

PFC/JA-87-40

Engineering Features of the Alcator C-Mod Tokamak

H. Becker, M. Besen, R. Childs
N. Diatchenko, K. Fertl, D. Gwinn, D. Humphries
I. Hutchinson, B. Lipschultz, D.B. Montgomery, N. Pierce
R. Pillsbury, J.H. Schultz, R. Vieira, S. Wolfe

General Editor: A. M. Dawson

To be published in Proceedings of the Twelfth Symposium on Engineering Problems of Fusion Research, Monterey, CA, October 12 - 15, 1987.

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

Engineering Features of the Alcator C-Mod Tokamak

H. Becker, M. Besen, R. Childs
N. Diatchenko, K. Fertl, D. Gwinn, D. Humphries
I. Hutchinson, B. Lipschultz, D.B. Montgomery, N. Pierce
R. Pillsbury, J.H. Schultz,† R. Vieira, S. Wolfe

M.I.T. Plasma Fusion Center

Introduction

Alcator C-Mod is a tokamak under construction at M.I.T. It is an upgrade to the Alcator C facility aimed at exploring ICRF heating, impurity control, fueling, and shaping in high performance tokamaks. It will be the first tokamak that combines high toroidal field with a high shaping and plasma current capability, and is thus prototypical of the Compact Ignition Tokamak^{1,2}. To achieve the simultaneous goals of high field and high current, Alcator C-Mod has incorporated several unique engineering design features^{1,2,3,4}. This paper describes the current status of the engineering design, concentrating on critical issues and those aspects which have changed since the previous descriptions.

Alcator C-Mod uses copper-plate TF magnets with sliding joints connecting the legs of each turn. The TF magnet is supported by a steel superstructure. Poloidal field coils are mounted internally from a thick, steel vacuum vessel. Magnets are inertially cooled by liquid nitrogen and the superstructure is contained within a nitrogen dewar, and supported from three legs. The machine's major parameters are shown in Table I.

Table I
Major Machine Parameters

R_o	0.665	(m)
B_t	9.0	(T)
I_p	3.0	(MA)
Elongation	2	
P_{RF}	6	(MW)
$P_{t,av}$	0.8	(MW/m ²)
I_{TF}	250	(kA)

† Principal author

The most novel design feature is the use of sliding joints in rectangular-plate toroidal field (TF) magnets. The ability of the joints to slide reduces tensile stress in the critical central column of the TF magnet, while the demountability of the joints allows the assembly of internal poloidal field (PF) magnets and removal of the vacuum vessel as a unit. The presence of sliding joints necessitates the use of an external superstructure to support the vertical, radial and out-of-plane loads on the TF magnet. The magnet system and assembly concepts are illustrated in Fig. 1. Although similar to Alcator C, inertial cooling of magnets by liquid nitrogen presents some new engineering issues, including the development of cooling channels for the central solenoid and of noncircular flanges that remain vacuum tight under large temperature gradients. The central solenoid also has the unique feature of a T-shaped 'notch coil.' The electrical systems require special analysis and design in the area of inspecting and upgrading the Alcator C pulsed alternator.

TF Sliding Joints

The sliding joints for the TF magnets have proven to be the most ambitious engineering development program for Alcator C-Mod. These joints must be capable of high current densities, while undergoing substantial deflections and out-of-plane loads. The overall joint and TF magnet assembly concepts are shown in Fig. 2. The current joint specifications and loads are shown in Table II. Early tests on sliding joint concepts identified surface preparations with excellent resistivity and wear properties. However, the addition of coatings to broad copper fingers failed in full-scale joint tests, because of the inability to achieve uniform contact over a broad area in a practical assembly. Multilams have been used with other jointed designs to provide multiple contacts over a broad area, but because of the long length of the lams, they have an intrinsically high resistance. Various multilam materials and shapes were tested. The current density was extended considerably over previous benchmarks, but the concept was marginal for C-MOD.

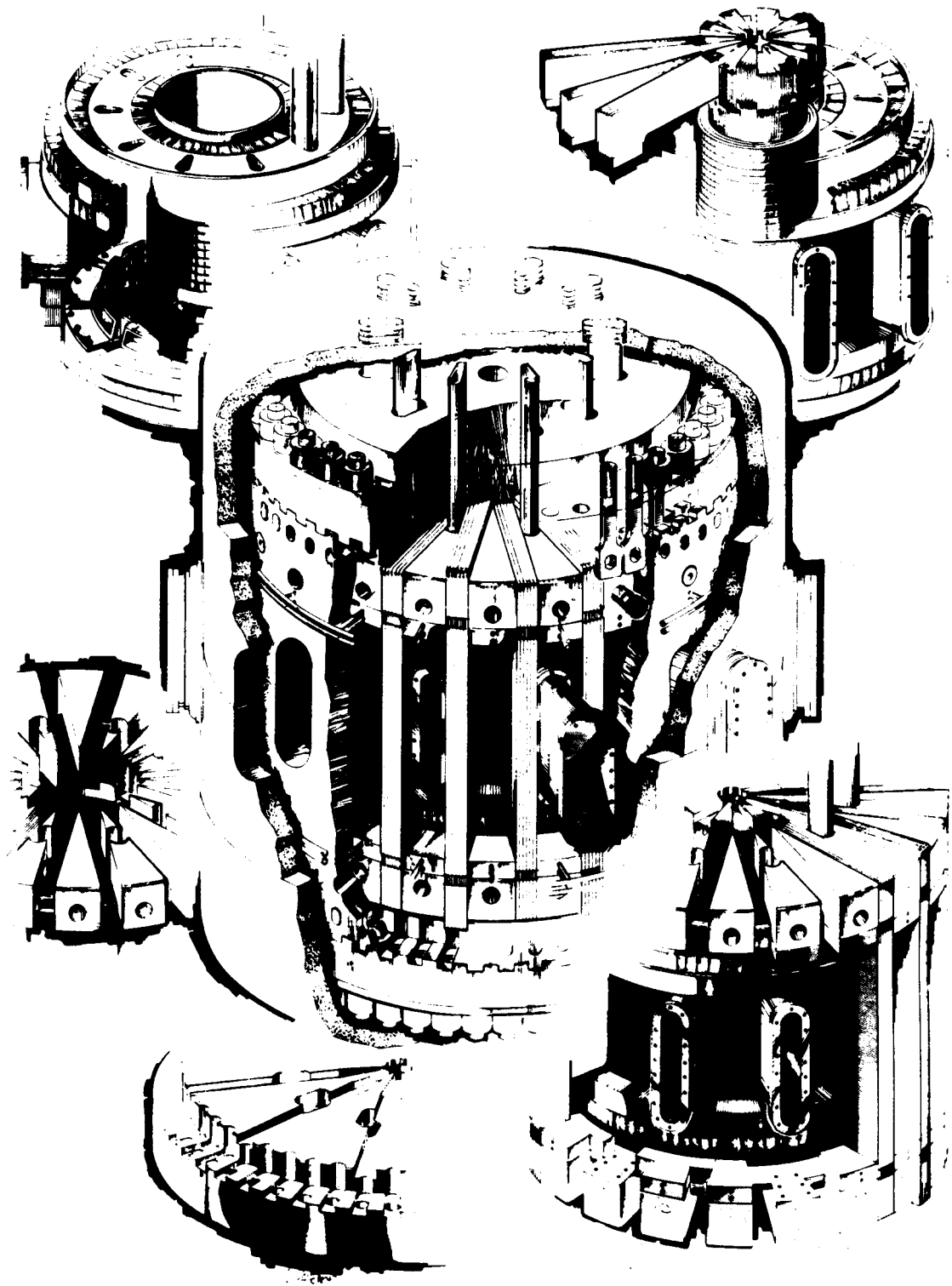


Fig. 1 – Major Components of Alcator C-Mod Magnets

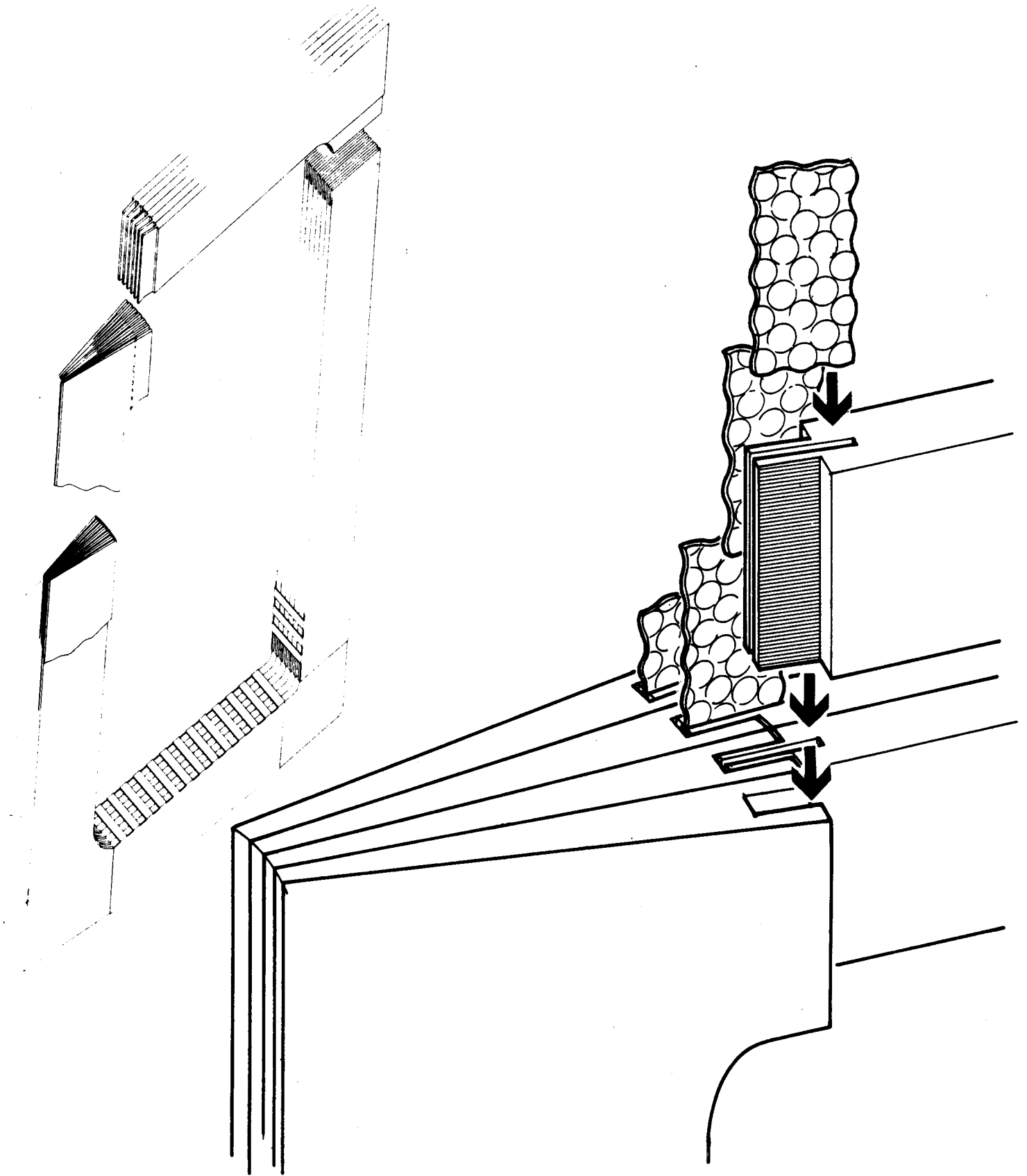


Fig. 2
TF Coil Joint Assembly Concept
for One 6-Plate Bundle

Table II
TF Magnet System Requirements

W_m	217	(MJ)
E_{pk}	346	(MJ)
$I_{plate,joint}$	250	(kA)
n_{turns}	120	
<u>Joints</u>		
n_{joints}	480	
$J_{av,face}$	2	(kA/cm ²)
$J_{pk,face}$	4.3	(kA/cm ²)
$J_{pk,finger}$	49	(kA/cm ²)
T_{pk}	275	(K)
ρ_{joint}	10	($\mu\Omega$ -cm ²)
<u>Relative Displacement</u>		
Vertical	± 2.5	(mm)
Radial	1.0	(mm)
Toroidal	0.33	(mm)
Preload	2.75	(MPa)

Feltmetal pads were identified as a new concept that combined the best features of flat plates and multilams. There are numerous contacts at the felt pad surfaces, but the underlying matrix is tough and has high conductivity. Separate spring plates provide a preload of 2.75 MPa, while allowing displacements up to 1/3 mm without losing electrical contact. The joints are also designed to allow the calculated relative vertical displacement of 2.5 mm and radial displacement of 1 mm. Finite-element analysis of stresses, displacements, current and temperature distribution in the finger region led to shaping of the fingers and feltmetal pads, as shown in Fig. 3. The fingers have been tapered to allow the contacts to follow out-of-plane displacements instead of rocking about the edge of the contact area. The feltmetal contacts were reduced to four pads, instead of covering the entire available contact surface, in order to ensure good contact in the leading edge region where the joint current is concentrated.

TF Central Column

The inside legs of the 120 turns in the TF magnet are assembled into a single central column of wedge-shaped vertical plates. This assembly supports the radial centering loads on the TF magnets through wedging, and supports a fraction of the vertical loads

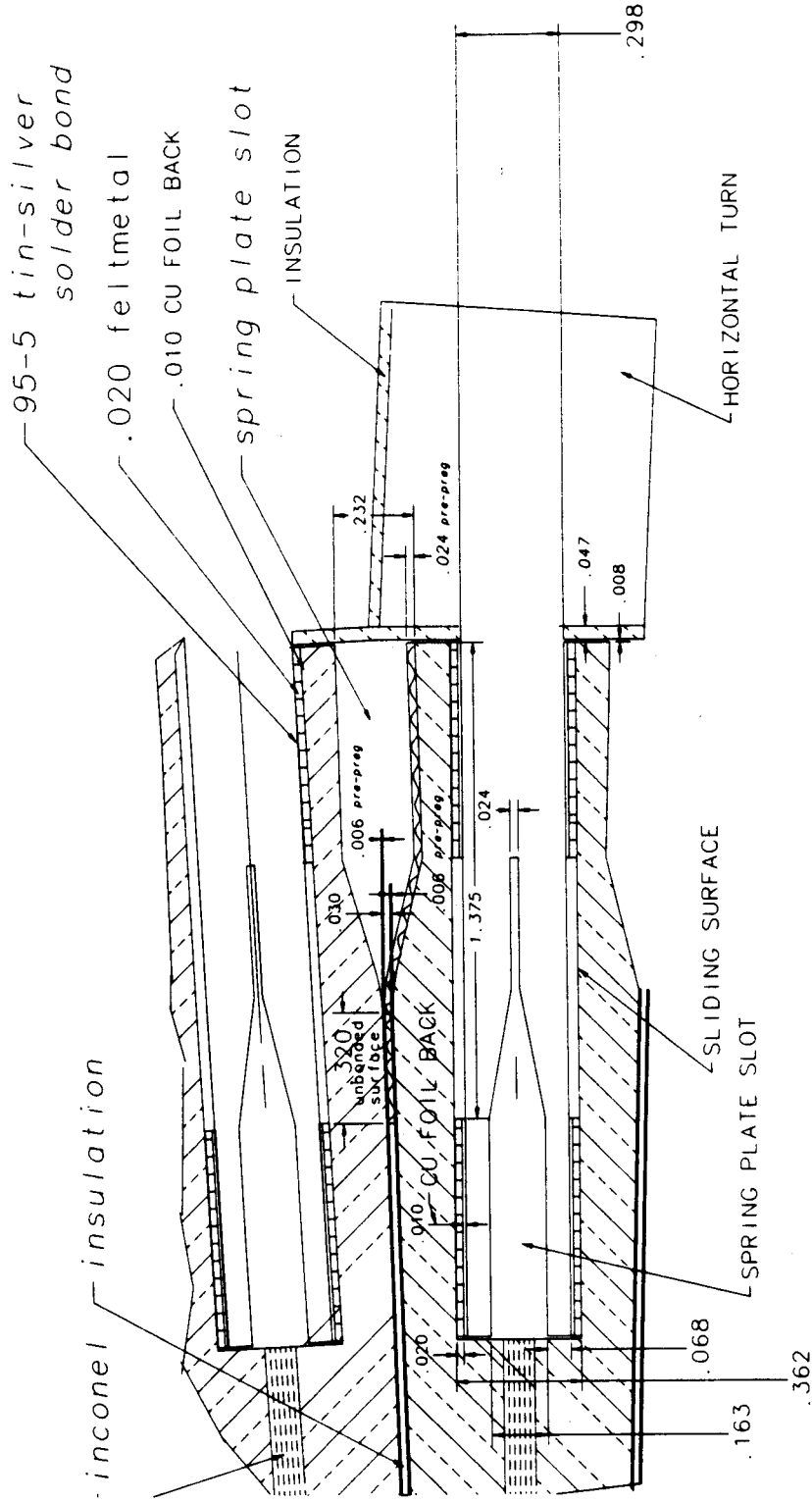


Fig. 3 - Detail of Sliding Joint between TF Horizontal Leg and Central Column

through tension. Without reinforcement, the combined loads on the plates cause a stress intensity higher than the allowable for copper. Explosively bonded steel plates between wedge-shaped copper half-conductors are used as reinforcement. The reinforcement plates are extended on the inside to serve double duty as cooling fins. The wedged conductors are CD107 copper, bonded to flat Inconel 718 plates, with a 4:1 copper/reinforcement ratio over the central column area. The yield strength of the copper is 310 MPa, up to 100° C, while the yield strength of the Inconel plates is 1130-1300 MPa. The peak Tresca stress on the Inconel at the inside radius is calculated to be 580 MPa, while that in the copper is 310 MPa.

External Superstructure

Because of the sliding joints, the forces on the TF magnets, other than those on the central column, must be supported by an external superstructure. Vertical forces on the TF horizontal legs are supported by the top and bottom domes. Out-of-plane loads are transmitted to wedge plates, between the horizontal legs of the TF coils. The domes and wedge plates are both bolted to an outer structural cylinder that supports vertical and out-of-plane loads through the bolted connections, and also directly supports the outward radial loads on the outer vertical legs of the TF magnet. These structures are illustrated in Fig. 1.

Each of the two domes is machined from a single 26 tonne 316 LN forging. The domes are sufficiently thick to support the distributed vertical load from the TF magnet legs in bending without approaching static allowables, so that cyclic loading governs the design. The highest Tresca stress in the cover is 370 MPa at the narrow tip of the vertical port aperture. The machine is inspected every 12-15,000 full-field cycles. Assuming initial cracks of 2.5 mm, a safety factor of five against crack growth to 25 mm was calculated.

The stresses in the outer cylinder are lower than those in the domes. Vertical forces are transmitted from the dome to the cylinder through vertical draw bars, pinned horizontally to the cylinder. The highest stress region in the cylinder is the hole where the draw-bar pins penetrate the cylinder wall. Because the cylinder is sized to accept the much-larger vertical loads, the torsional shear stress in the cylinder due to out-of-plane loads has a peak value of only a few MPa. The highest local stress anywhere in the superstructure is at the pin hole of the draw bars. Since the draw bars are made of high strength Inconel 718, this region is less limiting than the port cutouts in the domes.

Vacuum vessel, divertor collector and tiles

The vacuum vessel is a thick, welded 304L steel structure, with protective tiles mounted internally as divertor collector plates at the bottom of the vessel and bumper limiter on the inside wall, as shown in Figs. 4 and 5. The inner wall of the vacuum vessel is a 15-mm, solid-steel cylinder. The vessel is reinforced internally in the outer corners by gussets, in order to limit peak stresses during normal operation and disruptions. The gussets also serve as mounting platforms for the outside divertor collectors.

The inside horizontal port flanges are a critical area of the vacuum vessel assembly. The vacuum seals for these ports have a large, racetrack shape, while supporting potentially large thermal gradients. Seals must be vacuum tight from nitrogen (80 K) to bakeout (200° C) temperatures. An annealed, silver-coated Helicoflex gasket with an Inconel liner and a Nimonic 90 spring has produced the best results. The seal remained vacuum tight through several cycles from 80 K to 520 K. The seal leaked at a gradient above 100° C, but resealed when the gradient was reduced. The sealing surface will be polished, then scored parallel to the sealing surface to prevent creep under thermal cycling.

The divertor collectors are mounted at the bottom of the vacuum vessel in inner and outer poloidal rings, with clearance for vertical ports, as illustrated in Fig. 6. The power and energy absorption requirements of the collectors and limiters are shown in Table III.

Table III
Vacuum Vessel Wall Protection

Total Heat	6.0	(MW)
Charged particle heat	4.2	(MW)
<u>Bumper Limiter</u>		
n_{tiles}	400	
A_{surf}	1.04	m ²
<u>Collector</u>		
$n_{plates,i+o}$	40	
P_{av}	5	(MW/m ²)
P_{pk}	10	(MW/m ²)
$P_{av,disrupt}$	500	(MW/m ²)
$P_{pk,disrupt}$	1000	(MW/m ²)
$E_{av,disrupt}$	0.5	(MJ/m ²)

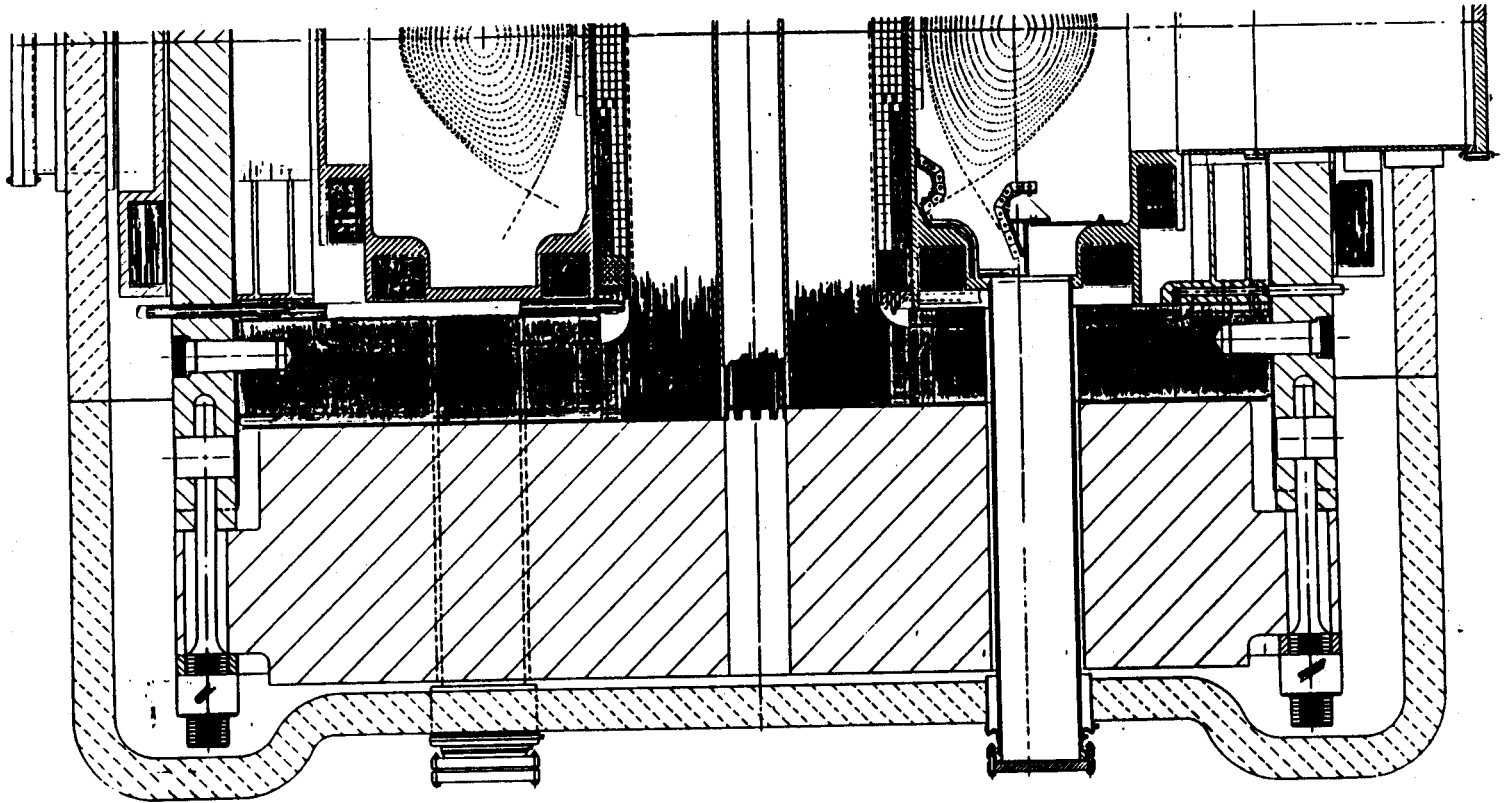


Fig. 4
Elevation View of Bottom Half of Alcator C-Mod

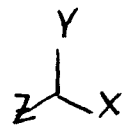
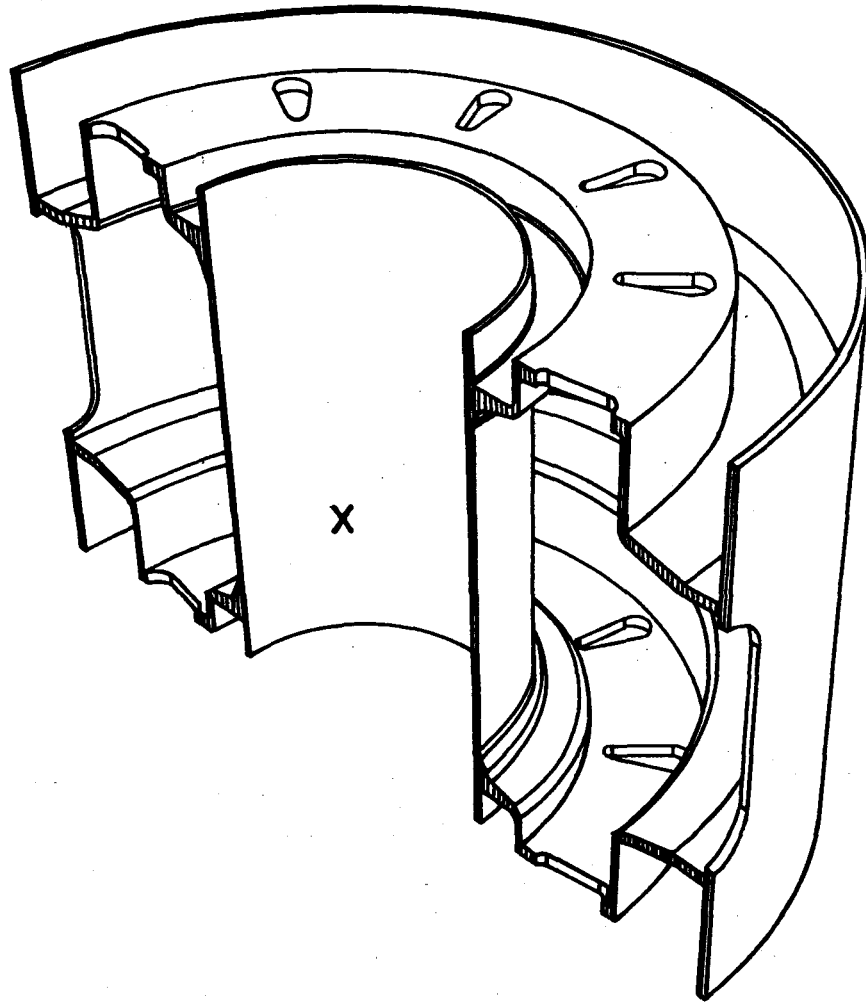


Fig. 5 – CAD Drawing of Vacuum Vessel

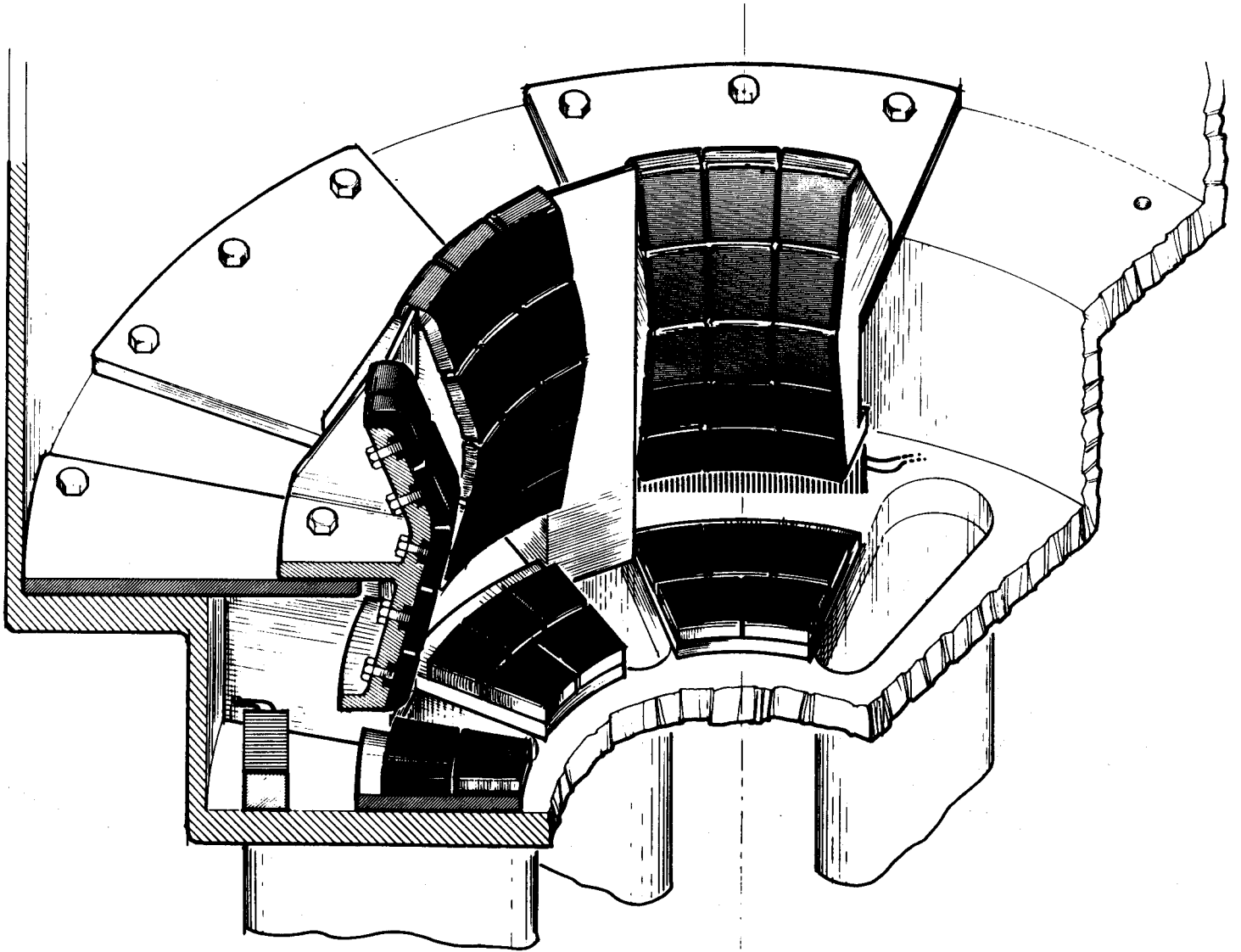


Fig. 6 – Divertor Collector Plate Mounting Concept

There are ten outer collector plates, one between each vertical port, each with 80 tiles, either a carbon composite or molybdenum. Each tile is typically 35-mm square and 20-mm thick. The selection of materials and dimensions has not been finalized. The tiles are slid into T-bar slots, then bolted into place. Thermal conduction from tiles to mounting surfaces is provided through bolted mechanical contact. Copper feltmetal backings are being considered for the tiles in order to reduce contact resistance.

Poloidal Field Coil System

The poloidal field (PF) coils are mounted from the vacuum vessel, inside the TF magnet, with the exception of one coil pair (EF4) mounted from the outside cylinder, as shown in Fig. 4. This coil is paired with EF3 to provide the main vertical field along with fine control of strike points during flattop.

The central solenoid stack consists of OH1, a single T-shaped notch coil, along with an OH2 solenoid pair, above and below the nose of OH1. This configuration permits the formation of highly elongated, triangular, and/or mildly indented plasmas with a simple PF system. The main simplifying features are that no leads have to be routed from within the central solenoid stack and that the conductors are externally cooled.

The poloidal field system has relatively few coils for the maintenance of highly shaped plasmas. Recent simulations showed that either moving the thick vessel wall in on the outside as close to the plasmas as the rf heating experiments permit or using stabilizing plates in the same region, stabilizes plasmas with elongations of two at the x-point. A fast power supply will be needed to drive an active control coil, adjacent to EF2, since the passive growth rates are close to $1,000 \text{ s}^{-1}$ for plasmas of this elongation.

Alternator and Power Supplies

Most of the controlled rectifiers used on Alcator C have been sent to the Lawrence Livermore National Laboratory for use with the Alcator C magnet in the Microwave Tokamak Experiment (MTX). The toroidal field magnet needs the single largest power supply, requiring 250 kA and no load voltages higher than 1200 V. This requirement will be met with six 50-kA twelve-pulse rectifiers.

The pulsed stored energy requirements of C-Mod are considerably higher than those for Alcator C, as shown in Table IV. The pulsed alternator used as the energy source for Alcator C has to be enhanced for the C-Mod experiment. Enhancement techniques being considered include overspeeding the generator at the high end, underspeeding at the low

end, and adding a flywheel, as illustrated in Fig. 7.

Table IV
Pulsed Energy Requirements and Options

<u>Requirement/Option</u>	Energy (MJ)
Alcator C	190
C-Mod TF	375
C-Mod PF	75
C-Mod Load	450
Generator, required	500
Alc C operation, 1.0 pu - 0.7 pu	270
Overspeed, 1.1 pu - 0.7 pu	383
Underspeed, 1.0 pu - 0.5 pu	405
Flywheel, H=1.9 s, 1.0 pu - 0.7 pu	500

The rotor of the alternator has already undergone substantial cycling, and a reliable method of inspection and crack detection must be developed for continued operation. A proposal is being considered to inspect the rotor shaft and retaining rings for cracks, using in-bore ultrasonic inspection. If cracks of a critical nature are discovered, they would be bottle bored out of the rotor shaft. Any detectable crack would require replacement of a retaining ring.

The flywheel concept being considered fits within the existing generator facility. The flywheel is a solid steel disk with a gas-tight shroud to reduce windage losses. A disk with a 3 m diameter and a weight of about 40 tonnes provides the additional 350-450 MJ of rotational energy needed for the magnet systems.

Conclusions

Several important issues have been identified and are in varying degrees of resolution in the engineering of Alcator C-Mod. The most difficult issues are those involved with upgrading the high-field approach of Alcator C to a larger size and noncircular shape in the plasma and vacuum vessel. Achievements in the solution of these problems include:

- Contracts have been awarded for the TF magnets, superstructure, and vacuum vessel. Requests for proposals have been issued for the superstructure fasteners and the TF power supplies, and will shortly be issued for the PF coils.

- A sliding joint concept was developed that has demonstrated acceptable surface resistivity and wear over 50,000 cycles and is within allowable temperatures and stresses in finite-element simulations.
- The TF central column, TF superstructure and PF magnets are analyzed to be within stress and temperature allowables during a full plasma discharge cycle and disruption.
- A vacuum flange seal concept has demonstrated sealing over several full-temperature cycles.
- A fabrication and mounting procedure has been identified for internal vacuum vessel components. Three-dimensional finite-element analyses confirm the possibility of operating within stress and temperature allowables during full-power discharges.
- A testing and analysis method has been identified to allow continued safe pulsed operation of the generator and flywheel.

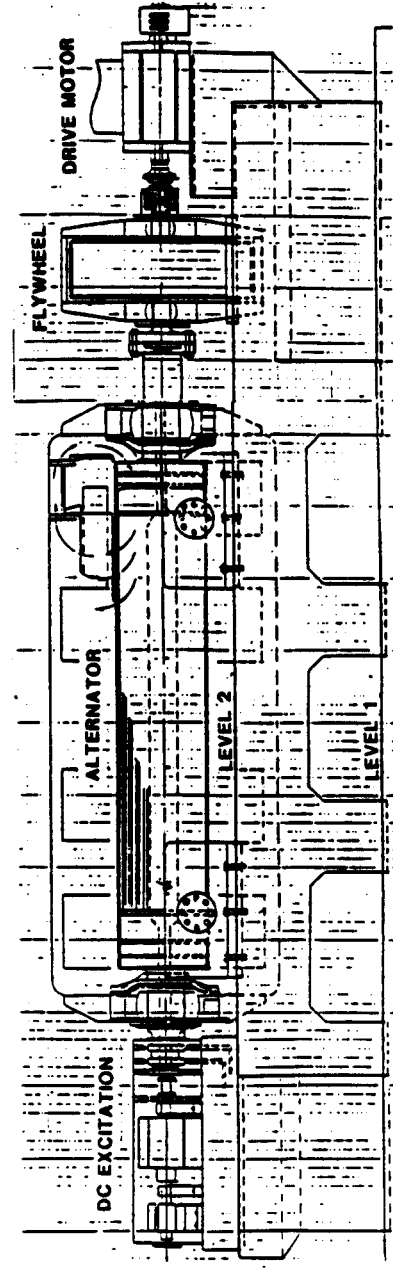
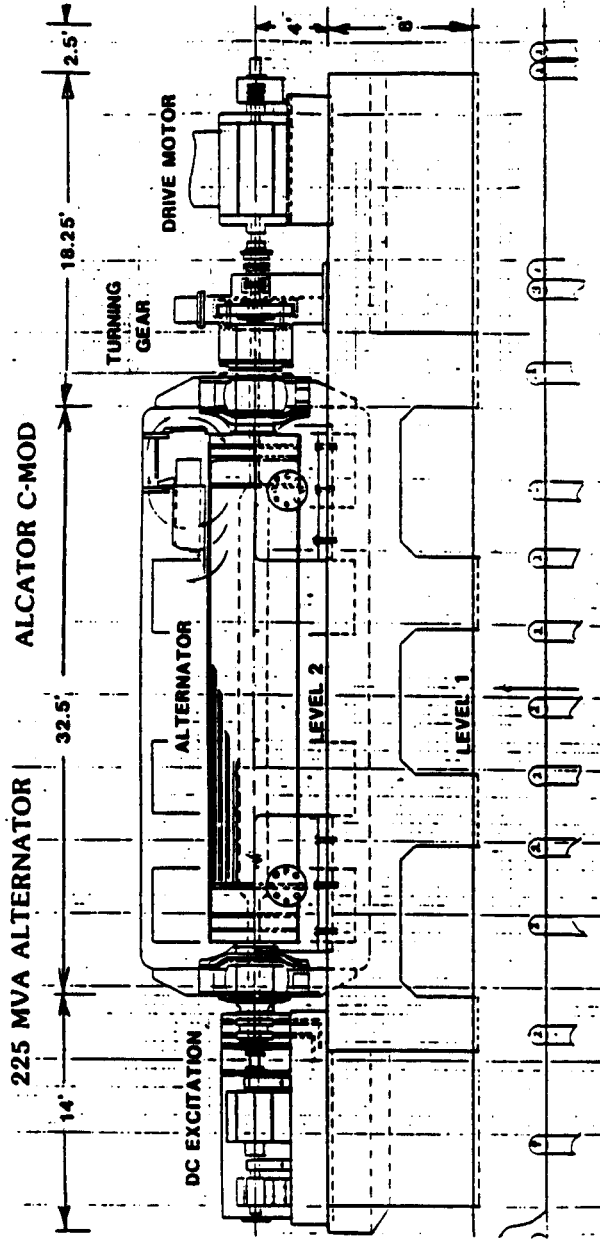


Fig. 7
 Addition of Flywheel to Existing Pulsed Alternator Drive

References

1. R.R. Parker et al., *Alcator C-Mod Proposal*, M.I.T. Plasma Fusion Center Research Report PFC/RR-85-18, Sept 1985.
2. R.R. Parker et al., *Alcator C-Mod Proposal Addendum*, April 1986.
3. J.H. Schultz, et al., 'Conceptual design of the Alcator C-Mod magnetic systems,' 11th Symp on Fusion Engineering, Austin, TX; Nov, 1985.
4. J.H. Schultz et al., 'Sliding joint and bond development program for the Alcator C-Mod toroidal field coils,' *Fusion Technology*, Proc 7th Topical Mtg on Tech of Fus Energy, 1536, Nov 1986.