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ETF SYSTEM CODE--COMPOSITION AND APPLICATIONS*

MASTER

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Summary

A computer code has been developed for application to ETF tokamak system and conceptual design studies. Contributions to the code were supplied by Argonne National Laboratory, General Atomic, Grumman Aerospace Corporation, Massachusetts Institute of Technology, Oak Ridge National Laboratory, Princeton Plasma Physics Laboratory, and Westinghouse Electric Corporation. The code determines cost, performance, configuration, and technology requirements as a function of tokamak parameters. The ETF code is structured in a modular fashion in order to allow independent modeling of each major tokamak component. The primary benefit of modularization is that it allows updating of a component module, such as the TF coil module, without disturbing the remainder of the system code as long as the input/output to the modules remains unchanged. The modules may be run independently to perform specific design studies, such as determining the effect of allowable strain on TF coil structural requirements, or the modules may be executed together as a system to determine global effects, such as defining the impact of aspect ratio on the entire tokamak system.

The systems code was used to perform sensitivity studies for ETF physics and engineering parameters. Based on these studies and a combination of considerations, i.e., cost, technology, maintenance, and margin, a set of ETF parameters was selected. Values of global parameters include: plasma minor radius = 1.3 meter, aspect ratio = 4.2, plasma temperature = 10 keV, plasma elongation = 1.6, beta = 6 percent, field on axis = 5.5 tesla, field at the TF coils = 11.4 tesla, safety factor = 3.8, burn time = 100 seconds, and fusion power = 750 MW.

Introduction

Two topics concerning the ETF system code are discussed in the following sections: (1) a brief description of the code; and (2) application of the code to arrive at interim ETF parameters, configuration, and cost. The code is constructed in a modular fashion so as to allow upgrades of the individual modules on a timely basis. The description of the code and the results produced in the following section represent a snapshot of the code as it currently exists. Improvements to the code are made on a continuing basis.

Code Description

A flow diagram of the ETF system code is presented in Figure 1. This figure shows 26 independent modules linked together with the required external iteration loops between the TF coil, shield, and neutral beam modules. These iteration loops insure that (1) the bulk shield will be sized to meet the most stringent requirement of either nuclear heating in the TF coil, DPA damage to the TF coil conductor, dose to the TF coil insulation, or limitation on shutdown dose rate for maintenance consideration, and that (2) there is adequate space between TF coils for neutral beam penetration. The modules may be run independently to analyze a single tokamak system or the modules may be executed serially by the use of a driver code to define an entire tokamak.

Features of selected modules include:

Physics. The physics routine is a time-independent, zero-dimensional model. Alcator, trapped particle, and ripple trapping scaling relationships are used. Profile effects on fusion power, plasma radiation, and ripple trapping are modeled. This module computes either the ignition point, ignition margin, or steady state beam power for a driven mode depending on the input options.

Bulk Shielding. The inboard and outboard shields are sized based on the limiting constraint of nuclear heating in the superconducting TF coil, DPA damage to the copper matrix, radiation dose to the insulation, or provision for hands-on maintenance for a given time duration after shutdown. Representative e-folding distances for candidate shielding materials are necessary input items to the module.

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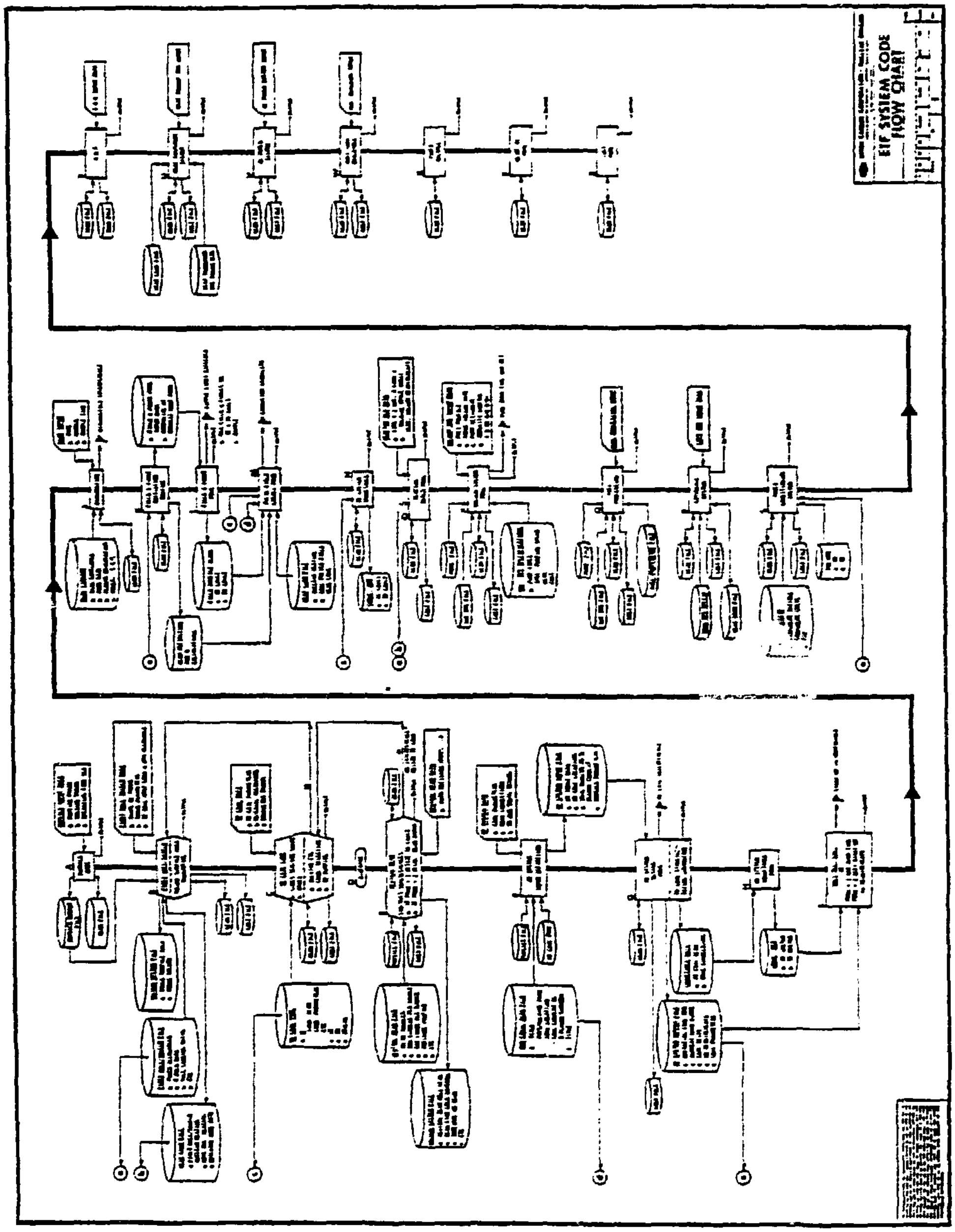

Figure 1

TF Coil. The TF coil bore is based either on magnetic field ripple considerations at the plasma edge, midpoint, or on axis, or on minimum size to encircle the shield. Bore size is also impacted by maintenance constraints of torus segment removal. Coil radial build is based on limiting conductor current density and allowable TF coil strain rates. Trapezoidal or rectangular coil cross sections are allowed.

Neutral Beam. Neutral beam performance is impacted by the allowable port size, required beam power, injection angle, and beam length. An iteration is necessary to insure adequate space between TF coils for beamline penetration. Optics for multi-source injectors are included.

Poloidal Field Coils. The poloidal field module consists of the EF and OH systems. The EF coil currents are scaled as a function of plasma current and coil locations from reference coil currents, location, and waveforms determined through detailed MHD analysis. Options exist for specifying all coils interior to the TF bore, exterior to the TF bore, or a combination thereof. The OH solenoid is sized for an input value of magnetic field and utilizes all available space in the toroidal bore. Coil and plasma inductance values are calculated, and, in conjunction with input current ramp rates, the available volt-seconds of the OH/EF system are determined. Plasma burn time is computed based on volt-seconds remaining after startup requirements are met. Burn time is maximized by swinging the OH solenoid from the plus to the minus value of the OH maximum magnetic field.

Power Conditioning. The power conditioning module determines the MVA requirement for the AC to DC power conversion equipment and the energy storage capacity of the motor generator flywheel sets used to buffer the electric utility power from the tokamak. Energy flow, peak MVA, average MVA over the cycle, peak voltages, and all electrical component ratings are generated for each coil circuit.

Torus Vacuum. The torus vacuum routine calculates the required torus pumping speed for a specified torus pumpdown pressure ratio, evacuation time, and total volume (torus plus duct). Torus post-burn gas pressure is calculated for nondivertor operation based on an estimated post-burn gas temperature and the mass of the plasma in the torus volume at the end of burn. For operation with a divertor, the post-burn gas pressure may be specified (by assuming the divertor aids in pumping during the shutdown scenarios) or may be calculated based on an estimated post-burn gas temperature and the mass of the plasma within the torus during burn. The number of ducts (pumps) is determined for a given speed at the pump and the dimensions (port size and length) of the duct.

Cost. The cost module collects and sums the costs projected in each module and stores the values in a table of standard cost accounts. The costs projected in the individual module are for building and equipment only (engineering, RDAC, contingency, etc., excluded) and are based on unit cost values or algorithms. Table 1 presents the major unit cost values and assumption currently used for the tokamak system, the support system, and the facilities.

Table 1. Cost Assumptions

	Composition	Unit Costs
Tokamak Systems		
TF Coils	Nb_3Sn	$225/kg
	SS Structure	26/kg
PF Coils	NbTi	90/kg
Blanket and Shield	Stainless Steel	26/kg
Support Structure	Stainless Steel (Simple Shapes)	13/kg
	Stainless Steel (Complex Shapes)	26/kg
Plasma Heating	Neutral Beams	Algorithm (~1.20/watt)
Divertor	Copper	44/kg
	SS Coil Structure	26/kg
	SS Shielding	13/kg
	Pumps	Algorithm
Vacuum Systems	Shielding	13/kg
	Pumps	Algorithm
Support Systems		
Electrical Systems	Power Conditioning & Energy Storage Equipment	Algorithms
Tritium Handling	Plasma Processing Equipment	Algorithm
Diagnostics and I&C		Based on JET
Maintenance Equipment		Based on INTOR
Cooling and Cryogenics	Heat Exchangers and Refrigeration	Algorithms
Facilities		
Reactor Building and Hot Cells	Reinforced Concrete Structures	Algorithms (~$320/m³)
Other Buildings		80/m³

ETF Trade Study

Trade studies using the system code were conducted to select self-consistent ETF parameters. The results of the trade study for ignited plasmas at 10 keV temperature are shown in Figure 2. Beta is assumed to vary inversely with aspect ratio from a value of 6 percent at an aspect ratio of 4.2. The combination of plasma minor radius and field on axis at each point along the curve of Figure 2 will provide an ignition margin of 1.0 based on Alcator scaling disregarding the beneficial effect of the noncircular plasma (ignition margin is estimated to be 1.6 allowing for a plasma elongation of 1.6). At each combination of plasma minor radius and field on axis, an aspect ratio was determined based on providing the volt-second requirements of the PF coil system to achieve 100 seconds of burn. The minimum in

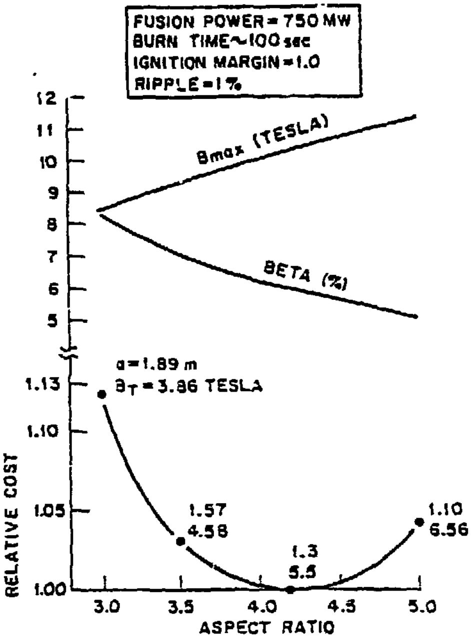

Fig. 2. ETF parameters were selected based on parametric analysis.

Table 2. ETF Baseline Parameters*

Aspect Ratio, A	4.2
Minor Radius, a	1.3 m
Major Radius, R_0	5.4 m
Beta, β	6.0%
Field on Axis, B_T	5.5 T
Field at Coil, B_{max}	11.4 T
Plasma Temperature, T	10 keV
Z_{eff}	1.5
Plasma Density, n	1.8×10^{20} m^{-3}
Plasma Elongation, κ	1.6
Safety Factor, q	3.8
Plasma Current, I_p	6.1 MA
Inboard Shield Thickness	0.5 m
Outboard Shield Thickness	1.2 m
Peak to Average Ripple, Maximum (Plasma Edge)	1%
Fusion Power (17.6 MeV), P_{fusion}	750 MW
Neutron Wall Loading at Plasma Edge, L_p	1.5 MW/m^2
Burn Time, τ_B	100 s
Field in Central Bore, B_{OH}	≤7 T

*Includes bundle divertor.

the relative cost curve of Figure 2 occurs at an aspect ratio of 4.2, plasma minor radius of 1.3 meters, and field on axis of 5.5 tesla. The minimum in the relative cost curve is due to the interaction of plasma minor radius and field on axis. At larger plasma sizes/lower fields, the cost of shielding, PF coils, and power conversion equipment is increased, while the cost of the TF coils is decreased. For smaller plasma sizes/higher fields, the reverse is true. These interactions optimize, on the basis of capital cost, at an aspect ratio of 4.2. This minimum cost configuration was selected as the ETF baseline. The major ETF baseline parameters are shown in Table 2. The projected cost of the ETF is approximately 1 billion dollars as shown in Table 3. This value includes building and equipment costs only and is based on algorithms and unit cost values.

The sensitivity of cost and performance to the initial fixed values of ignition margin, beta, ripple, and burn time were also evaluated with the ETF system code. Reducing the ignition requirements on $n\tau$ by 20 percent allows a reduction in cost of approximately 25 percent as shown in Figure 3. Plasma size is reduced to 1.2 meters, and field on axis to 5.2 tesla with an accompanying decrease in fusion power to 440 megawatts. Increasing the value of beta from 6 percent to 9

Table 3. Preliminary ETF Cost Projections (M$, FY 1980)

	Design I
Tokamak Systems	
TF Coils	246
PF Coils	65
Blanket and Shield	90
Support Structure	56
Plasma Heating Systems	165
Divertor	26
Vacuum System	5
Support Systems	
Electrical Systems	78
Tritium Handling System	36
Diagnostics and I&C	35
Maintenance Equipment	25
Cooling and Cryogenic Systems	56
Facilities	
Reactor Building and Hot Cells	142
Other Structures	58
TOTAL EQUIPMENT AND BUILDINGS	1083

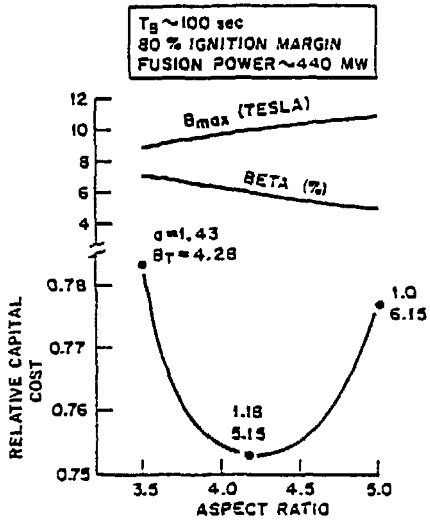

Fig. 3. Decreasing ignition requirements 20 percent results in a 25 percent cost reduction.

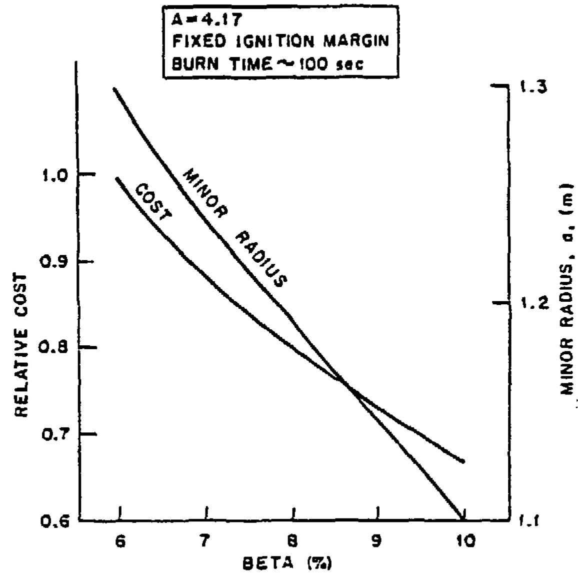

Fig. 4. Increasing beta from 6% to 9% reduces cost by 25% at a constant burn time.

percent reduces capital cost by approximately 25 percent, as shown in Figure 4. Plasma minor radius is decreased, as beta is increased, in order to maintain a tokamak size consistent with a constant 100 second burn. Increasing the allowable value of ripple at the plasma edge, from the base value of one percent to two percent, for 10 TF coils achieves a cost reduction of approximately 10 percent for the baseline ETF as shown in Figure 5. The smaller TF coils, allowed by the higher ripple, however, will have a detrimental impact on torus sector removal. An increase in burn time, based on volt-second limitations, can be accomplished by increasing the plasma minor radius at constant aspect ratio as shown in Figure 6. Increasing the burn time from the base value of 100 seconds to 600 seconds can be accomplished by utilizing a plasma minor radius of 1.4 meters with an accompanying increase in cost of 7 percent. Employing a combination of these effects, if feasible, i.e., reduced ignition requirement, increased allowable ripple, increased value of beta, would significantly reduce the projected capital cost of ~1 billion dollars for the ETF presented in Table 3.

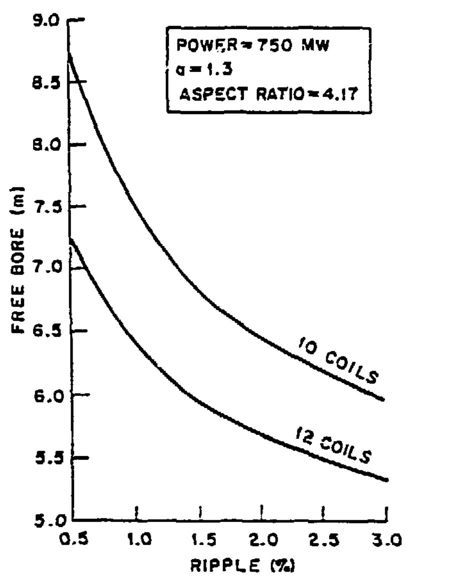

Fig. 5. Capital cost is reduced by allowing larger values of ripple or by using an increased number of smaller coils.

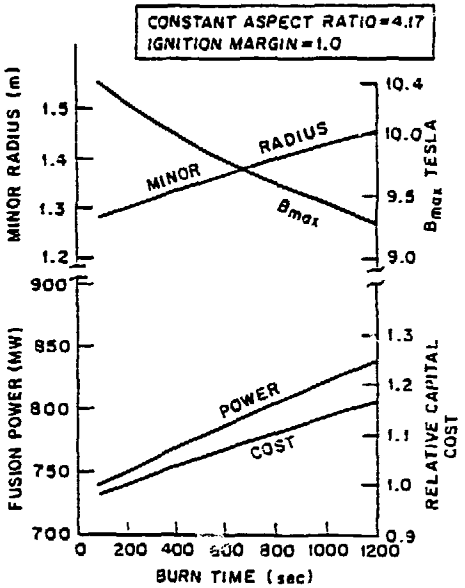

Fig. 6. Increasing the burn time from 100 to 600 sec can be achieved by utilizing a larger tokamak at a cost increase of 7%.

Conclusion

The baseline ETF was selected based on a sensitivity study using the ETF system code which optimized capital cost as a function of tokamak parameters for fixed ignition requirements. The projected cost of the ETF is approximately 1 billion dollars. These costs could be reduced by favorable changes in ignition requirements, allowable beta, and allowable ripple.