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PARAMETRIC INVESTIGATION OF TNS CONCEPTUAL DESIGNS

by

D. W. GRAUMANN

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PARAMETRIC INVESTIGATION OF TNS CONCEPTUAL DESIGNS*

D. W. Graumann
General Atomic Company
P.O. Box 81608
San Diego, California 92138

Parametric studies have been performed as part of the General Atomic/Argonne National Laboratory TNS scoping effort to aid in the selection of initial conceptual design parameters. A systems analysis computer code, SCOPE, which incorporates plasma physics models to describe the plasma ignition and burn performance, and engineering and costing algorithms to define and cost the reactor components, support systems, and balance of plant was the primary tool utilized in the parametric studies. Studies were performed for moderate burn time (30 sec), low duty factor (0.1) ignition test reactors. Doublet shaped plasmas were assumed for high β (10%) operation, and based upon power and cost considerations derived in separate TNS scoping studies, superconducting toroidal field coils were assumed. Surveys over a broad range of parametric space indicated that minimum cost machines are obtained for maximum fields of 8 to 10 tesla at the TF coils, with larger, more costly machines resulting at higher and lower fields. Major radii of 3.5 to 4.0 meters are required, with the size increasing for higher margin machines. Investigations of normal conducting and superconducting OH coils over the narrower parameter range of interest indicated a strong cost incentive for incorporating superconducting coils. On the basis of these parametric studies, a 3.8 m major radius, 1.1 m minor radius Ignition Test Reactor was selected as an initial conceptual design for TNS.

Introduction

During the past year, scoping studies have been performed by a General Atomic/Argonne National Laboratory design team assisted by several industrial subcontractors in order to initiate definition of TNS, the next major tokamak device beyond DIII and TFTR. As part of the overall scoping effort, parametric studies have been conducted to aid in the selection of initial conceptual design parameters. With a parametric investigation it was possible to evaluate numerous potential designs and to identify the impact of each design modification. Two bases upon which potential TNS machines can be compared are the cost and the ignition margin, and an additional objective of the parametric study was to investigate the tradeoffs between these two parameters. Moreover, the study was performed to show the cost tradeoffs involved in changing design parameters, to provide information as to the relative cost of different basic design approaches (ITR, ITR upgradable to EPR, etc.), and to explore parametrically the impact of alternative physics scaling laws.

Methods and Approach

A systems analysis computer code, SCOPE,[1,2] was the main tool utilized in the parametric studies. This code 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 parameters such as overall geometry, maximum toroidal field, desired burn and dwell times, allowable stresses and current densities, unit costs, etc., the code calculates the dimensions, heating, stresses, fluence, etc., of individual components as well as the overall machine performance (power level, wall-loading, required volt-seconds, beam energy, etc.) and the cost of the various components and systems.

A simplified flow diagram indicating the calculation sequence and the types of input and output variables is shown in Fig. 1. Initial calculations are performed to establish the existence of ignition and burn equilibria utilizing three types of input variables. Geometrical parameters describe the size and shape of the plasma and the machine. The second group of parameters relates to the hardware of the machine

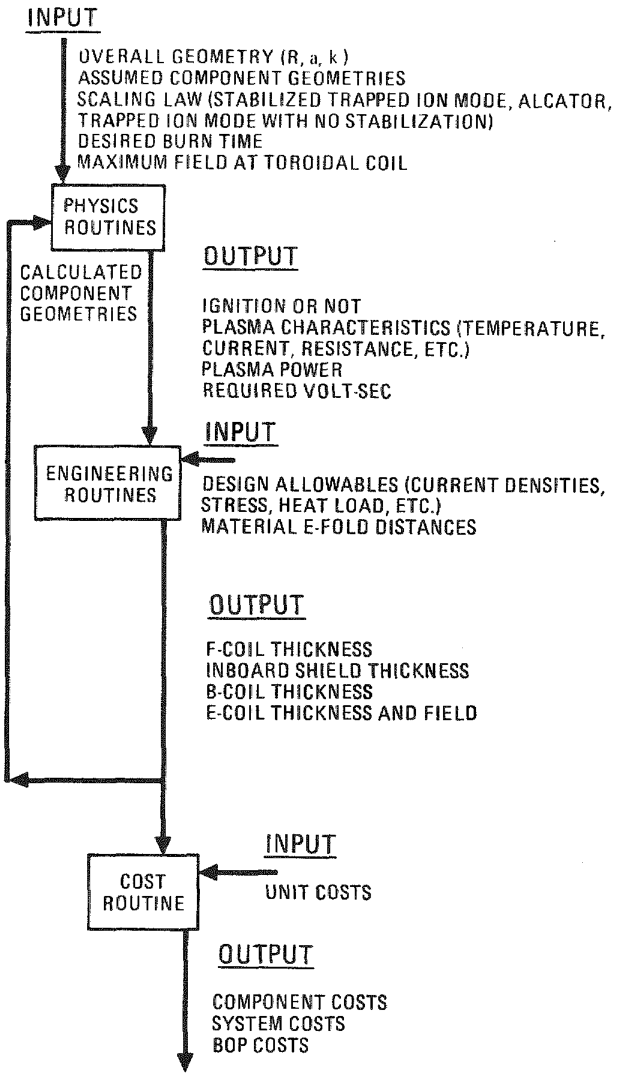

Fig. 1. SCOPE — systems analysis code

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and includes the magnetic field at the toroidal coil and the auxiliary heating power and type. The final group of input parameters amounts to a specification of the plasma itself: the form of the temperature and density profiles, the values of q or β at ignition and burn, and the impurity levels.

This information is processed by a static zero-dimensional code which examines the energy balance of the plasma at ignition and burn. The zero dimensional approach is ideal for scoping since it is fast and sufficiently accurate. Important physical phenomena that are modeled include the conduction losses with choice of several scaling laws, the radiation losses, the alpha particle losses, and impurity and alpha particle contribution to the β of the system. Ignition and burn are determined by a search in n-T space subject to constraints on q and β_p.

If the code determines that an ignition point exists, it then does a simple dynamic start-up calculation. This calculation allows estimates of both the resistive volt-seconds and the time required for startup. If neutral beams are chosen for auxiliary heating then the required beam energy, based on penetration of the ignition density, is calculated. An rf option is also available.

Power levels and wall loadings are accurately calculated by integrating the local power density over the plasma cross section with the assumed profiles. Information from the physics routines, 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 sizing begins at the major radius and progresses inward, establishing in turn the radial thicknesses of the field-shaping coils, the shield, the toroidal field coil, the ohmic heating coil, and the support column. As indicated in Fig. 1, the calculated component geometries are then utilized 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.

The tokamak geometry utilized in the code is shown in Fig. 2. The doublet shaped plasma which was assumed for the present studies is defined by input variables which specify the plasma half width, the height-to-width ratio, and the neck width-to-maximum plasma width ratio. Gaps and clearances between all inboard components are input variables as are the thicknesses of the vacuum vessel and the toroidal field coil cryostat.

Because the vacuum vessel wall thickness is determined primarily by plasma imposed resistance requirements, static buckling considerations, and the loading imposed during a plasma disruption, it is not a strong driver in the geometrical tradeoffs. Nevertheless, because it is not an insignificant cost item, it is included in the SCOPE code and defined by input values of inboard and outboard wall thickness and solid fraction.

The field-shaping coils (F-coils) are idealized as a single thickness set of inboard coils (all coils inside the plasma chamber outer radius) and a set of outboard coils. With coil packing factors as input variables, the F-coils are sized to meet allowable current density and allowable stress criteria, with the more limiting case determining the coil thicknesses. (In general, the current density limit is almost always controlling.) The coil volume as well as the I^2R power is calculated and utilized in the costing routine to establish the cost of the F-coils and their power supplies.

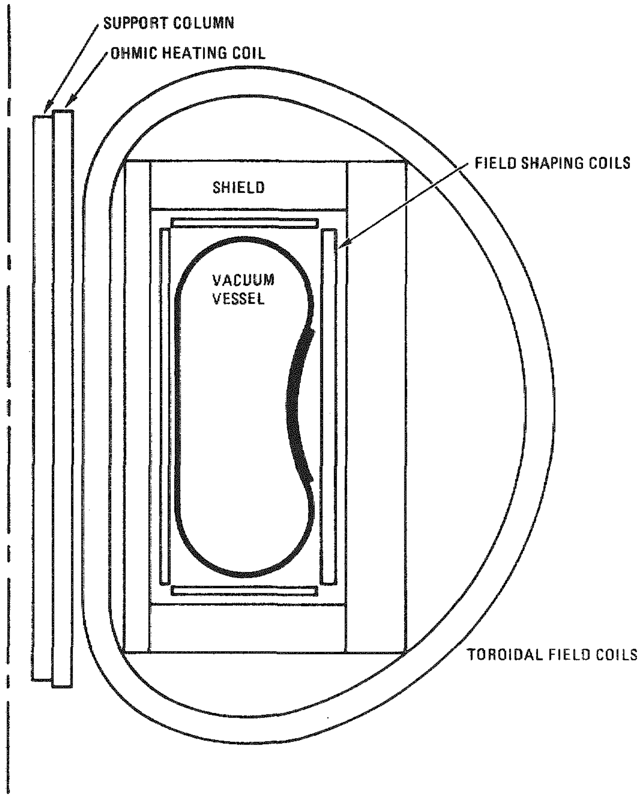

Fig. 2. Reactor geometry utilized in SCOPE code

The shield is also divided into inboard and outboard sections, each with its own design criterion. The function of the inboard shield is to protect the inboard leg of the toroidal field coil from excessive neutron heating and damage. Input e-folding distances for the shield and all components between the shield and the plasma are utilized to determine the radial thickness of shield required to limit the total nuclear heating of the toroidal field coil to 1 MJ during a burn. The outboard shield which is designed to limit the activation of external equipment is defined by an input value of shield thickness.

The toroidal field coil (B-coil) may be either superconducting or normal conducting copper. For the superconducting case, the coil is contained in a 5 cm thick cryostat and incorporates a support column (integrated with the S/C E-coil) on the inside of the inboard leg. Input variables relevant to the B-coil include the field at the inner leg of the coil, the number of coils, the desired current densities in the copper stabilizer and in the superconductor, the allowable ripple, the allowable stress in the copper, and the allowable stress in the support column.

Constant tension coil shapes are utilized, and the outer radius of the coil is calculated based upon the ripple and the number of coils. The cross-sectional area of conductor is calculated from the required amp turns and input values of current densities. Because the strain in the copper is limited to about 0.2% due to its strain versus resistivity characteristics, the stress is also limited, and reinforcement of the coil may be necessary. The code calculates the required cross sectional area of conductor based on the constant tension loading using an input maximum allowable stress, and if more conductor is required based on stress considerations than is available based on current carrying requirements, the code adds stainless steel reinforcing structure as required according to the ratio of the effective modulii of copper and steel. The B-coil cross sectional area exclusive of dewars, helium vessel, and support column is then calculated by dividing the sum of the Cu, superconductor, and reinforcing steel areas by an appropriate packing factor which accounts for insulation, spacers, and coolant channels. The thickness of the helium vessel is sized to contain a pressure of 50 psi and is calculated assuming the vessel wall is a clamped plate with uniform pressure loading. From the total area and the known outer radius of the inboard leg, the coil radial thickness is calculated. The total nuclear heat deposited in the inboard leg of the B-coil is calculated utilizing the heating rate at the edge of the B-coil from the shielding calculations. The thickness of the epoxy-fiberglass support column is calculated to resist the radial load without exceeding the maximum allowable stress in the column, an input value.

The ohmic heating coil (E-coil), which may be specified as either normal or superconducting, is assumed to be an air core coil with uniform current density. The code sizes the F-coils, shield, and B-coils before calculating the E-coil parameters so that the E-coil outer radius is determined by the geometry for a particular run.

For a normal conducting E-coil, the hole radius is fixed at 0.6 of the outside radius as this is the value at which maximum flux is obtained. The input parameters are the maximum stress and the thickness of the reinforcing steel band. For a specified solenoid outside radius and maximum stress, the normal E-coil is generally evaluated in a fully biased mode with the coil fully stressed to produce the maximum possible (negative) flux, in which case the ohmic heating losses during the burn period are reduced. The E-coil may be prestressed in compression with a steel band whose thickness may be specified. For a superconducting coil, half biasing is assumed because ohmic losses are negligible. The coil thickness and required field are calculated from an input allowable current density, an assumed packing factor of 0.7, and the volt-second requirement as determined in the physics routines.

The code calculates four types of losses for the E-coil. These include ohmic losses during startup, ohmic losses during the burn, stored energy in the E-coil magnetic field at full back bias, and stored energy in the E-coil magnetic field at the end of the burn. It is assumed that none of the stored energy is recovered. The ohmic losses which are calculated for the E-coil solenoid are increased by 40% to account for the outer turns. The energy losses are summed and divided by the cycle time to determine an average E-coil power requirement. The E-coil peak power is used for costing of the power supplies.

The power supplies for the normal conducting E- and F-coils are rated for the peak power requirements of these coils. Energy storage costs are calculated for the normal E-coil assuming a motor-generator set is utilized, and for the superconducting E-coil assuming a homopolar machine. The total energy is the sum of the E-coil ohmic and stored energy losses described above. No allowance is made for F-coil energy storage as it is assumed that the F-coil power will be drawn from the line. Neutral beam energy storage and power supply costs are included in the neutral beam costs.

Neutral beam efficiency and costs are calculated from the beam energy, the beam power delivered to the plasma, and the length of the beam pulse (taken as the time to get to ignition). The beam energy is utilized to calculate the neutralization efficiency which decreases rapidly with increasing beam energy. Combining this neutralization efficiency with the fraction deuterons in the incident beam, the fractional loss of the beam in the acceleration system, and the efficiency with which the neutral component of the beam is transported into the plasma, an overall injector power efficiency is obtained. The beam costing includes the cost of accelerating grid power supplies and controls, injectors, auxiliary power supplies, and beam line controls. A motor-generator set is assumed for neutral beam energy storage.

The balance of plant total cost is calculated by summing the costs of approximately 30 individual components and systems which make up the BOP. These include site improvements and the various buildings, radioactive waste equipment, heat transport and rejection systems, electric plant equipment, the power conversion system components, and other reactor plant equipment. For the most part, these costs are scaled from the General Atomic EPR detailed cost estimates utilizing appropriate functions of machine size, plasma power, duty factor, and, in the case of an electricity producing device, the gross electrical power. Construction facilities, services and indirects as well as engineering services are included in the BOP costs for these studies.

The SCOPE code has proved to be a versatile tool for parametric studies and has been used in several modes. For parametric studies, individual components are sized to meet certain design constraints, however the code can also be used to evaluate the performance of a specific reactor design. In this mode, the machine geometry is input completely and component stresses, heating levels, current densities, etc., are output along with the plasma performance characteristics. The code has also been utilized for optimization studies by coupling it to an optimizing driver code.

While the bulk of the parametric calculations were carried out with the SCOPE code, a crucial facet of the overall parametric study were discussions among, and criticism by, staff with expertise in the various areas addressed in the code. The SCOPE code has not been a static tool, but rather has evolved throughout the study and has been constantly updated with improved physics and engineering models, revised design allowables, and expanded capabilities. As the design philosophy of individual components or the overall machine changed, these modifications have been incorporated.

Parametric Studies

The TNS parametric studies have been evolutionary in that the bases of machine comparison have developed with changes in TNS design philosophy, with increased understanding of the tradeoffs involved, and with the expansion of code capabilities. While early evaluations were made on the basis of cost alone, it became obvious that some measure of the assurance of physics success with the machine should be factored in, and consideration of the machine margin as well as the cost became an important factor.

Both the cost and the ignition margin are difficult parameters to define accurately because of the preliminary nature of the TNS study, the relatively new and developing technologies involved, the complex interaction among variables, and the uncertainties of the plasma scaling laws. While the code models are not intended to be the last word with respect to cost and margin, they are thought to be good measures of both these parameters consistent with a scoping study. The costing methods include scaling from EPR detailed cost estimates, scaling from actual costs incurred in the Doublet III program, scaling from detailed cost information developed at General Atomic for the High Temperature Gas-cooled Reactor, and, where applicable, substantiating cost data by comparison with TFTR estimates and information from the General Atomic cost development group. The ignition margin is defined for a particular design by reducing the confinement time by a factor of 2, 3, etc., and determining the minimum density at which the device ignites. The relative margin is defined for the purposes of this study as the ratio of the theoretical confinement time to the reduced confinement time and is therefore a function of the particular scaling law.

Broad Range Survey

In order to narrow the range over which a more detailed parametric study could be performed, an initial survey was conducted over a broad range of major machine parameters. The major radius was varied between 3.5 and 6.0 meters in increments of 0.5 meter, while the minor radius ranged from 0.7 to 1.3 meters in 0.15 meter steps. The maximum field at the toroidal field coil was set at 5, 8, 10, 12, 14, and 16 tesla. The analysis was done for an ignition test reactor (not upgradable to an EPR) incorporating superconducting toroidal field and ohmic heating coils, normal copper field shaping coils, a high efficiency tungsten/B_4C inboard shield, and assuming auxiliary heating by neutral beams which penetrate to the center of the plasma, and EPR scaling.[3] A superconducting toroidal field coil was selected over a normal coil based upon an evaluation of both overall systems.[1] The cost of the normal system is more than twice that of the superconducting system, due primarily to the larger cost of power supplies and energy storage. Utilizing the code, ITR machines with ignition margins from 1 to 5 were sized on a self-consistent basis for all combinations of these variables and their costs determined. There were, of course, in this parameter space a certain number of designs that either could not ignite or which did not have sufficient space in the inboard region for all necessary components, and such machines were not considered.

The information thus generated yielded many designs, each with a different cost at each value of maximum field and margin investigated. The lowest cost machines are plotted in Fig. 3 as a function of field and ignition margin. It is seen that the machine costs minimize in the 8 - 10 T region with the optimum field (from a cost viewpoint) shifting upward with increasing margin. At lower and higher fields, self-consistent ignition devices were obtained only for relatively larger sizes. At high fields the B-coils become quite thick in order to withstand the large tensile loads, and the major radius must increase to provide room for the coils. At low fields, the coils are relatively thin, however, because of the low on-axis field, a relatively large minor radius is required to improve confinement, resulting again in an increased major radius. In the region of overall minimum cost, machine sizes of 3.5 to 4.0 meters major radius were obtained. It was concluded therefore that additional parametric studies would concentrate on machines with major radii of 3.5 to 4.0 m and with maximum B-coil fields of 8 to 10 tesla.

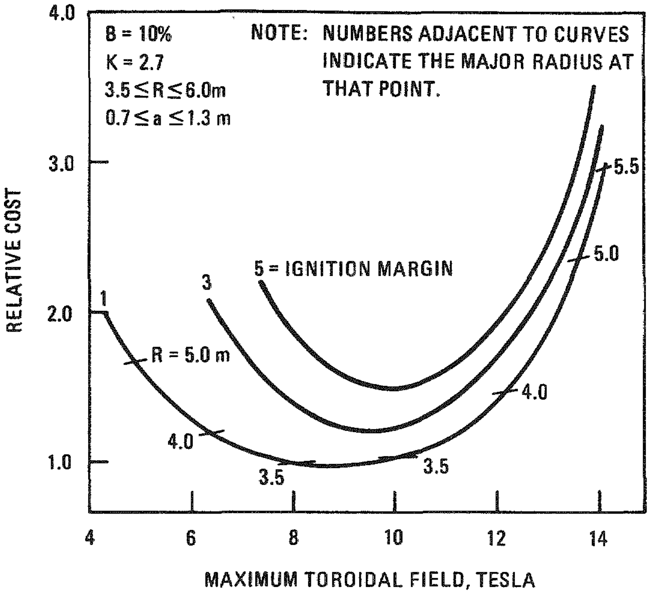

Fig. 3. Broad range analysis showing effect of field on cost

Limited Range Evaluation

With the range of variables limited to a narrower area of interest, more detailed scoping studies were performed utilizing smaller increments of the design variables and incorporating the plasma height-to-width ratio as an additional design variable. Major radii of 3.6, 3.7, and 3.8 m, minor radii of 0.9, 1.0, and 1.1 m, height-to-width ratios of 2.5, 2.7, and 3.0, and B-coil fields of 8, 9, and 10 tesla were investigated. Again, machines with varying ignition margin were sized and their costs determined to provide a basis for selection of a machine size around which an initial conceptual design could evolve.

The cost penalty associated with providing margin is shown in Fig. 4 where the relative costs of the least expensive machines required to achieve a given margin are indicated. The locus of minimum cost solutions does not represent one particular machine but rather is generated by the least expensive device at each margin value. A survey of all solution points indicated that low field, small size machines form the lower portion of the curve while the high field, larger machines are most cost effective for the more conservative higher margin cases.

A similar evaluation was performed for an ignition test reactor incorporating a normal conducting E-coil rather than a superconducting one. Whereas the superconducting coil was assumed to be half-biased, the normal coil was fully stressed to produce the maximum possible (negative) flux, thereby reducing the ohmic heating losses during the burn. The locus of least expensive solutions for the ITR with a normal E-coil is shown as a broken line in Fig. 4 where it can be compared with the superconducting case. The costs range from 15 to 25 percent higher for the normal coils, due primarily to increased energy storage and power supply costs. While it is realized that the technology essential for a superconducting OH-coil is not as developed as that for a normal copper design,

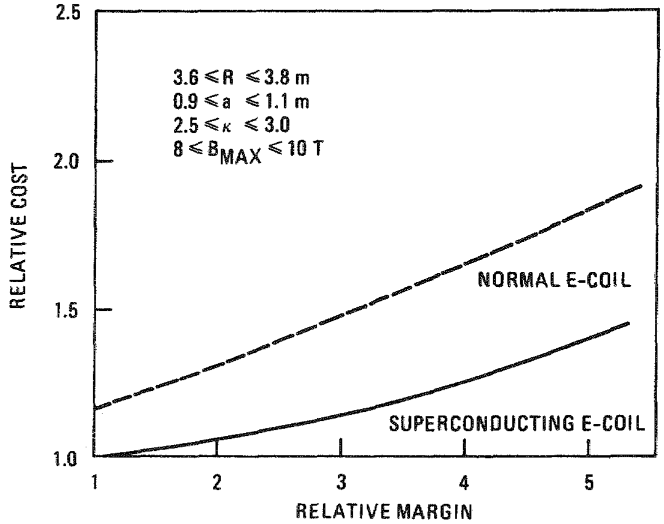

Fig. 4. Limited range analysis showing effect of ignition margin on cost

the projected cost differential is sufficient to make the s/c design the preferred approach at this time.

The effect of the toroidal field is shown in Fig. 5 with the other design variables fixed. With barely ignition machines (relative margin = 1.0) the cost increases with the field, essentially because the size and cost of the coils increase. As the margin increases, the costs are higher because the larger plasma densities result in increased neutral beam costs. It is seen that the margin potential of a particular machine reaches a limit and, as expected, this limit increases with increasing field. The cost of providing margin is also seen to increase rapidly as the margin limit is approached. Examination of these curves and the positions at which they cross, indicates that for little margin, the minimum cost is achieved with an 8 tesla coil, whereas for moderate and large margins, the least expensive devices are obtained with 9 and 10 tesla respectively. A rigorous selection of the toroidal field would depend therefore on the level of margin desired in the design. However, because of the uncertainties associated with the scaling laws, it appears prudent to design with 10 tesla in order to retain the potential for greater margin, even though the cost may be somewhat greater.

It is noted that the same general trend of these curves is obtained for machines of different size, with the margin limits and cost cross-overs occurring at different locations.

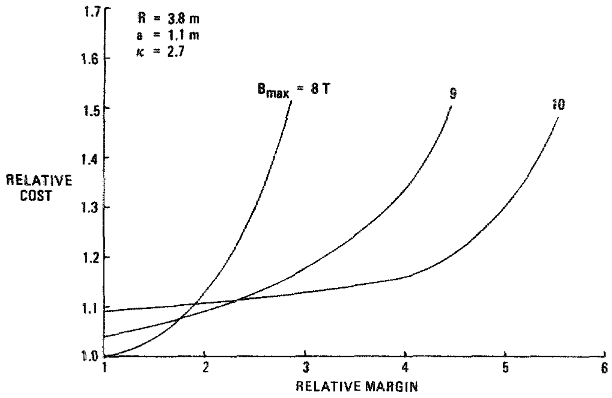

Fig. 5. Effect of maximum field on cost and margin

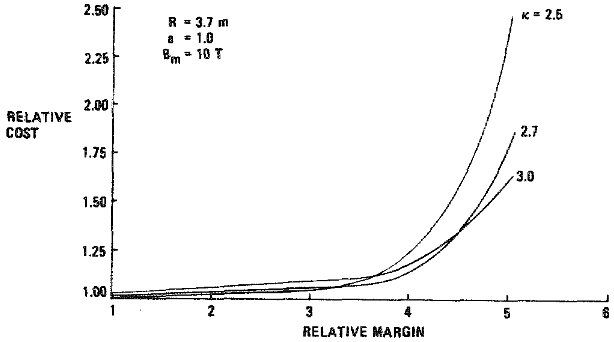

Fig. 6. Effect of height-to-width ratio on cost and margin

The plasma height-to-width ratio, κ, when varied between 2.5 and 3.0, was found to have only a minor effect on the cost in the low to moderate range of margin. The costs of 3.7 m major radius, 1.0 m minor radius machines with height-to-width ratios of 2.5, 2.7, and 3.0 are shown in Fig. 6. At low margin the smallest κ (which yields the smallest machine) is least expensive by a small amount. As the margin increases, the κ = 2.7 machine and then the κ = 3.0 machine become the most economical designs. Because the cost differences are not large, there are really no strong incentives for selecting one κ over another over most of the range of margin. It was noted, however, in parametric investigations utilizing Alcator scaling as well as EPR scaling that ignition was more likely with more elongated plasmas. On the other hand, plasma stability considerations seem to indicate a preference for a height-to-width ratio of 2.7.[1]

Figure 7 shows how the plasma minor radius affects the cost and achievable margin of an ignition test reactor. For low margins, as was the case for toroidal field and height-to-width ratio, the smallest machine (indicated by the smallest minor radius) is least costly. As the margin increases, the smallest device reaches its margin potential first and its cost increases rapidly and successively larger machines become the optimum cost designs. Because the 0.9 meter minor radius does not permit the flexibility to design for high margin by adding additional auxiliary heating, it was eliminated from candidate designs. In addition, in parametric runs with Alcator scaling, 10 tesla machines with R = 3.7 and 3.8, and κ = 2.7 did not ignite with a 0.9 meter minor radius whereas they did for 1.0 and 1.1 m.

The purpose of Fig. 7 is not to provide an absolute basis upon which to select the minor radius of the initial conceptual design, but rather to show the effect of minor radius when it alone is the independent variable. Selection of the minor radius must be made in conjunction with an evaluation of major radius because a cost-margin tradeoff exists when major and minor radii are varied. Figure 8 shows two of the "best" designs resulting from the parametric study which show this tradeoff, one with R = 3.7, a = 1.0 m, and the other with R = 3.8, a = 1.1 m. Both incorporate 10 T coils and a plasma height-to-width ratio of 2.7. The larger machine is more expensive (9% more)

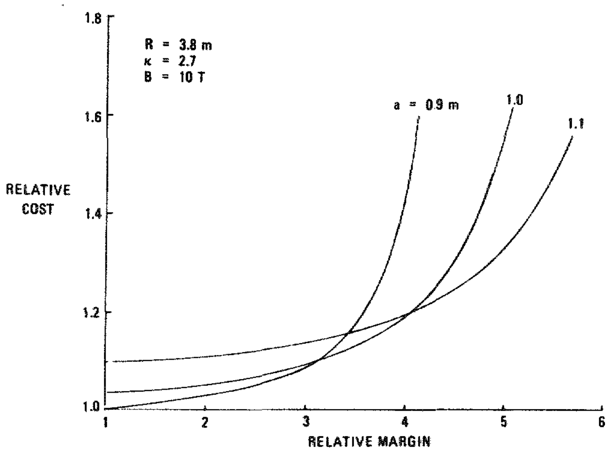

Fig. 7. Effect of minor radius on cost and margin

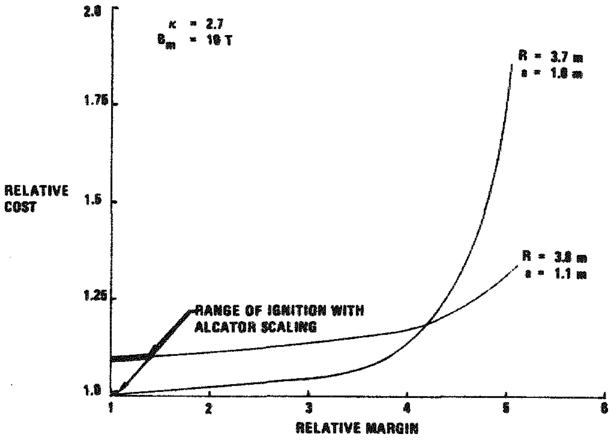

Fig. 8. Cost-margin comparison of candidate TNS configurations

until, at high margin, the beam costs become increasingly significant as the smaller machine first reaches its margin potential. Also shown as the heavy portion of the curves is the relative margin area over which these two machines ignite based upon Alcator scaling. The greater margin potential of the larger minor radius machine is evident. Because of the increased margin potential, the 3.8 m major radius, 1.1 m minor radius machine was selected as the initial conceptual design despite its higher cost.

Conclusions

A systems analysis code, SCOPE, which utilizes coupled physics and engineering routines has been modified and utilized in parametric investigations of potential TNS machines. Based upon the parametric studies performed to date, the most economical TNS Ignition Test Reactor is a machine of 3.5 to 4.0 m major radius with a maximum toroidal field of 8 to 10 tesla. Rigorous selection of the exact design parameters depends upon the amount of margin desired. A major radius of 3.8 m, minor radius of 1.1 m, doublet elongation of 2.7 and design toroidal field at the coil of 10 T have been selected as the basis for an initial conceptual design.

The TNS parametric studies are a continuing aspect of the overall scoping effort. While the bulk of the studies to date have been performed with EPR scaling, similar evaluations have been initiated utilizing Alcator scaling modified for a doublet plasma configuration based on Doublet IIA results, and these efforts are continuing.

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