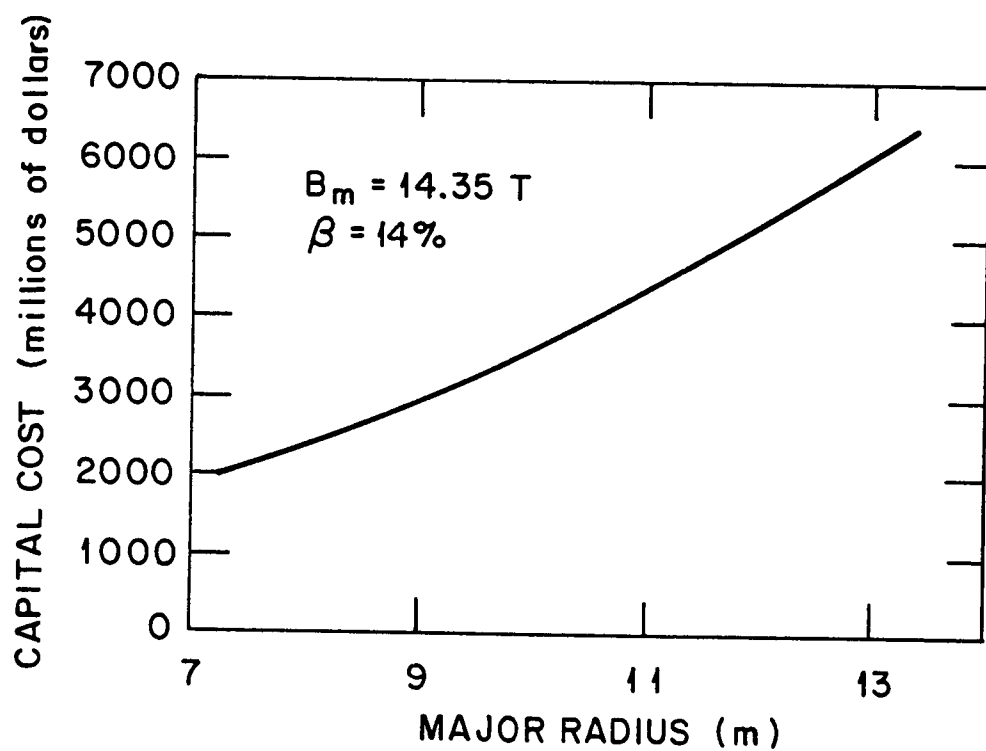


Fig. 10. Variation in capital cost with machine major radius.

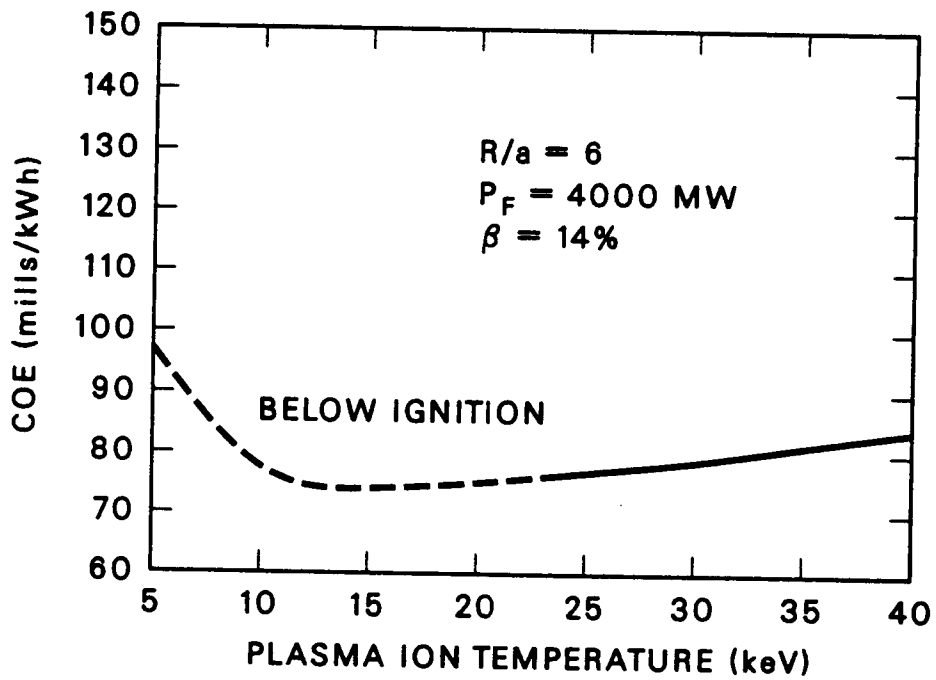


Fig. 11. Cost of electricity versus plasma ion temperature.

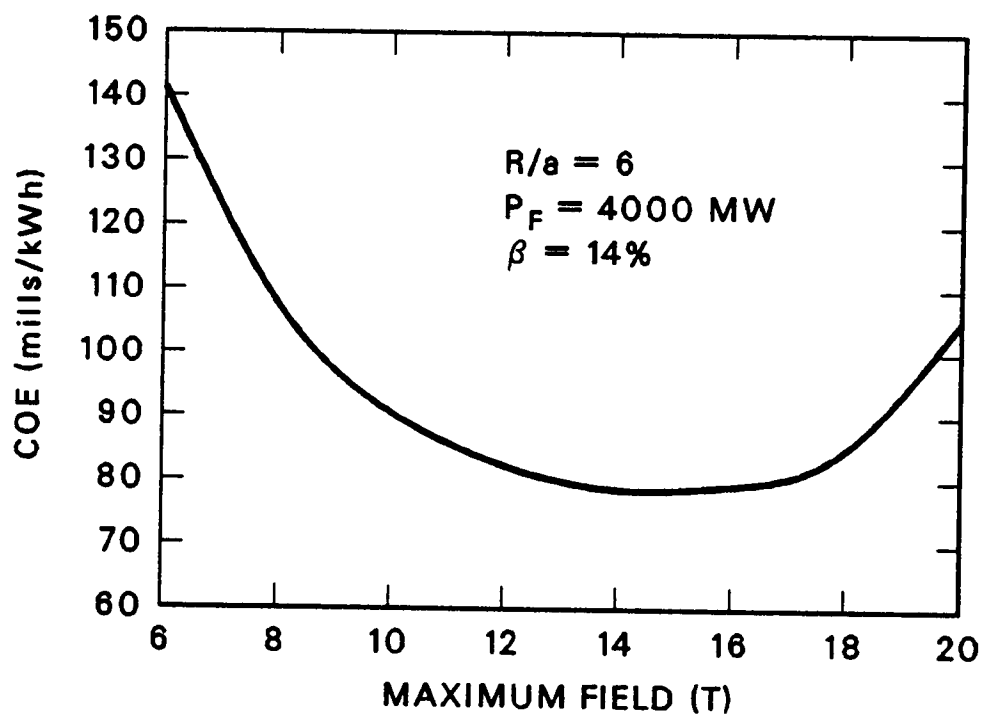


Fig. 12. Variation in cost of electricity with maximum magnetic field in the TF coil, showing a minimum at 14.3 T.

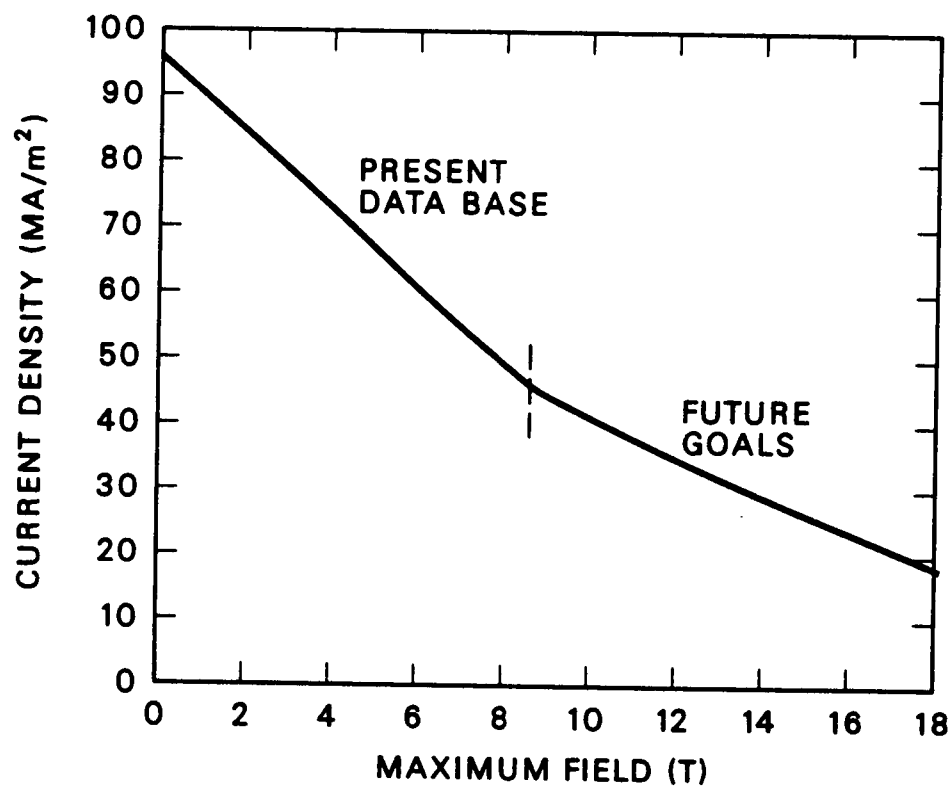


Fig. 13. Assumed design value of current density in the magnet winding pack versus maximum field.

4. Plasma Beta

The CoE for variation in plasma beta is shown in Fig. 14. Increased beta is a strong factor for reducing the CoE because the plasma power density varies as the square of beta. For this reason, plasma beta is a major issue in the worldwide plasma physics research programs. Plasma instabilities, characterized by many features of present plasma confinement experiments,²⁰ tend to limit the maximum attainable beta to values well below those desirable for an attractive reactor design.

5. Plasma Aspect Ratio

The CoE for variation in plasma aspect ratio is shown in Fig. 15. The minimum range is very broad from 4 to 8. However, the absolute minimum occurs at an aspect ratio of 6, identical to the optimum value determined by Sheffield in the D-T study. For a constant beta value, the CoE sharply increases below an aspect ratio of 3. There is evidence that the critical beta value for tokamaks increases at low aspect ratio.²¹ Since CoE decreases with increasing beta, small aspect ratio tokamaks will have lower cost than indicated in the generic study.

6. Plasma Elongation

From a consideration of only CoE, the plasma elongation, as shown in Fig. 16, has almost no impact. Other physics considerations, however, such as plasma stability will ultimately influence this selection. A value of 1.6 was chosen from this study, representing a very weak minimum CoE.

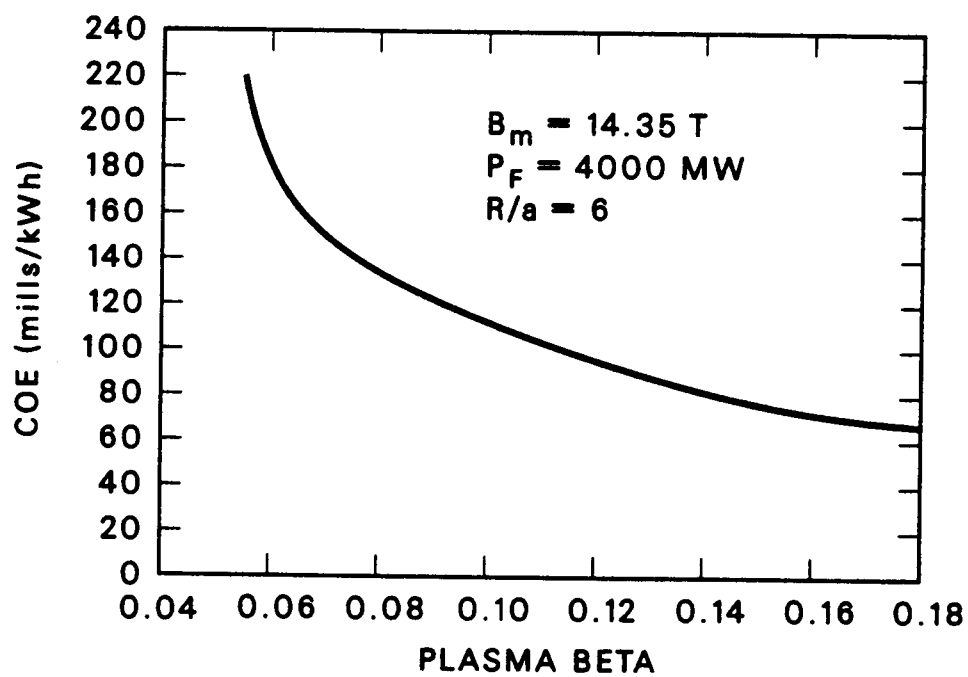


Fig. 14. Dependence of cost of electricity on plasma beta, illustrating importance of high beta.

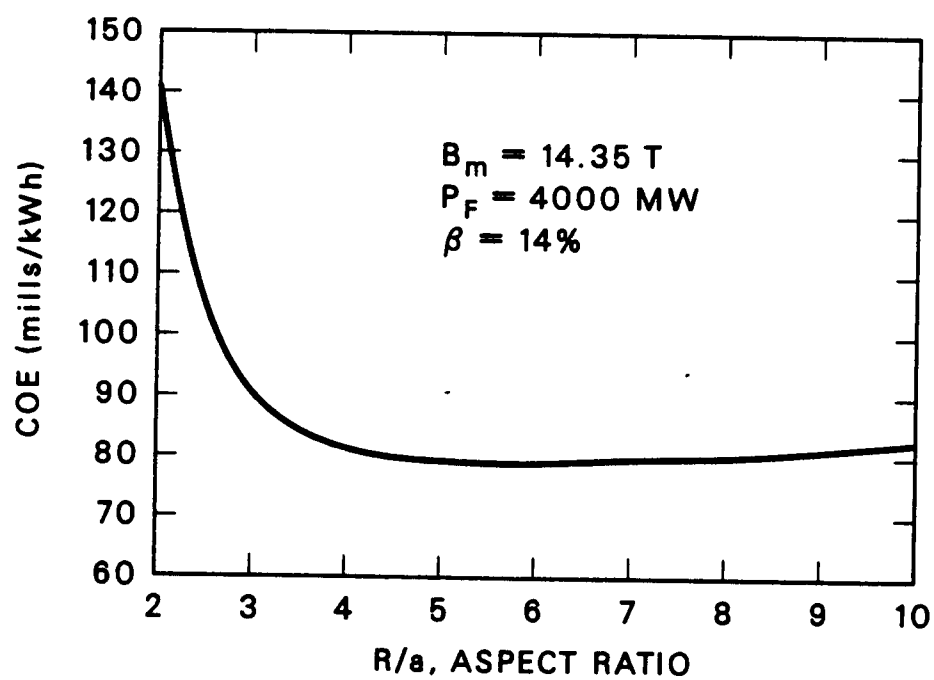


Fig. 15. Cost of electricity versus plasma aspect ratio.

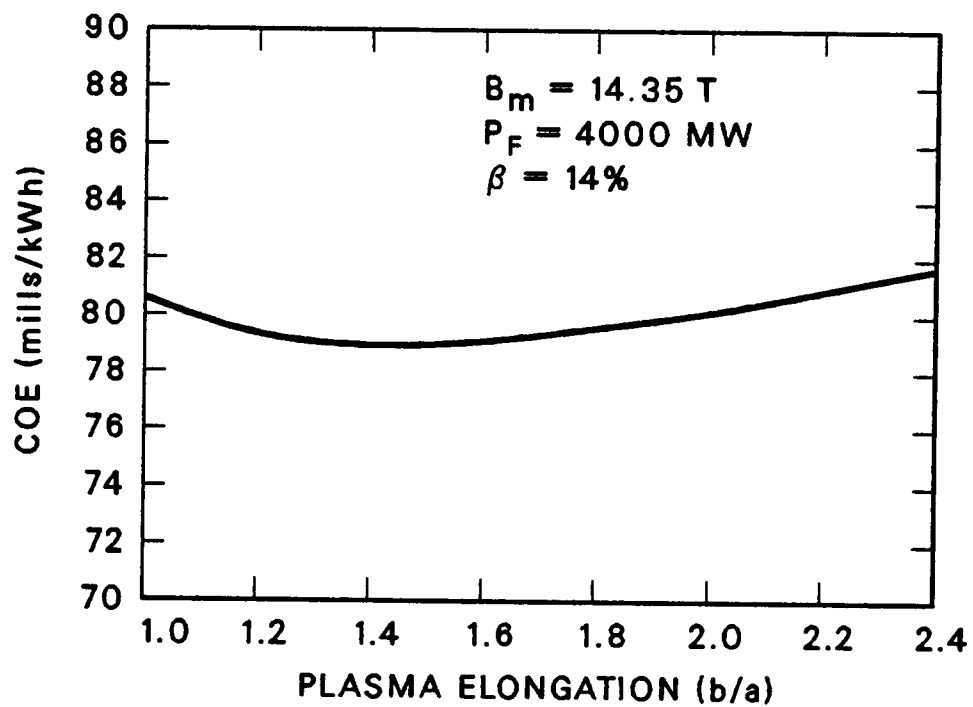


Fig. 16. Dependence of cost of electricity on plasma elongation, neglecting plasma physics effects.

7. Magnet Stress Level

The large plasma volume and magnet size are dominant features of the CAT-D design. In the process of evaluating this design, it was discovered that the model for the structural magnet system, taken from the Sheffield study, was inadequate for the CAT-D system because of the large extrapolation from the size of Starfire, on which the cost scaling was based. An improved structural model was derived based on a D-shaped toroidal magnet configuration.

This improved structural model (discussed in Chapter IV), based on an allowable stress value, showed that CoE is a very strong function of stress. Interestingly, this is not the case for the D-T system, which has much smaller magnets. Figure 17 illustrates the CoE for variation in the nominal stress value for both systems.

The nominal stress value used for the reactor optimization process, 40 ksi, was selected to be representative of limits based on fatigue crack growth for stainless steel structural material operating at 4 K.²² If the allowable stress could be increased (e.g., by a factor of 3), the CoE would be reduced to 1.5 times the cost for the D-T system.

Given the strong incentive for improving the cost of the D-D reactor system, it would seem that an improved structural design concept could be developed. Advanced composite materials, for example, which have less sensitivity to crack propagation because of their non-isometric properties, represent a class of material having strength in the desired range. An example of such a concept is discussed in Chapter IV.

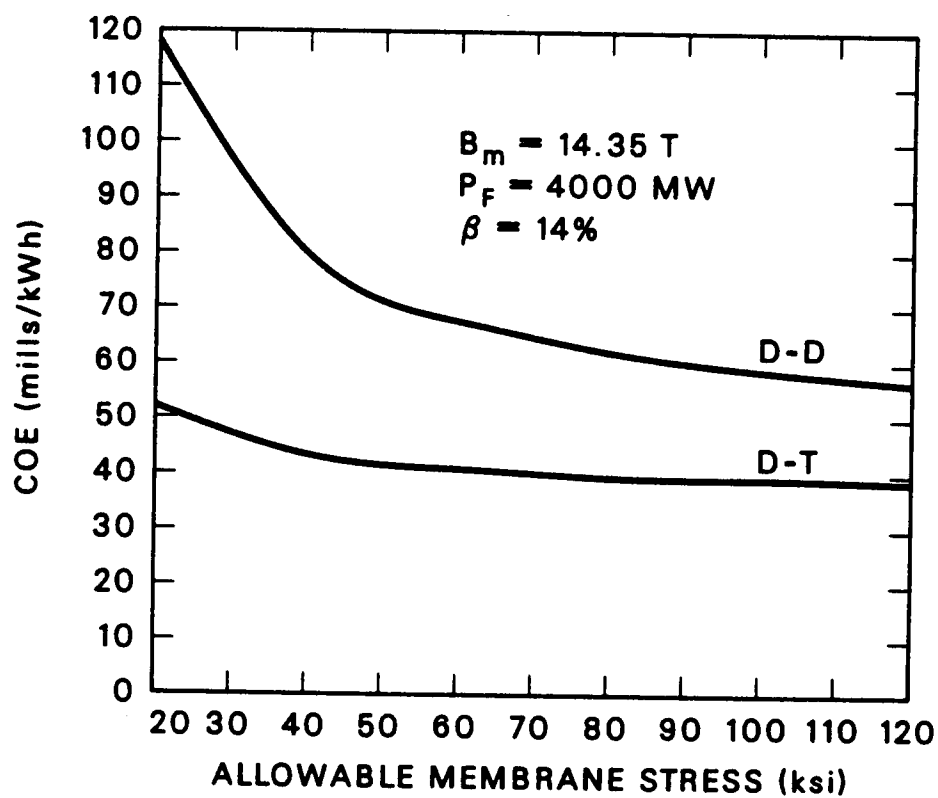


Fig. 17. Comparison of the cost of electricity versus allowable membrane stress in the TF magnet between the D-D and D-T reactors.

B. Implications of Tokamak Physics

The tokamak is the only fusion confinement concept with a sufficient experimental data base on which to extrapolate required performance parameters for a power reactor. Recent experimental results,²³ however, have not supported the primary physics scaling relationships that have been used as the basis for reactor studies such as Starfire. For the tokamak to compete with other near-term energy options, it is imperative that improved operating characteristics be developed.

1. Tokamak Physics Calculations

The optimum CAT-D reactor parameters derived in the previous section were based on the generic zero-dimensional power balance equations and engineering models of the reactor systems. The resulting performance parameters were optimized on the basis of minimum CoE with minimum consideration given to the limitations that present tokamak experiments may imply. Plasma beta, plasma density, and energy confinement time required for ignition and steady-state burn all show serious limitations and are of particular interest because of the size and cost impact on tokamak reactor design.

The maximum operating value of plasma pressure, normally expressed as a fraction of the toroidal magnetic field pressure, beta, appears to be limited in present tokamak experiments by the onset of instabilities in the plasma. The maximum or critical value of beta has been found experimentally to be constrained in the first stability regime by the Troyon limit²⁴

$$\beta_c = 3 \times 10^{-2} \frac{I}{aB_o} ,$$

where I is the plasma current in megamperes, a is the plasma minor radius, and B_o is the magnetic field on axis. The plasma current, a distinguishing characteristic of the tokamak, is not calculated in the generic plasma model.

The required current is related to another tokamak parameter, the safety factor, q . The safety factor is a measure of the influence of the poloidal magnetic field (created by the plasma current) on the toroidal field. Superposition of the two fields results in a field that is twisted into helices, as shown in Fig. 18. The safety factor, q , is defined as the number of times that the field line rotates around the major axis for one full revolution around the minor axis.²⁵ Plasma stability is also influenced by the magnitude of q , with a preferred value of >3 at the plasma edge in present experiments.

A major advantage of elongated plasmas in tokamaks is the influence that the elongated field lines have on the safety factor. For elongated plasmas, the safety factor is given approximately as²⁶

$$q^* = \left(\frac{5a^2 B_o}{IR_o} \right) \left[\frac{(1 + \kappa^{*2})}{2} \right] ,$$

where κ^* is an adjusted value of the plasma elongation to account for D-shaped cross sections. For elliptical cross sections, κ^* is simply equal to the elongation, b/a .

To evaluate the impact of beta limits on the D-D reactor design, the spreadsheet program was expanded to include a calculation for plasma current and critical beta. Figure 19 illustrates the relatively low value of critical beta for an aspect ratio $>2-3$. The optimum reactor design based on the minimum CoE is obviously different and more costly if the present physics scaling for critical beta is used.

The operating temperature and thus the pressure of tokamak plasmas have also been found to be limited by a maximum density. As shown in Fig. 20, the generic D-D reactor has a plasma density more than 3 times the Greenwald

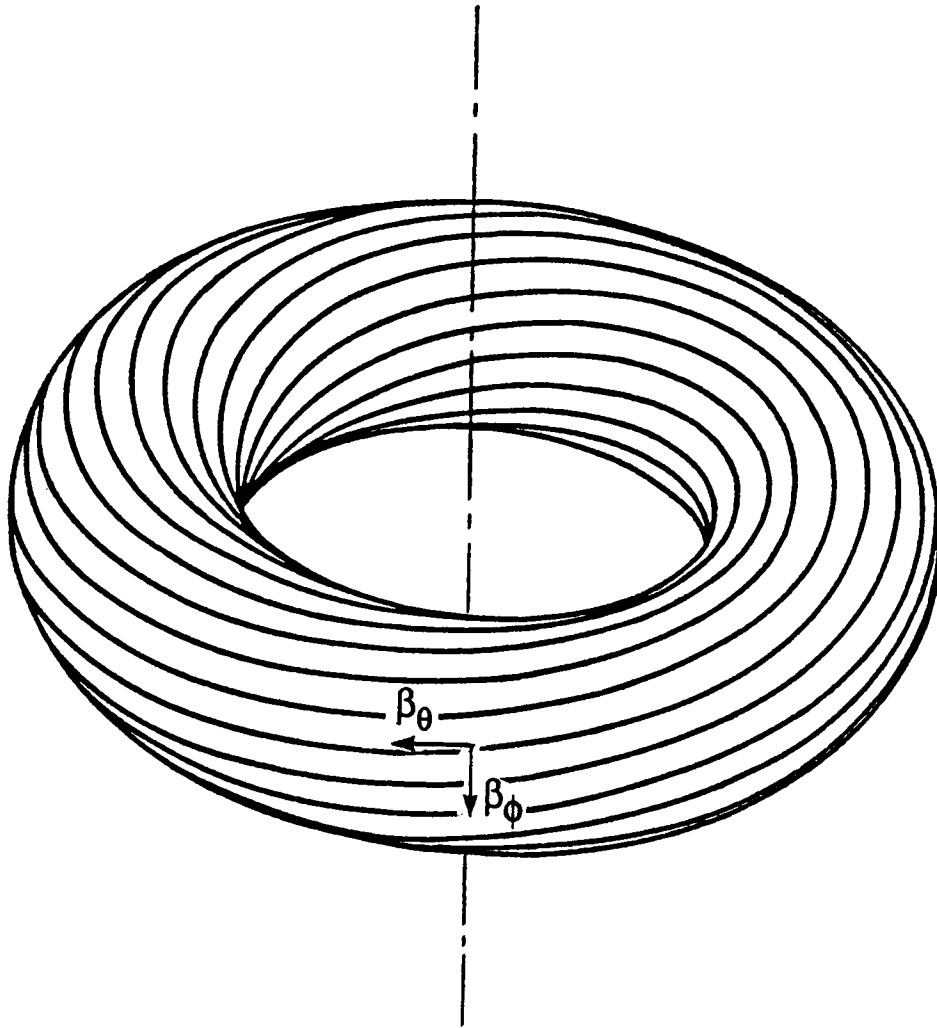


Fig. 18. Magnetic field lines in a tokamak plasma, illustrating the helix caused by the poloidal field from the plasma current.

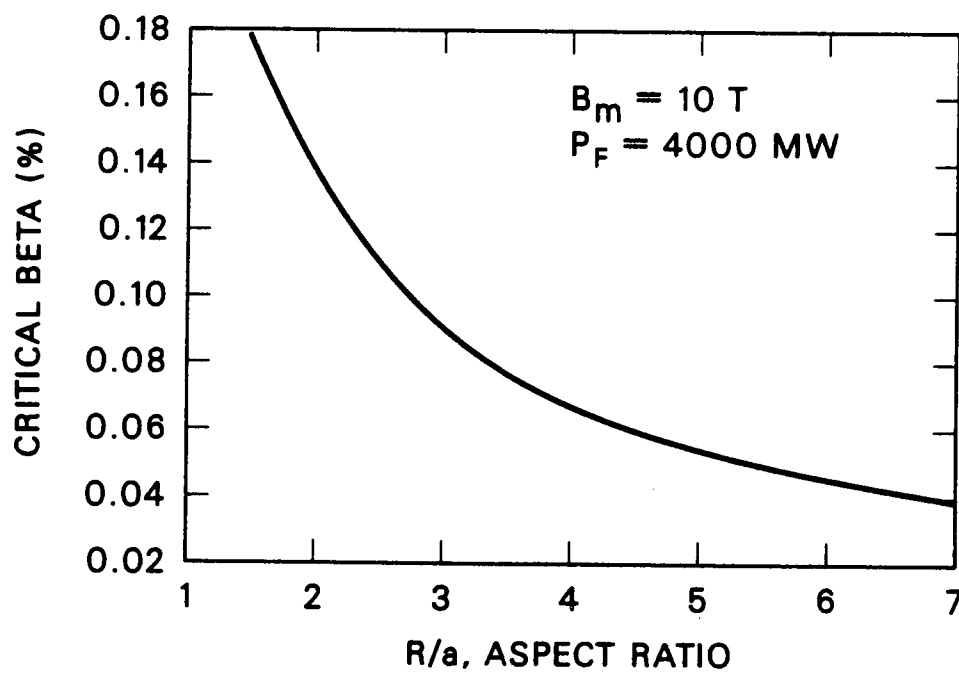


Fig. 19. Critical value of beta versus plasma aspect ratio as predicted by the Troyon limit.

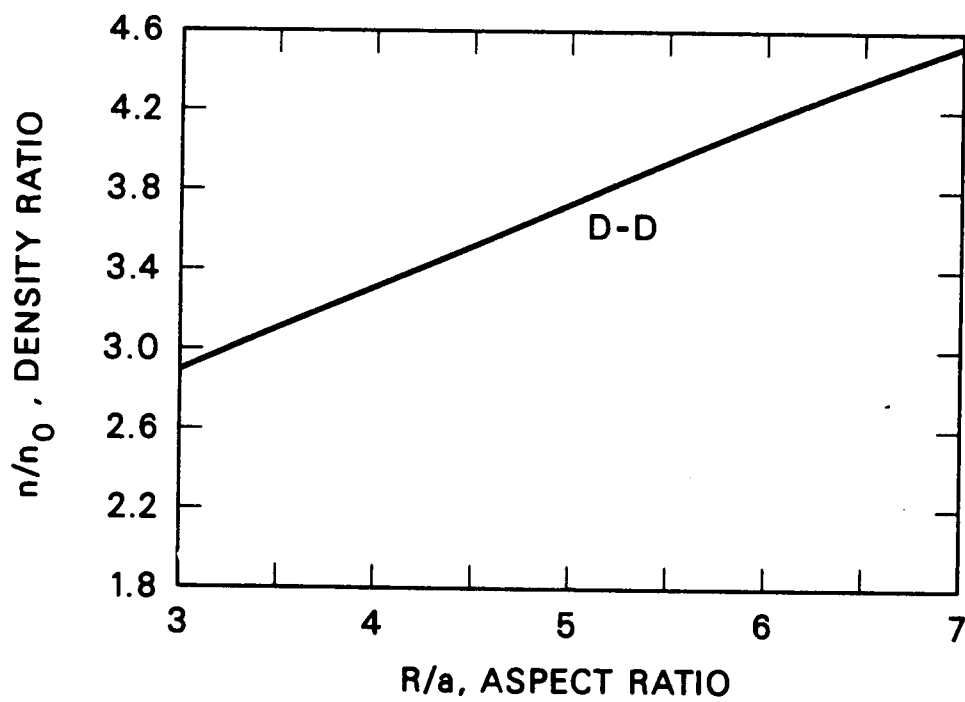


Fig. 20. Ratio of the plasma density to limiting value as predicted by the Greenwald limit.

limit.²⁷ A substantial reduction in magnetic field and assumed beta is required to operate below the presently observed density limit.

A more serious physics issue limiting present tokamak operation and future reactor designs is poor energy confinement time. The plasma energy must be contained long enough for the fusion fuel to react and for the released ions to transfer energy to sustain the reaction. This occurs at temperatures beyond that for the condition called ignition.²⁸ Present scaling relationships for the confinement time of the D-D reactor would likewise not support the optimum parameters based on the power balance model.

For an engineering-oriented study such as this, it was decided not to impose physics constraints that are not well understood at this time. Furthermore, a second stability regime has been identified for higher beta operation in tokamaks²⁹ so that present estimates of critical constraints may not apply to future reactor designs. Improved energy confinement must be obtained if the tokamak is to survive as an attractive reactor concept.

C. Evaluation of D-D Versus D-T Systems

1. Reactor Availability

In the comparison of the D-D and D-T reactors in Chapter II, several features assumed for the D-T concept result in a lower cost than is warranted. The generic model does not adequately account for all cost impacts. Neutron flux, for example, will cause damage to the first wall and blanket materials, requiring increased maintenance and replacement. The neutron wall loading versus maximum field and beta is shown for the D-T reactor in Figs. 21 and 22.

Reactor design studies³⁰ have produced concepts that could withstand wall loadings up to 18 MW/m². The ultimate lifetime of the material, however, will

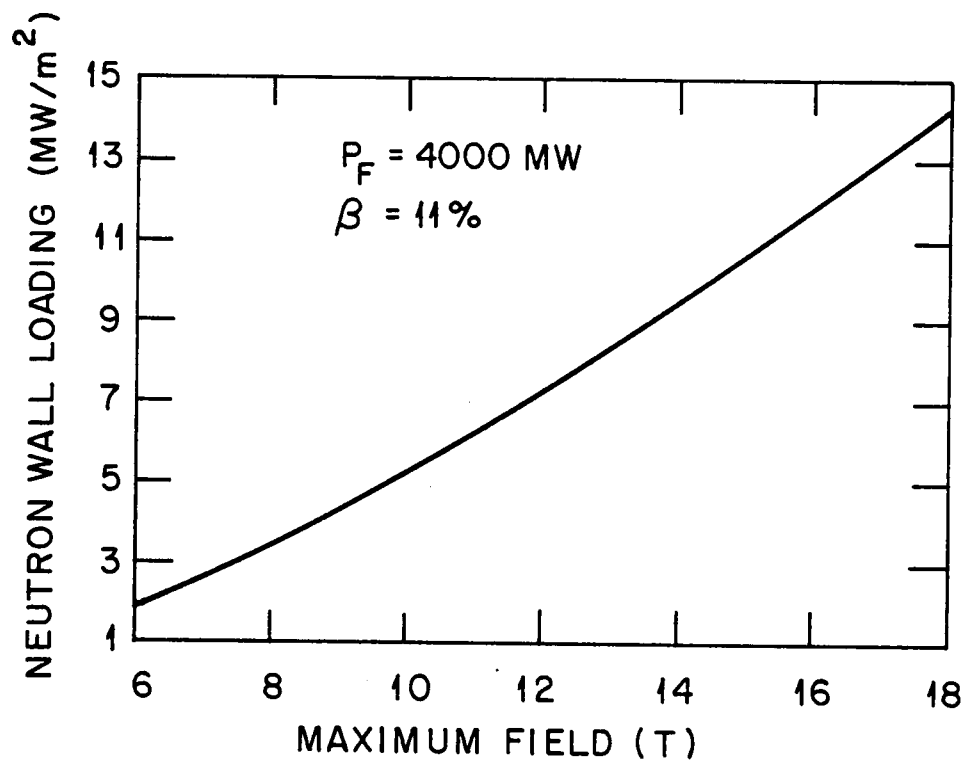


Fig. 21. Average neutron wall loading versus maximum field in the magnet for the reference D-T reactor.

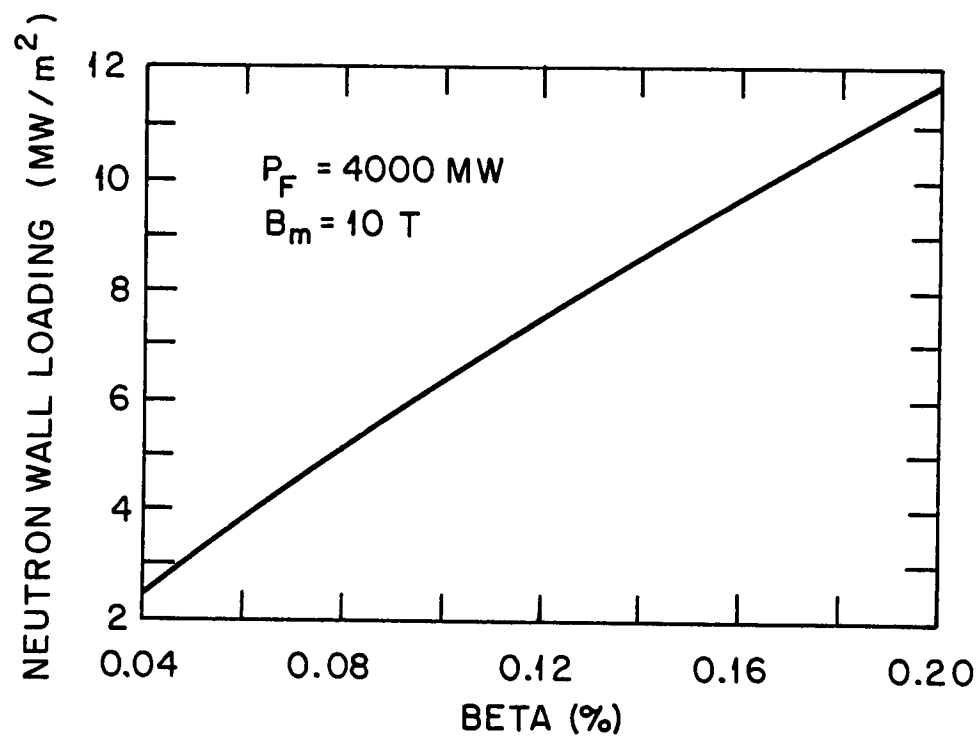


Fig. 22. Average neutron wall loading versus beta for the reference D-T reactor.

likely be limited to only about one year at that level of flux. The fusion materials development program has set a neutron fluence of 20 MW-year/m² as a long-range goal.³¹ A reduction in reactor availability is the obvious outcome of high neutron wall loading.

Using an assumed lifetime fluence of 20 MW-year/m², an algorithm was added to the generic code to allow a variation in availability with increased neutron flux. Assuming that a six-month downtime would be required to shut down the reactor, change out the first wall, and start back up, the assumed constant availability of 75% would be reduced.

$$\text{Availability} = \frac{TBF}{TBF + TTR} ,$$

where TBF is the time between failures and TTR is the repair time. The total availability then becomes

$$f_{AV} = \frac{\frac{20}{p_{wn}}}{\frac{20}{p_{wn}} + \frac{6}{12}} - 0.25 , \quad (30)$$

where f_{AV} is the total availability, p_{wn} is the neutron wall loading, $\frac{6}{12}$ is the six-month replacement time as a fraction of a year, and 0.25 is the reduction due to all other outages. The availability as a function of neutron wall loading, obtained by using Eq. (30), is shown in Fig. 23.

The impact of the reduced availability on the D-T reactor is shown in Figs. 24 and 25, where CoE is plotted as a function of beta for 10 and 14 T. The impact on the D-D system shown in Fig. 25 is almost negligible since the wall loading is $\lesssim 1$ MW/m². A more realistic comparison of the D-D and D-T systems is shown in Table 6, where the availability algorithm has been applied to the D-D system at 14.35 T [the reference case in Table 3 (see page 31)] and the D-T system has been reduced to 10 T and 8% beta to reduce the neutron wall loading to 5.7 MW/m².

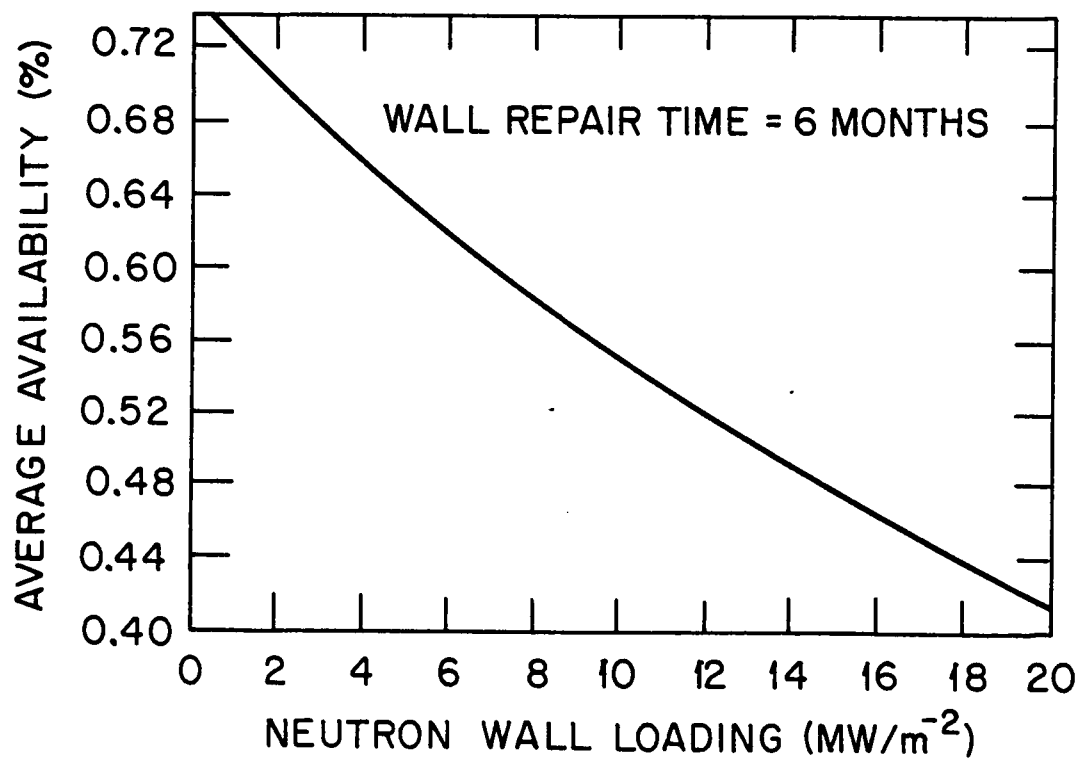


Fig. 23. Illustration of the influence of neutron wall loading on reactor plant availability.

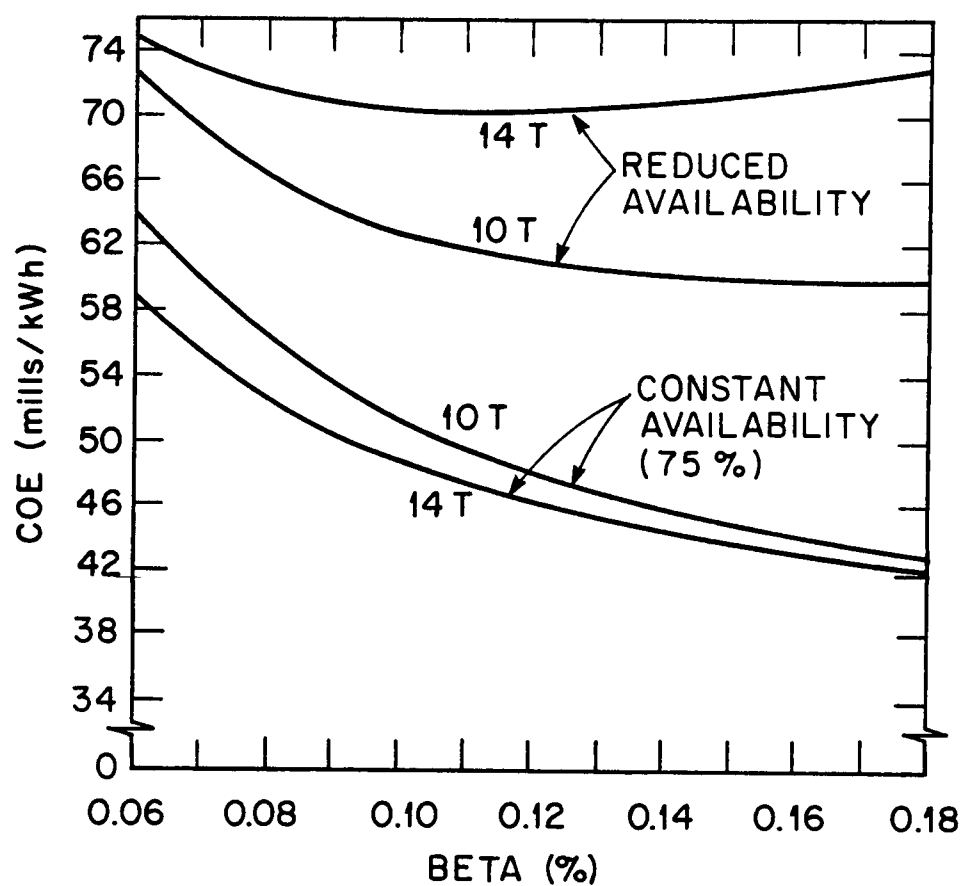


Fig. 24. Cost of electricity versus beta for the D-T reactor, illustrating the possible strong influence of neutron wall loading.

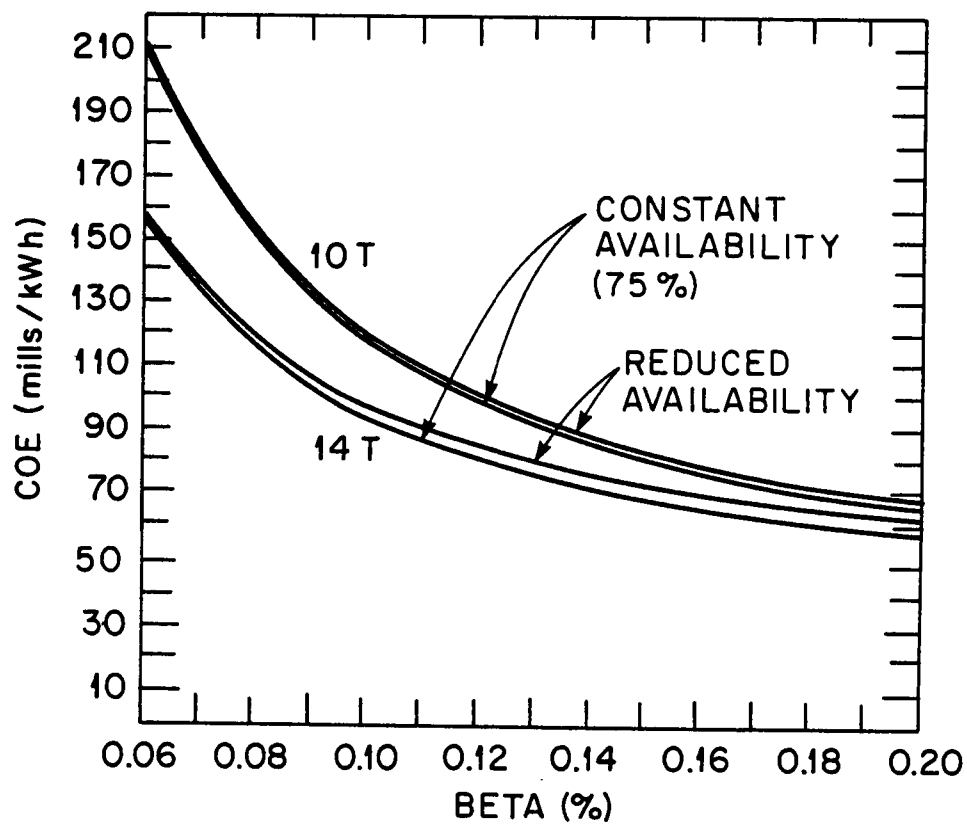


Fig. 25. Cost of electricity versus beta for the D-D reactor, showing the weak influence of neutron wall loading.

Table 6. Comparison of the Reference D-D Reactor to a D-T System with Reduced Wall Loading

	D-D	D-T
Total fusion power, P_f (MW)	3,500	4,000
Thermal/electric conversion efficiency, N_e	0.36	0.36
Maximum field at coil, B_m (T)	14.35	10
Total beta, $\langle\beta\rangle$	0.11	0.08
Aspect ratio, R/a	6	6
Plasma elongation, b/a	1.6	1.6
Field on axis, B_o (T)	10.46	6.15
Plasma major radius, R (m)	11.40	7.46
Plasma minor radius, a (m)	1.90	1.24
Plasma power density, P_f (MW/m ³)	2.69	10.98
Neutron wall loading, p_{wn} (MW/m ²)	0.97	5.68
Surface heat flux (MW/m ²)	1.64	1.42
Total thermal power, P_t (MW)	4,784	4,758
Net electric power, P_e (MWe)	1,155	1,150
Direct capital cost, CD (M\$)	4,483	2,210
Availability	0.73	0.63
Cost of Electricity, CoE (mills/kWh)	107	64

There is a wide range of uncertainty in availability predictions due to lack of operating experience with reactor-like fusion systems. Therefore, it is felt that the previous comparisons, neglecting the impact of the high wall loading, although conservative and more favorable to the D-T system, are a better benchmark by which to evaluate the potential of D-D fuel.

D. Influence of Coil Magnet Structural Design on Costs

1. Comparison of the D-D and D-T Magnets

The large plasma volume and magnet size are dominant features of the reference design. Figure 26 shows an elevation view of the D-T and D-D magnet and plasma cross sections for the two designs compared in Table 3 (see page 31).

Table 7 lists features for each magnet.

Table 7. Comparison of D-D and D-T Primary Magnets

	D-D	D-T
Radius to inside bore, m	8.31	2.44
Maximum field, T	14.35	14.35
Current per coil, MA	29.82	8.75
Winding current density, MA/m ²	28.40	28.40
Winding area, m ²	1.05	0.31
Structure area, m ²	1.96	0.32
Total area, m ²	3.01	0.63
Inside width, m	6.96	5.37
Inside height, m	11.14	8.59
Mass of conductor, kg	260,000	62,000
Mass of structure, kg	569,000	74,000
Total mass, kg	829,000	136,000

From the table it can be seen that the D-D magnet has six times the mass of the D-T magnet. The large plasma volume required for the D-D reactor increases the overall radius of the machine, requiring a current three times greater than the current for the D-T magnet. Increased current combined with the larger coil size results in increased tension on the magnet and significantly more required structural material.

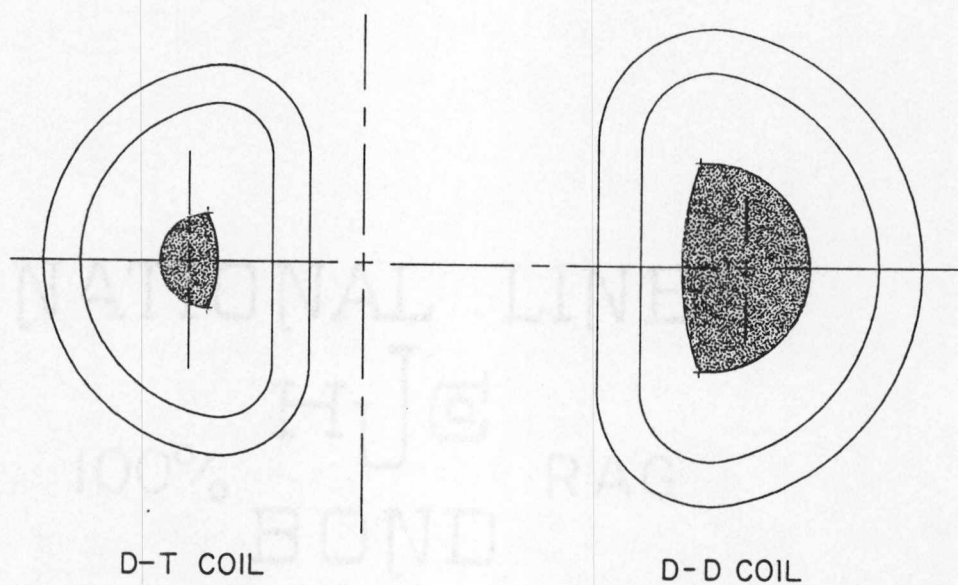


Fig. 26. Elevation view of the reference design D-D and D-T plasma and magnet systems.

In the bar chart of Fig. 27, the relative capital costs seven major plant systems are shown for both the D-D and D-T power plants. The size and mass of the D-D magnets result in a capital cost that dominates the total fusion plant cost. Since the structural material accounts for 65% of the total magnet mass and a large fraction of the cost, there is considerable incentive to seek ways in which the amount of structural material can be reduced.

2. Design Stress Level

Figure 28 shows the cost sensitivity of the allowable design stress in the magnet structure. The CoE for the D-T system is relatively insensitive to the stress, whereas the D-D system cost is strongly influenced by it. The allowable stress level in the baseline design is 40 ksi. If this could be increased to 100 ksi or greater, the CoE could be reduced by more than 25%. The significance of this finding is that it is an improvement that reduces the cost difference between the D-D and D-T systems.

The stainless steel structural materials used in present superconducting magnet designs have shown a strong sensitivity to crack propagation when tested at around 4 K.³² Figure 29 shows the number of cycles versus recommended design stress for an initial flaw size of 0.1 in., relatively small for the D-D magnet structure with a thickness ranging from 3 to over 20 inches. Note the steep reduction in cycles at 60 ksi. For this reason, the allowable stress level used in the generic model was limited to 40 ksi since the stress equation considers only the nominal membrane tensile stress in the magnet.

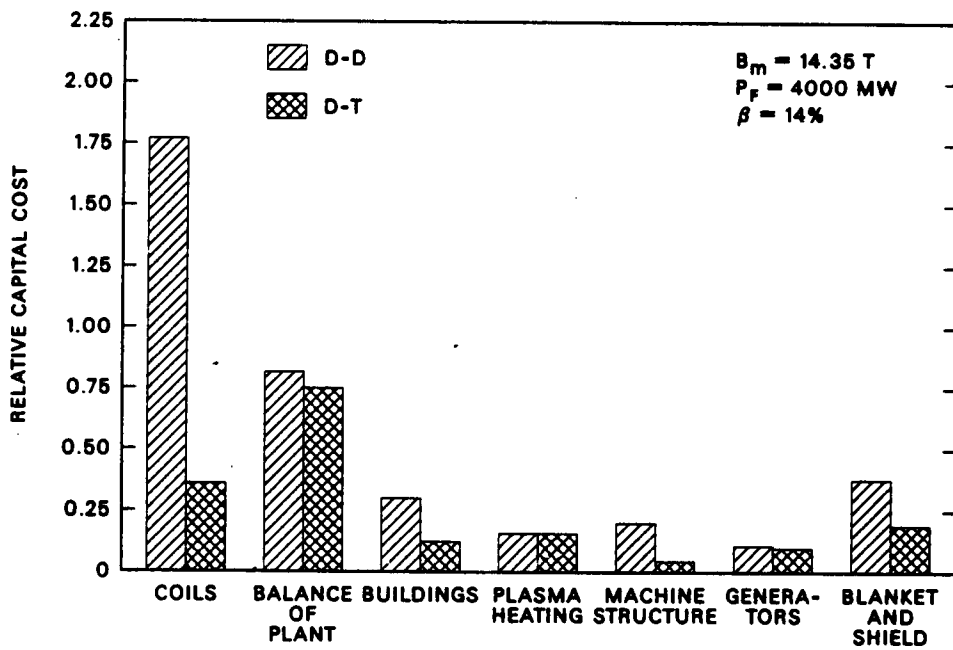


Fig. 27. Breakdown of relative capital costs for major systems of the D-D and D-T reactor plants.

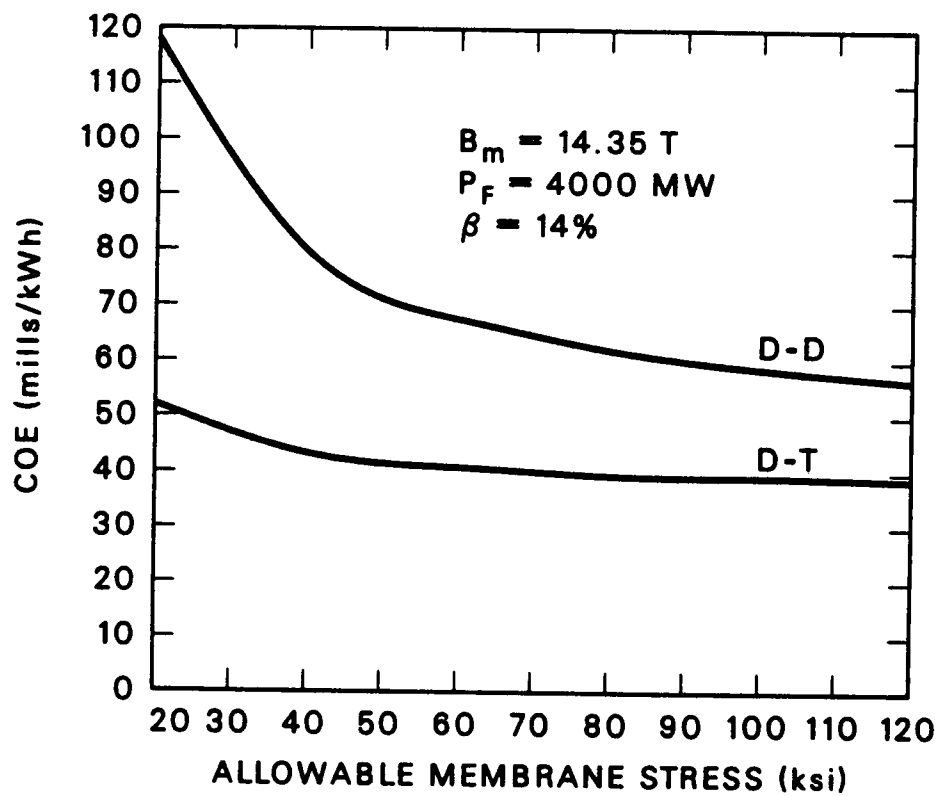


Fig. 28. Relative sensitivity of cost of electricity to allowable stress level in the TF magnet structure for D-D and D-T reactors.

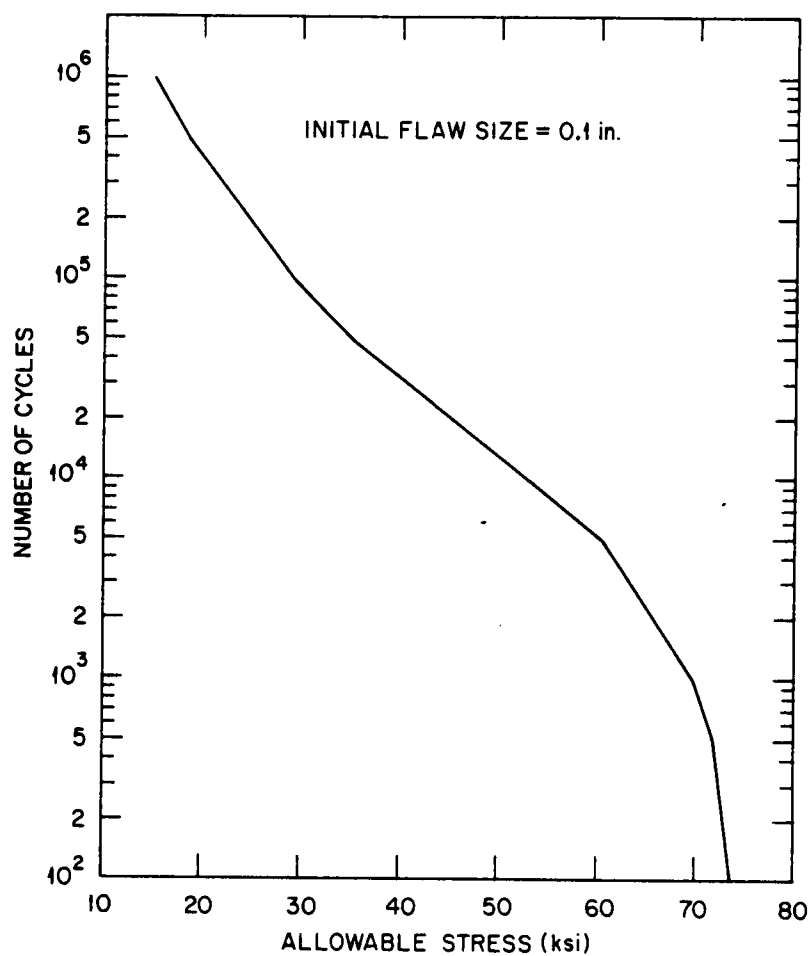


Fig. 29. Stainless steel design lifetime versus stress level at 4 K. [Ref. 32, Hooper, R. J., and Hunter, B. L., "Structural Design Procedures for FED Magnets," *Proceedings of the 9th IEEE Symposium on Engineering Problems of Fusion Research*, October 1981.]

E. Improved Physics Performance — High Beta

The single most important parameter to improve the performance and cost of fusion power is the plasma beta. Figure 30 shows the CoE as a function of total beta for the reference D-D reactor and the reduced wall loading D-T system. The cost ratio reduces to around 1.1 for beta values over 30%. Considering the impact of high wall loading at high beta for the D-T system, the limiting value of field is 8–10 T for the high-field case. The maximum field in the D-T reactor could also be reduced and the beta increased for reduced wall loading. The two systems have almost equal CoE for 8% D-T beta and 26% D-D beta. The bar chart in Fig. 31 shows the relative capital cost breakdown for these cases. Note that the higher cost of the D-D coils is offset by higher blanket and shield cost in the D-T system. The system parameters are given in Table 8.

Table 8. High-Beta D-D Equal CoE

	D-D	D-T
Total fusion power, P_f (MW)	3,500	4,000
Thermal/electric conversion efficiency, N_e	0.36	0.36
Maximum field at coil, B_m (T)	14.35	10
Total beta, $\langle\beta\rangle$	0.26	0.08
Aspect ratio, R/a	6	6
Plasma elongation, b/a	1.6	1.6
Field on axis, B_o (T)	9.82	6.15
Plasma major radius, R (m)	6.99	7.46
Plasma minor radius, a (m)	1.17	1.24
Plasma power density, P_f (MW/m ³)	11.66	10.98
Neutron wall loading, p_{wn} (MW/m ²)	2.58	5.68
Surface heat flux (MW/m ²)	4.36	1.42
Total thermal power, P_t (MW)	4,784	4,758
Net electric power, P_e (MWe)	1,155	1,150
Direct capital cost, CD (M\$)	2,390	2,210
Cost of Electricity, CoE (mills/kWh)	57	54

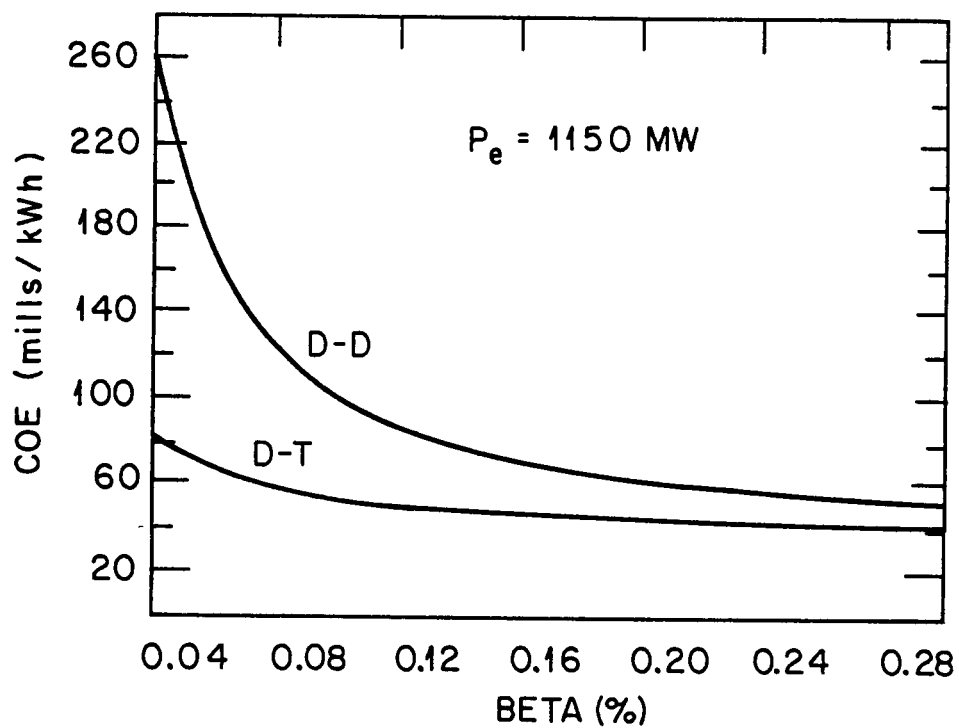


Fig. 30. Cost of electricity versus beta for D-D and D-T, showing the stronger influence of high beta on the D-D reactor.

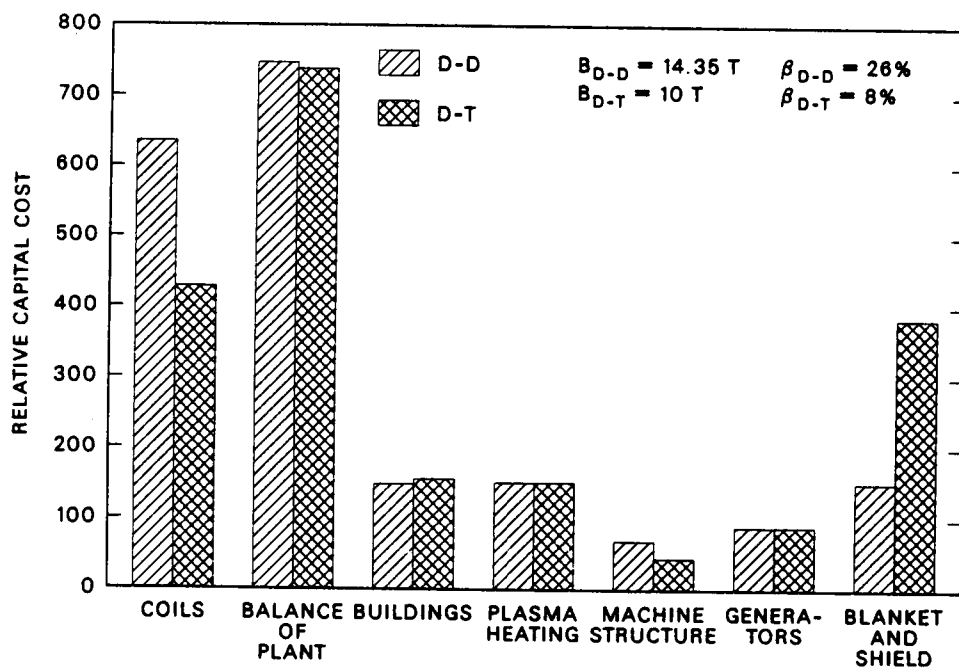


Fig. 31. Relative capital cost breakdown for equal cost of electricity for a high-beta D-D reactor and a low-beta D-T reactor limited by neutron wall loading.

Just as high neutron wall loading is a concern for high power density D-T reactors, the high surface heat flux is a concern for the high beta D-D reactor. The average surface heat flux of 4.4 MW/m^2 is approximately 75% radiation and 25% charged particles at the first wall. The first wall and other particle collectors such as divertors will experience fatigue and erosion damage that must be considered in the design of the reactor.

Fusion confinement concepts with potential for high-beta operation such as the stellarator, RFP, and ST appear to be the most attractive options for the D-D fuel cycle. If second stability operation²⁹ can be accomplished in conventional tokamaks, this would also improve the prospect for D-D as a viable competitor for D-T.

CHAPTER IV

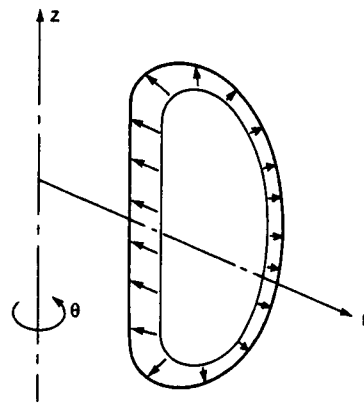
STRUCTURAL DESIGN OF A HIGH-PERFORMANCE, LOW-COST MAGNET SYSTEM

The fusion reactor magnet systems are subjected to a combination of structural loadings induced by electromagnetic effects, thermal gradients, hydraulic pressure, and gravity. Gravity-induced loads are usually of secondary importance when compared with the other three and can be easily reacted in a support structure. Earthquake loading, however, will be an important consideration for reactor design. Hydraulic pressure loads are dependent on the type of conductor and cooling system used. Only the electromagnetic loads and thermal gradients have been included here since it is beyond the scope of this study to produce a complete reactor design. Design concepts have been developed to compare with present designs on the basis of the electromagnetic and thermally induced loads.

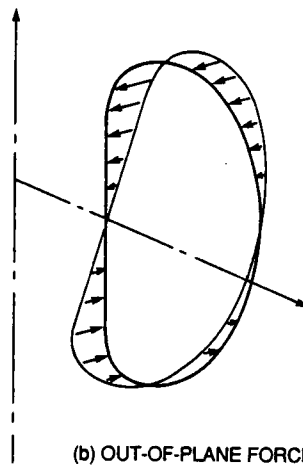
The TF coils are the most massive and structurally complex of the magnet systems. Detailed design and analysis have been carried out for only these magnets; however, the concept designs will apply equally to the poloidal magnets. The system models assumed similar designs for both systems.

A. Structural Design Requirements and Considerations

The electromagnetic forces acting on a TF magnet are shown in Fig. 32. The forces are in the plane of the magnet (f_{rz}) and normal to it ($f_{r\theta}$). The in-plane forces result from the crossing of the coil current, I_c , and the toroidal magnetic field, B_θ . The out-of-plane forces are caused by the crossing of I_c and the poloidal field, B_{rz} . In a tokamak, the poloidal field is caused by the plasma current.



(a) IN-PLANE FORCES- f_{rz}



(b) OUT-OF-PLANE FORCES- $f_{r\theta}$

Fig. 32. Electromagnetic forces on a TF coil.

$$f_{rz} = \frac{1}{2}(I_c \times B_\theta)$$

$$f_{r\theta} = \frac{1}{2}(I_c \times B_{rz})$$

The in-plane forces vary from a maximum at the inner radius of the reactor to a minimum at the outermost radius. This variation results in a net inward force called the centering force, which requires a structural support system. This support can be provided by the magnets themselves, by wedging the inner portion of the coils to form a continuous cylinder. A separate structure called a bucking cylinder may also be used in which the magnets "buck" against the cylinder to resist the centering force. A combined system of both bucking and wedging has been shown to be the most efficient for very compact tokamak designs.³³ The remainder of the balanced in-plane forces tend to stretch and bend the magnet, producing internal forces and moments.

The out-of-plane forces, such as in a tokamak, produce a torque about the machine central axis due to a reversal of the $(I_c \times B)$ force from the top to the bottom of the TF coil. Additional structural support must be provided to resist the overturning motion of the magnets. This is normally provided by friction or shear members on the inner radius and by coil-to-coil structure at the top, bottom, and outside radius of the coil.

The in-plane forces are the predominant drivers in setting the magnet structural configuration. The analysis and design concept has therefore been derived on the basis of these forces. Once a new concept has been developed and a specific reactor design established, the various support structures can be designed.

B. Structural Analysis of the TF Magnet System

1. Magnetic Field Equation

Development of the field and force equations for the TF magnet begins with the application of Ampère's Law to a linked system of toroidal magnetic field and poloidal current, as shown in Fig. 33.

$$\oint_c H \cdot dl = \oint_s J \cdot ds , \quad (31)$$

where H is the magnetic intensity and J is the electric current density. Solution of the line integral at a radius, r , is simply

$$\oint_c H \cdot dl = H(2\pi r) , \quad (32)$$

where H is the magnetic intensity at r .

The solution to the surface integral is the total current in the TF coils.

$$\oint_s J \cdot ds = NI_c , \quad (33)$$

where N is the number of TF coils and I_c is the current per coil. Substituting B , the magnetic induction for H ,

$$B = \mu_o H , \quad (34)$$

the equation relating field and current is thus

$$NI_c = \frac{B}{\mu_o}(2\pi r) . \quad (35)$$

Note that B , more commonly called the magnetic field, varies inversely to the radius, with a maximum value at the inside radius, r_1 . Equation (35) can therefore be written in terms of the maximum field as

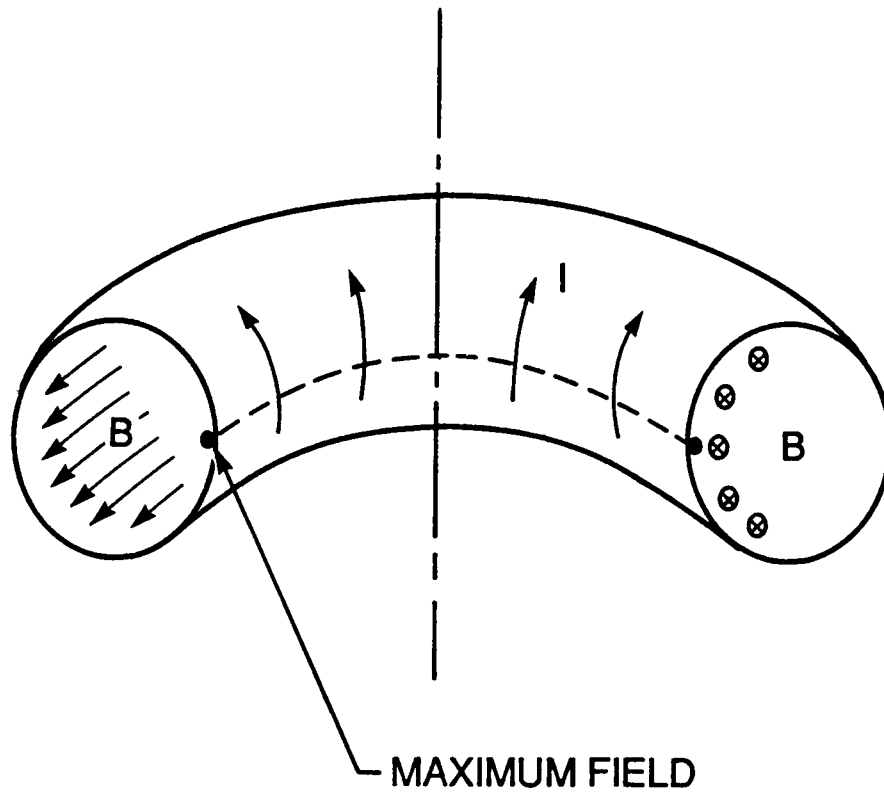


Fig. 33. A toroidal magnetic field linked by a poloidal current sheet.

$$NI_c = \frac{B_m}{\mu_o}(2\pi r_1) \quad . \quad (36)$$

2. Membrane Stress Equation

The ideal shape for most structural members is one in which the bending is minimized. A TF magnet configuration in the shape of a "D" has been shown by File, Mills, and Sheffield³⁴ to be a pure tension shape for a thin membrane under the in-plane loading caused by the toroidal magnetic field in Eq. (35).

A small segment of TF magnet under constant tension, T , shown in Fig. 34, carries a current I_c and is perpendicular to the magnetic field, B . The outward force caused by the magnetic field is

$$F = \frac{1}{2}(I_c \times B)\rho d\theta \quad . \quad (37)$$

The factor of $1/2$ arises from the fact that the field decreases to zero through the coil thickness, giving an average value of $B/2$.

Force balance of the segment yields

$$2T\left(\frac{d\theta}{2}\right) = \frac{1}{2}I_c B \rho d\theta \quad (38)$$

or

$$T = \frac{1}{2}I_c \rho B \quad . \quad (39)$$

Since B has been shown to vary inversely with the radius, r , the coil tension can be expressed in terms of the maximum field as

$$T = \frac{I_c \rho B_m r_1}{2r} \quad (40)$$

or

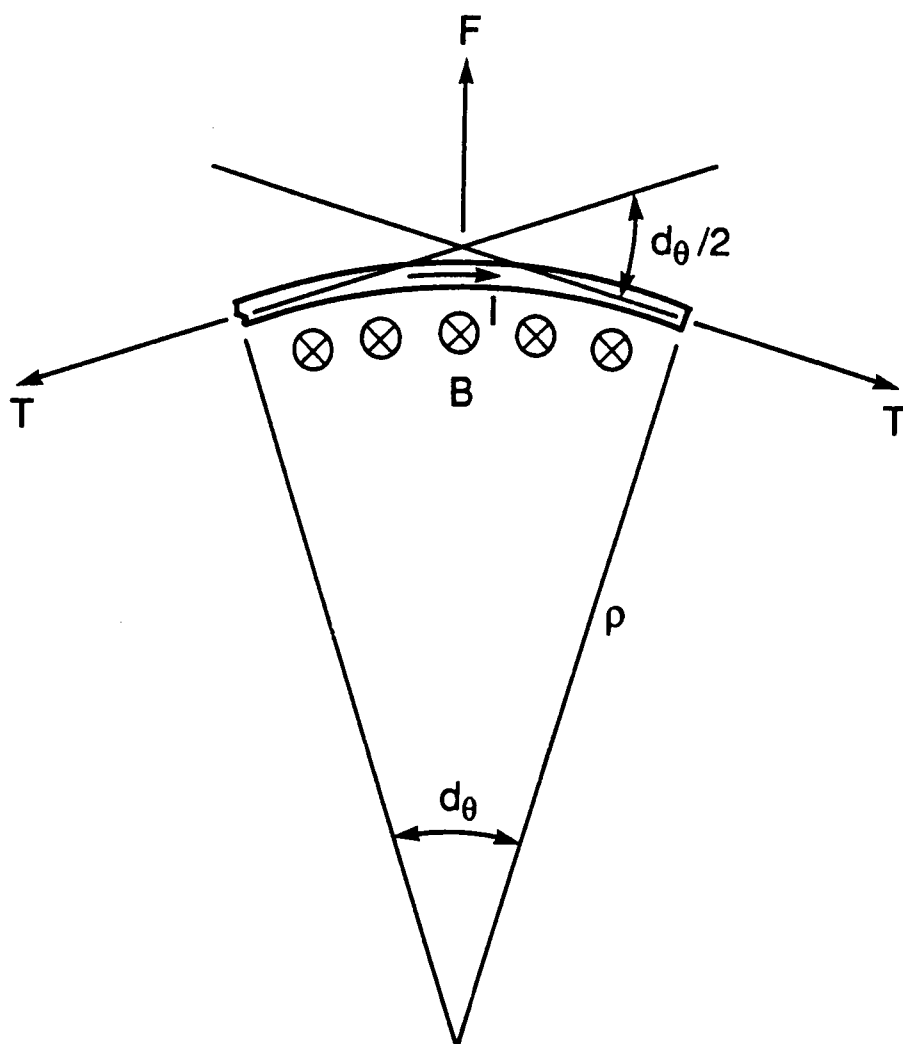


Fig. 34. Differential element of a TF coil in constant tension.

$$\rho = \frac{2rT}{I_c B_m r_1} \quad (41)$$

Note that the radius of curvature, ρ , varies directly with the radius since all other terms in Eq. (41) are constants. Equation (41) can be rewritten as

$$\rho = Cr \quad (42)$$

where C is a constant:

$$C = \frac{2T}{I_c B_m r_1} \quad (43)$$

Substituting the value of B_m from Eq. (36),

$$C = \frac{4\pi T}{\mu_o N I_c^2} \quad (44)$$

From basic calculus, the radius of curvature of a line segment is given by

$$\rho \frac{d^2 z}{dr^2} = \left[1 + \left(\frac{dz}{dr} \right)^2 \right]^{3/2} \quad (45)$$

Substituting from Eq. (42),

$$r \frac{d^2 z}{dr^2} = \frac{1}{C} \left[1 + \left(\frac{dz}{dr} \right)^2 \right]^{3/2} \quad (46)$$

A solution to the differential equation [Eq. (46)] has been shown by File et al.³⁴ for the D-shaped magnet shown in Fig. 35. Note that the boundary condition at the inside radius, r_1 , requires a rigid support such as the bucking cylinder, which was described previously.

The value of the constant for this particular shape is

$$C = \frac{1}{2} \ln \left(\frac{r_2}{r_1} \right) \quad (47)$$

Combining this with the previous definition of C , Eq. (43), and substituting the value of I_c from Eq. (36) yields

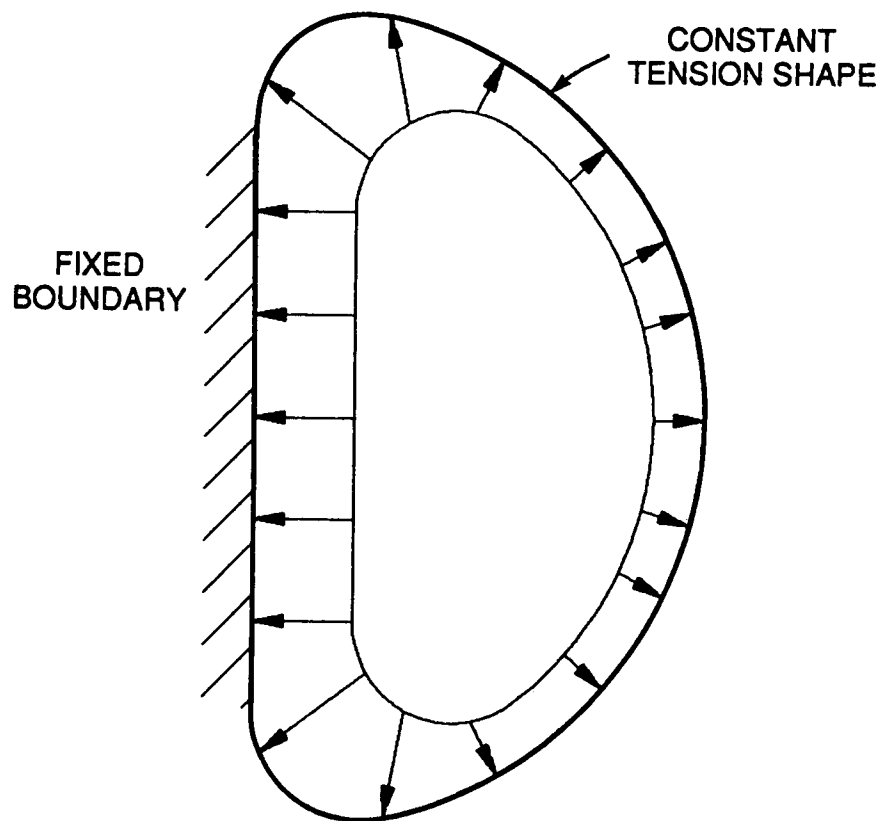


Fig. 35. Load diagram and assumed constraints for a constant-tension D-shaped TF magnet.

$$T = \frac{B_m^2 r_1^2 \pi}{2\mu_o N} \ln\left(\frac{r_2}{r_1}\right) . \quad (48)$$

For a given number of coils, N , the tensile force is completely determined by the size of the magnet, r_1 and r_2 , and the maximum magnetic field, B_m . This is a most convenient form for the equation since the maximum field is limited by the magnet technology, and the size is the most important factor in estimating the magnet cost.

For the detailed design of a TF magnet, it is obvious that a more exact expression for the internal forces is desired. Three-dimensional finite-element calculations are routinely used even at the conceptual design level. The constant tension membrane assumption, however, is an excellent starting point to evaluate a design based on the generic reactor parameters.

3. D-D Reactor TF Magnet Structure

Solving the membrane force equation [Eq. (48)] for the reference D-D reactor design results in a tensile force of 540.9 million newtons (121.6 million lb) for each of the 20 TF magnets. For the 300 series stainless steel material, considered as the primary candidate for next-generation fusion devices, the required cross-sectional area of structural material is 1.96 m². The required coil cross section is shown in Fig. 36. Additional design parameters for the coil are given in Table 9.

Table 9. D-D Reactor TF Coil Design Parameters

Maximum field, B_m (T)	14.35
Number of coils	20
Current per coil, I_c (MA)	29.8
Winding current density, J_p (MA/m ²)	28.4
Conductor area (m ²)	1.05
Bore width (m)	6.96
Coil tension, T (lb)	1.216E+8
Structural area (m ²)	1.96
Total coil area (m ²)	3.01

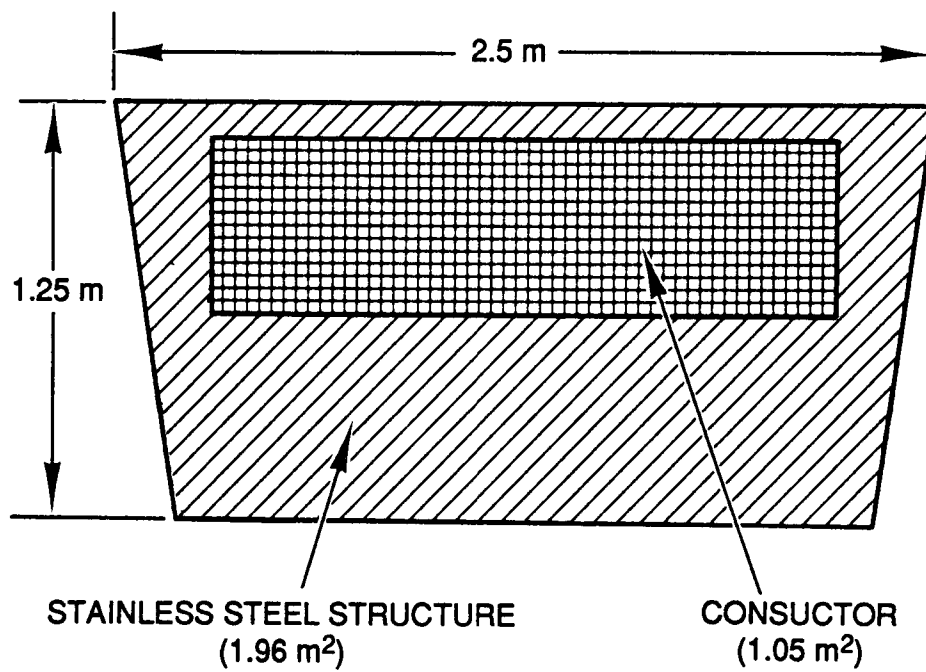


Fig. 36. Cross section of the required stainless steel structure for the TF magnet.

The conductor material is a forced-flow cooled high-field superconductor³⁵ with a current density of 28 MA/m². The massive structural cross section accounts for two-thirds of the total magnet weight and hence a large fraction of its cost. In the Starfire tokamak reactor design study, the magnet structure unit cost was estimated as one-fourth to one-half of the conductor cost.

The weight of each magnet is estimated to be 829,000 kg (1.83 million lb). Moving a structure of this weight presents a sizeable problem for the design of the reactor buildings, cranes, and repair facilities.

The key to reducing the cost of the magnet system is to reduce the required size, weight, and unit cost of the structural material. The magnet conductor, consisting of a superconducting filament material and a copper matrix, is assumed to be a forced-flow-cooled cable in conduit.³⁶

C. High-Performance Materials

Advanced composite materials appear to offer the most desirable features for the possibility of a lighter-weight, reduced-cost magnet system. High-strength fibers such as glass and carbon, when used in a matrix of epoxy, are wound in a fashion similar to the magnet conductor materials. Carbon fiber, which combines high strength and stiffness at moderate cost, was selected as the material for the improved D-D reactor magnet design. The most important characteristic of carbon fibers is the ability to resist fatigue. The fatigue stress limit approaches the static fracture stress for most carbon composites.³⁷ A carbon epoxy support structure is being developed for advanced superconducting magnets at the Fermi Laboratory,³⁸ and some limited strength data are available at 4 K.

The combination of conductor, carbon fiber, epoxy, and coil case forms a complex composite structure. The distribution of load among the various materials can be determined to a good approximation by assuming equal strain

in each component. Consider a magnet under a uniform membrane loading as previously described. The total tensile force on the section is related to the strain in each material, the modulus of elasticity, and the cross-sectional area:

$$T = \epsilon_1 E_1 A_1 + \epsilon_2 E_2 A_2 + \epsilon_3 E_3 A_3 + \dots + \epsilon_n E_n A_n , \quad (19)$$

where $\epsilon_1 \dots \epsilon_n$ are the strains, $E_1 \dots E_n$ are the values of the modulus of elasticity, and $A_1 \dots A_n$ are the cross-sectional areas for each of the material elements in the hybrid coil system. For a relatively thin coil, compatibility of deformation in the continuous structure requires that each individual material element in the cross section have the same amount of strain:

$$\epsilon = \epsilon_1 = \epsilon_2 = \dots = \epsilon_n ;$$

therefore,

$$T = \epsilon(E_1 A_1 + E_2 A_2 + \dots + E_n A_n) .$$

It is clear from this equation that each material element carries a fraction of the total force in proportion to the modulus and the area. Since the strain in all elements is equal,

$$\epsilon = \frac{T_i}{A_i E_i} ,$$

the tensile force in any one element is

$$T_i = \frac{T E_i A_i}{(E_1 A_1 + E_2 A_2 + \dots + E_n A_n)} .$$

The total tensile force can be distributed among the elements in any desired proportion by increasing or decreasing the areas. Since the strain in all elements is equal, the stress in a given element depends only on the modulus. Therefore,

reinforcing material of high strength should have a higher modulus than the lower-strength materials in the composite.

D. Development of a Fiber-Reinforced Magnet

1. Materials Selection

Starting with the required superconducting material for the D-D magnet system, the first step in the design process is to select the reinforcing material. It is assumed that a case structure is necessary to resist bearing stress between adjacent coils and to provide bending strength for the out-of-plane loading. To reduce stress in the metal components, the fiber reinforcement ideally must have a modulus of elasticity greater than that of the metal. It is also assumed that a matrix material is required to provide a bond for the fiber composite to distribute the loading around any failed fibers.

The choice of available fiber materials is therefore limited to those with a modulus of elasticity somewhat greater than the metals that may be used for the conductor and case structures. Aluminum has the lowest value with a modulus of 71 GPa. Table 10 lists properties of other commonly available composites. Glass fiber has approximately the same modulus as aluminum and is widely used for its high strength, light weight, and low cost, but it is not an ideal candidate to use for reinforcement of the magnet where the goal is to increase the overall stress level in the cross section. There is a trade-off, however, between the cost of aluminum and the glass fiber composite as the primary structural material. An additional problem with aluminum as a component for the superconducting magnet is related to manufacture of the conductor.³⁹ The relatively low melting point of aluminum would not permit the use of Nb_3Sn for the superconductor. The high-field conductor typically uses forced-flow cooling in a metal conduit, as

shown in Fig. 37. Niobium titanium (NbTi) is a possible candidate for use with an aluminum conduit, but the field would be limited to a maximum of ~ 10 T, not a good choice for the D-D reactor where high field is desirable.

Table 10. Engineering Properties of High-Strength Fibers and Metals

Material	Modulus (GPa)	Strength (MPa)	Density (kg/m ³)	Thermal Exp. Coefficient (C ⁻¹)
<u>Fibers</u>				
S glass	84	4600	2490	7.20E-06
Carbon HM	400	1900	2000	-1.00E-06
Aramid (K 49)	124	3620	1480	-2.00E-06
Steel	200	3000	7900	
<u>Metals</u>				
Aluminum	71	80	2710	2.20E-05
Stainless steel	200	600	7930	1.60E-05

The choice of high-modulus fibers includes carbon, aramid, boron, and alumina. Cost considerations, however, limit the fibers for this application to carbon and aramid, both widely used in commercial and aerospace applications.

Accurate cost estimating is always difficult for new design concepts. Since cost is the primary measure of attractiveness of a high-strength magnet design, the proposed concept uses present technology for the high-field forced-flow superconductor using a high-modulus metal for the conduit. The fiber reinforcement is carbon. Several difficult design problems that were found using this approach may be avoided if different design concepts and materials could be developed.

Assuming that the composite will carry all of the tensile membrane load, the minimum required cross-sectional area is 0.373 m^2 . The fiber and composite design assumptions are given in Table 11.

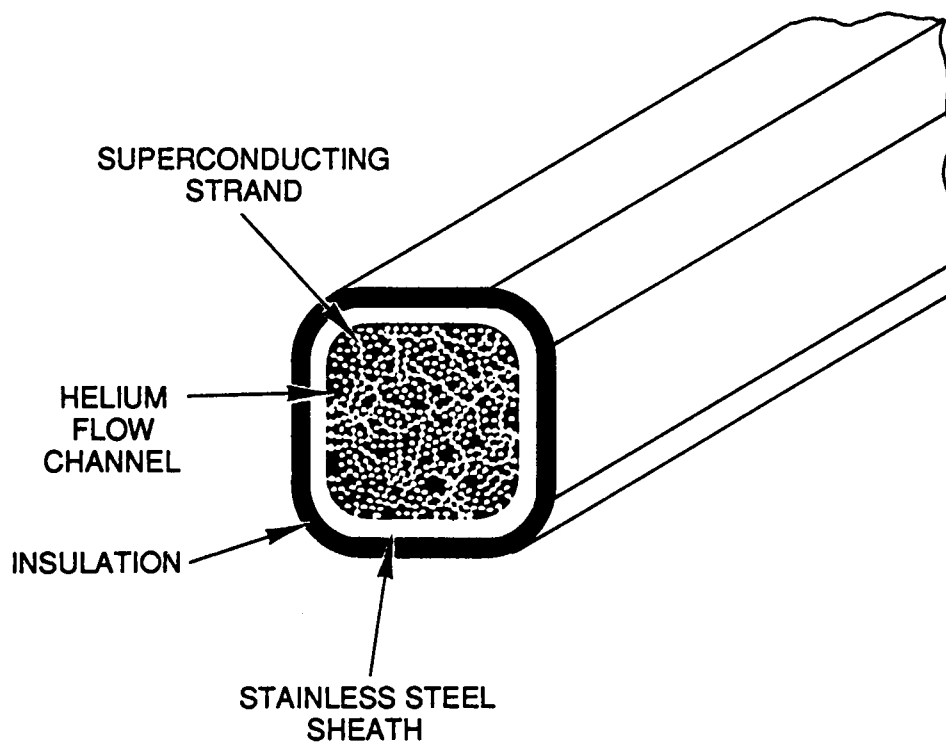


Fig. 37. Cable-in-conduit, force-flow-cooled conductor for a high-field superconducting magnet.

Table 11. Carbon/Epoxy Composite Properties Assumed for Design

Ultimate tensile strength (UTS), fiber	2760 MPa
Volume percent fiber	75%
Composite design stress (70% UTS)	1450 MPa
Composite modulus of elasticity	200 GPa

The cross section of the conductor and composite reinforcement is shown in Fig. 38. An isometric drawing of the magnet is shown in Fig. 39.

2. Thermal Compatibility

A primary disadvantage of the carbon fiber for superconducting magnet design is its low coefficient of thermal expansion and contraction relative to the other materials. This is an attractive feature of the material for some applications such as the proposed NASA space station, where structural members are required to have little or no movement with changes in temperature.

A good measure of the magnitude of thermal stress caused by the constraint of a material against expansion or contraction is to assume that the material is completely restrained in one direction. The resulting thermal stress is

$$S = E\alpha\Delta T \ ,$$

where E is the modulus of elasticity, α is the coefficient of thermal expansion or contraction, and ΔT is the temperature change.

Assuming that the conduit of the superconductor is stainless steel and that it is completely constrained against movement in its axial direction by the carbon, the associated thermal stress is equal to

$$S = 207E^9 \times 16E^{-6} \times 300 = 994 \text{ MPa} \ .$$

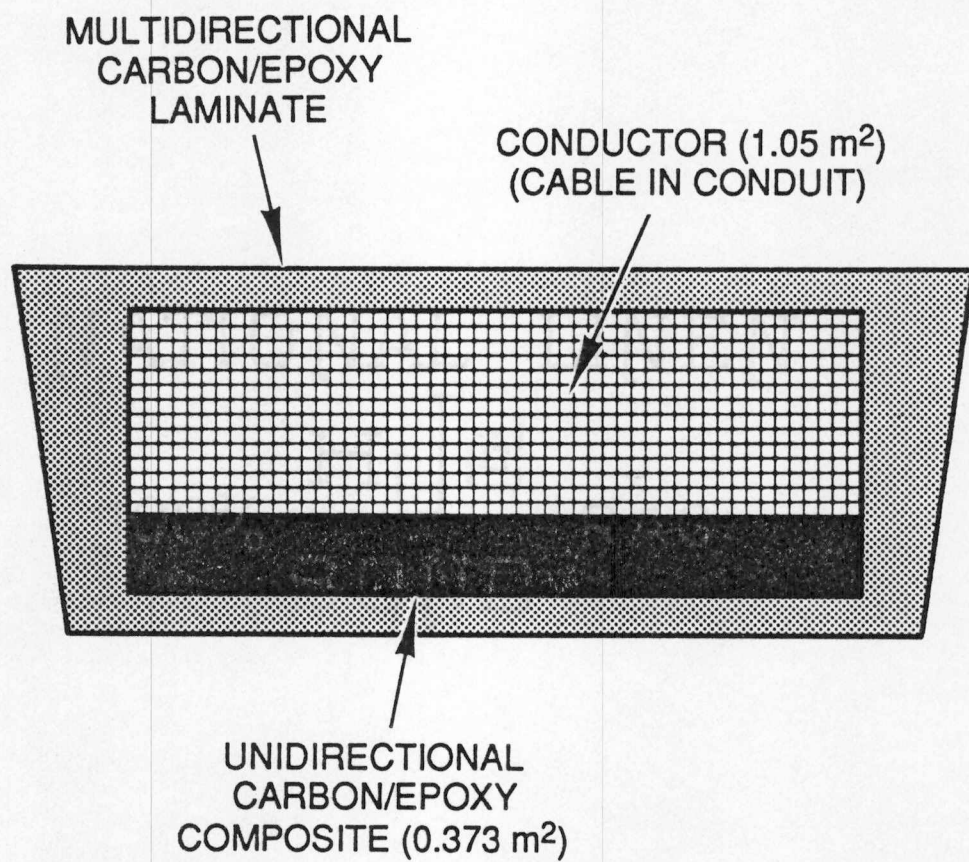


Fig. 38. Cross section of a composite-reinforced TF magnet.

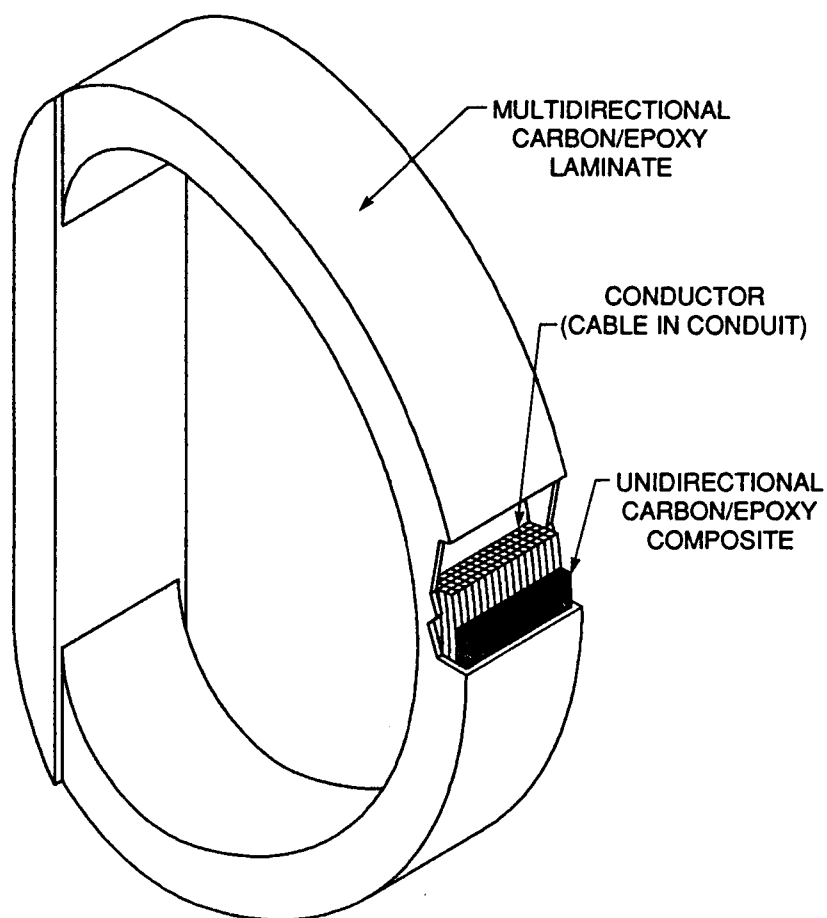


Fig. 39. Isometric drawing of the fiber-reinforced TF magnet.

Since this is well above the yield strength for most common stainless steel materials, the material will experience plastic strain cycling. The strain for the above condition is approximately 0.5%, a fairly low value for stainless steel for limited cycles.

3. Coil Design for Thermal Compatibility

The low coefficient of thermal contraction of the graphite/epoxy composite presents a large mismatch between the composite and most metal structures by cooling down from room temperature to 4 K. A conservative approximation to the magnitude of the thermal stress can be derived if there is no bending of the coil cross section and if the bond between the metal and the composite is strong enough to force equal displacement of each.

A small segment of the coil with the assumed boundary conditions is shown in Fig. 40.

Equilibrium requires that the force in each material be equal, $P_c = P_W$, where c is the composite and W is the coil winding. The total deflection of each section must also be equal:

$$\left(\frac{P\Delta l}{AE}\right)_c + \left(\frac{P\Delta l}{AE}\right)_W = (\alpha\Delta l\Delta T)_W - (\alpha\Delta l\Delta T)_c .$$

The force is therefore

$$P = \frac{(\alpha\Delta T)_W - (\alpha\Delta T)_c}{\left(\frac{1}{AE}\right)_W + \left(\frac{1}{AE}\right)_c} .$$

The membrane stress in the conductor and the composite is shown in Fig. 41 as a function of the conductor modulus of elasticity. It is assumed that the conductor itself has a very low value relative to the conduit. To avoid high

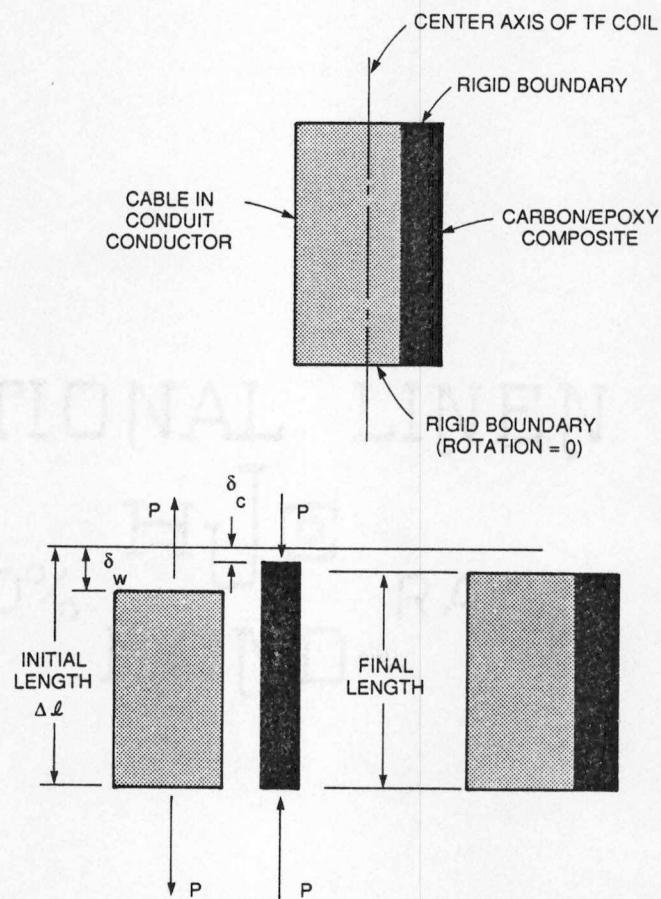


Fig. 40. Force diagram for thermal strain compatibility between conduit and structure.

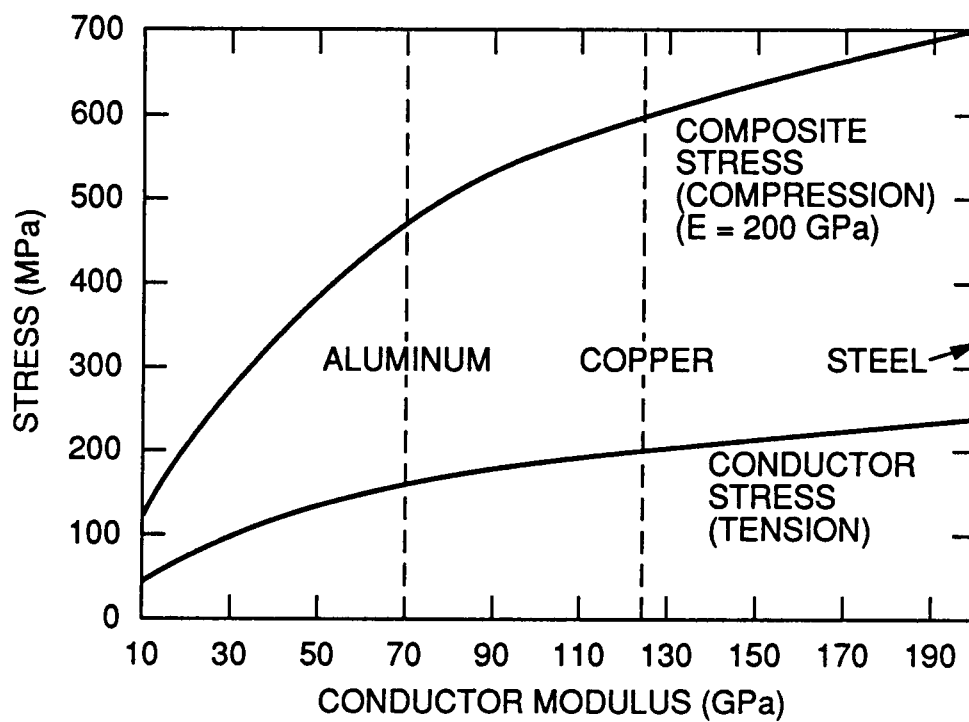


Fig. 41. Variation in stress in the composite and conductor with modulus of elasticity of the conductor.

thermal stress, the winding conduit must have a modulus much lower than common metals such as steel, copper, and aluminum.

Another solution would be to have a winding conduit material with a low coefficient of thermal contraction. It would appear that a conduit fabricated from graphite/epoxy would provide a better match while at the same time providing the strength necessary to support the helium pressure inside the conduit.

4. Carbon/Epoxy Metal-Wound Conduit

One important function of the superconducting conduit is to contain the base materials of the superconductor during the reacting process in which the Nb_3Sn material is formed. The conduit material must withstand approximately 700°C for 25–30 h.³⁹ To provide an epoxy matrix conduit that is limited to several hundred degrees, a conduit having a very low stiffness along its longitudinal axis such as shown in Fig. 42 is proposed. The metal wrap may be steel, copper, or other metal alloy used to control the superconductor in the react cycle. After the reaction is complete, the conductor is finally wrapped in a layer of carbon/epoxy, which seals the metal conduit and strengthens it for the high-pressure helium containment. The entire winding is later impregnated with a glass epoxy coating between each winding, which provides an additional sealing surface. The outer surface of the conductor and composite magnet is also covered with a layer of carbon/epoxy for overall strength and leaktightness of the magnet cross section, as shown in Fig. 42.

E. Cost Estimate

The generic reactor model uses a unit cost value of \$80/kg for the structural material of the magnet system. This was derived as an average cost of materials

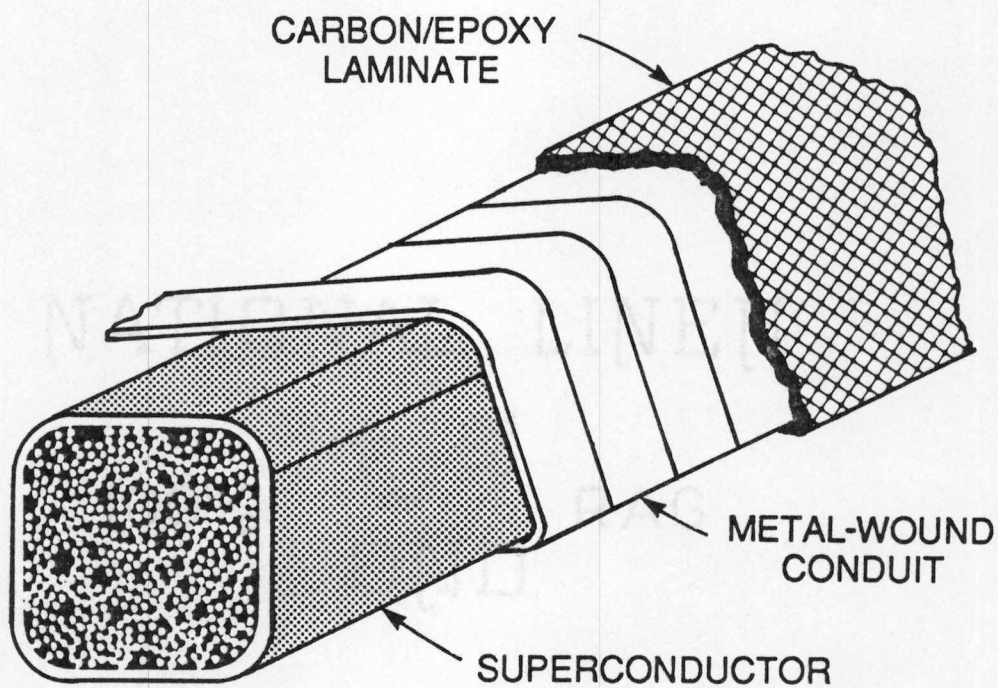


Fig. 42. Cable-in-conduit conductor concept for thermal strain compatibility with carbon/epoxy structure.

for the major components of a high-field superconducting magnet system in the Starfire study. New material costs have recently been proposed by Miller⁴⁰ for the design of the magnet system for the International Thermonuclear Experimental Reactor (ITER). A summary of the costs is shown in Table 12, which compares the Starfire, ITER, and generic unit cost data.

Table 12. Magnet Materials Unit Cost Data
(\$/kg)

	Starfire (1980)	ITER (1987)	Generic Study (1983)
Nb ₃ Sn S/C	109	300*	
Winding	-	132	80
Structure	26	82	Avg Cost
Cryostat	26	28	

* For 50% copper fraction.

The cost of the Nb₃Sn is the dominant portion of the cost. To effectively reduce the magnet system cost, both the conductor and structural material cost must be reduced. The conclusion drawn in the generic systems study regarding the sensitivity of coil structural strength on the overall CoE cannot be used to justify only a reduction in structural material. The cost of the conductor must also be included when considering a specific magnet design. The use of carbon/epoxy as the structural member for both the conductor conduit and the primary coil structure will thus more nearly approximate the systems model estimate.

Conceptual design cost estimating, based on fabricated unit cost of structures, is an accepted and validated method that has been used for most major fusion projects.^{41,42} A data base of unit costs has been collected and is maintained in the U.S. Fusion Program.

The cost advantage of using carbon/epoxy as a structural material is based on three well-known and quantifiable facts relating to composite materials. The first advantage and primary incentive for the composite material is its structural

strength. The tensile strength of a modest grade of carbon/epoxy composite with uni-directional fibers is three times that of 304 stainless steel. Furthermore, the design stress level of the composite is normally a higher fraction of ultimate strength than is used for structural steel due to the superior fatigue and fracture toughness of the carbon/epoxy.

The second advantage is the ultra-low density of the composite. The density of the carbon/epoxy is $<1/5$ that of stainless steel. This advantage is much more obvious in aerospace applications where weight is a predominant design driver. The low density is a more subtle cost advantage in the magnet design where the cost is estimated based on the fabricated weight of the material. Even though the fabricated unit cost of the composite is higher than stainless steel by as much as a factor of 5 or 6, this is offset by an equal reduction in total weight.

Assuming a fabrication cost of \$200/kg for the carbon/epoxy, the relative cost of the fabricated structural material is a factor of 3 less than stainless steel. Using the data in Table 13, the relative cost is calculated as

$$\text{RELATIVE COST} = \frac{\text{DENSITY} \times \text{UNIT COST}}{\text{STRENGTH}}$$

Table 13. Comparison of Coil Cost Factors

	Carbon/epoxy	304 stainless
Ultimate tensile strength (MPa)	2000	520
Density (kg/m ³)	1600	8300
Fabricated coil structure unit cost (\$/kg)	200	30
Relative cost	160	479

The relative simplicity of composite materials fabrication is the third cost advantage relative to stainless steel. The very large magnet system can be much more easily fabricated from composite and conductor winding than the metal working processes necessary to form, weld, and machine stainless steel to close dimensional tolerance.

CHAPTER V

CONCLUSIONS

A fusion reactor systems code has been developed to evaluate the generic aspects of the D-D fuel cycle. The code has been used to compare, on an equivalent basis, design and performance parameters of the D-D and D-T reactor systems. Based on the results of these studies, it is concluded that both physics and technology improvements in the D-D reactor system can substantially narrow the previously projected CoE difference between the two.

A. The Catalyzed D-D Reactor Model

The catalyzed D-D generic reactor model has been shown to be a valuable system for studying the sensitivity of physics and technology operating parameters. As in past reactor studies, design features were optimized to minimize the estimated CoE. When the same basic methodology was used to compare D-D and D-T reactors, new insights were gained on how the intrinsically larger and more costly D-D reactor can be improved.

When compared on an equivalent level of operating performance and engineering design parameters, the D-D reactor can produce electricity at two times the cost of a D-T reactor. Variations in performance assumptions, however, show that due to the large reactor components, improvements in some of the D-D design constraints are relatively more important in reducing the cost. Higher plasma beta and high-strength, low-cost structural materials were identified as two of the most promising areas with the potential for reducing the cost ratio to 1.5 or less.

B. Improved Physics Performance — High Beta

A high-power-density plasma at moderate magnetic field is a definite advantage for the D-D fuel. If a confinement concept can be developed to operate at a volume-averaged beta of over 25%, it is conceivable that the D-D reactor could be reduced in size and cost equal to the D-T reactor, which is limited in power density due to neutron damage to the blanket and first wall. The power density in the D-D reactor may also be limited by high heat and particle flux to the first wall and divertor components.

C. High-Strength, Low-Cost Magnet System

If the idea for a new structural design concept for superconducting magnets can be developed, the cost of the large D-D magnets could become a much smaller fraction of the total cost, thereby reducing the cost difference with the D-T reactor. Advanced composite materials such as carbon/epoxy appear to have strength and low-temperature fatigue resistance superior to the stainless steel alloys presently used. Because these materials are still in the early stages of large-scale application, future reductions in cost and improved fabrication methods can reasonably be expected.

D. Future Work

The fusion energy research program will continue to focus on methods by which the performance of fusion plasmas can be improved. High-beta operation is an important goal of several experimental tokamaks and alternate concepts such as the stellarator and RFP. The findings of this study relative to the importance

of high beta rather than high magnetic field may help to further focus the efforts of the national fusion program.

The composite-reinforced superconducting magnet concept suffers from a total lack of fabrication and test data. A small-scale experiment has been proposed and is already in the planning stages at the Oak Ridge National Laboratory. If funding can be obtained, it is anticipated that a prototype coil will be fabricated and tested. A composite materials research facility is in place at the Oak Ridge Gaseous Diffusion Plant with experience in winding and fabrication of carbon/epoxy components.⁴³ The superconducting magnet test facilities in the ORNL fusion program are adequate for the experimental program.

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APPENDIX
COMPLETE LISTING OF PROGRAM EQUATIONS

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A1: 'DD vs DT Models (11/23/88)  FINAL
A2: '*****
B2: ^CAT-D
C2: ^TCD
D2: ^DT
A3: '  Total Fusion power, Pf (MW)
B3: 3500
C3: 3500
D3: 4000
A4: '  Plasma Ion temperature, Ti (eV)
B4: 30000
C4: 30000
D4: 10000
A5: '  Reaction Rate DT, <sv> (m^3/s)
B5: @VLOOKUP(+B4/1000,F167..L195,1)
C5: @VLOOKUP(+C4/1000,F167..L195,1)
D5: @VLOOKUP(+D4/1000,F167..L195,1)
A6: '  Reaction Rate DDp, <sv> (m^3/s)
B6: @VLOOKUP(+B4/1000,F167..L195,3)
C6: @VLOOKUP(+C4/1000,F167..L195,3)
A7: '  Reaction Rate DDn, <sv> (m^3/s)
B7: @VLOOKUP(+B4/1000,F167..L195,2)
C7: @VLOOKUP(+C4/1000,F167..L195,2)
A8: '  Reaction Rate DDp+DDn, <sv> (m^3/s)
B8: @VLOOKUP(+B4/1000,F167..L195,4)
C8: @VLOOKUP(+C4/1000,F167..L195,4)
A9: '  Reaction Rate Par. DHe3, <sv> (m^3/s)
B9: @VLOOKUP(+B4/1000,F167..L195,5)
C9: @VLOOKUP(+C4/1000,F167..L195,5)
A10: '  Tritium Concentration, nT/nD
B10: (F4) +B6/(2*B5)
C10: (F4) +C8/(2*C5)
A11: '  He3 Concentration, nHe3/nD
B11: (F4) +B7/(2*B9)
C11: (F4) 0
A12: '  Deuterium/Ion Fraction, nD/ni
B12: (F4) 1/(1+B10+B11)
C12: (F4) 1/(1+C10+C11)
A13: '  Deuterium/Electron Fraction, nD/ne
B13: (F4) 1/(1+B10+2*B11)
C13: (F4) 1/(1+C10+2*C11)
A14: '  Deuterium Fraction, nD/(ne+ni)
B14: (F4) 1/(1/B12+1/B13)
C14: (F4) 1/(1/C12+1/C13)
A15: '  Tritium Fraction, nT/(ne+ni)
B15: (F4) +B10*B14
C15: (F4) +C10*C14

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A16: ' He3 Fraction, $n_{\text{He3}}/(n_e+n_i)$
 B16: (F4) $+B_{11}*B_{14}$
 C16: (F4) $+C_{11}*C_{14}$
 A17: ' Electron Fraction, $n_e/(n_e+n_i)$
 B17: (F4) $1/B_{13}*(B_{14})$
 C17: (F4) $1/C_{13}*(C_{14})$
 A18: ' Total Beta, $\langle \text{Beta} \rangle$
 B18: (F2) 0.11
 C18: (F2) 0.11
 A19: ' Electron Beta, $\langle \text{Beta} \rangle_e$
 B19: (F2) $+B_{17}*B_{18}$
 C19: (F2) $+C_{17}*C_{18}$
 A20: ' Deuterium Beta, $\langle \text{Beta} \rangle_D$
 B20: (F2) $+B_{14}*B_{18}$
 C20: (F2) $+C_{14}*C_{18}$
 A21: ' Auxiliary heating power, Pa (MW)
 B21: 100
 C21: 100
 D21: 100
 A22: ' Thermal/Electric Conv. eff., Ne
 B22: 0.36
 C22: 0.36
 D22: 0.36
 A23: ' Recirculating Power Fraction, fre
 B23: 0.04
 C23: 0.04
 D23: 0.04
 A24: ' Maximum field at coil, Bm (T)
 B24: 14.35
 C24: 14.35
 D24: 14.35
 A25: ' Total Beta, $\langle \text{Beta} \rangle$
 B25: (F2) $+B_{18}$
 C25: (F2) $+C_{18}$
 D25: (F2) 0.11
 A26: ' Fuel Beta, $\langle \text{Beta} \rangle_F$
 B26: (F2) $+B_{20}$
 C26: (F2) $+C_{20}$
 D26: (F2) $0.5*D_{25}$
 A27: ' Aspect ratio, R/a
 B27: 6
 C27: 6
 D27: 6
 A28: ' Plasma elongation, b/a
 B28: 1.6
 C28: 1.6
 D28: 1.6

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A29: ' Blanket Energy Gain for DDn, g1
B29: 3.43
C29: 3.43
D29: 1.93
A30: ' Blanket Energy gain for DTn, g2
B30: 0.54
C30: 0.54
D30: 0.24
A31: ' Overall thickness, dbgs1 (m)
B31: 0.73
C31: 0.73
D31: 1.3
A32: ' Dewar thickness, dd (m)
B32: 0.08
C32: 0.08
D32: 0.08
A33: ' Ratio of wall/plasma radius, aw/a
B33: 1.2
C33: 1.2
D33: 1.2
A34: ' Wall Reflectivity
B34: 0.95
C34: 0.95
D34: 0.95
A35: '*****
A36: 'Calculations
A37: '*****
B37: '
A38: ' Plasma Minor radius, a (m)
B38: +B48
C38: +C48
D38: +D48
A39: ' Coef 1
B39: 2.1066000E+38*B8*B26^2
C39: 9.7529000E+36*(21.618*C6+20.853*C7)*C26^2
D39: 8.5757000E+37*D5*D26^2
A40: ' Coef 2
B40: (B3-0.5*B21)*B4^2
C40: (C3-0.5*C21)*C4^2
D40: (D3-0.5*D21)*D4^2
A41: ' Coef 3
B41: +B28*B27
C41: +C28*C27
D41: +D28*D27
A42: ' a^3*Bo^4
B42: +B40/(B39*B41)*1000000
C42: +C40/(C39*C41)*1000000
D42: +D40/(D39*D41)*1000000

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A43: '      Coef 4
B43: +B31+B32
C43: +C31+C32
D43: +D31+D32
A44: '      Coef 5
B44: (B27-B33)*B24/B27
C44: (+C27-C33)*C24/C27
D44: (+D27-D33)*D24/D27
A45: '      Coef 6
B45: +B43*B24/B27
C45: +C43*C24/C27
D45: +D43*D24/D27
A46: '      a^3 (trial)
B46: +B42/(B44-B45/B38)^4
C46: +C42/(C44-C45/C38)^4
D46: +D42/(D44-D45/D38)^4
A47: '      a (trial)
B47: +B46^0.3333333333
C47: +C46^0.3333333333
D47: +D46^0.3333333333
A48: '      Plasma minor radius
B48: (+B47+B38)/2
C48: (+C47+C38)/2
D48: (+D47+D38)/2
B49: '
C49: '
D49: '
A50: '*****
A51: 'Results
A52: '*****
A53: 'Field on axis, Bo (T)
B53: (F2) +B44-B45/B38
C53: (F2) +C44-C45/C38
D53: (F2) +D44-D45/D38
A54: 'Plasma Major Radius, R (m)
B54: (F2) +B27*B38
C54: (F2) +C27*C38
D54: (F2) +D27*D38
A55: 'Plasma Minor Radius, Large, b (m)
B55: (F2) +B28*B38
C55: (F2) +C28*C38
D55: (F2) +D28*D38
A56: 'Plasma Volume, Vp (m^3)
B56: (F2) 19.7392*B54*B48*B55
C56: (F2) 19.7392*C54*C48*C55
D56: (F2) 19.7392*D54*D48*D55

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A57: 'Plasma Power Density, Pf (MW/m³)
 B57: (F2) +B3/B56
 C57: (F2) +C3/C56
 D57: (F2) +D3/D56
 A58: 'First Wall Area, Aw (m²)
 B58: (F2) 39.4784*B27*(B28^{0.5})*B33*(B38²)
 C58: (F2) 39.4784*C27*(C28^{0.5})*C33*(C38²)
 D58: (F2) 39.4784*D27*(D28^{0.5})*D33*(D38²)
 A59: 'Deuterium density, nD (m⁻³)
 B59: ((B26²)*(B53⁴)*(6.1680000E+48)/B4²)^{0.5}
 C59: ((C26²)*(C53⁴)*(6.1680000E+48)/C4²)^{0.5}
 D59: 0.5*((D26²)*(D53⁴)*(6.1680000E+48)/D4²)^{0.5}
 A60: 'Tritium density, nT (m⁻³)
 B60: +B59*0.5*@VLOOKUP(+B4/1000,F167..L195,3)/
 @VLOOKUP(+B4/1000,F167..L195,1)
 C60: +C59*C10
 D60: +D59
 A61: 'Helium Density, nHe (m⁻³)
 B61: +B11*B59
 C61: +C11*C59
 D61: 0
 A62: 'Total Ion Density, ni (m⁻³)
 B62: +B59/B12
 C62: +C59/C12
 D62: +D59+D60
 A63: 'Electron Density, ne (m⁻³)
 B63: +B59/B13
 C63: +C59/C13
 D63: +D62
 A64: 'Impurity Concentration, Zeff
 B64: (F2) (B59+B60+B61*4)/B63
 C64: (F2) (C59+C60+C61*4)/C63
 D64: (F2) (D59+D60+4*D61)/D63
 A65: 'DT Power, PDT (MW)
 B65: (F2) +B59*B60*@VLOOKUP(B4/1000,F167..L195,1)*
 17.586*1.6021000E-19*B56
 C65: (F2) +C59*C60*@VLOOKUP(C4/1000,F167..L195,1)*
 17.586*1.6021000E-19*C56
 D65: (F2) ((1.6021000E-13)*17.586*(D59²)*(D5)/1000000)*D56
 A66: 'DDn Power, PDDn (MW)
 B66: (F2) +B59²*B7*3.27*1.6021000E-13/1000000*B56/2
 C66: (F2) +C59²*C7*3.27*1.6021000E-13/1000000*C56/2
 A67: 'DDp Power, PDDp (MW)
 B67: (F2) +B59²*B6*4.04*1.6021000E-13/1000000*B56/2
 C67: (F2) +C59²*C6*4.04*1.6021000E-13/1000000*C56/2
 A68: 'DHe Power, PDHe (MW)
 B68: (F2) +B59²*B11*B9*18.34*1.6021000E-13/1000000*B56
 C68: (F2) +C59²*C11*C9*18.34*1.6021000E-13/1000000*C56

A69: 'Charged Particle Power, Pcp (MW)
 B69: (F2) $0.618*(B3-B21/2)$
 C69: (F2) $+C65*0.2+C66*0.25+C67*0.75+C68*1$
 D69: (F2) $3.517/17.586*D65$
 A70: 'Charged Part. Power Density, pcp (MW/m³)
 B70: (F2) $+B69/B56$
 C70: (F2) $+C69/C56$
 D70: (F2) $+D69/D56$
 A71: 'Neutron Power, Pn (MW)
 B71: (F2) $0.8*B65+0.75*B66$
 C71: (F2) $0.8*C65+0.75*C66$
 D71: (F2) $14.069/17.586*D65$
 A72: 'Neutron Wall Loading, pwn (MW/m²)
 B72: (F2) $+B71/B58$
 C72: (F2) $+C71/C58$
 D72: (F2) $+D71/D58$
 A73: 'Total Thermal Power, Pt (MW)
 B73: (F2) $(B59^2/2)*(B6*(4.032+3.517+14.069*(1+B30))$
 $+B7*(18.341+0.817+2.45*(1+B29)))*B56*1.6021000E-13/$
 $1000000+B21/2$
 C73: (F2) $(C59^2/2)*(C6*(4.032+3.517+14.069*(1+C30))$
 $+C7*(18.341+0.817+2.45*(1+C29)))*C56*1.6021000E-13/$
 $1000000+C21/2$
 D73: (F2) $(D59^2)*(D5*(3.517+14.069*(1+D30)))$
 $*D56*1.6021000E-13/1000000+D21/2$
 A74: 'Total Electric Power, Peg (MWe)
 B74: (F2) $+B73*B22*0.7$
 C74: (F2) $+C73*C22*0.7$
 D74: (F2) $+D73*D22*0.7$
 A75: 'Net Electric Power, Pe (MWe)
 B75: (F2) $+B74*(1-B23*(4150/B3)^0.2)$
 C75: (F2) $+C74*(1-C23*(4150/C3)^0.2)$
 D75: (F2) $+D74*(1-D23*(4150/D3)^0.2)$
 A76: 'Bremsstrahlung Pwr. Density, pb (MW/m³)
 B76: (F2) $5.3500000E-37*B64*B63^2*(B4/1000)^0.5*0.000001$
 C76: (F2) $5.3500000E-37*C64*C63^2*(C4/1000)^0.5*0.000001$
 D76: (F2) $5.3500000E-37*D64*D63^2*(D4/1000)^0.5*0.000001$
 A77: 'Synchrotron Power Density, ps (MW/m³)
 B77: (F2) $6.2000000E-17*B63*(B4/1000)*B53^2*0.0014*$
 $(B4/1000)^1.75*(1+(B4/1000)/204)*(1-B34)^0.5/$
 $0.0000000078*(B63*(B48*B55)^0.5/B53)^-0.5*0.000001$
 C77: (F2) $6.2000000E-17*C63*(C4/1000)*C53^2*0.0014*$
 $(C4/1000)^1.75*(1+(C4/1000)/204)*(1-C34)^0.5/$
 $0.0000000078*(C63*(C48*C55)^0.5/C53)^-0.5*0.000001$
 D77: (F2) $6.2000000E-17*D63*(D4/1000)*D53^2*0.0014*$
 $(D4/1000)^1.75*(1+(D4/1000)/204)*(1-D34)^0.5/$
 $0.0000000078*(D63*(D48*D55)^0.5/D53)^-0.5*0.000001$

A78: 'Total Radiation Power Loss, prad (MW/m³)
 B78: (F2) +B76+B77
 C78: (F2) +C76+C77
 D78: (F2) +D76+D77
 A79: 'Radiation Power Fraction, frad
 B79: (F2) +B78/B57
 C79: (F2) +C78/C57
 D79: (F2) +D78/D57
 A80: 'Conduction Power loss, pcon (MW/m³)
 B80: (F2) +B70-B78
 C80: (F2) +C70-C78
 D80: (F2) +D70-D78
 A81: 'Power fraction for Conduction, fcp
 B81: (F2) 1-B79
 C81: (F2) 1-C79
 D81: (F2) 1-D79
 A82: 'Thermal Diffusivity, XE (m²/s)
 B82: (F2) +B80*B48*B55/(6*(B62+B63)*B4*1.6021000E-19)*1000000
 C82: (F2) +C80*C48*C55/(6*(C62+C63)*C4*1.6021000E-19)*1000000
 D82: (F2) +D80*D48*D55/(6*(D62+D63)*D4*1.6021000E-19)*1000000
 A84: '*****
 A85: 'Cost Model
 A86: '*****
 A87: ' RadialBuild
 A88: ' Plasma Major Radius, R (m)
 B88: (F2) +B54
 C88: (F2) +C54
 D88: (F2) +D54
 A89: ' Plasma Minor Radius, a (m)
 B89: (F2) +B48
 C89: (F2) +C48
 D89: (F2) +D48
 A90: ' Wall Minor Radius, aw (m)
 B90: (F2) +B89*B33
 C90: (F2) +C89*C33
 D90: (F2) +D89*D33
 A91: ' Blanket Thickness, inboard, db1 (m)
 B91: (F2) 0.21
 C91: (F2) 0.31
 D91: (F2) 0.45
 A92: ' Blanket Thickness, Outboard, db2 (m)
 B92: (F2) 0.41
 C92: (F2) 0.51
 D92: (F2) 0.9
 A93: ' Maintenance gap, inboard, dgl(m)
 B93: (F2) 0.1
 C93: (F2) 0.1
 D93: (F2) 0.1

A94: ' Maintenance gap, outboard, dg2 (m)
 B94: (F2) 0.3
 C94: (F2) 0.3
 D94: (F2) 0.3
 A95: ' Shield thickness, inboard, ds1 (m)
 B95: (F2) 0.42
 C95: (F2) 0.52
 D95: (F2) 0.75
 A96: ' Shield thickness, outboard, ds2 (m)
 B96: (F2) 0.8
 C96: (F2) 0.8
 D96: (F2) 0.8
 A97: ' Coil Dewar thickness, dd (m)
 B97: (F2) 0.08
 C97: (F2) 0.08
 D97: (F2) 0.08
 A98: ' Blanket
 A99: ' Bore Minor Radius, m
 B99: (F2) +B33*B38
 C99: (F2) +C33*C38
 D99: (F2) +D33*D38
 A100: ' Minimum Volume, Vbm (m³)
 B100: (F2) $0.333*6.2832*(B99+(B91)/2)*(((1+B28^2)/2)^{0.5})*$
 $B91*6.2832*B88$
 C100: (F2) $0.333*6.2832*(C99+(C91)/2)*(((1+C28^2)/2)^{0.5})*$
 $C91*6.2832*C88$
 D100: (F2) $0.333*6.2832*(D99+(D91)/2)*(((1+D28^2)/2)^{0.5})*$
 $D91*6.2832*D88$
 A101: ' Maximum Volume, Vmmx (m³)
 B101: (F2) $0.667*6.2832*(B99+(B92)/2)*(((1+B28^2)/2)^{0.5})*$
 $B92*6.2832*B88$
 C101: (F2) $0.667*6.2832*(C99+(C92)/2)*(((1+C28^2)/2)^{0.5})*$
 $C92*6.2832*C88$
 D101: (F2) $0.667*6.2832*(D99+(D92)/2)*(((1+D28^2)/2)^{0.5})*$
 $D92*6.2832*D88$
 A102: ' Total Volume, Vb (m³)
 B102: (F2) +B100+B101
 C102: (F2) +C100+C101
 D102: (F2) +D100+D101
 A103: ' Density, rb (kg/m³)
 B103: (F2) 6400
 C103: (F2) 6400
 D103: (F2) 6400
 A104: ' Unit cost, \$b (\$/kg)
 B104: (F2) 70
 C104: (F2) 70
 D104: (F2) 70

A105: ' Blanket cost, Cb (\$)
 B105: (F2) +B102*B103*B104/1000000
 C105: (F2) +C102*C103*C104/1000000
 D105: (F2) +D102*D103*D104/1000000
 A106: ' Shield
 A107: ' bore minor radius, m
 B107: (F2) +B33*B38+B91+B93
 C107: (F2) +C33*C38+C91+C93
 D107: (F2) +D33*D38+D91+D93
 A108: ' Minimum Volume, Vsm (m³)
 B108: (F2) 0.333*6.2832*(B107+(B95)/2)*(((1+B28²)/2)^{0.5})*
 B95*6.2832*B88
 C108: (F2) 0.333*6.2832*(C107+(C95)/2)*(((1+C28²)/2)^{0.5})*
 C95*6.2832*C88
 D108: (F2) 0.333*6.2832*(D107+(D95)/2)*(((1+D28²)/2)^{0.5})*
 D95*6.2832*D88
 A109: ' Maximum Volume, Vsmx (m³)
 B109: (F2) 0.667*6.2832*(B107+(B96/2))*(((1+B28²)/2)^{0.5})*
 B96*6.2832*B88
 C109: (F2) 0.667*6.2832*(C107+(C96/2))*(((1+C28²)/2)^{0.5})*
 C96*6.2832*C88
 D109: (F2) 0.667*6.2832*(D107+(D96/2))*(((1+D28²)/2)^{0.5})*
 D96*6.2832*D88
 A110: ' Total Volume, Vs (m³)
 B110: (F2) +B108+B109
 C110: (F2) +C108+C109
 D110: (F2) +D108+D109
 A111: ' Density, rs, (kg/m³)
 B111: (F2) 6400
 C111: (F2) 6400
 D111: (F2) 6400
 A112: ' Unit cost, \$s (\$/kg)
 B112: (F2) 22
 C112: (F2) 22
 D112: (F2) 22
 A113: ' Shield cost, Cs (\$)
 B113: (F2) +B110*B111*B112/1000000
 C113: (F2) +C110*C111*C112/1000000
 D113: (F2) +D110*D111*D112/1000000
 A114: ' Coils
 A115: ' Maximum field, Bm (T)
 B115: (F2) +B24
 C115: (F2) +C24
 D115: (F2) +D24
 A116: ' Number of TF coils
 B116: (F2) 20
 C116: (F2) 20
 D116: (F2) 20

A117: ' Current per coil, Ic (MA)
 B117: (F2) +B53*5*B54/B116
 C117: (F2) +C53*5*C54/C116
 D117: (F2) +D53*5*D54/D116
 A118: ' Winding current density, Jp (MA/m²)
 B118: (F2) @IF(B24<8,(9.6-0.6*B24)*10,(7-0.29*B24)*10)
 C118: (F2) @IF(C24<8,(9.6-0.6*C24)*10,(7-0.29*C24)*10)
 D118: (F2) @IF(D24<8,(9.6-0.6*D24)*10,(7-0.29*D24)*10)
 A119: ' winding area (m²)
 B119: (F2) +B117/B118
 C119: (F2) +C117/C118
 D119: (F2) +D117/D118
 A120: '*****
 A121: ' Radius of coil inside bore, r1 (m)
 B121: (F2) +B88-B90-B91-B93-B95-B97
 C121: (F2) +C88-C90-C91-C93-C95-C97
 D121: (F2) +D88-D90-D91-D93-D95-D97
 A122: ' Radius of coil outside, bore, r2 (m)
 B122: (F2) +B88+B90+B92+B94+B96+B97
 C122: (F2) +C88+C90+C92+C94+C96+C97
 D122: (F2) +D88+D90+D92+D94+D96+D97
 A123: ' Coil free bore width, (m)
 B123: (F2) +B122-B121
 C123: (F2) +C122-C121
 D123: (F2) +D122-D121
 A124: ' Coil Tension, T (lbs)
 B124: (S3) +B24^2*3.14159*(B121)^2*@LN(B122/B121)/
 0.0000012566/B116/4.4482/2
 C124: (S3) +C24^2*3.14159*(C121)^2*@LN(C122/C121)/
 0.0000012566/C116/4.4482/2
 D124: (S3) +D24^2*3.14159*(D121)^2*@LN(D122/D121)/
 0.0000012566/D116/4.4482/2
 A125: ' Allowable Coil Membrane Stress, S (psi)
 B125: (F0) 40000
 C125: (F0) +B125
 D125: (F0) +B125
 A126: ' Coil Structural Area, Acs (m²)
 B126: (F2) +B124/B125/1550
 C126: (F2) +C124/C125/1550
 D126: (F2) +D124/D125/1550
 A127: ' Total coil Area, Atc (m²)
 B127: (F2) +B119+B126
 C127: (F2) +C119+C126
 D127: (F2) +D119+D126
 A128: ' Coil area, all coils (m²)
 B128: (F2) +B116*B127
 C128: (F2) +C116*C127
 D128: (F2) +D116*D127

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A129: '    Max. available space, coil area (m^2)
B129: (F2) 3.14159*B121^2
C129: (F2) 3.14159*C121^2
D129: (F2) 3.14159*D121^2
A130: '    Coil current density, Jm (MA/m^2)
B130: (F2) +B116*B117/B128
C130: (F2) +C116*C117/C128
D130: (F2) +D116*D117/D128
A131: '    Coil thickness, dtf (m)
B131: (F2) (-@SQRT((2*B121)^2-4*B128/3.14159)+2*B121)/2
C131: (F2) (-@SQRT((2*C121)^2-4*C128/3.14159)+2*C121)/2
D131: (F2) (-@SQRT((2*D121)^2-4*D128/3.14159)+2*D121)/2
A132: '    Coil avg radius
B132: (F2) +B123/2+B131/2
C132: (F2) +C123/2+C131/2
D132: (F2) +D123/2+D131/2
A133: '    Avg coil perimeter (m)
B133: (F2) 2*3.14159*(B132)*((1+B28^2)/2)^0.5
C133: (F2) 2*3.14159*(C132)*((1+C28^2)/2)^0.5
D133: (F2) 2*3.14159*(D132)*((1+D28^2)/2)^0.5
A134: '    Coil Magnetic Pressure (psi)
B134: (F2) +B24^2/(2*0.0000012566)/6894.76
C134: (F2) +C24^2/(2*0.0000012566)/6894.76
D134: (F2) +D24^2/(2*0.0000012566)/6894.76
A135: '    Primary coil volume, Vcp (m^3)
B135: (F2) +B133*B128
C135: (F2) +C133*C128
D135: (F2) +D133*D128
A136: '*****
A137: '    Total coil volume, Vct (m^3)
B137: (F2) 1.25*B135
C137: (F2) 1.25*C135
D137: (F2) 1.25*D135
A138: '    Density, rc (kg/m^3)
B138: 8000
C138: 8000
D138: 8000
A139: '    Unit cost, $c ($/kg)
B139: 80
C139: 80
D139: 80
A140: '    Coil cost, Cc (M$)
B140: (C2) 1.2*B137*B138*B139/1000000
C140: (C2) 1.2*C137*C138*C139/1000000
D140: (C2) 1.2*D137*D138*D139/1000000
A141: 'Structure

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A142: ' Volume, Vst (m³)
 B142: (F2) 0.75*B135
 C142: (F2) 0.75*C135
 D142: (F2) 0.75*D135
 A143: ' Density, rst (kg/m³)
 B143: 6000
 C143: 6000
 D143: 6000
 A144: ' Unit cost, \$st (\$/kg)
 B144: 23
 C144: 23
 D144: 23
 A145: ' Structure cost, Cst (M\$)
 B145: (C2) +B142*B143*B144/1000000
 C145: (C2) +C142*C143*C144/1000000
 D145: (C2) +D142*D143*D144/1000000
 A146: 'Auxiliary Power
 A147: ' Unit cost, \$a (\$/W)
 B147: 2
 C147: 2
 D147: 2
 A148: ' Auxiliary power cost, Cap (M\$)
 B148: (C2) 0.75*B147*B21
 C148: (C2) 0.75*C147*C21
 D148: (C2) 0.75*D147*D21
 A149: 'Steam Generators
 A150: ' Steam generator cost, Csg (M\$)
 B150: (C2) 84*(B73/4150)^{0.6}
 C150: (C2) 84*(C73/4150)^{0.6}
 D150: (C2) 84*(D73/4150)^{0.6}
 A151: '*****
 A152: 'Total Fusion Island Cost, CFI (M\$)
 B152: (C2) +B150+B148+B145+B140+B113+B105
 C152: (C2) +C150+C148+C145+C140+C113+C105
 D152: (C2) +D150+D148+D145+D140+D113+D105
 A153: '*****
 A154: 'Balance of Plant, (M\$)
 B154: (C2) 685*(B73/4150)^{0.6}
 C154: (C2) 685*(C73/4150)^{0.6}
 D154: (C2) 685*(D73/4150)^{0.6}
 A155: 'Reactor Buildings, (M\$)
 B155: (C2) 319*((B137+B142+B102+B108)/5100)^{0.67}
 C155: (C2) 319*((C137+C142+C102+C108)/5100)^{0.67}
 D155: (C2) 319*((D137+D142+D102+D108)/5100)^{0.67}
 A156: 'Direct Capital Cost, CD (M\$)
 B156: (C2) 1.15*(B152+B154+B155)
 C156: (C2) 1.15*(C152+C154+C155)
 D156: (C2) 1.15*(D152+D154+D155)

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A157: '*****
A158: 'COST OF ELECTRICITY
A159: '*****
A160: 'Indirect Cost, IC (M$)
B160: (F2) 0.35*B156
C160: (F2) 0.35*C156
D160: (F2) 0.35*D156
A161: 'Contingency, CONT (M$)
B161: (F2) 0.2*B152
C161: (F2) 0.2*C152
D161: (F2) 0.2*D152
A162: 'Constructed Cost, CC (M$)
B162: (F2) +B156+B160+B161
C162: (F2) +C156+C160+C161
D162: (F2) +D156+D160+D161
A163: 'Interest
B163: (F2) 0.11
C163: (F2) 0.11
D163: (F2) 0.11
A164: 'Interest During Construction, IDC (M$)
B164: (F2) +B163*B162
C164: (F2) +C163*C162
D164: (F2) +D163*D162
A165: 'Total Capital Cost, TCC (M$)
B165: (F2) +B162+B164
C165: (F2) +C162+C164
D165: (F2) +D162+D164
A166: 'Annual Operating Cost, AOC (M$)
B166: (F2) (B74/1100)^0.7*49
C166: (F2) (C74/1100)^0.7*49
D166: (F2) (D74/1100)^0.7*49
A167: 'Fixed Charge Rate
B167: (F2) 0.1
C167: (F2) 0.1
D167: (F2) 0.1
A168: 'Capacity Factor
B168: (F2) 0.75
C168: (F2) 0.75
D168: (F2) 0.75
A169: 'Cost of Electricity, COE (mills/kWh)
B169: (F2) (+B167*B165+B166)/(8760*B75*B168)*1000000
C169: (F2) (+C167*C165+C166)/(8760*C75*C168)*1000000
D169: (F2) (+D167*D165+D166)/(8760*D75*D168)*1000000

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Database, Reaction Rate Parameters

T , keV	DT	DD,n	DD,p	DD,n+p	^3HeD
1.00	5.48E-27	6.92E-29	8.30E-29	1.52E-28	3.02E-32
1.50	5.89E-26	6.47E-28	7.29E-28	1.38E-27	1.32E-30
2.00	2.63E-25	2.60E-27	2.82E-27	5.42E-27	1.42E-29
3.00	1.71E-24	1.45E-26	1.50E-26	2.95E-26	2.75E-28
4.00	5.58E-24	4.23E-26	4.24E-26	8.47E-26	1.77E-27
5.00	1.29E-23	8.94E-26	8.77E-26	1.77E-25	6.66E-27
6.00	2.42E-23	1.57E-25	1.52E-25	3.09E-25	1.83E-26
7.00	3.98E-23	2.46E-25	2.35E-25	4.81E-25	4.09E-26
8.00	5.94E-23	3.55E-25	3.35E-25	6.90E-25	7.96E-26
9.00	8.26E-23	4.82E-25	4.51E-25	9.33E-25	1.40E-25
10.00	1.09E-22	6.26E-25	5.82E-25	1.21E-24	2.27E-25
15.00	2.65E-22	1.56E-24	1.41E-24	2.97E-24	1.27E-24
20.00	4.24E-22	2.73E-24	2.43E-24	5.16E-24	3.79E-24
25.00	5.59E-22	4.03E-24	3.57E-24	7.60E-24	8.18E-24
30.00	6.65E-22	5.41E-24	4.76E-24	1.02E-23	1.45E-23
35.00	7.45E-22	6.83E-24	5.98E-24	1.28E-23	2.27E-23
40.00	8.03E-22	8.26E-24	7.21E-24	1.55E-23	3.23E-23
45.00	8.43E-22	9.69E-24	8.44E-24	1.81E-23	4.30E-23
50.00	8.71E-22	1.11E-23	9.66E-24	2.08E-23	5.44E-23
60.00	8.97E-22	1.39E-23	1.21E-23	2.60E-23	7.82E-23
70.00	9.00E-22	1.66E-23	1.44E-23	3.10E-23	1.02E-22
80.00	8.90E-22	1.93E-23	1.67E-23	3.60E-23	1.24E-22
90.00	8.71E-22	2.18E-23	1.90E-23	4.08E-23	1.44E-22
100.00	8.49E-22	2.43E-23	2.12E-23	4.55E-23	1.61E-22
150.00	7.28E-22	3.58E-23	3.17E-23	6.75E-23	2.20E-22
200.00	6.28E-22	6.42E-23	4.14E-23	1.06E-22	2.44E-22
250.00	5.52E-22	5.59E-23	5.03E-23	1.06E-22	2.51E-22
300.00	4.95E-22	6.50E-23	5.85E-23	1.24E-22	2.50E-22

VITA

Thomas E. Shannon was born and raised in Newark, Ohio. After graduating from Ohio University in 1962, he moved to West Palm Beach, Florida, where he was part of the design team at Pratt and Whitney Aircraft that developed the first hydrogen-fueled rocket engines for the space program. Tom played a major role in the initial development of the technology for the second-generation concepts for the space shuttle main engines. During that time, he was also an Adjunct Professor of Engineering Mechanics at the University of Florida.

In 1969, he came to Oak Ridge and initially was involved in the design and development of the gas centrifuge process. He was the first to apply the finite-element technique to the design of the centrifuge machines. In 1969, he joined the Fusion Program at ORNL as Manager of the Fusion Reactor Engineering Department. He was one of the founding members of the Fusion Engineering Design Center (FEDC) in 1979, and served as Manager of the Systems Engineering Department until 1981, when he became the FEDC Manager. As a consultant to the IAEA in Vienna, from 1979 to 1983, he was Chairman of the Engineering Group for INTOR, the first International Tokamak Reactor Design Project.

Presently, the FEDC has major responsibility for design of the International Tokamak Experimental Reactor (ITER). In addition to the ITER responsibility, Tom is also Engineering Project Manager for Oak Ridge participation in the Compact Ignition Tokamak (CIT) experiment at the Princeton Plasma Physics Laboratory.

Tom received his B.S. degree in Civil Engineering in 1960 and his M.S. degree in 1962, both from Ohio University. He is a Registered Professional Engineer, a member of the American Nuclear Society, and a member of the American Society

of Mechanical Engineers. He and his wife, Pat, have four children and three grandchildren. His two oldest children, Sherrie and Andrew, are graduates of the University of Tennessee. The two younger children, Sandra and Ryan, are still in school.