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THE ADVANCED TOROIDAL FACILITY*

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Abstract: The Advanced Toroidal Facility (ATF) is a new magnetic confinement plasma device under construction at the Oak Ridge National Laboratory (ORNL) that will lead to improvements in toroidal magnetic fusion reactors. The ATF is a type of stellarator, known as a "torsatron" which theoretically has the capability to operate at ≥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 2 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 Impurities Studies Experiment (ISX-B) tokamak at ORNL and will use the ISX-B auxiliary systems including 4 MW of electron cyclotron heating. The ATF is scheduled to start operation in late 1986. An overview of the ATF device is presented, including details of the construction process envisioned.

Introduction

The ATF [1-3] is a torsatron type of stellarator that has been developed at the ORNL with the twin goals of improving toroidal confinement in the areas of high beta and steady-state operation. 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 that increases in depth as beta increases. This capability is predicted to give the ATF access to the so-called "second stability" region and to a volume-average beta ≥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 rendering of the ATF is shown in Fig. 1. The main device parameters are given in Table 1, with the major coil characteristics indicated in Table 2.

Table 1. ATF DEVICE PARAMETERS

Major radius R_0, m	2.10
Average Plasma minor radius <a>, m	0.30
Average HF coil minor radius a_c, m	0.46
Toroidal field-on-axis B_0, T	2.0 (for 2 s) 1.0 (continuous)

The ATF Device

As shown in Fig. 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 many of the existing facilities of the ISX-B tokamak — power supplies, cooling, diagnostics, data acquisition, control, and heating systems.

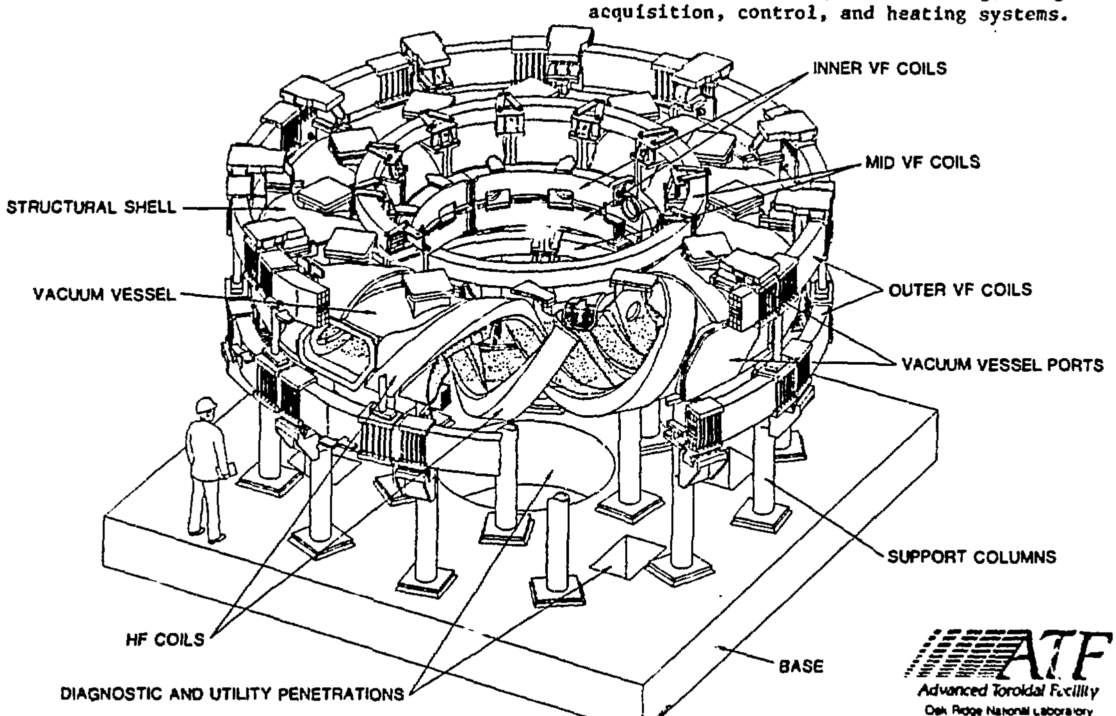

Fig. 1. ATF conceptualization showing principal features.

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Table 2. MAJOR COIL CHARACTERISTICS

Coil Set	Current per coil (MA-turns)	Current per turn (kA)	Current Density (A/cm²)	Voltage per coil set (V) Peak	Flattop
HF	1.750	125.0	3350	1000	600
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

Coils

The HF set consists of a pair of coils that forms a (ℓ = 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 the 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 (Fig. 2). 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 that has an accuracy of 1/100 mm. This machine is also used to check the completed segment. Following assembly, the segment is potted in epoxy resin. Components for a full-scale prototype segment have been built by the Chicago Bridge and Iron Company (Birmingham, Ala.) [4].

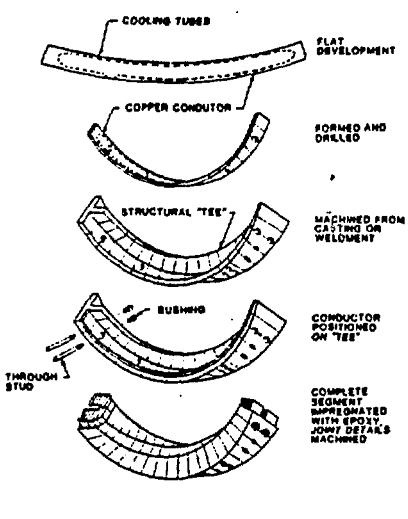

Fig. 2. HF coil segment assembly.

A critical design issue is the demountable joint. A large number of designs was 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 (Fig. 3).

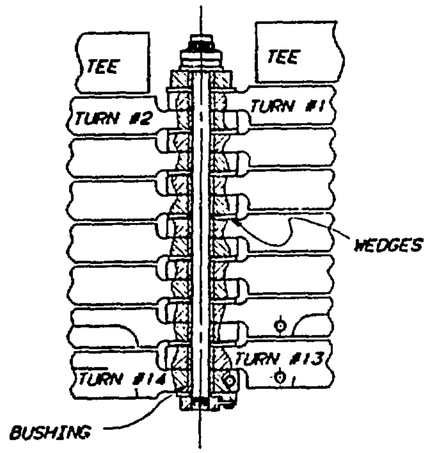

Fig. 3. Joint concept.

The lap configuration is comprised 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 while the copper is still in a flat development stage. A typical joint end is shown in Fig. 4. Precise control of each tab's position in the segment stack, including the through-bolt holes, is by use of tooling fixtures at the initial forming stage and again during segment assembly.

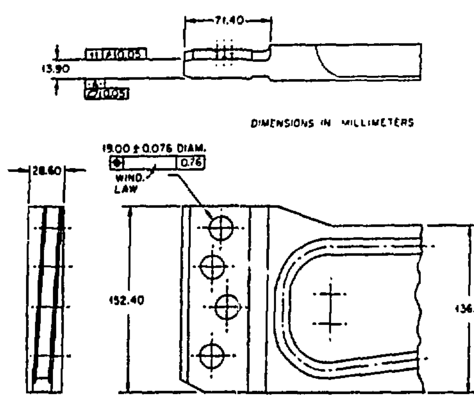

Fig. 4. Joint tab detail - typical.

Field assembly of these HF coil joints is based on optical alignment to a particular joint control hole feature on each segment end [5]. 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-11CR insulating wedges are installed between turns to fill the gap and to provide a solid block for through-bolt load transfer to each turn.

The through-bolts are a sliding fit to match honed G-11CR bushings in each joint tab hole. The bolts are actually studs that 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 the lowest resistance is at the inner joints. All joints had a measured resistance less than the required 1 μΩ.

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 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 Fig. 5 and show that adequate cooling can be provided for all joint configurations [6].

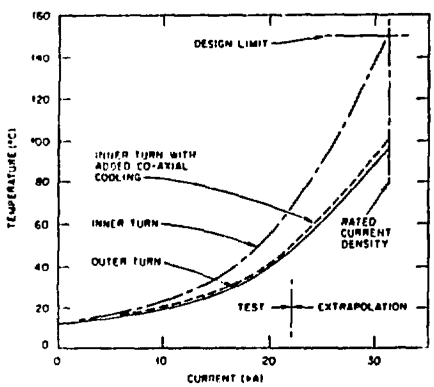

Fig. 5. Joint hot spot temperature.

Fatigue tests were conducted to provide detailed material property data for low-cycle fatigue analysis of the HF coil joints. Also, two test specimens consisting of partial two-turn joints were load cycled in tension and compression with peak operating loads. Results of these tests confirm the mechanical performance of this joint design [7].

The major joint parameters are summarized in Table 3, where the differences between the inner and outer turns can be seen. Geometry constraints required the inner turns to be slightly thicker and narrower and to be clamped by only three bolts.

The three sets of PF coils, manufactured by Princeton Plasma Physics Laboratory (PPPL), are of a more conventional design and use a wound, square-section, hollow copper conductor that is insulated with glass cloth and is epoxy impregnated [8].

Table 3. SUMMARY OF JOINT PARAMETERS

MATERIAL		DESIGN LIMITS	
Copper	OFHC	11,000 psi 25,000 psi	= Endurance Limit = 100,000 cycles
Bushing	G-11CR	20,000 psi	= 1/3 S_{ult}
Insulation	G-11CR	20,000 psi	= 1/3 S_{ult}
Bolts	Inconel 718	220,000 psi	= 1/3 S_{ult}
		100,000 ± 30,000	= S_{ult}

DIMENSIONS – cm^2	OUTER	INNER
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		
	OUTER	INNER
Turns	3205	3048
Joint tab	6378	6918
Contact Area	1965	2717
	OUTER	INNER
CURRENT/BOLT – kA	31	42

Vacuum Vessel

The vacuum vessel [9] is a stainless steel shell that fits closely to the inner bore and side walls of the HF coil, as shown in Fig. 6. 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 discharge cleaning. For steady-state operation, cooling panels will be mounted on the inside of the vacuum vessel to take the heat from the plasma.

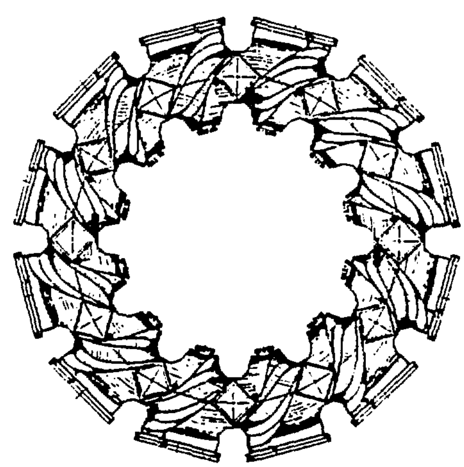

Fig. 6. Vacuum vessel design.

Support Structure

The principal loads on the HF coils are due to thermal and magnetic forces that 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 Fig. 7. First, the lower PF coils are positioned, then the

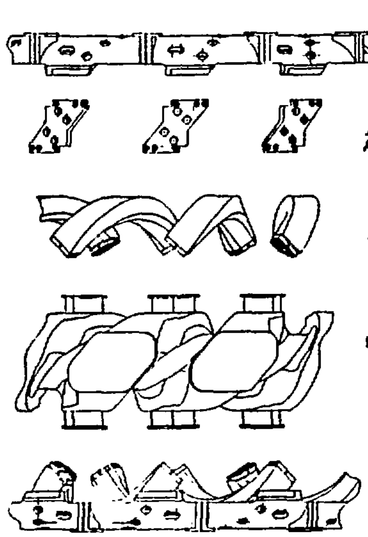

Fig. 7. ATF assembly concept.

lower shell is 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, and 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.

Acknowledgments

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