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# THE ADVANCED TOROIDAL FACILITY (ATF)*

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## ABSTRACT

The Advanced Toroidal Facility (ATF) is a new magnetic plasma confinement device, under construction at Oak Ridge National Laboratory (ORNL), which will lead to improvements in toroidal magnetic fusion reactors. ATF is a type of stellarator known as a torsatron which theoretically has the capability to operate at $\geqslant 8\%$ beta in steady state. The ATF plasma has a major radius of 2.1 m, an average minor radius of 0.3 m, and a field of 2 T for a 5-s duration or 1 T steady state. The ATF device consists of a helical field (HF) coil set, a set of poloidal field (PF) coils, an exterior shell structure to support the coils, and a thin helically contoured vacuum vessel inside the coils. The ATF replaces the ISX-B tokamak at ORNL and will use the ISX-B auxiliary systems including 4 MW of neutral injection heating and 0.2 MW of electron cyclotron heating. ATF is scheduled to start operation in the fall of 1986. An overview of the ATF device is presented including details of the construction process envisioned.

## INTRODUCTION

The ATF[1,2,3] is a type of stellarator, known as a torsatron, which has been developed at the Oak Ridge National Laboratory (ORNL) with the twin goals of improving toroidal confinement in the areas of high beta and steady-state operation. Beta ($\beta$) is the ratio of plasma pressure to the pressure of the confining magnetic fields; hence, it is a measure of the cost-effectiveness of a magnetic fusion device. The ATF has high beta capability owing to the self-stabilizing effect of a magnetic well which increases in depth as beta increases. This capability is predicted to give ATF access to the so-called second stability region and to a volume-averaged beta $\geqslant 8\%$. Like all stellarators, the ATF configuration is intrinsically steady state because the confining magnetic fields are produced entirely by currents in external coils. As a reactor, such a device will require no external power to sustain the plasma. An artist's impression of the ATF is shown in Figure 1. The main device parameters are given in Table I with the major coil characteristics indicated in Table II.

## PHYSICS CONSIDERATIONS

Stellarators are toroidal confinement devices in which nested magnetic surfaces are produced by currents in external coils. These flux surfaces are produced by the spiraling motion of the field lines as they orbit the torus. In a stellarator, pairs of helical conductors carrying current in opposite directions is used to produce the poloidal field, and additional coils produce a toroidal field. In a torsatron,[4] the helical conductors carry currents in the same direction, and no toroidal coils are needed. These helical coils are characterized by their toroidal periodicity (m) and by the number of helical conductors (pairs in a stellarator) ($\ell$).

A key issue in stellarator design is finding a magnetic configuration which has both a high beta capability and good low collisionality transport. Good stability of a plasma-field configuration may be obtained by two basic routes: through the use of a magnetic well to contain the plasma, which means that on average the field strength increases away from the plasma, and through a changing twist in the field (magnetic shear), which stiffens the configuration against attempts of the plasma to cross the field.

In ATF, a combination of magnetic well and shear is used to provide a high beta capability. In the development of ATF, a variety of magnetohydrodynamic (MHD) codes were used to optimize the ATF configuration for high beta. The maximum beta for circular axis stellarators is "traditionally" obtained when the device parameters lie at the junction of the equilibrium and stability limits, as shown in Figure 2. In the ATF studies, small aspect ratio devices were investigated because as an experiment, for a given scale device, they have a larger plasma minor radius (which makes heating and diagnostics easier) and because they lead to a more attractive reactor.[5] The equilibrium limit occurs because the surfaces are distorted by increasing beta (see Figure 3) and are eventually destroyed. The stability limit occurs because of interchange of the plasma and field, either locally or globally. The ATF studies led to an $\ell = 2$ torsatron in which it has been possible to maintain stability and enter the so-called second stability region (Figure 2 "optimized"). At the same time, the configuration has a high equilibrium beta limit. To date, ATF has been shown to have stable equilibria up to beta = 8%.

Studies of stability in a conventional tokamak and in ATF show the presence of a second stability region in both

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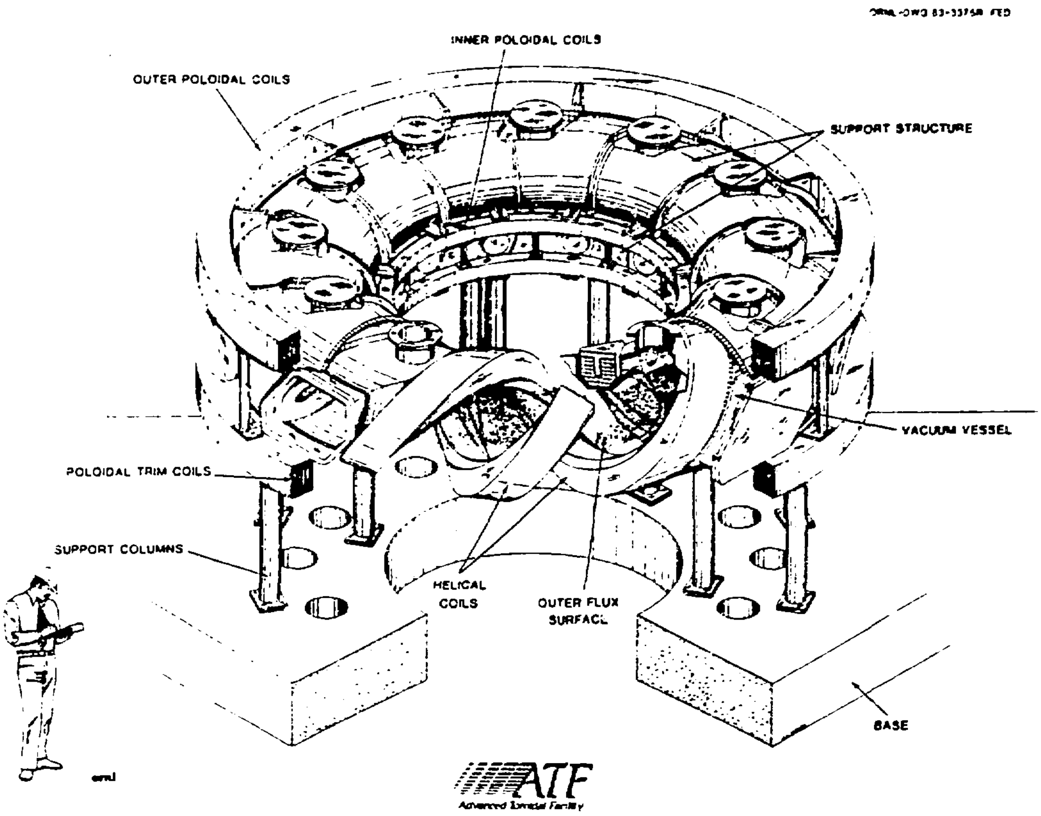


Fig. 1

TABLE I
ATF device parameters

| | |
|---|---|
| Major radius $R_0$, m | 2.10 |
| Average plasma minor radius $\langle a \rangle$, m | 0.30 |
| Average HF coil minor radius $a_c$, m | 0.46 |
| Toroidal field on axis $B_0$, T | 2.0 (for 5 s)<br>1.0 (continuous) |
| Ion and electron temperature ($T_i = T_e$), keV | 1–2 |
| Plasma density $\langle n \rangle$, $cm^{-3}$ | $1\text{–}10 \times 10^{13}$ |
| Average plasma beta $\beta$, % | 4–8 |

TABLE II
Major coil characteristics

| Coil set | Current per coil (MA·turns) | Current per turn (kA) | Current density ($A/cm^2$) | Voltage per coil set (V) | |
|---|---|---|---|---|---|
| | | | | Peak | Flattop |
| HF | 1.750 | 125.0 | 3350 | 1000 | 500 |
| VF inner | 0.263 | 16.4 | 2540 | 650 | 121 |
| VF outer | | | | | |
| Main | 0.375 | 125.0 | 2600 | 1000 | 63 |
| Trim | 0.159 | 15.9 | 2420 | 650 | 166 |

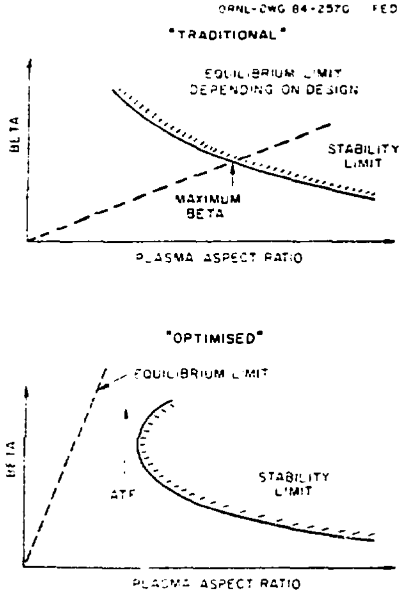


Fig. 2

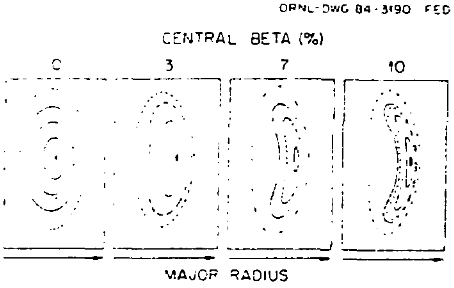


Fig. 3

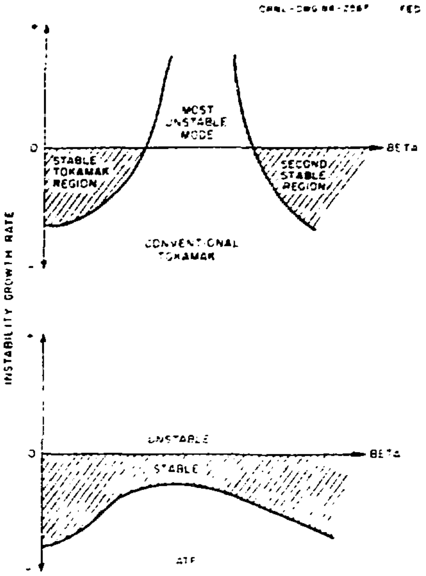


Fig. 4

devices at high beta. As indicated in Figure 4, in the conventional tokamak this region is not readily accessible because of the unstable region at intermediate beta. In ATF, there is direct access to the high-beta region.

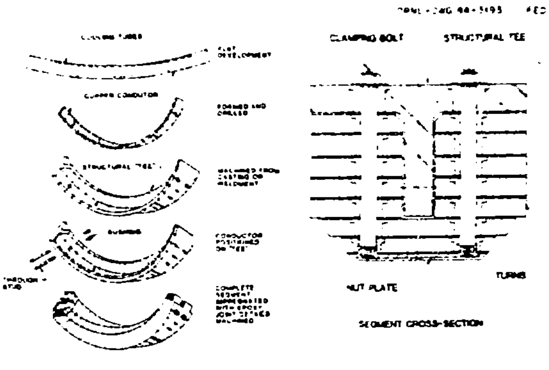
The coil set gives ATF great flexibility to compare theory and experiment in a variety of configurations. By varying the vertical field, the magnetic well may be converted to a hill and the plasma becomes unstable at lower beta. A different configuration with a helical magnetic axis may be obtained by reducing the current in one of the helical coils.

## THE ATF DEVICE

As shown in Figure 1, the ATF device consists of an HF coil set, a set of PF coils, an exterior shell structure to support the coils, and a thin helically contoured vacuum vessel inside the coils. The ATF will use the existing facilities of the ISX-B tokamak: power supplies, cooling, diagnostics, data acquisition, control, and heating systems.

### Coils

The HF set consists of a pair of coils that forms an $(\ell = 2,\ m = 12)$ torsatron helix. The coils must be constructed so that the current winding law is within 1 mm of the theoretical winding law. In other stellarators, similar accuracies have been achieved by winding the HF conductor into an accurately machined groove on a toroidal vacuum vessel. Such a procedure requires serial production of the vessel and coils. In ATF, the HF coil will be made in 24 segments with joints in the equatorial plane of the machine. This permits parallel production of the coils and vacuum vessel. Each coil segment consists of 14 insulated copper conductors mounted on a structural T-section steel brace (see Figure 5). Each conductor is made from plate and contains a water cooling tube brazed into a milled groove. The conductors are rough formed to shape, and then a complete set of conductors is clamped into a precision die and stress relieved to achieve the final form tolerance. The stainless steel T-piece is cast to the shape to fit it in its tolerance window and is then machined to provide accurate location points for mounting the conductors and assembling the coil. These components are tested to see that they fit within the tolerance windows using a coordinate measuring machine which has an accuracy of ~0.01 mm. This machine is also used to check the completed segment. Following assembly, the segment is potted in epoxy



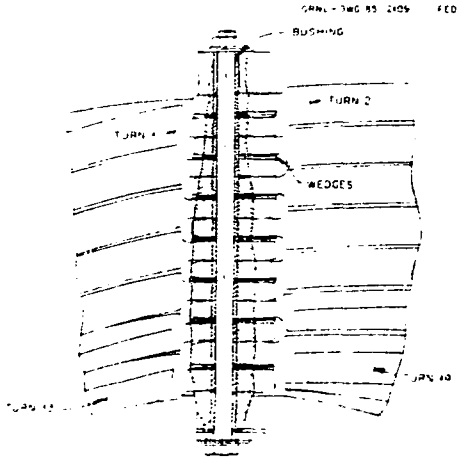
HF COIL SEGMENT ASSEMBLY

Fig. 5

resin. Components for a full-scale prototype segment have been built by the Chicago Bridge and Iron Company in Birmingham, Alabama.

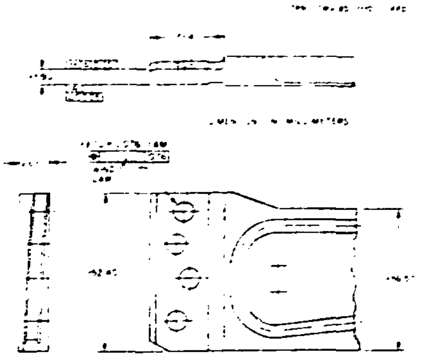
A critical design issue is the demountable joint. A large number of designs were tested, and a few met all the initial requirements for both pulsed and steady-state operation. The selected joint concept is a simple lap geometry for each turn with bolts through the entire segment stack made up during HF coil assembly (see Figure 6).

The lap configuration is composed of a half-lap machined tab at the end of each turn of a coil segment which mates with corresponding half-laps when upper and lower segments are joined together during the HF coil assembly process. The tabs on each turn are machined



JOINT CONCEPT

Fig. 6



JOINT TAB DETAIL - TYPICAL

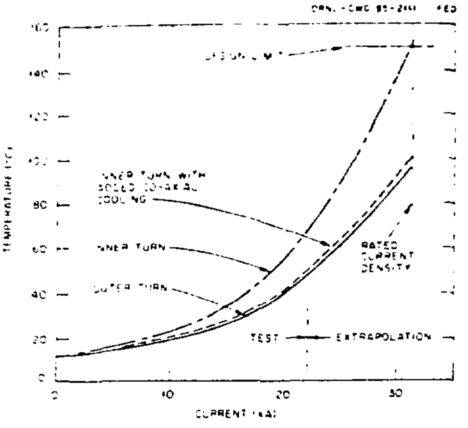
Fig. 7

while the copper is still in a flat development stage. A typical joint end is shown in Figure 7. Precise control of each tab's position in the segment stack including the through-bolt holes is accomplished by use of tooling fixtures at the initial forming stage and again during segment assembly.

Field assembly of these HF coil joints is based on optical alignment to a particular joint control hole feature on each segment end. Tab misalignments (nonparallel surfaces) are corrected by assembly forces as the upper and lower segments are engaged. Tests of actual joint ends have been conducted and verify this characteristic. Once aligned, tapered G-10 insulating wedges are installed between turns to fill the gap and provide a solid block for through-bolt load transfer to each turn.

The through-bolts are a sliding fit to match honed G-10 bushings in each joint tab hole. The bolts are actually studs which engage a floating nut plate located at the innermost turn joint. The studs are tensioned and the load secured by a nut applied to the outer end of the stack to provide joint contact pressure. Preliminary tests of joint resistances through the stack have been made, and the results show that all joints had a measured resistance less than the required 1 $\mu\Omega$.

Thermal-electric tests have also been made on joint specimens to verify cooling capability and margins relative to the hot spot temperature limit of 150°C. These specimens were half-width turns in order to match the current density required to available power supply limits. Actual tests were possible up to about 0.7 of the rated joint current density. Extrapolation, verified by tests of an appropriate copper specimen, was then used to analytically predict peak temperatures for the joint configurations. Two joints were evaluated since the inner and outer turns differ slightly. The results of these tests are summarized in Figure 8 and show that adequate cooling can be provided for all joint configurations.



JOINT HOT SPOT TEMPERATURE

Fig. 8

The major joint parameters are summarized in Table III where the differences between the inner and outer turns can be seen. Geometry constraints required the inner turns to be slightly thicker, narrower, and clamped by only three bolts.

The PF coils are of a more conventional design and use a wound, square section, hollow copper conductor that is insulated with glass cloth and epoxy impregnated. They are being manufactured by the Princeton Plasma Physics Laboratory.

### Vacuum Vessel

The vacuum vessel is a stainless steel shell which fits closely to the inner bore and side walls of the HF coil as shown in Figure 9. The vessel is relieved in the area above and below the HF coil joint to allow clearance for installation and assembly of the segments. Twelve large ports on the outside (1.0 by 0.60 m), inside (0.15 m diam), top (0.4 by 0.5 m), and bottom (0.4 by 0.5 m) provide access for diagnostics, fueling, and heating systems. The wall thickness is 6.4 mm. Metallic seals on the port flanges permit the vessel to operate at 150°C for cleaning. For steady-state operation, cooling panels will be mounted on the inside of the vacuum vessel to take the heat from the plasma.

### Support Structure

The principal loads on the HF coils are due to thermal and magnetic forces which lead to radially outward hoop loads and overturning loads. The principal PF coil loads include a radial hoop force and the vertical force of interaction with the other coils. The structure consists of a toroidal shell composed of identical upper and lower shell panels and intermediate panels. The panels are joined by bolts, and the entire shell is tied to the HF coil segments by additional special bolted fasteners.

### Assembly Sequence

The assembly sequence is shown in Figure 10. First, the lower PF coils are positioned. The lower shell is then

Table III
Summary of joint parameters

| | | |
|---|---|---|
| Design limits | | |
| OFHC copper | 11,000 psi = endurance limit | |
| | 25,000 psi = 100,000 cycles | |
| G-10 bushing | 20,000 psi = 1/3 $S_{ult}$ | |
| G-10 insulation | 20,000 psi = 1/3 $S_{ult}$ | |
| A286 bolts | 200,000 psi = $S_{ult}$ | |
| | 100,000 ± 30,000 = 100,000 cycles | |
| | **Outer** | **Inner** |
| Dimensions, cm$^2$ | | |
| Joint cross-sections | | |
| Full copper turn | 39.0 | 41.0 |
| Full tab | 19.6 | 18.07 |
| Tear-out | 54.2 | 51.7 |
| Tab tension | 10.2 | 14.9 |
| Contact area | 63.6 | 46.0 |
| Current density, A/cm$^2$ (at 125 kA) | | |
| Turns | 3205 | 3048 |
| Joint tab | 6378 | 6918 |
| Contact area | 1965 | 2717 |
| Current per bolt, kA | 31 | 42 |

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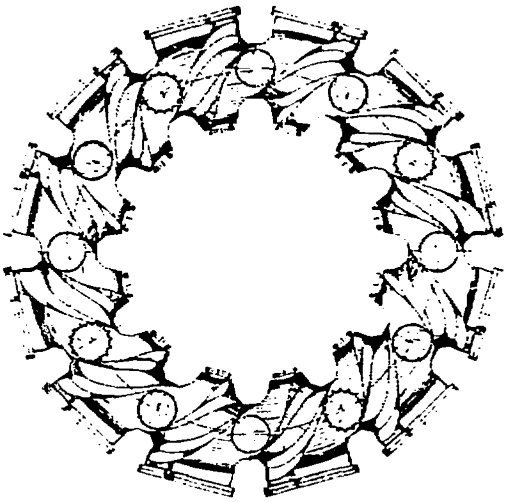

Fig. 9

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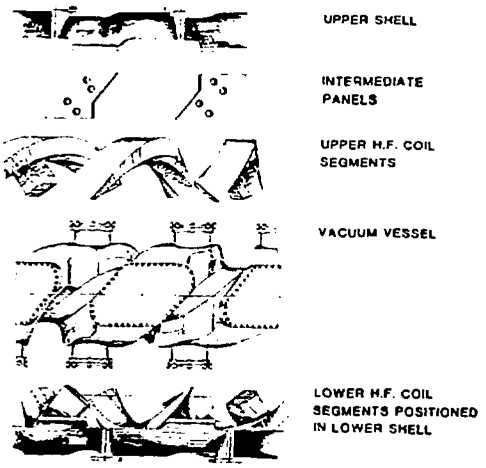

A.T.F. ASSEMBLY CONCEPT

Fig. 10

assembled and aligned. Next, the lower halves of the HF segments are installed and positioned accurately with an optical alignment system. The vacuum vessel is then lowered into place. Next, the upper HF segments are attached. The intermediate shell panels and the upper panels are mounted. Finally, the upper PF coils are mounted and aligned.

## CONCLUSION

The ATF torsatron has been designed to operate steady state at high beta with good transport properties. It will make major contributions to the U.S. Toroidal Confinement Program in the near term by providing a better understanding of the fundamentals of toroidal confinement and in the longer term through improvement of the toroidal reactor.

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