GA-A14932

PARAMETRIC SYSTEMS STUDIES OF TNS TOKAMAKS

by

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This is a preprint of a paper to be presented at the Third ANS Topical Meeting on The Technology of Controlled Nuclear Fusion, May 9-11, Santa Fe, New Mexico.

Work supported by
Department of Energy
Contract EY-76-C-03-0167, Project Agreement No. 38

GENERAL ATOMIC PROJECT 3235.871.001
MARCH 1978

GENERAL ATOMIC COMPANY

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PARAMETRIC SYSTEMS STUDIES OF TNS TOKAMAKS*

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The results of parametric systems studies of a Power Generating Fusion Reactor (PGFR) proposed for TNS are reported. The cost of incorporating ignition margin by designing for operation at a reduced ignition beta is given. The additional costs are modest ($\sim$ 10%) down to an ignition beta of 6% with increasing cost increments at lower betas. The basis for the selection of the 3.6 m PGFR reference design parameters is given, and the sensitivity of the design to the number of TF-coils, the burn time, the duty factor, and the inboard shield material is presented.

INTRODUCTION

Parametric studies performed in 1976-77 as part of the DOE sponsored TNS (The Next Step) program at General Atomic concentrated on the Ignition Test Reactor (ITR), a low duty factor (0.1), moderate burn time (30 sec) device utilizing a doublet plasma.(1) On the basis of these studies, a conceptual design of a 3.8 m major radius, 1.1 m minor radius device incorporating superconducting TF coils was developed.(2) The major emphasis of the current TNS study effort has been directed toward a tokamak device incorporating "reactor like" components which, in addition to performing as an ignition test reactor, will operate at a moderate duty factor (0.5) and demonstrate the generation of a nominal amount of electricity. A parametric investigation of this Power Generating Fusion Reactor (PGFR) was performed to aid in the selection of the reference design parameters.

ANALYTICAL APPROACH AND METHODS

A TNS version of SCOPE, a systems analysis computer code,(1,3) was utilized in these studies. Prior to the investigation, the code was extensively updated based on the design work and detailed costing information generated in the development of the 3.8 m ITR conceptual design. SCOPE incorporates plasma physics models to describe the plasma ignition and burn performance, and engineering and costing algorithms to define and cost the reactor components and systems. Utilizing input geometrical parameters which describe the size and shape of the plasma and the tokamak (major radius, minor radius, elongation, component geometries, etc.) as well as those parameters which describe the plasma (temperature and density profiles, q and β values at ignition and burn, impurity levels, etc.), the energy balance of the plasma at ignition and at burn is examined with static zero-dimensional models in the physics routines. The generated information such as the plasma power, the plasma current, and the required volt-seconds is then utilized in the engineering routines in conjunction with design allowables (*e.g.*, current densities, stresses, etc.) and other design data to define the geometry of the various machine components. The calculated component geometries are then used in the physics routines to re-calculate the ignition and burn parameters. In this manner, the code iterates through the physics and engineering routines until the design parameters are within specified tolerances. At that point the cost routine is called and input unit costs are utilized in conjunction with the code generated component geometries, power levels, energy storage requirements, etc., to determine the costs of components, systems, and the balance of plant.

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*Work supported by Department of Energy Contract EY-76-C-03-0167, Project Agreement No. 38.

The basic approach in the evolution of the SCOPE code has been to develop the models to a detail consistent with scoping studies. Modifications have continually been made as the design philosophy changes and as improved physics and engineering models are developed. The code has become a versatile tool which evaluates the impact of changes in individual components on the overall system.

The primary objective of the parametric study was to provide a basis for the selection of a PGFR reference design. This was accomplished by defining a parameter space within which the code designs and costs many different tokamaks. Comparison of these designs could then be made on the basis of cost and some measure of the probability of success (margin). In specifying the parameter space, major design variables were identified, including the major radius, the minor radius, the maximum field at the TF-coil, and the beta at ignition. A secondary objective was to establish the sensitivity of the design to other so-called minor design variables, such as the number of TF-coils, the duty factor, and the burn time.

Certain machine parameters were fixed in the present study, either by definition of the PGFR objectives or upon the basis of studies performed during the previous phase of the TNS program. In all cases, a doublet-shaped plasma was assumed. The height-to-width ratio was fixed at 2.7 as this appears to be near optimum with respect to plasma control and to β-limits set by ballooning modes.(3) The ohmic heating (OH) coil was chosen as superconducting rather than room temperature copper, as the superconducting OH system total cost (coil, power supply, energy storage, and refrigeration) has been shown to be least expensive by more than a factor of two.(3) Superconducting NbTi was assumed for the toroidal field coils. Previous TNS parametric studies(1) indicated that for high beta tokamaks, optimum cost designs are obtained with fields of 8 - 10 T at the coil. Therefore, there appears to be no incentive for going to the higher field Nb_sSn superconductor. This same conclusion was reached in the Doublet Demonstration Fusion Power Reactor Study where the maximum field at the TF-coil is less than 9 tesla.(4) Moreover, reliable performance of large Nb_3Sn magnets has yet to be demonstrated in order to establish this material as a viable candidate for TNS. Room temperature copper toroidal field coils were found to yield smaller yet slightly more expensive TNS devices than those incorporating NbTi, primarily due to the large energy storage costs incurred for the 30 sec burn time.(3) This fact as well as recognition that copper TF-coils will probably not be practical in commercial fusion plants makes the copper option an inappropriate choice for a device which is to incorporate "reactor like" components. Other parameters which were fixed include a normal conducting field-shaping coil system, negative ion source neutral beams for auxiliary heating, and a water-cooled stainless steel non-breeding blanket in the outboard region.

Alcator scaling normalized to Doublet IIA results was utilized for plasma transport calculations. Density and temperature profiles were assumed parabolic, and the effective Z of impurities was fixed at 2. The ignition beta, the ratio of the volume averaged plasma pressure to the magnetic pressure, was selected as the parameter upon which the margin, or "likelihood of achieving ignition" would be based. The lower the value of beta at which a given doublet machine ignites, the greater the "likelihood of success" for that particular device. In all cases the equilibrium burn beta was taken as one percentage point greater than the ignition value.

The major design variables were surveyed over the following ranges:

Major radius	3.0 to 6.0 m
Minor radius	0.6 to 1.6 m
Toroidal field at coil	6 to 13 T
Ignition plasma beta	4 to 10%

The burn time, duty factor, and number of toroidal field coils were set at 30 sec, 0.5, and 12 respectively, although sensitivity studies for these variables were later performed.

While the PGFR will incorporate those features necessary to demonstrate electricity generation, it is nevertheless primarily an ignition experiment. For this reason, certain factors which are important aspects of parametric studies for commercial plants, e.g., maintaining a particular power level, or the economics of plant availability and wall change-outs, etc., are not applicable to TNS. Therefore it will be noted that some of the results reported in this work are unique to the particular type of TNS device considered and may not be relevant to other types of tokamaks such as power reactors.

EFFECT OF MAJOR DESIGN VARIABLES

The toroidal field strength, of course, has a major impact on the size, cost, and likelihood of success of an ignition device such as the PGFR. High field is desirable because plasma performance improves as the on-axis field increases, resulting in smaller and cheaper machines. However, this trend to less expensive devices as the field increases has been shown to reverse itself as the inboard components are pushed to their engineering limits. Therefore, it is not always cost effective to continually increase the toroidal field. This is shown in Fig. 1 where PGFR relative costs are shown as a function of the toroidal field at the coil for several values of ignition β. The costs shown represent the locus of minimum cost machines at each value of the toroidal field, and have been normalized to the cost of the PGFR reference design described below.

Several trends are evident in these curves. For a particular ignition β, as the field strength increases, costs decrease to a minimum and then increase. Examination of the particular minimum cost machines along these lines indicates that the major radius decreases with increasing field until the minimum cost is reached. For example, at a 6% ignition beta, the major radius of the minimum cost machine at 7 T peak field is 5.25 m whereas at 10 T it is 3.5 m. For further increases in the field strength, there is no more usable space in the centerpost region and the major radius increases very slightly as, among other effects, the thicker TF-coils and inboard shield tradeoff against a decreasing minor radius. The plasma power increases with the increasing field, and higher costs are incurred primarily because of thicker TF-coils, increased neutral beam costs, and larger capacity heat rejection systems.

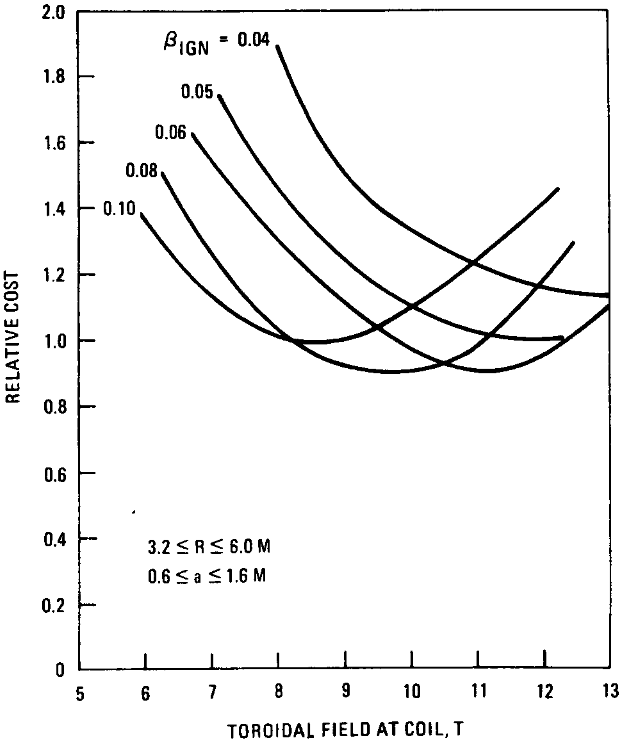

FIGURE 1. Effect of maximum toroidal field and ignition beta on PGFR cost

The effect of the major radius on the cost is shown in Fig. 2 for two values of ignition beta. The toroidal field and the minor radius were not held fixed and were selected to yield the minimum cost machine at each major radius. In general, the smaller machines incorporate the smaller minor radii and the higher fields. The costs are a strong function of the major radius as expected for this type of device. Costs are reduced by decreasing the major radius until all the inboard components have been pushed to their limits and the central bore limit has been reached. Over a range of β from 6 to 10%, the minimum major radius achievable was about 3.2 m and was independent of β. In the case of a 10% ignition β, the toroidal field has increased to 9 tesla at the coil when the central bore limit is reached, whereas the field for 6% ignition β is about 11 tesla at this

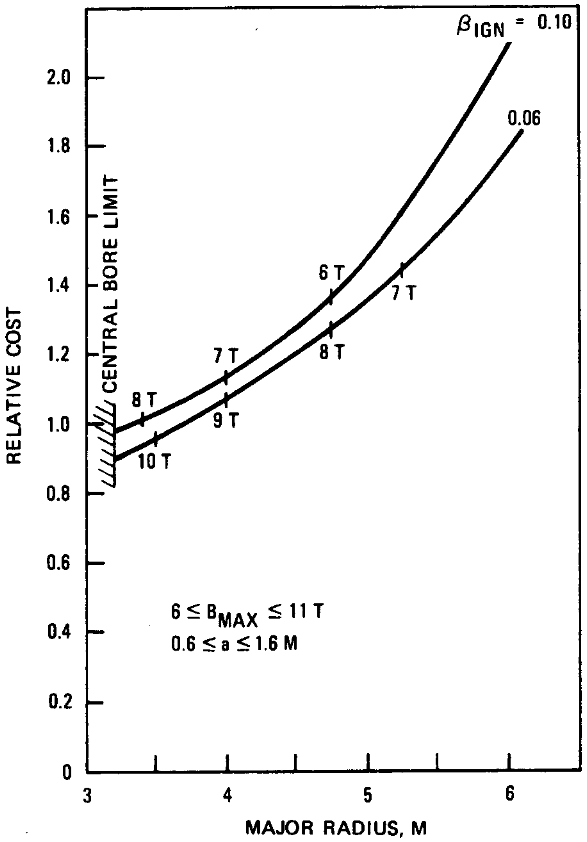

FIGURE 2. PGFR cost as a function of major radius

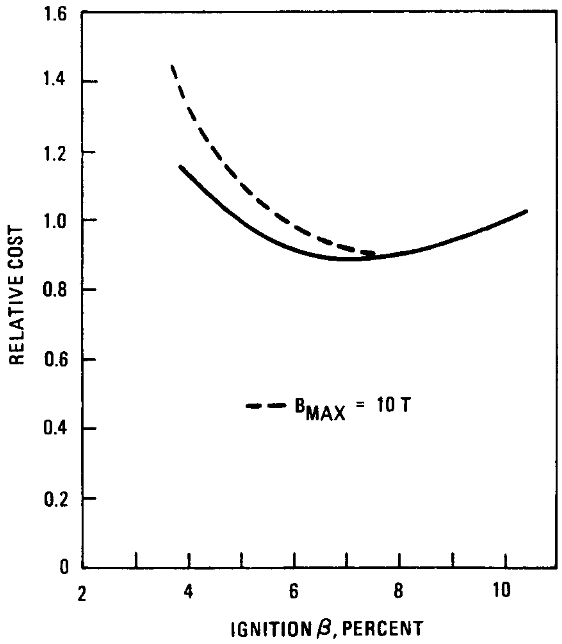

FIGURE 3. PGFR minimum cost as a function of ignition beta

limit. Near the central bore limit, however, the field increases rapidly and one need back off only slightly from this limit to operate at the 10 T maximum field achievable with bath-cooled cryogenically stabilized NbTi superconductor. This 10 T limit which occurs at R = 3.5 m is shown in Fig. 2 along with the minimum major radii for other values of the field strength.

From Fig. 1 it was seen that there exists a minimum cost machine for each value of the ignition beta, and these are shown in Fig. 3. With no restriction on the maximum toroidal field (solid line in Fig. 3), the cost decreases fairly rapidly with increasing beta until it reaches a minimum at around 6% to 7% β. With further increases in β, the cost increases although somewhat less sharply. If the maximum toroidal field is limited to 10 T, as in the case for NbTi as adopted in this study, the costs are somewhat higher at the lower betas (broken line in Fig. 3). At first glance, the increasing costs at higher ignition beta are unexpected because it implies that upon taking margin out of the machine (i.e., designing such that it need not ignite at low β), the costs increase rather than decrease. However, examination of the details of the minimum cost devices at 6 and 10% beta reveals the reasons for this behavior. The minimum cost 6% β device was obtained at a maximum toroidal field of 11 tesla and major and minor radii of 3.2 and 0.7 m. With 10% beta, the major radius is the same, however the optimum toroidal field of 8.5 tesla requires a minor radius of 1.0 m for acceptable alpha confinement. The plasma power is comparable in the two devices because the lower field offsets the higher beta, and the balance of plant (BOP) costs differ only slightly. The cost of the lower field TF-coils of the 10% β device is significantly less than that of the 11 tesla coils, however this cost advantage is more than offset by factors directly or indirectly related to the larger minor radius of the higher β machine. For example, the plasma chamber surface area for the 10% β device with its 1.0 m minor radius is 50% greater than that of the 6% β machine, yielding a sizable increase in chamber cost. This effect is further reflected in the outboard field-shaping coils, blanket, and shield which have a larger perimeter and height, and in the inboard components which, despite their smaller circumference, are still more massive because of their increased height. In addition, the larger minor radius requires higher energy neutral beams for penetration of the plasma, again at an increased cost. These increases in the cost of most of the components and systems more than offset the less expensive TF-coils made possible by the higher β, accounting for the higher total cost. It appears, therefore, that even without exceeding 10 T at the TF-coil, it is possible to design for ignition at 6% β with only a modest cost penalty relative to a higher β PGFR.

According to theoretical investigations, the maximum allowable β consistent with MHD stability is about 10% for doublets.(5) There is, of course, much uncertainty associated with these estimates, and it remains to be seen whether or not the experimental limits agree with theoretical predictions. It is prudent, therefore, to design the PGFR for an ignition beta somewhat below the theoretical value. For the current PGFR design study, an ignition β of 6% (with $Z_{eff} = 2.0$) has been selected as this represents a reasonable retreat from the theoretical limit while allowing for a design without unreasonable cost penalties.

On the basis of the parametric results shown in Figs. 1 and 2 and the selection of 6% beta, it was concluded that the optimum PGFR design would have a major radius close to 3.5 m with a maximum field at the coil of about 10 T. Therefore, additional parametric surveys were made about these points utilizing finer increments in the design variables and incorporating a few minor modifications in the design specifications. (These minor modifications included a slightly flatter density profile, a more efficient TF-coil cross section, a slight reduction in the allowable superconducting OH-coil field, etc.) These studies, which were similar to those discussed above, yielded a preliminary reference design for the PGFR consisting of major and minor radii of 3.6 and 0.95 m, respectively, a maximum toroidal field of 10 T, and a plasma power of 960 MW. Other characteristics of this machine are shown in Table 1 and a description of the device is given in Ref. (6).

TABLE 1. PGFR reference design parameters

Major radius	3.6 m	
Minor radius	0.95 m	
Plasma height-to-width	2.7	
Field on axis	5.1 T	
Burn time	30 sec	
Duty factor	0.5	
Number of TF-coils	12	
Peak plasma power	960 MW	
Z effective	2.0	1.0
Ignition beta	6%	5%
Burn beta	7%	

SENSITIVITY STUDIES — MINOR DESIGN VARIABLES

Utilizing the PGFR reference design, the impact of changes in some of the minor design variables was investigated. The toroidal field coil system is one of the major cost items, and therefore the effect of changing the number of TF-coils is of interest. The two primary effects on the overall design of changing the number of coils is shown in Fig. 4 where the cost relative to the reference design and the maximum clearance between outboard legs of the coils are given. Constant tension coils were assumed, and the ripple at the outer edge of the plasma was held to a constant 0.5% until the minimum TF-coil toroidal bore which can still accommodate the necessary tokamak components was reached. The coil size was held constant beyond this point and the ripple allowed to decrease. For fewer then twelve coils, the cost increases significantly. The components which contribute most to this effect are the TF-coils themselves, the OH-coil, and the tokamak building. With a constant ripple, a decrease in the number of coils means an increase in the coil horizontal and vertical bores with a corresponding increase in the coil perimeter. The cross-sectional area

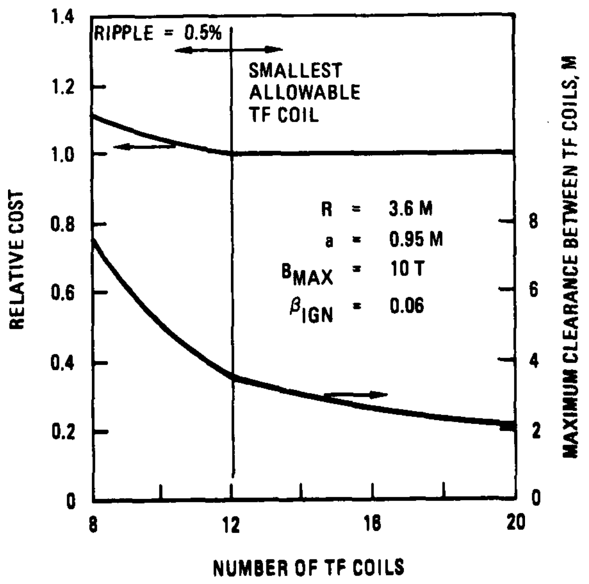

FIGURE 4. Effect of number of TF-coils on PGFR cost and access

of superconductor for the entire coil set does not vary with the number of coils, however the longer conductor length results in a more expensive coil set. Because of the taller TF-coil, the ohmic heating coil solenoid must be longer and thus is more expensive. It is also necessary to provide a larger tokamak building to accommodate the larger TF-coils and there is a corresponding increase in the building cost.

For more than twelve coils, it is no longer possible to decrease the coil size to maintain 0.5% ripple because the coil bore is essentially filled with the chamber, field-shaping coils, shield and other related supports, coolant piping, etc. Therefore, the coil size remains fixed and, as indicated in Fig. 4, the total cost remains essentially constant.

The clearance between coils is significant because all maintenance operations inside the shield must be performed remotely and sufficient space must be available for removal of components between TF-coils. The clearance varies inversely with the number of coils with the effect becoming more pronounced as the number of coils decreases. The knee in the curve occurs because at twelve coils the controlling factor is no longer the 0.5% ripple but rather the constraint on minimum coil size. In selecting the number of coils for the reference design, the only incentive for increasing the number of coils beyond 12 would be to decrease the ripple below 0.5%. Recent theoretical studies have indicated that further reductions in ripple are probably not required.(7) Reducing the number of coils below 12 becomes a tradeoff between additional cost and increased access. It is felt that the 3.5 m maximum clearance afforded by 12 TF-coils is probably adequate for the reference design and that the additional cost that would be incurred by increasing this clearance is not warranted.

A duty factor of 0.5 was tentatively selected for the PGFR as adequate to demonstrate operation approaching that of a power reactor. The effects of changing this variable were investigated and the results are shown in Fig. 5. The burn time was held fixed at 30 seconds and the dwell time was varied so that the effect of the duty factor on the cost might be established. Between duty factors of 0.1 and 0.7, the cost is essentially linear. It was found that all of the cost change is attributable to items associated with the balance of plant. This includes primarily the heat rejection systems, the electric plant equipment, the turbine plant equipment and the deuterium-tritium handling system. Because it is assumed that the cooling systems include load

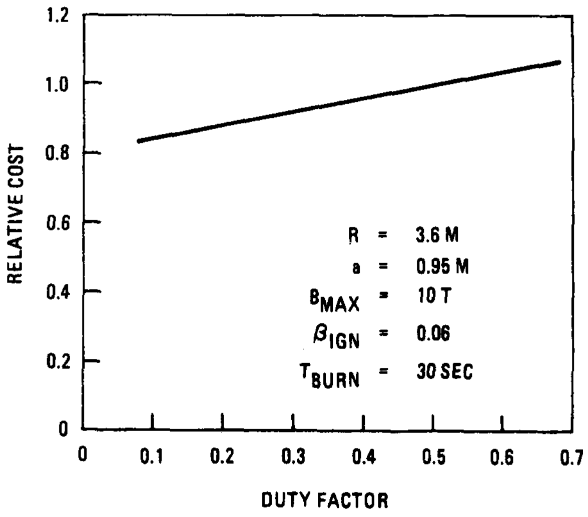

FIGURE 5. Effect of duty factor on PGFR relative cost

leveling capabilities whereby the ultimate heat rejection takes place over the entire cycle, not just during the burn, the heat load to be dissipated varies directly with duty factor. The heat rejection systems for a 0.7 duty factor must therefore be sized at 7 times the capacity of those at 0.1, and with the appropriate cost scaling relationships, the cost of this system increases by more than a factor of 3. Similar arguments apply to the other BOP systems, each with their appropriate cost scaling factors.

While a burn time of 30 seconds was tentatively selected for the reference design, it was nevertheless desired to examine the sensitivity of the design selection to variations in this parameter. Accordingly, minimum cost designs were identified for specified burn times ranging from half to twice the reference case. The duty factor was held constant at 0.5. The ignition beta was maintained at 6% and the 10 T constraint on the NbTi superconductor was applied. As shown in Fig. 6, variations in the burn time between 15 and 60 seconds have very little effect on the total cost (at 15 seconds the cost is only 2% greater than at 60 seconds). Examination of the costs of individual components and systems reveals that the cost insensitivity is due to decreases in the cost of the tokamak equipment which offset increases in the BOP systems as the burn time is shortened. Because the criterion for the inboard shield thickness is to limit the total energy deposited in the TF-coil during the burn period, the shorter burns result in thinner, less expensive inboard shielding. With a fixed maximum field at the TF-coil, the thinner shield allows the plasma to move closer to the coil, yielding a greater on-axis field. This, coupled with the smaller, less expensive, OH-coil (because fewer volt-seconds are required for the shorter burn), allows a reduction in the major radius with additional small cost savings in almost all tokamak components. The increases in the BOP system costs are due primarily to the refrigeration system and to the electric plant equipment. Because the rates of eddy current heating in the OH-coil and nuclear heating in the TF-coil are both inversely proportional to the cycle time, the cost of refrigeration increases as the burn time (and cycle time since duty factor is fixed) decreases. A similar situation exists with the electric plant equipment, the cost of which increases with the parasitic power. While the cycle averaged power requirements of some components such as the field-shaping coils do not change with the burn time, other components in which the energy transfer is relatively fixed, reflect significant increases in average power requirements for reduced cycle times. Examples of these are the OH-coils, the neutral beams, and the refrigeration system. These higher parasitic powers reflect increased costs for electric plant equipment when the burn time (and thus cycle time) is reduced.

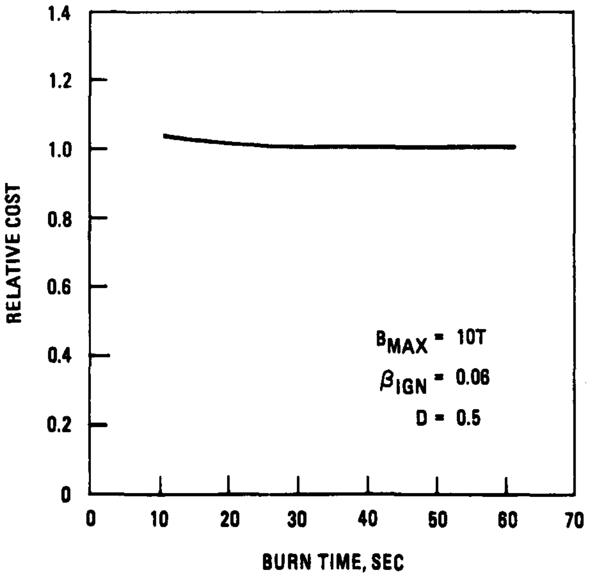

FIGURE 6. Effect of burn time on minimum cost

The recent TNS Ignition Test Reactor design effort[(8)] yielded a highly effective inboard shield design incorporating tungsten bricks. A comparative study of stainless steel and tungsten performed at that time indicated that despite the significantly greater shield cost, a machine incorporating the more effective shield material tungsten is smaller and less expensive overall. Such an analysis is of course sensitive to the cost of the fabricated shield blocks. Because the cost of tungsten has increased significantly during the last year, it was decided to again compare these two shield materials, this time for the PGFR. Vendor information and in-house estimates were used to establish current unit costs for fabricated tungsten and stainless steel shield blocks of $44/kg and $5/kg, respectively. Parametric surveys were performed to identify the minimum cost designs for both shield approaches. The burn time, duty factor, number of TF-coils, maximum field, and ignition beta were held fixed at the reference design values. The 3.6 m reference design is the least expensive design utilizing a tungsten inboard shield. The cost of the 40 cm thick W shield (including installation and contingency) is estimated to be $22 million. The smallest (minimum cost) machine incorporating a stainless steel inboard shield has a major radius of 3.9 m. The stainless steel inboard shield thickness is increased by 15 cm, and the shield cost is reduced by about $17 million because of the less expensive shielding material. However, because of the larger major radius of this design, most of the reactor components are slightly larger and therefore more expensive. The net effect is that the sum of the small cost increases in individual components more than offsets the large reduction in shield cost with the SS shield design, yielding a slightly higher overall cost. It appears therefore that at the current prices of tungsten and stainless steel, the former shield material is more cost effective for a doublet PGFR, however significant changes in material costs could alter this conclusion.

SUMMARY AND CONCLUSIONS

Parametric studies of a Power Generating Fusion Reactor for TNS were performed to investigate the tradeoffs between machine cost and margin (ignition beta). A reference PGFR design was selected, and the sensitivity of the design to changes in certain parameters was explored. On the basis of these studies, the following conclusions, some of which are unique to a PGFR because of the particular requirements of TNS, can be made:

1. At each value of the beta at ignition, there exists an optimum toroidal field strength at which the cost of the PGFR is minimized. In general, this optimum field increases with decreasing beta.
2. Over the range of ignition beta explored in the present study (4 to 10 percent), the overall minimum cost PGFR is obtained at a beta of about 7%. Further increases in beta do not yield less expensive devices.
3. Incorporating margin into the PGFR by designing to a reduced ignition beta of 6% (at $Z_{eff} = 2.0$) and by limiting the maximum toroidal field to 10 T at the coil is possible at a modest cost penalty of about 10% above that of the overall minimum cost device.
4. Within the ground rules established for a doublet PGFR, the minimum cost design is obtained with a 3.6 m major radius 0.95 m minor radius machine.
5. Reducing the number of TF-coils below the 12 of the PGFR reference design while maintaining the ripple at 0.5% provides additional clearance between coils but at an increased cost. Because the current 3.5 m clearance appears adequate, such a reduction was judged to be unnecessary.
6. Because the TF-coil toroidal bore in the reference design is essentially filled, the coil may not be reduced in size, and increases in the number of coils beyond 12 results in reduced ripple, reduced clearance, and virtually unchanged costs. Because ripple reductions appear unnecessary, no incentive exists for such changes.
7. The PGFR cost increases linearly with the duty factor; over the range explored, this

increase is about 4 or 5% for each 0.1 increment in duty factor.

8. Increases in the burn time yield larger minimum cost machines, however the total costs of these devices are relatively insensitive to the burn time because increases in tokamak equipment costs are offset by decreases in the costs of BOP equipment.
9. Utilization of a relatively expensive tungsten inboard shield provides a smaller overall less expensive PGFR design as compared to one incorporating a stainless steel shield.

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