THE USA/TNS PROGRAMS: ENGINEERING CONSIDERATIONS

T. E. SHANNON
Oak Ridge National Laboratory,
P.O. Box Y, Oak Ridge, Tennessee 37830, U.S.A.

J. M. RAWLS
General Atomic Company, P.O. Box 81608, San Diego, California 92138, U.S.A.

ABSTRACT

Studies at the Oak Ridge National Laboratory (ORNL) and the General Atomic Company (GA) have defined basic characteristics and requirements for The Next Step (TNS) in the U.S. Tokamak Development Program. The Reference Design concepts include engineering innovations that have enhanced the feasibility of the tokamak as a power reactor. A major emphasis has been placed on configuration changes to improve access for maintainability, a serious concern and frequent criticism of previous studies. In addition, system designs have been incorporated using existing or modest extensions of engineering technology.
1. Introduction

For the past three years, the United States Department of Energy (DOE) has supported design studies directed toward definition of The Next Step (TNS) in the development of magnetic fusion confinement concepts. As presently perceived, TNS will represent a shift in emphasis of fusion energy development from physics research to engineering testing and demonstration. Studies at the Oak Ridge National Laboratory (ORNL) [1] and the General Atomic Company (GA) [2] have defined basic characteristics and requirements for a tokamak TNS.

Previous design studies by the Argonne National Laboratory (ANL) [3], GA [4], and ORNL [5] considered an Experimental Power Reactor (EPR) as the next step. While these studies specifically advanced the level of sophistication of the tokamak as a reactor candidate, they also indicated that the data base available was insufficient to accurately predict either the thermal power or the dissipative losses. As a consequence of this uncertainty, the requirement of net power production translated into a design with unacceptably high cost and unrealistic technological risks. Furthermore, these and other early tokamak reactor designs were met with criticism (e.g. Metz [6]) due to their complex configuration, large size, high cost, and relatively low power output. The TNS Program was initiated in an attempt to redefine a more modest next step than the EPR. In this paper, two TNS Reference Designs are described, with particular emphasis on innovations that have enhanced the engineering feasibility of the tokamak as a power reactor.

2. Design Description

The striking similarity between the two designs is shown in Table 1, a compilation of the principal parameters characterizing the devices. Overall reactor size is determined by the toroidal field (TF) coils, which in both cases are a set of 12 superconducting magnets approximately 6 × 10 m in bore. The startup requirements are quite similar with respect to both energy storage and auxiliary heating. Furthermore, the operating characteristics that determine the usefulness of the devices in providing engineering test data, namely duty cycle and wall loading, are comparable. The major difference between the two designs is the plasma cross sectional shape. The ORNL and GA designs employ a dee and a doublet, respectively, a distinction that is reflected in Table 1 in the value of plasma elongation. Assembly drawings of the two designs are shown in Figures 1 and 2.

A number of suggestions to improve the tokamak as a reactor concept have emerged from the TNS Studies. The engineering innovations, listed below, give rise to improved maintainability and reduced technological uncertainty, and, it is hoped, ultimately to better reactor economics.

2.1 Vacuum Topology

One of the most important engineering feasibility issues relates to the overall mechanical assembly and maintenance of the tokamak device. A feature of both designs which most significantly impacts the maintenance concept is the use of a secondary vacuum enclosure to maintain a vacuum environment external to the plasma chamber. The need for high vacuum joints is thus
### TABLE I
TNS ENGINEERING PARAMETERS

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Number of TF-coils</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>TF-coil conductor</td>
<td>NbTi</td>
<td>Nb$_3$Sn</td>
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<td>TF-coil vertical bore (m)</td>
<td>9.2</td>
<td>9.9</td>
</tr>
<tr>
<td>TF-coil horizontal bore (m)</td>
<td>5.8</td>
<td>6.2</td>
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<tr>
<td>Plasma minor radius, a (m)</td>
<td>0.95</td>
<td>1.2</td>
</tr>
<tr>
<td>Plasma major radius, R (m)</td>
<td>3.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Plasma elongation, δ</td>
<td>2.7</td>
<td>1.6</td>
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<tr>
<td>Aspect Ratio, A</td>
<td>3.0</td>
<td>4.2</td>
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<tr>
<td>Field at TF-coil, B_m (T)</td>
<td>10.0</td>
<td>10.9</td>
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<tr>
<td>Field on axis, B_0 (T)</td>
<td>5.0</td>
<td>5.3</td>
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<tr>
<td>Plasma current, I_p (MA)</td>
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<tr>
<td>Total volt-seconds</td>
<td>38</td>
<td>83</td>
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<tr>
<td>Plasma volume, V_p (m$^3$)</td>
<td>180</td>
<td>230</td>
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<td>Neutron wall load (MW/m$^2$)</td>
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<tr>
<td>Total fusion power (MW)</td>
<td>650</td>
<td>1135</td>
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<tr>
<td>Fusion power density (MW/m$^3$)</td>
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<td>Microwave power (MW)</td>
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<tr>
<td>Neutral beam power (MW)</td>
<td>60</td>
<td>40</td>
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<td>Steady-state burn time (s)</td>
<td>30</td>
<td>300</td>
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<tr>
<td>Time between pulses (s)</td>
<td>30</td>
<td>95</td>
</tr>
<tr>
<td>Impurity control</td>
<td>Low Z coating and flow reversal</td>
<td>Bundle divertor</td>
</tr>
<tr>
<td>Vacuum topology</td>
<td>Plasma chamber</td>
<td>Vacuum building</td>
</tr>
</tbody>
</table>

eliminated and remote maintenance is made easier.

In a commercial power reactor, rapid blanket module replacement is a major factor in determining plant availability and hence the cost of electricity. Elimination of the welded joints at the primary vacuum boundary is expected to reduce downtime for blanket replacement by a factor of two.

The alternative concepts considered were a controlled atmosphere between the first wall and the shield, a toroidal enclosure around the TF coils, a belljar enclosure around the tokamak, and finally a complete evacuated reactor cell or "vacuum building." The GA study adopted the first of these alternatives. A more far-reaching design decision was taken in the ORNL study, where the vacuum building was selected as the preferred concept because of the relative ease of penetration for maintenance operations and the unrestricted access for inspection and adjustments during normal operations. The technical feasibility of such a structure has been established in a study by Warner [7] referencing an existing NASA facility at Sandusky, Ohio.
1 ORNL TNS Reference Design

2 GA TNS Reference Design
The vacuum building for the ORNL Reference Design is a 56 m diameter, 33 m high, cylindrical concrete structure with a spherical dome. The concrete structure supports the atmospheric pressure load and also serves as the biological radiation shield. An inner metallic chamber is the high vacuum barrier designed for a base operating pressure of $10^{-4}$ torr. Pumpdown of the building is by a combination of mechanical and roots pumps requiring 6 hours from atmospheric to base pressure.

2.2 Coil Configuration

The discrete nature of the TF coils of a tokamak introduces amplitude modulation on the toroidal magnetic field. These modulations called "ripple" lead to particle excursions and hence energy loss in the plasma. Allowable ripple can be determined on the basis of plasma energy transport calculations, such as developed by Uckan [8]. The maximum allowable ripple can then establish the relationship between the size and number of TF coils. The ripple may in fact turn out to be a suitable burn control mechanism as shown by Petrie and Rawls [9].

The EPR designs mentioned previously used 16, 16, and 20 TF coils, respectively, for the ANL, GA, and ORNL concepts, a factor which added to the overall design complexity. The TNS designs have reduced the number of coils to 12. The reduced number of larger coils increases the device cost by 5–10% based on cost sensitivity studies by Graumann and Reid [10,11] but provides sufficient room between coils to replace blanket sectors without moving the coils. Figures 3 and 4 illustrate the results of the ORNL study showing the relationship between coil size, number of coils, and cost for a range in ripple from 1 to 5%. The increase in coil bore (\%30%) also provides room to relocate poloidal field (PF) coils inside the TF coils during a sector replacement operation, thus eliminating PF
coil segmentation in the ORNL study for this operation. The GA doublet design, however, requires a more complete PF coil system and still requires such segmentation.

2.3 Radial Compactness

Overall reactor cost depends sensitively on the plasma major radius, which basically determines the amount of structure required. This cost sensitivity has been documented in the TNS studies [10,12]. In the GA Reference Design, a minimum thickness plasma chamber inboard shield has been selected using tungsten bricks in place of stainless steel (see Fig. 5). The high shielding efficiency of the tungsten results in a reduction of the shield thickness of approximately 12 cm. The decrease in major radius results in an overall cost savings in excess of $15 M.

The limited access to the inboard region of the shield led to a tank enclosure concept in which the tungsten bricks are located. A tank is markedly suited to simultaneously meeting the structural, coolant and removability requirements. The external walls of the tank form concentric cylinders which are notably sound structures. Also, the flow of coolant through the tank in a bath flow mode negates most coolant line problems. Finally, by forming the shield of loosely arranged small units, the shield proper is optimally removable.

Shield Assembly Showing Details of the Thin Inboard Tungsten Shield
By extending the tank to include the F-coils, the F-coil access problem is relieved and the overall thickness of the inboard region is substantially reduced, the latter achieved through the elimination of the space required for independent F-coil coolant headers and support structure. As part of the tank assembly, the F-coils are supported directly off the tank and are cooled by the bath flow of coolant. Further reductions in overall thickness are achievable because the immersion of the components within a liquid coolant forms a continuous gap-free medium that enhances the shielding capability of the entire region.

A cross sectional view of the inboard tank assembly is shown in Fig. 5 which is a sketch of the overall reactor shield assembly. In addition, a more detailed (but idealized) view of the inboard tank assembly is shown. Progressing radially inward in the figure, the tank is shown to consist of a 1 cm tank wall, 4 cm of coolant channel, a 10 cm F-coil, 4 cm of coolant channel, 38 cm of shield, 0.5 cm of coolant channel, and a 4 cm tank wall. The total radial thickness of the inboard tank is 61.5 cm.

2.4 Magnetics

An important reactor prototypical element of the GA design is the 12-coil-superconducting toroidal field coil system, in which bath-cooled NbTi/Cu conductor is employed to generate a peak field of 10 tesla. The energy stored in the toroidal field is 10 gigajoules. The toroidal bore aperture is 9.2 m × 5.8 m (see Fig. 6).

The coil is subjected to 1 MJ of neutron heating during the 30-second burn. An elevated helium supply reservoir provides the hydrostatic head and hence convective flow necessary to insure that this neutron heating is removed without the development of two-phase flow within the coil. Although the flow rate is high (36 liters per second per coil), the conductor is maintained at a temperature no greater than 4.4°K.

The coils are pancake wound with interturn stainless steel support strip. The 10.2 kA cabled conductor is graded upon the basis of magnetic field and bearing load, yielding an average conductor current density of 3400 A/cm². The conductor is cryogenically stabilized against hypothetical "maximum credible" transient mechanical disturbances. The "equivalent" heat transfer rate in the graded zones varies from 0.46 to 0.58 watts/cm², which is consistent with current practice.

The coil centering loads are borne by the cold, non-metallic centerpost support cylinder, into which the solenoidal E-coils are embedded. The out-of-plane (overturning) loads are reacted by ground supports and by a series of cold circumferential and diagonal intercoil struts.

The guiding principles of this design are fabrication economy, reactor compatibility, and operational reliability.
3. **Conclusions**

Two independent TNS studies have arrived at designs with a number of common features and have provided engineering innovations that have improved the viability of the tokamak as a power reactor concept. Specific conclusions are as follows:

1. A secondary vacuum enclosure significantly improves the remote maintenance and assembly features of the tokamak by elimination of high vacuum welds in the plasma chamber.
2. By reducing the number of TF coils while increasing the bore size to maintain reasonable ripple loss, access to the inner reactor chamber can be provided for replacement of blanket segments without moving the TF coils or segmenting the inner PF coils.
3. The cost of the tokamak device, primarily a function of the major radius, can be reduced by modifying the inner shield and structural support to provide a more compact radial build.
4. Toroidal magnetic field requirements can be provided by modest extensions of existing technology for superconducting magnet design.
References


