ELSEVIER

Fusion Engineering and Design 31 (1996) 323–332

Fusion Engineering and Design

# Exploration and assesment of design windows for a Tokamak-based volumetric neutron source

S.K. Ho, M.A. Abdou

*Mechanical and Aerospace Engineering Department, University of California at Los Angeles, Los Angeles, CA 90095, USA*

Received 4 April 1996; accepted 29 April 1996

## Abstract

Design options for a Tokamak volumetric neutron source (VNS) for fusion nuclear technology testing are explored using well-defined and consistent sets of requirements and constraints. Optimum designs with a peak value of the neutron wall load and minimum cost are obtained with intermediate-to-high aspect ratios of about 3.4–3.6. Sensitivity analysis shows that the nuclear technology testing requirements can be achieved in a realistic Tokamak VNS design within the expected uncertainty ranges of the physics and engineering assumptions database. A typical optimum VNS design has an average neutron wall load of 1.5 MW m$^{-2}$, peak wall load of about 2 MW m$^{-2}$, major radius of about 1.6 m, minor radius of about 0.5 m, aspect ratio of 3.6, fusion power of about 100 MW, plasma amplification factor $Q \approx 2$ and on-axis magnetic field of about 7 T. Normal conducting magnets are used with an overall inboard shield thickness of 0.3 m.

## 1. Introduction

Recent studies [1–3] indicated the need for a small-size Tokamak facility to serve as a dedicated facility for testing fusion nuclear technology (FNT) components and materials. The facility, called volumetric neutron source (VNS), should provide a database that is sufficient to construct the fusion nuclear components (blanket, first wall and divertor) for a demonstration power plant (DEMO). Examples of issues to be addressed through testing of FNT components in VNS are as follows: (1) tritium self-sufficiency; (2) materials interactions and compatibility; (3) thermomechanical loads, interactions and responses; (4) failure modes, effects and rates; (5) reliability, maintainability and availability.

The work of Abdou [1] and the recently completed International Energy Agency (IEA) study [2,3], with participants from the US, Japan, the European Union and the Russian Federation, have clearly identified the need for VNS and provided in-depth investigations of the mission, scope and requirements for it. These can be summarized as follows [1–3].

*VNS mission.* The mission is to serve as a test facility for FNT and to provide a database sufficient to construct FNT components for DEMO.

*Testing requirements.* VNS must satisfy the following FNT testing requirements: wall load, 1–2 MW m$^{-2}$; neutron fluence, 6 MW year m$^{-2}$ or more; plasma mode of operation, steady state, or long plasma burn with duty cycle over 80%; minimum test area per test article, 0.5 m$^2$;

*PII* S0920-3796(96)00524-8

total test area, over 10 $m^2$ (up to about 20 $m^2$); device availability, over 25%; minimum continuous operating times (periods with 100% availability), 1-2 weeks; magnetic field at the test region, over 2 T.

*Design features and constraints.* VNS design should be consistent with the following features and constraints:

(i) the configuration, remote maintenance and other design features must emphasize rapid replacement of device components and test articles;
(ii) the device must be able to test all candidate blanket concepts of DEMO, including liquid metal and beryllium;
(iii) the fusion power must be low enough that the tritium consumption does not exceed that available from external sources (e.g. the fusion power should be less than 150 MW with 30% of the first wall occupied by test modules);
(iv) the capital cost of VNS should be kept as low as possible (e.g. less than 25% of that for ITER);
(v) the power consumption of the VNS site (e.g. from normal copper coils, current drive, etc.) should be kept reasonably low (e.g. less than 700 MW).

*Figures of merit.* In determining an attractive design envelope for VNS, cost-benefit-risk analysis and trade-off studies should be conducted. Suggested figures of merit include the following:

(i) the extent of meeting FNT requirements (wall load, fluence, test area, etc.);
(ii) the total capital and operating costs;
(iii) the contribution to nuclear testing for DEMO components;
(iv) additional contributions to satisfy DEMO database requirements other than testing;
(v) minimal R&D to construct VNS;
(vi) confidence in achieving VNS goals;
(vii) contributions to ITER (such as reduced technological burden and possible cost savings);
(viii) contributions to improvements in the development schedule of DEMO.

The IEA study explored briefly options for designs but recommended that further effort be devoted to identifying the design window for attractive, credible and low-cost VNSs.

In this paper, we follow up on the recommendations of the IEA study. We performed systems studies to explore and improve the VNS designs. A near-term physics and engineering database and assumptions were used. We focus on the normal-conducting toroidal field coils with standard aspect ratio, based on the observations from refs. [2,3] that this option has reduced radial build with adequate in-board shielding, as well as minimizing the extrapolation of the near-term Tokamak physics database. Of particular importance in this work is the selection of the best aspect ratio to optimize the design and ensure physics and engineering credibility.

A brief review of the previous work under the IEA study is presented in Section 2. The basic assumptions for modelling are described in Section 3. Section 4 presents the major results in the design window exploration from the systems studies. Section 5 presents a summary of this work.

## 2. Review of previous work

The IEA phase I study on VNS [2,3] briefly investigated three basic variations of Tokamak VNS designs based on the use of superconducting (SC) or normal conducting (NC) toroidal field coils (TFCs) as follows:

(i) SC TFCs and adequate inboard radiation shielding to protect the SC magnets;
(ii) multi-turn (MT) TFCs and adequate inboard shielding to limit damage to TFC insulators and normal conductor, requiring standard aspect ratio;
(iii) single-turn (ST) TFCs and essentially no inboard nuclear shielding with aspect ratio less than 2.

Steady state non-inductive current drives were used for all three design options. Moderately projected Tokamak physics databases are used in the studies. These include somewhat higher elongations ($\kappa_{95} = 2.1$), safety factors ($q_{95} \geq 3.5$-$4.5$), plasma Troyon beta factor [4] ($g_T \leq 3.5$, with $\beta$ defined relative to the average magnetic field in the plasma) and confinement improvement factor [5] $H_f$ (relative to the ITER-89P scaling, less than or equal to 2.5).

Design constraints that strongly affect the design iteration are the maximum fusion power (for option 1); the required neutron wall load (for all options); the maximum site power consumption (for normal conducting options); the minimum surface area for the test module (for option 3); and the inboard material thickness between the plasma and the TFC (all options). The plasma duty cycle, burn duration and availability determine the rate of tritium consumption, as well as the usefulness in technology testing. The outboard shield thickness affects the torus and magnet sizes.

The configuration for VNS using SC TFCs is expected to be roughly similar to that of ITER [6], though much smaller in size and plasma current. Relative to ITER, the VNS with SC TFCs has typically about half the device liner size, and one-quarter the plasma current and fusion power. It is comparable with ITER for toroidal field, average density and temperature, and steady state power consumption. The plasma fusion amplification required for the VNS is modest ($Q \approx 1$–$3$) and corresponds to an ignition parameter of $\langle T \rangle_n \langle n_e \rangle \tau_E \approx 7 \times 10^{20}$ keVm$^{-3}$s, which is about a factor of 3 below that required for ignition. Relative to ITER, this VNS is about a factor of 13 lower in plasma volume and a factor of 4 lower in plasma surface area. The total wall area accessible from outboard between the outer TFC legs and the outboard poloidal field coils is estimated to be about 56 m$^2$.

A significant reduction in device linear size from the SC option is obtained by using MT NC TFCs, despite the doubled wall loading. The NC coils permit a reduction in the inboard radiation shield. The values for the plasma current and density remain similar to those for the SC option. Reduction in the plasma drive power and fusion power are significant, without leading to a significant change in the ignition parameter $\langle T \rangle_n \langle n_e \rangle \tau_E$. A major drawback for this option, however, is the large increase in power consumption (700 MW), which is dominated by the NC TFCs that produce 5–6 T. A wall area of about 35 m$^2$ is accessible from the outboard side in this device. Our results, shown in Section 4, suggest that Tokamak VNSs with NC TFCs can be similar to present-day DT Tokamaks, with regard to several important parameters. However, important differences exist. These include about twice the plasma current, 3–4 times the density, three times the divertor heat flux factor, 3–4 times the neutral beam energy, more than three times the fusion power, a difference of about three orders of magnitude in the plasma duration.

The IEA study and the spherical Tokamak study of Ref. [7] assumed, without calculations, that the use of an ST NC inner leg for the TFCs permits the elimination of the inboard radiation shielding leading to a further reduction in device size for constant neutron wall loading. However, a more recent study [8] shows that significant inboard shielding is required to protect the copper from undergoing severe degradation of its mechanical properties. With the incorrect assumption of no inboard shield, the device would be reduced to about 7 m in overall linear size, with the major radius less than 1 m. The values for the plasma current, temperature and density remain similar to those in the preceding case, but a large reduction in the toroidal field would be obtained as a result of the low aspect ratio. Further reductions in plasma drive power and fusion power would be obtained. The relatively small change in the fusion amplification $Q$ results from the reduced plasma volume and a large contribution in fusion power from a strong suprathermal ion component. A key issue for this approach is the survivability and design of this ST NC, inner leg for the TFC, under the assumption of no inboard shielding.

The results for these representative VNS parameters with varying toroidal field magnet approaches show a wide design envelope for size, field strength, drive power, fusion power and electric power consumption. Over this range, similar values of plasma current, density, temperature and divertor heat flux are achieved in producing a constant neutron wall loading of 1–2 MW m$^{-2}$ in the present study. Tokamak designs with NC TFCs result in the smallest size and desired low fusion power.

## 3. Modelling

### 3.1. Characteristics of VNS

To minimize the tritium supply requirement, the fusion power in VNS has to be restricted to a reasonably low level. Hence, the VNS plasma must be in a driven mode with low $Q$ value (about 1–3), where $Q$ is the ratio of the fusion power output to the input drive power. A driven plasma is acceptable for VNS, since FNT testing requires only that neutrons be produced steadily over a large area, regardless of whether neutrons are produced by ignited or driven plasmas. Moreover, a driven machine is compatible with the non-inductive current-drive scenario, which can sustain steady state operation that is essential for FNT testing.

Tokamak VNS design configuration and engineering features are driven by the nuclear testing requirements. To ensure a capability for achieving a high fluence (6 MW year m$^{-2}$ or more) and a high availability factor (25% or more), critical components in the VNS toroidal chamber will require ready access for repair or replacement. These components include divertor plates, first-wall protection tiles and nuclear test modules.

Features common to all neutron-producing Tokamaks include inboard shielding to protect magnets with electrical insulation; outboard shielding to minimize reactor hall activation and ensure personnel safety and access; accessible and removable blanket test modules at the outboard mid-plane; and removable divertor cassettes between the TFCs. It is advantageous to minimize the size of VNS, provided that an adequate test area can be obtained. A smaller machine with the required neutron wall load will have a low fusion power at a relatively low cost. The use of NC TFCs can significantly reduce the radial build and, hence, the overall size of VNS.

### 3.2. Design assumptions and modelling

Based on the characteristics of VNS and near-term Tokamak physics database, we have defined a set of physics and engineering constraints for the design optimization of VNS, as shown in Table 1. We intended to follow the near-term Tokamak database to avoid our VNS design depending too much on optimistic projection of the Tokamak database to fusion-power-producing machines. Our work employed relatively near-term Tokamak physics assumptions compared with those used in Ref. [1]. For example, our limits of three critical plasma parameters, i.e. the normalized plasma beta, confinement enhancement factor and plasma elongation, are more restrictive than the corresponding values from Refs. [1–3].

From the insights of Refs. [2,3], we focused on the VNS design with the utilization of NC TFCs. For this NC TFC option, a 30 cm inboard shield is adequate [8], and a 30 cm inboard shield was used throughout our study here. We used an outboard radial build of 1.7 m to include various outboard components, including the outboard shield and TFCs. We have not varied this ouboard radial build, because the design performance is not very sensitive to this radial build thickness.

We limited the VNS fusion power to 150 MW to reduce the tritium supply requirement and direct the design to a low-$Q$, small machine. We have also restricted the site power consumption to 700 MW for economic and feasibility reasons.

Table 1
Major physics and engineering assumptions

| Physics constraint/parameter | Value |
|---|---|
| Normalized plasma beta $\beta_N$ (%) | $\leq$3.5 |
| Confinement enhancement factor $H$ | $\leq$2.0 |
| Plasma elongation $\kappa_{95}$ | $\leq$2.0 |
| Plasma triangularity $\delta_{95}$ | $\leq$0.3 |
| Plama MHD-$q$, $q_{95}$ | 3.0 |
| Radial build | |
| OH coil bore (m) | 0.2 |
| Inboard shield (m) | 0.3 |
| Inner scrape-off layer (m) | 0.08 |
| Outer scrape-off layer (m) | 0.10 |
| Outboard radial build (m) | 1.7 |
| Power constraint | |
| Fusion power (MW) | $\leq$150 |
| Site power consumption (MW) | $\leq$700 |

The site power consumption mainly results from the TFC resistive power and plasma current drive and heating power.

In this work, design optimization and parametric study were performed using SUPERCODE [9]. SUPERCODE is a Tokamak reactor design code developed at Lawrence Livermore National Laboratory. The code attempts to fill the gap between existing, comprehensive but simplified 0-D systems codes and highly sophisticated, multi-dimensional, specialized plasma performance codes. SUPERCODE is a systems code with greatly enhanced engineering and physics modules. Specifically, the code calculates the 1-1/2-D MHD transport configuration of a plasma in a realistic engineering environment.

SUPERCODE has capabilities to solve a typical optimization problem. The number of independent variables exceeds that of the governing equations. The code then solves for an optimized figure of merit under a set of constraint equations. The governing equations are based on fusion Tokamak plasma physics, as well as applying fusion engineering and technology design criteria. The VNS Tokamak physics and engineering limits are formulated as various forms of constraints. We used the 'core cost' [10], which is the direct cost of Tokamak hardware, power injection system and power supplies, as our figure of merit for optimization.

## 4. Design window exploration

In this section, we summarize the main findings observed by exploratory system studies, by varying the major design parameters and constraints.

### *4.1. Variations with aspect ratio*

We used the same physics and engineering constraints to examine the VNS design configurations over a range of aspect ratios. The general trends of trade-off in aspect ratio ($A$) are as follows.

Increasing the aspect ratio will drive the design to having a smaller plasma current and a larger toroidal field. For plasma power balance, the minor radius decreases with increasing aspect ratio, while the major radius has a minimum at the intermediate range of the aspect ratio. The minimized plasma size that can sustain plasma power balance leads to the power consumption and core cost being optimized at some intermediate values of the aspect ratio. Thus, this enables intermediate aspect ratio plasmas to produce the same wall load as lower and higher aspect ratio machines, with lower fusion power and lower cost of the hardware.

The VNS design configurations with an average neutron wall load of 1 MW $m^{-2}$ for a range of aspect ratios are shown in Table 2. The cost-optimized design is at an intermediate aspect ratio of about 3.5. We could not achieve a neutron wall load of 1 MW $m^{-2}$ for an aspect ratio less than 2.5. The core cost for various 1 MW $m^{-2}$ wall load designs as a function of the aspect ratio is shown in Fig. 1.

Fig. 2 shows the maximum achievable average wall load as a function of the aspect ratio. An optimum peak value of the wall load is obtained at an aspect ratio of about 3.5. We continued to explore the cost effectiveness of the designs in terms of their efficiency in producing neutron wall loads for testing. We defined the 'normalized unit cost' as the core cost divided by the maximum wall load. The differences in normalized unit cost between the optimum intermediate aspect ratio and other aspect ratios are due to both decreasing wall load and increasing core cost.

### *4.2. Reference design candidates*

After exploring the optimum Tokamak aspect ratio for VNS, we proceeded to iterate and obtained two VNS reference design candidates with average neutron wall loads of 1 MW $m^{-2}$ and 1.5 MW $m^{-2}$ respectively. The major design parameters for the two configurations are shown in Table 3.

The two design candidates have essentially the same geometry, i.e. aspect ratio, and major and minor radii. Hence, the plasma volume, plasma surface area and first-wall surface area for the two cases are very similar. The 1.5 MW $m^{-2}$ design has a slightly larger plasma current,

Table 2
Design options with various aspect ratios $A$

| | Min cost | | | | |
|---|---|---|---|---|---|
| | $A = 2.5^a$ | $A = 3.0$ | $A = 3.45$ | $A = 4.0$ | $A = 5.0$ |
| Average wall load (MW $m^{-2}$) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Major radius (m) | 1.77 | 1.63 | 1.58 | 1.73 | 1.99 |
| Minor radius (m) | 0.71 | 0.54 | 0.46 | 0.43 | 0.40 |
| Plasma current (MA) | 7.4 | 5.2 | 4.2 | 3.7 | 3.0 |
| Toroidal field (T) | 4.4 | 5.3 | 6.0 | 6.6 | 7.7 |
| Average density ($\times 10^{20}$ $m^{-3}$) | 1.4 | 1.7 | 2.0 | 2.2 | 2.3 |
| Average temperature (keV) | 10.0 | 8.9 | 8.2 | 8.0 | 8.2 |
| Drive power (MW) | 53 | 48 | 44 | 46 | 48 |
| Fusion power (MW) | 108 | 80 | 66 | 70 | 75 |
| Power consumption (MW) | 627 | 593 | 589 | 605 | 682 |
| Plasma $Q$ | 2.0 | 1.7 | 1.5 | 1.5 | 1.6 |
| Plasma volume ($m^3$) | 34.1 | 18.9 | 12.8 | 12.7 | 12.3 |
| Plasma surface area ($m^2$) | 74.5 | 53.6 | 43.4 | 45.4 | 48.1 |
| First-wall surface area ($m^2$) | 76.6 | 56.5 | 46.9 | 49.3 | 52.7 |
| Relative cost (wrt $A = 3.45$) | 1.17 | 1.04 | 1.00 | 1.05 | 1.19 |

[a] Minimum $A$ obtained for the specified wall load.

toroidal field, plasma density and plasma temperature than the 1 MW $m^{-2}$ design. This results in a 50% increase in fusion power and 30% increase in plasma $Q$ value from the lower wall load design to the higher wall load design. The site power consumption also increases from about 600 to 700 MW. It should be noted that there are design solutions to reduce the major part of the site power consumption, i.e. the resistive power in the TFC. Examples include increasing the TFC cross-section on the top, bottom and outboard regions. We have not explored these design options.

It can be concluded that a moderate increase in the values of the plasma parameters without changing the geometry can raise the wall load significantly from 1 to 1.5 MW $m^{-2}$ within the parameter space permitted by the physics and engineering constraints. For our design candi-

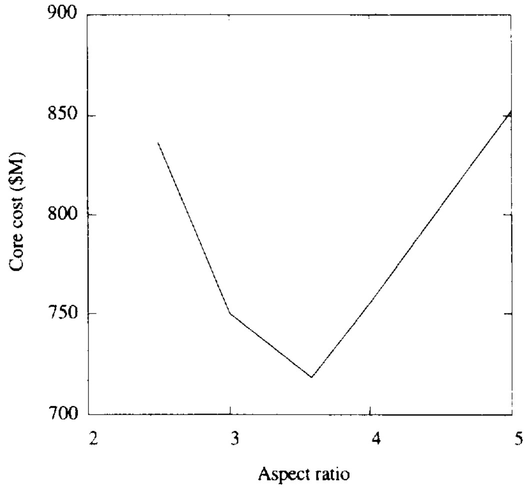

Fig. 1. VNS Tokamak core cost vs. aspect ratio.

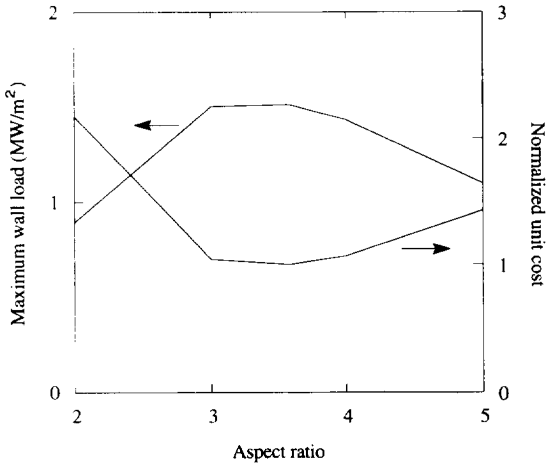

Fig. 2. Variations of maximum neutron wall load and normalized unit cost with aspect ratio.

Table 3
Reference VNS design candidates

| Major design parameter | 1 MW m$^{-2}$ | 1.5 MW m$^{-2}$ |
|---|---|---|
| Average wall load (MW m$^{-2}$) | 1.0 | 1.5 |
| Peak wall load (MW m$^{-2}$) | 1.4 | 2.2 |
| Major radius (m) | 1.58 | 1.64 |
| Minor radius (m) | 0.46 | 0.46 |
| Aspect ratio | 3.45 | 3.58 |
| Plasma current (MA) | 4.2 | 4.5 |
| Toroidal field (T) | 6.0 | 6.8 |
| Average density ($\times 10^{20}$ m$^{-3}$) | 2.0 | 2.4 |
| Average temperature (keV) | 8.2 | 8.6 |
| Drive power (MW) | 44 | 52 |
| Fusion power (MW) | 66 | 103 |
| Power consumption (MW) | 589 | 698 |
| Plasma $Q$ | 1.5 | 2.0 |
| Plasma volume (m$^3$) | 12.8 | 13.3 |
| Plasma surface area (m$^2$) | 43.4 | 45.2 |
| First-wall surface area (m$^2$) | 46.9 | 48.7 |
| Relative cost (wrt $A = 3.45$) | 1.00 | 1.17 |

dates, the increase in the direct capital cost for this enhanced performance, with a 50% increase in wall load, is a mere 17%.

### 4.3. *Sensitivity of neutron wall load to major design parameters*

We have selected a list of major design constraints and parametes, and have performed sensitivity studies to investigate their impacts on the design configuration. These constraints and parameters include the normalized plasma beta, confinement enhancement factor, plasma elongation, plasma triangularity, alpha ash fraction, inner and outer scrape-off layers, center bore thickness, inboard shield thickness, FTC current density, fusion power and site consumption power. The results in terms of the maximum achievable average neutron wall load and the normalized unit cost for the assumed bounding limits of these parameters are shown in Figs. 3 and 4 respectively. The bounding lower and upper uncertainty ranges are also indicated in Fig. 3.

The maximum average neutron wall load for our reference parameters is about 1.5 MW m$^{-2}$. For the cases of reducing the normalized plasma beta confinement enhancement factor and site power to their respective lower uncertainty limits, the resulting three cases have designs with less than 1 MW m$^{-2}$ of neutron wall load. Configurations with a reduction of all other parameters to their individual lower uncertainty limits can maintain a wall load of 1 MW m$^{-2}$.

However, if the normalized plasma beta, inboard shield thickness and site power consumption are elevated to their projected higher limits, the resulting design configurations can attain a

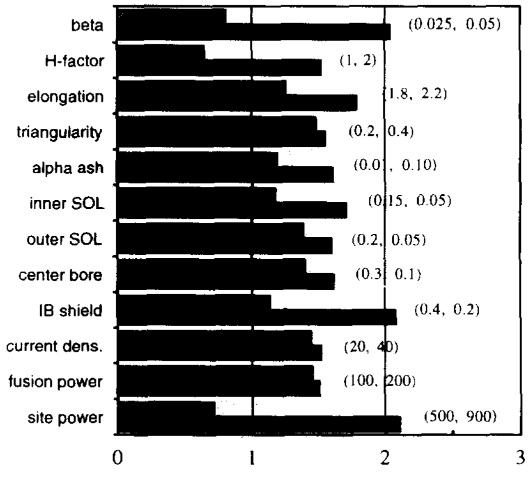

Fig. 3. Maximum average neutron wall load at bounding limits of design parameters.

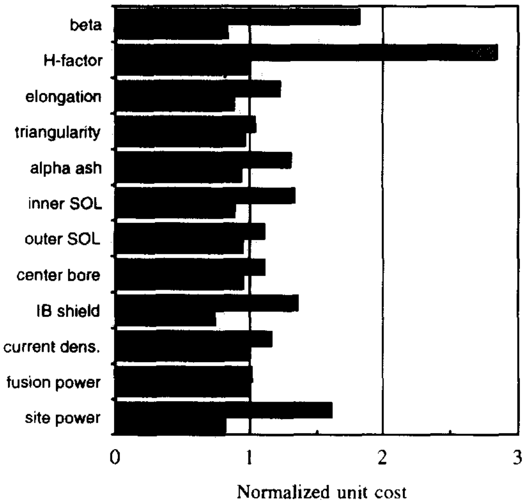

Fig. 4. Normalized unit cost at bounding limits of design parameters.

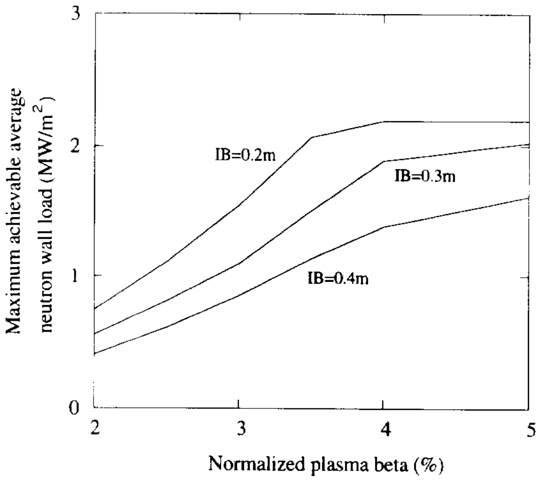

Fig. 5. Variations of neutron wall load with normalized beta for three values of the in-board shield thickness.

neutron wall load that exceeds 2 MW $m^{-2}$. The increase in plasma elongation and decrease in inner scrape-off layer can also improve the neutron wall load to a lesser extent.

The saving in normalized unit cost is not very significant with the design constraints and parameters at their better performance limits. However, the lower limits of normalized plasma beta and site power will increase the cost by more than 50%, while the lower limit of confinement enhancement factor of 1 can nearly double the cost.

There are uncertainties in the VNS design constraints and parameters that need to be resolved. However, the most dominant factors are the normalized plasma beta, confinement enhancement, in-board shield thickness and site power. The VNS design, in general, can produce satisfactory testing performance in light of the parameter uncertainty ranges considered in this work.

### 4.4. *Options for design improvement*

In this subsection, we first examine the variations of the maximum achievable average neutron wall load with three important VNS design parameters, i.e. the normalized plasma beta, inboard shield thickness and plasma elongation. Approaches to improve performance will be discussed later.

Fig. 5 shows the maximum achievable neutron wall load as a function of the normalized plasma beta for three values of inboard shield thickness. It can be observed that reducing the shield thickness can reduce the overall size of the machine, leading to a higher wall load with a constant fusion power. However, the minimum shield thickness is constrained by the requirement for adequate shielding of the inner TFCs. The normalized beta is critical to achieving a higher neutron wall load. The rate of increase of the achievable wall load with normalized beta is quite steep, especially at a normalized beta of less than 4%.

Similar behavior can be observed for the variations of the maximum achievable neutron wall load with plasma elongation and normalized beta, as shown in Fig. 6. A higher elongation permits a larger plasma current to be sustained for the same MHD constraint. The elevated plasma current can partially compensate for the lack of plasma beta margin, so increasing the achievable wall load. This approach of improving the wall load is limited, because the plasma elongation is restricted to approximately less than 2, because of the problem of plasma vertical instability. In general, the availability of a beta margin via a demonstrated higher normalized plasma beta database or other trade-offs in the plasma charac-

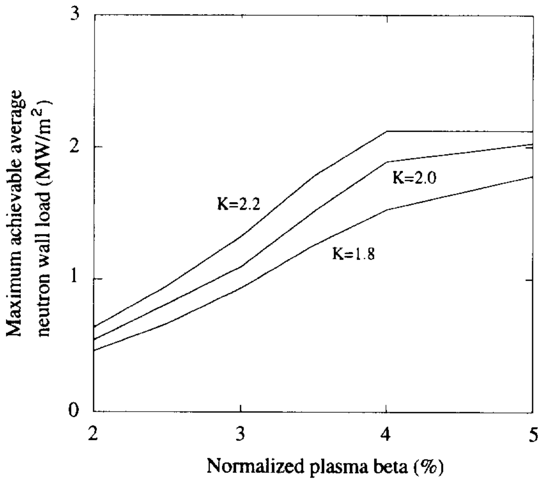

Fig. 6. Variations of neutron wall load with normalized beta and plasma elongation.

teristics is vital to the attainment of a higher neutron wall load.

For example, there is a trade-off between neutral beam (NB) power and TFC resistive power. Reducing the NB power (i.e. less plasma heating) requires a larger energy confinement time ($\tau_E$) for power balance for roughly the same fusion power. This is achieved by raising the plasma current $I_p$ and, to a lesser extent, raising the magnetic field on axis ($B$). The plasma also shifts to the lower-$n$, higher-$T$ regime for better current drive efficiency. The normalized beta may drop below the limiting value (the plasma is $\tau_E$ limiting and not beta limiting). The TFC resistive power increases as a result of the higher $B$ value.

Similarly, reducing the Troyon coefficient will result in higher $B$ and $I_p$ values to satisfy the beta limit constraint, leading to larger $\tau_E$, smaller confinement enhancement factor $H$, larger major radius, a high $T$, lower $n$ plasma, lower NB power, and higher TFC resistive power. The scenario is similar to the case of reducing NB power discussed above, with different triggering constraints.

In general, for a normalized plasma beta of less than 4%, the plasma is in a beta-limited regime. There are three approaches to increase the plasma operating window within the beta limit: increasing the toroidal field and plasma current, and reducing the plasma minor radius. For VNS performance, we have shown that it is advantageous to reduce the size and push the components inward with the design constraints. The design is already at a minimum minor radius. Also, the allowable plasma current cannot be increased by a large fraction for fixed plasma elongation and MHD safety factor. Hence, increasing the toroidal field is the only effective way to raise the plasma pressure (density and temperature) to generate greater fusion power. The TFC resistive power increases accordingly, leading to higher site power consumption.

Fig. 7 shows the required site power as a function of the normalized plasma beta for wall loads of 1 and 1.5 MW m$^{-2}$, and confinement enhancement factors of 2 and 3. For a normalized plasma beta less than 4, the site power required to compensate for the lack of a beta margin is about the same for $H = 2$ and $H = 3$. The excessive confinement capability with $H = 3$ cannot be utilized, because the beta limit prevents the plasma from going to a higher fusion power regime. Fig. 7 also indicates that a higher neutron wall load requires a larger site power for the same normalized beta.

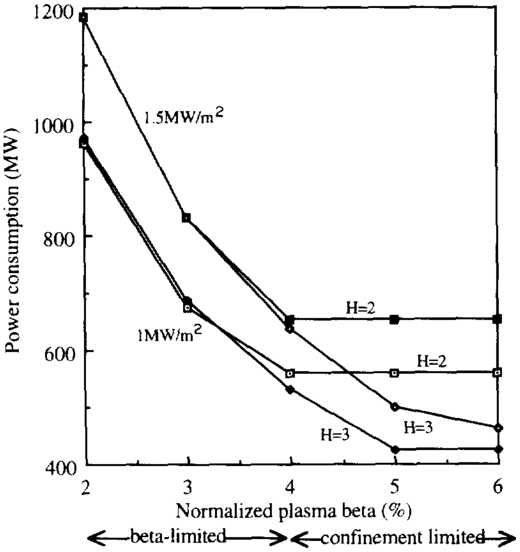

Fig. 7. Power consumption required for various confinement enhancement factors and normalized betas at neutron wall loads of 1 and 1.5 MW m$^{-2}$.

The smaller the normalized beta is, the larger is the site power consumption needed to overcome the beta limitation. It should be noted again that options to reduce the resistive power loss in the TFC, such as increasing the cross-section of the coils, are available but have not been explored in this study.

For the confinement-limited plasma with a normalized plasma beta greater than 4%, the roles of confinement and beta limits are switched. A further increase in the beta margin by increasing the normalized beta cannot reduce the site power consumption. However, the plasma power balance will improve with better confinement, such as increasing $H$ from 2 to 3. As a result, the site power will be reduced by the enhancement of confinement in this regime.

## 5. Conclusions

We have performed constrained optimization systems studies using SUPERCODE to explore the design options of a Tokamak-based VNS. With moderate near-term physics and engineering assumptions, our study indicated that the Tokamak-based VNS can provide sufficient (1) test area and volume, and (2) neutron flux and fluence for integrated component and material testings in a fusion environment. Design candidates with average neutron wall loads for 1 and 1.5 MW $m^{-2}$ have been obtained with direct capital cost of less than US $1 billion.

VNS designs are characterized by small size, low fusion power, low $Q$ operation with non-inductive current drive. VNS performance, such as increasing wall load and reducing cost, improves with a reduction in size, by pushing the components inward within the design constraints (such as the thickness of the inboard shield). VNS designs with NC TFCs provide better performance than their SC counterparts, as a result of the reduced radial build and size.

Optimal VNS designs are obtained at intermediate values of the aspect ratio, i.e. $A \approx 3-4$. A VNS with an intermediate aspect ratio has a higher maximum achievable neutron wall load and a lower direct capital cost than do the design configurations with higher and lower aspect ratios. Viable designs could not be obtained at very low aspect ratios ($A < 2$).

An adequate neutron wall load can be achieved within the expected uncertainty ranges of physics and engineering design parameters, as indicated by our sensitivity analysis. The maximum achievable neutron wall load and normalized unit cost of the machine are affected adversely by worse projection of the confinement, beta and site power consumption limits.

Plasmas with a normalized plasma beta less than about 4% are in a beta-limited regime, whereas an increment of the beta limit (not with confinement) will enhance the VNS performance in terms of the neutron wall load. The lack of a beta margin can be compensated for by increasing the magnetic field with a larger site consumption power to supply for the elevated TFC resistive loss. However, plasmas with a normalized plasma beta greater than about 4% are in a confinement-limited regime, where the wall load performance can be improved with better confinement (but not with normalized plasma beta). Improvements in other aspects of the Tokamak physics database, such as the ability to sustain a larger plasma elongation, will also result in better VNS performance.

## Acknowledgements

The authors acknowledge helpful discussions with Drs. John Galambos, Scott Haney and Alice Ying. This work has been supported by the US Department of Energy.

## References

[1] M.A. Abdou, A volumetric neutron source for fusion nuclear technology testing and development, Fusion Eng. Des. 27 (1995) 111 153.

[2] M.A. Abdou et al., Results of an international study on high volume plasma-based neutron source for fusion blanket development, Fusion Technol. 29 (1996) 1–57.

[3] M. Abdou et al., Phase I report of the IEA study on high volume plasma-based neutron source (HVPNS), Rep. UCLA-FNT-94 UCLA-ENG-95-111, December 1994.

[4] F. Troyon et al., MHD limits to plasma confinement, Plasma Phys. Controlled Fus. 26 (1984) 209.

[5] P.N. Yushmanov et al., Scaling for Tokamak energy con-finement, Nucl. Fusion 30 (1990) 1999.

[6] R. Aymar et al., ITER outline design report, summary and overall physics issues, and ITER outline design report, engineering, ITER TAC-4-01, paper presented to the 4th Meeting of the Technical Advisory Committee, San Diego, CA, 10–12, January 1993.

[7] Y.M. Peng et al., Small Tokamaks for fusion technology testing, Fusion Technol. 21, (1992) 1729.

[8] S. Sharafat, M. Abdou and M. Youssef, Assessment of advanced copper alloys for normal conducting coils, Proc. ICFRM-7, Obinsk, Russia, September 1995.

[9] S.W. Haney et al., A SUPERCODE for systems analysis of Tokamak experiments and reactors, Fusion Technol. 21 (1992) 1749.

[10] John Galambos, Private Communications, Oak Ridge National Laboratory, 1995.