DESIGN DESCRIPTION OF THE ADVANCED TOROIDAL FACILITY*

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Abstract: The Advanced Toroidal Facility (ATF) is a large torsatron being designed at Oak Ridge National Laboratory (ORNL) to replace the Impurity Study Experiment (ISX-B) tokamak. ATF will have a major radius of 2.1 m and an average plasma minor radius of 0.3 m. Major components of the device include the coil sets, structure, and vacuum vessel. The coil sets are designed for broad operating envelopes, including the capability to drive up to 100 kA of plasma current, to produce helical axis configurations, and to operate continuously at one-half the baseline currents. The ATF structure consists of a 40-mm-thick stainless steel toroidal shell encasing the helical coil set. The shell is constructed from 24 identical upper and lower segments, with 12 pairs of intermediate panels to provide access to the helical field (HF) coil joints. The lower portion of the shell also serves as an assembly fixture for the HF coil set. The vacuum vessel is a highly contoured 6-mm-thick stainless steel shell closely fitting the bore and sidewalls of the HF coil winding to provide maximum volume for the plasma. Forty-eight large ports allow good access for diagnostics and neutral beam injection.

Introduction

The goal of the Advanced Toroidal Facility (ATF) is to investigate improvements in the toroidal confinement concept, with emphasis on high-beta, steady-state operation. Of the options considered (the current-driven tokamak, the stellarator, and the tokamak/stellarator hybrid), the stellarator is the most appropriate for a new facility [1]. Extensive theoretical studies have identified a moderate-aspect-ratio torsatron that exhibits high-beta stability limits (>7%) and the flexibility to vary the configuration to study experimentally the influence of configuation properties on plasma performance. This torsatron geometry is the basis for the ATF design.

The primary ATF parameters are listed in Table 1. As shown in Fig. 1, the device consists of a helical field (HF) coil set, a set of inner and outer vertical field (VF) coils, an exterior shell structure to support the coils, and a thin, helically contoured vacuum vessel closely conforming to the HF coils for maximum volume. In addition, provisions will be made to add a set of twelve toroidal field (TF) coils as an upgrade. Figure 2 shows the complete ATF coil set, and Table 2 lists the coil design parameters. All the coils use water-cooled copper conductor.

Table 1. ATF parameters

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

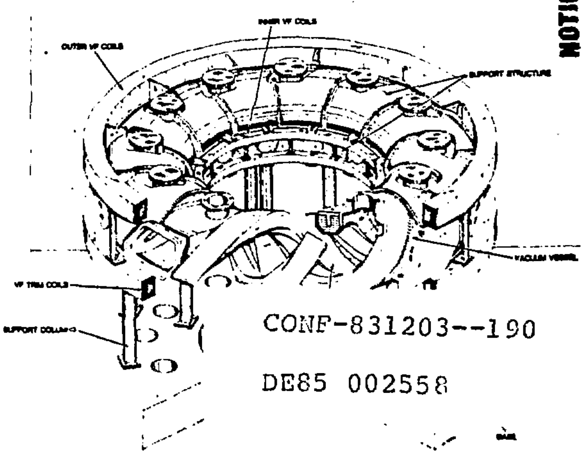

Fig. 1. Advanced Toroidal Facility (ATF).

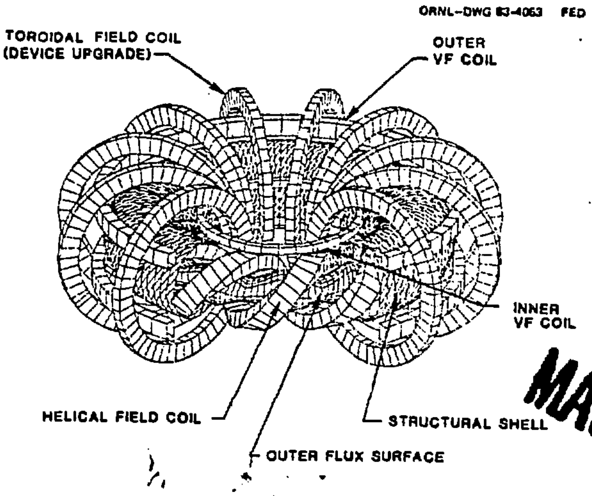

Fig. 2. ATF coil system.

ATF will be located in the present ISX-B enclosure and will make use of existing ISX-B power supplies, utility systems, diagnostics, and heating systems. The device is scheduled to begin operation at the end of 1986, and the total estimated cost is $19.3 million.

Helical Field Coils

The HF coil set consists of a pair of coils that form an ($M=12, \ell=2$) constant ratio torsatron helix with the design parameters shown in Tables 1 and 2. In

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Table 2. ATF coil parameters at maximum field

Coil set	Current per coil (MA-turns)	Current per turn (kA)	Current density (A/cm^2)	Voltage per coil set (V) Peak	Voltage per coil set (V) Flattop	Water flow rate (L/s)
HF	1.750	125.0	3350	1000	500	178
VF, inner	0.263	16.4	2540	650	121	6
VF, outer						
Main 1	0.375	125.0	2600	1000	63	23
Main 2	0.375	125.0	2600	1000	63	23
Trim	0.159	15.9	2420	650	166	5
TF	0.440	54.7	1000	350	177	27

addition to these requirements, the coils must be constructed so that the actual current path is within ±1 mm of the theoretical current path [2]. Other torsatron and stellarator coils have been successfully constructed by carefully winding hollow copper conductor onto the vacuum vessel, but this puts the manufacturing steps in series and requires that the vacuum vessel be completed before any winding can begin. In addition, problems or mistakes can interrupt the winding process and must be corrected before the winding can proceed. To allow for parallel assembly operations, the HF coils for ATF will be manufactured as a set of 24 identical upper and lower segments (Fig. 3). The segments are joined in the field to form the continuous coils. Each segment consists of 14 copper conductors separated with fiberglass insulation, bolted to a T-shaped structural support member and vacuum-impregnated with epoxy. The epoxy and glass form a compressive load path to transfer the magnetic forces on the conductors into the structural member.

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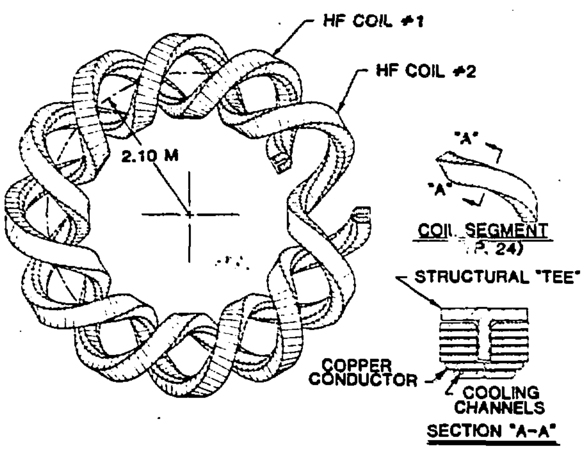

Fig. 3. Segmented HF coil concept.

As shown in Fig. 4, the conductors are made by machining flat developments from CDA101 copper plate, brazing a cooling tube into a milled groove, and rough-forming to shape. A complete set of conductors *with suitable spacers is clamped to* a precision die and stress-relieved to obtain the final form tolerance. The structural T is fabricated as either a 304 stainless steel weldment or a casting and is finish-machined. During segment assembly, each conductor is positioned on the stack relative to reference points machined in the structural T with the aid of a coordinate measuring machine. By retaining the measured location of each conductor, a "best fit" position for the completed segment relative to the theoretical helical current path can be calculated. This "best fit" position is also used to locate the segment during device assembly.

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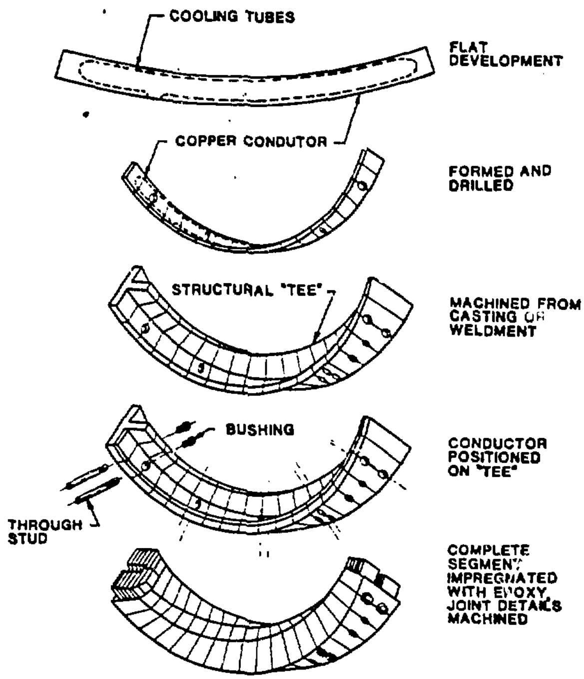

Fig. 4. HF coil segment assembly.

After the segment is assembled and epoxy-impregnated, the joint details are machined at the ends. Obviously, the joints are the most critical HF coil design problem. The baseline concept is a bolted splice joint that is acceptable for pulsed operation but requires additional cooling for continuous operation. Welded and electroformed concepts are also being considered. A special joint on the outside of each coil will provide for the crossover and current leads. Since only one-fourteenth of the total coil current is introduced at the leads, the field errors are acceptable.

To verify the segmented coil design concept, a full-scale prototype segment is being built. Chicago Bridge and Iron, Birmingham, will supply the conductor and structure piece-parts, and the segment will be assembled at ORNL. A special facility — the Verification, Assembly and Test Facility (VATF) — is being prepared for this task. In addition to the assembly facility, the VATF program is in the process of testing prototype joint designs.

Vertical Field Coils

Two sets of VF coils are required — an inner pair and an outer pair (Fig. 5). The coils are all wound from hollow copper conductor, insulated with glass cloth and epoxy-impregnated in a stainless steel case. In addition to the design parameters listed in Table 2, the windings must be accurate to within ±5 mm of the theoretical current path.

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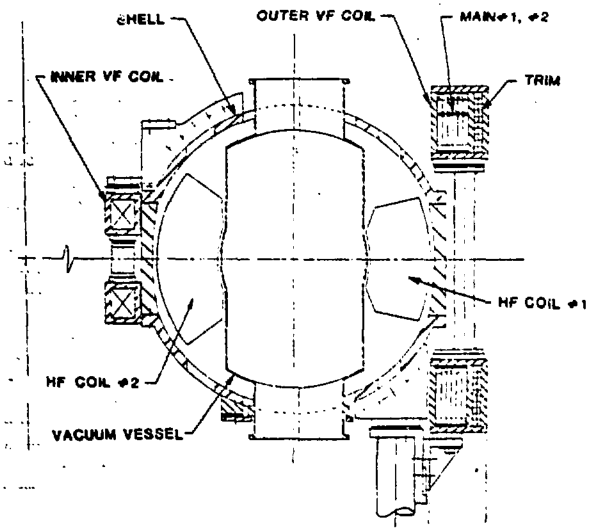

Fig. 5. Radial section showing VF coils.

The inner VF coils provide shaping and trim functions and are operated in series from a single power supply. The outer VF coils each have three independently connected windings, including two main sections and a trim section. The main sections are connected in series with the HF coils and provide the field that offsets the vertical field from the helix. Two main sections are required in each outer VF coil to maintain symmetry during helical axis operation, when one of the HF coils is operated at a reduced current. The trim section is powered from a separate power supply and can be energized with full current in either direction.

Vacuum Vessel

The vacuum vessel is a stainless steel shell, closely fitting the inner bore and sidewalls of the HF coils to maximize plasma/wall separation [3]. As shown in Figs. 6 and 7, the vessel is slightly relieved in the area above and below the HF coil joint to allow clearance for installation of the HF coil segments. Twelve large outer ports (1.0 by 0.6 m), twelve inner ports (0.15 m diam), and twelve upper and lower ports (0.4 m diam) provide access for diagnostics and tangential neutral beams.

Because the vessel carries only atmospheric pressure and a slight (0.3-atm) induced electromagnetic load, the wall thickness is only 6.4 mm. This provides sufficient toroidal resistance (0.5 mΩ) to avoid the need for bellows or insulating breaks. Although there is no active cooling initially, space is provided for water-cooled panels inside the vacuum

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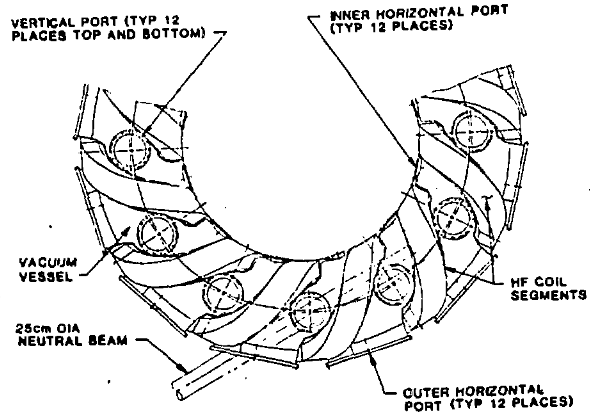

Fig. 6. Plan view of vacuum vessel and HF coil set.

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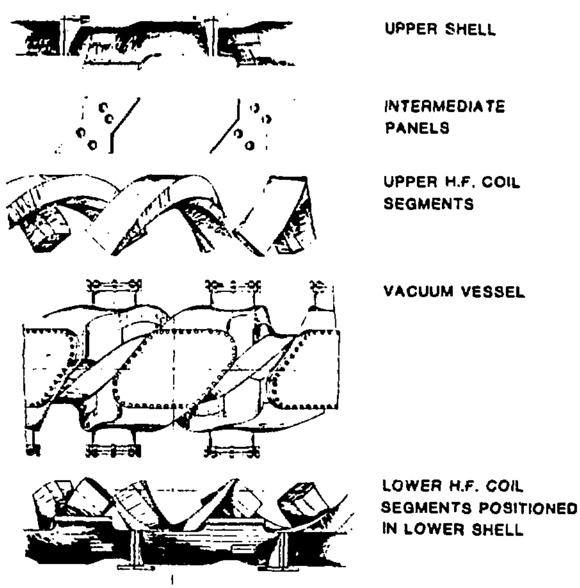

Fig. 7. Overall assembly concept.

vessel to permit high duty cycle or continuous operation. Metallic seals on the port flanges permit temperatures of 200°C for discharge cleaning and initial operation. Limiters will be used to prevent deposition of high plasma heat flux on the vessel wall.

Vacuum pumping is accomplished with the existing ISX-B mechanical pump-blower packages and turbomolecular pumps.

Machine Support Structure

The machine support structure is designed to accurately position the HF and VF coil sets and support them against the electromagnetic and gravity forces. The principal loads on the HF coils are radially outward hoop loads and overturning or side loads. These loads have been calculated using both the BARC16 and MAGFOR [4] computer programs; a typical load pattern is shown in Fig. 8. The principal VF

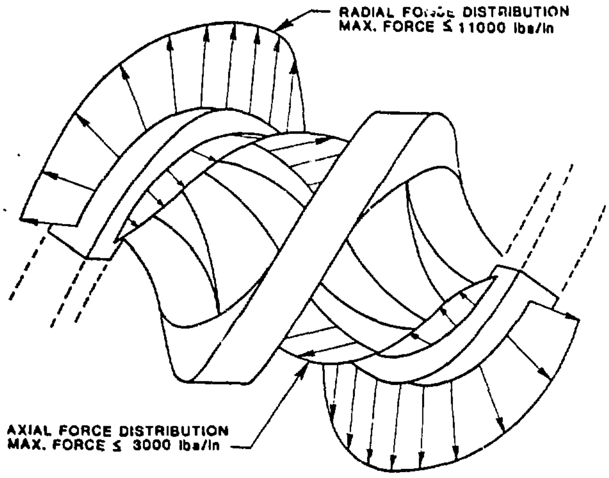

Fig. 8. HF coil force distribution (side view).

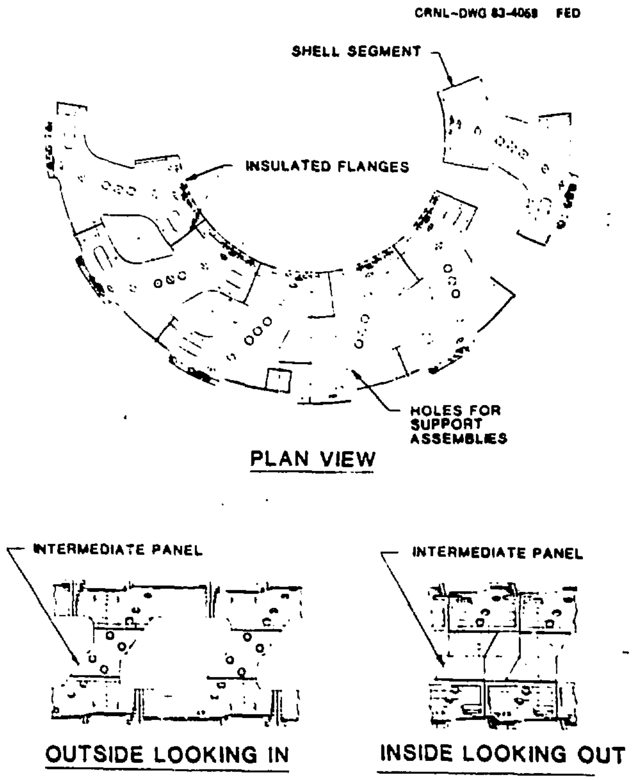

Fig. 9. Segmented shell support structure.

oil loads include a radial hoop force and a vertical force of interaction between the HF and VF coils and between VF coils in a pair.

The structural concept for supporting the HF coils is an external shell composed of identical upper and lower toroidal shell segments and intermediate shell panels. The shell forms a compact structure that allows maximum access for diagnostics and neutral beams. As shown in Fig. 9, the shell segments are joined at insulated, bolted flanges to prevent circulating eddy currents. During assembly, adjustable tooling balls are accurately located in the lower shell to form a reference datum for positioning each lower HF coil segment. The vacuum vessel is then installed, followed by the upper HF coil segments. The intermediate shell panels and upper shell assembly are added to complete the structure. Brackets attached to the shell flanges locate the inner and outer VF coil pairs and columns between VF coil pairs that carry the principal loads. Adjustable interfaces between the shell and the coils relax the tolerance requirements on the shell.

When the HF coil set is energized, the radial force is transmitted from the coil structural T through epoxy-filled bladders into the structural shell, where it is carried in hoop and axial tension. The side or overturning moments are transmitted through special shear attachments into the shell and are carried as a torsional load between the upper and lower shell assemblies. The side load is minimized by connecting the HF and outer VF coil sets in series to ensure a minimum net vertical field.

The vacuum vessel weight is supported from the lower half of the shell on sliding supports that allow thermal expansion in the radial direction. The entire device rests on 18 columns located under the shell segment flanges.

A detailed finite-element stress analysis using MSC NASTRAN will be used to check the behavior of the structural support system, as well as the individual components under various design and fault conditions. Design conditions include loads due to any combination of normal coil operating currents and temperatures, while fault conditions include abnormal coil currents and temperatures due to shorted coils or loss of cooling. Single HF coil and shell segments are modeled as a superelement and are reflected four times to form a 60° slice of the entire device. This permits a very detailed representation of these components, including separate elements for each turn and layer of epoxy/glass insulation.

Conclusion

ATF is designed as a versatile torsatron experiment with maximum diagnostic and heating access. The segmented fabrication concept takes advantage of symmetry to minimize construction time and to provide for repairs and maintenance. Prototypes of critical components are now being built to develop tooling and to verify the design.

References

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