PFC-JA/86-40

Sliding Joint and Bond Development Program for the Alcator C-Mod Toroidal Field Coils †

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June 1986

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† Submitted for publication in Fusion Technology

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Abstract

The Alcator C-Mod toroidal field (TF) magnets include several advanced magnet concepts that are planned or considered for a compact ignition tokamak experiment (*C.I.T*). Two concepts in particular, sliding joints and explosively-bonded composite plates, require a development program to assure feasibility and performance.

Introduction

Alcator C-Mod is an upgrade of the Alcator C tokamak at M.I.T. with the mission of investigating ICRF-heated plasmas at the high fields and densities most relevant to a compact tokamak ignition experiment.[1] An elevation view of the machine, showing its rectangular TF magnet and vacuum vessel and its internal poloidal field coils is shown in Figure 1. Major dimensions and performance goals of Alcator C-Mod are shown in Table I. The toroidal magnet system in C-Mod is required to be both high performance and flexible, in order to allow experiments over a broad range of plasma fields and shapes. These goals define a unique set of engineering problems, described previously by the authors.[2] The most challenging requirement is to develop a toroidal magnet that is simultaneoulsy high-field and high strength, but that can be disassembled, in order to install internal poloidal field coils and a single-piece vacuum vessel. The solution to this challenge requires the development of sliding joints and bonded plates in the TF magnet.

The Alcator C-Mod TF magnet is fabricated in 20 picture-frame coils, each coil consisting of four stacks of 6 conducting plates. The stacks form the vertical and horizontal sides of the frame and are connected by sliding joints at the corners. The inner legs are assembled in a central TF cylinder, consisting of 120 copper-Inconel laminate tapered plates. The plates are wedged together into a homogeneous cylinder, with thin epoxy-fiberglass sheets between them. The central cylinder is in the highest field and most highly stressed region of the tokamak. The maximum field at the TF magnet is 20 T. In order to remain within stress allowables, the inner leg requires both removal of tension and bending through the sliding joints and composite bonding of copper to high strength reinforcement.

Sliding Joints

The benefits of sliding joints in tokamak TF magnets have been described previously by Puhn.[3] These include flexibility in the assembly of the vacuum vessel and internal poloidal field coils and elimination of bending and vertical forces on the TF inside column. Sliding joints using multilaminates have been tested successfully at General Atomic for 3 seconds, up to a burnout current density of at least 4 kA/cm^2 for small multilaminates with a compression range of 0.3 mm .[4]

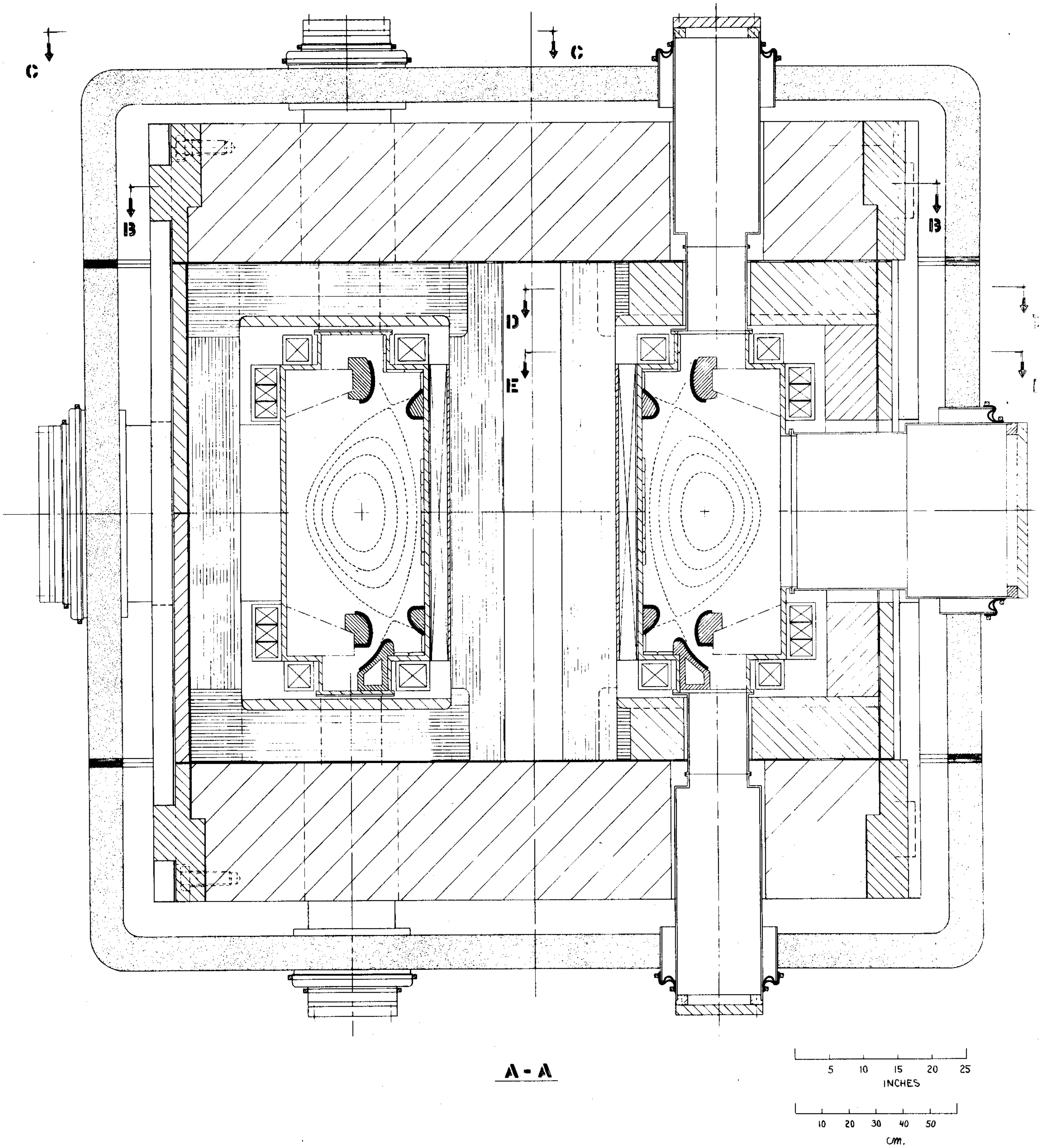

Fig. 1. Elevation View of Alcator C-Mod.

Table I
Alcator C-Mod Machine Parameters

Parameter	Value	Units
R_o	0.64	(m)
a_{minor}	0.21	(m)
B_t	9.5	(T)
Elongation	1.8	
Triangularity	0.3	
I_p	3.5	(MA)
$t_{flattop}$	1	(s)
PF flux-swing	9	(V-s)
RF Heating	6	(MW)

Table II
Inside TF Joint Stress and Displacement

R_o - R_i	0	25	50	75	(mm)
$p_{face,av}$		413	138	62	(kPa)
σ_{bend}		70.9	41.4	32.3	(MPa)
τ_{shear}	30			2.1	(MPa)

Joint Concept

Each leg of the TF coil is made up of a rectangular plate, joined along a broad mating surface to orthogonal plates on either end. The currently favored topology of the joint itself is mortise-and-tenon. A lap joint has also been analyzed and tested. Pressure and displacement on the joint are controlled by a dimpled spring plate in the center of each joint, as illustrated in Figure 2. At the operating point, the dimples exert a pressure of 250 psi over plates with a width of 76.2 mm and a length of 241 mm. Each dimple can travel 0.838 mm from the undeflected to the bottomed position. In order to exert 250 psi of pressure over the face, the inserted position of the dimples is 0.25 mm from the bottomed position.

Structural Analysis

The structural requirements of the joint are to stay within allowable stresses in the joint region and to limit deflections within a range that allows adequate electrical contact but still permits sliding to relieve vertical forces in the inner TF leg. The dominant forces on the joint are Lorentz forces. In-plane forces have been decomposed into wedging and bucking in the joint region. Although a 5 cm radial extent of the joint was adequate from electrical and thermal considerations, the joint width was extended to 7.6 cm, in order to allow wedging of the radially inward force on the horizontal arms, if necessary. The out-of-plane forces on the joint were examined at several points in time in order to find the worst cases. The worst-case stresses usually occurred immediately before plasma initiation. Out-of-plane stresses are due to pressure on over the face of the joint, bending of the fingers about their horizontal and vertical axes, and the relative twist of the horizontal arms and the central cylinder. The bending due to differential twist was the dominant source of bending stress, using a simplified model, in which torsion in the horizontal arms and central cylinder were computed separately. When a more sophisticated model included the torsion applied on the inner cylinder by the horizontal arms through the joints, relative displacements were reduced by greater than a factor of two. A potted intercoil structure was also added to the structure to reduce the twist of the horizontal arms. With these improvements in design and analysis, the stresses and displacements in the joint were calculated to be within allowable limits. The results of the analysis for the lap joint are shown in Table II.

Thermal and Electrical Analysis

The current density capabilities of the joint depend on detailed finite element analysis, because the inertial cooling of the joint depends on both thermal and magnetic diffusion. A detailed finite element analysis has been performed for the most demanding TF magnet scenario, a 1 s flattop at 9 s. (The TF coils are designed for structural adequacy at 10 T, while the most demanding experiment being planned requires 9 T for 1 s.) The model used includes thermal and magnetic diffusion with temperature-dependent properties, regulation and speed reduction of the pulsed generator-rectifier supply and detailed

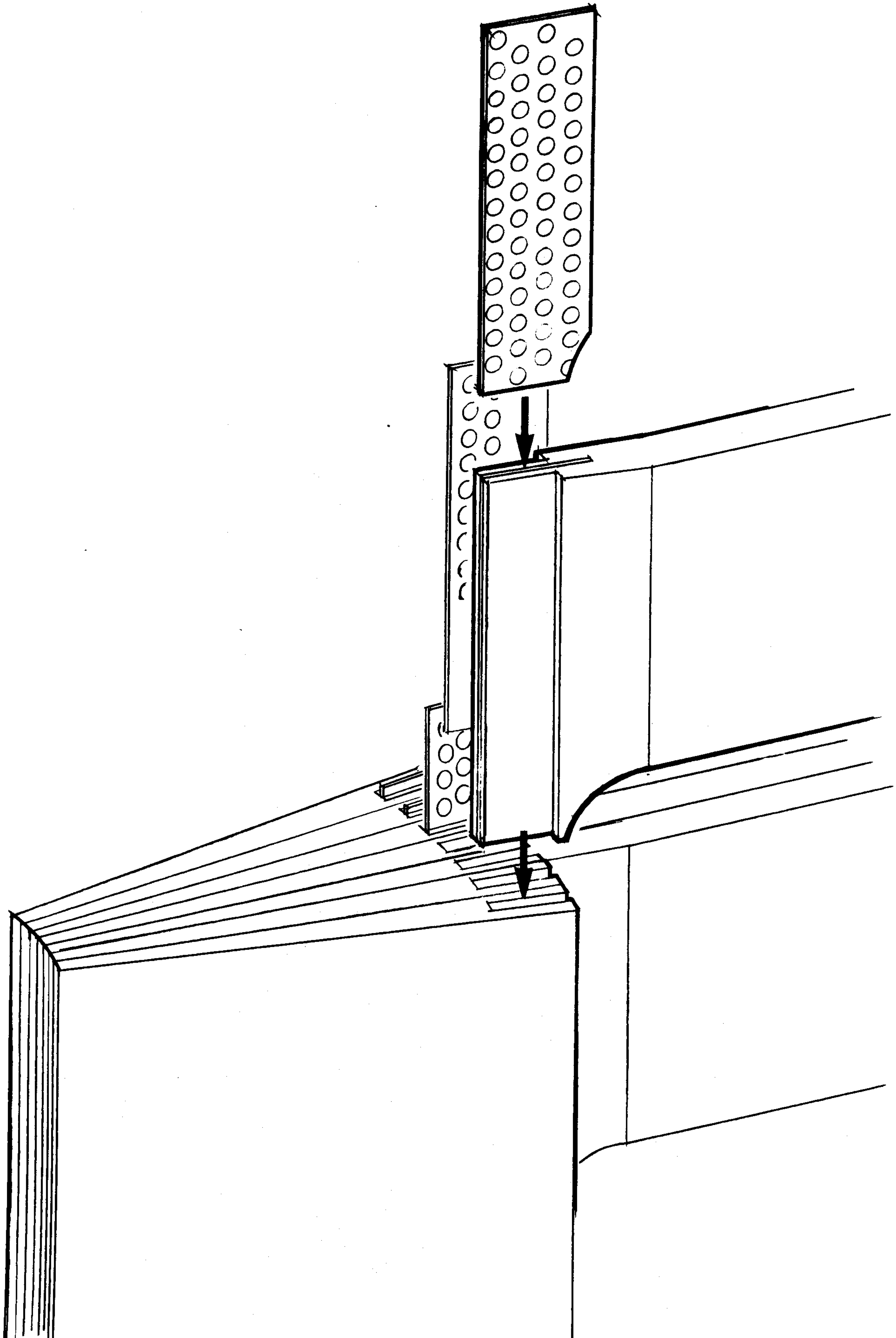

Fig. 2. Detail of inner TF joint showing dimpled spring plates.

current constriction in the four joint regions. Surface resistivity is not included due to modelling difficulties. Joint specifications have been set so that current constriction must be the dominant cause of joint losses. With this model, the peak hot-spot temperature at the inside corner of the joint is 276, occurring at the end of the TF flattop, as shown in Figure 3. Extremely high transient, local current densities exist in the inside corner of the joint, early in the pulse when the largest skin currents are flowing through the TF plates, but the current densities and temperature rises are broadened considerably by the end of a pulse. For a specific TF ramp scenario, the specification of average and peak instantaneous current densities through the inside joints are shown in Table III.

Joint Dissipation

The local Joule heating in the joint region is higher than that in the bulk conductor because of two effects: current constriction and the surface resistance of the joint. In the joint region, each half of the joint must carry the entire conductor current through a reduced cross section. As current enters the joint region, before any current stream lines have crossed the joint, the local current density is double that in the bulk conductor. The joint itself consists of a coating with resistivity considerably higher than that of copper and also consists microscopically of matching ridges and valleys with imperfect contact. This effect is usually defined in terms of an equivalent surface resistivity of the joint. A code has been developed to evaluate the total steady-state dissipation in a joint region with a fixed surface resistivity. This code was used to analyse the lap joint evaluated in the 1985 Alcator C-Mod proposal, parametrically varying the surface resistance of the joint. The results are shown in Figure 4. At room temperature, the surface resistance of the joint is a second-order effect over a broad range of practical resistances, out to an inflection point of 150 $\mu\Omega{-}\mathrm{cm}^2$, at which the total dissipation is doubled. For the Alcator C-Mod there is a further broadening effect of magnetic diffusion, in that higher surface resistance will lead to faster diffusion and broader current profiles over the course of a pulse. A specification of 30 $\mu\Omega$ - cm^2 was developed in order to avoid unnecessary heating of the joint region.

Small-scale Joint Tests

A large number of tests of resistance vs. mechanical cycles have been performed on 4 cm^2 square tests samples with a variety of surface preparations. In each test, surface resistance was measured before and after a number of mechanical cycles. Each mechanical cycle was designed to simulate the actual mechanical cycle at the joint. Typically 200 psi was applied to the sample, and the sample was moved 5 mm with respect to its mating surface. This corresponds to the predicted vertical displacement of the coil horizontal arms during a 10 T discharge.

The best overall mechanical-electrical performance has been exhibited by the Ag-AgW contact, while the best performing lubricant has been Penetrox A, which has been used successfully at M.I.T. for busbar connections. Selected test results are shown in Table IV. Ag-Ag has the best static performance, but exhibits both galling and significant

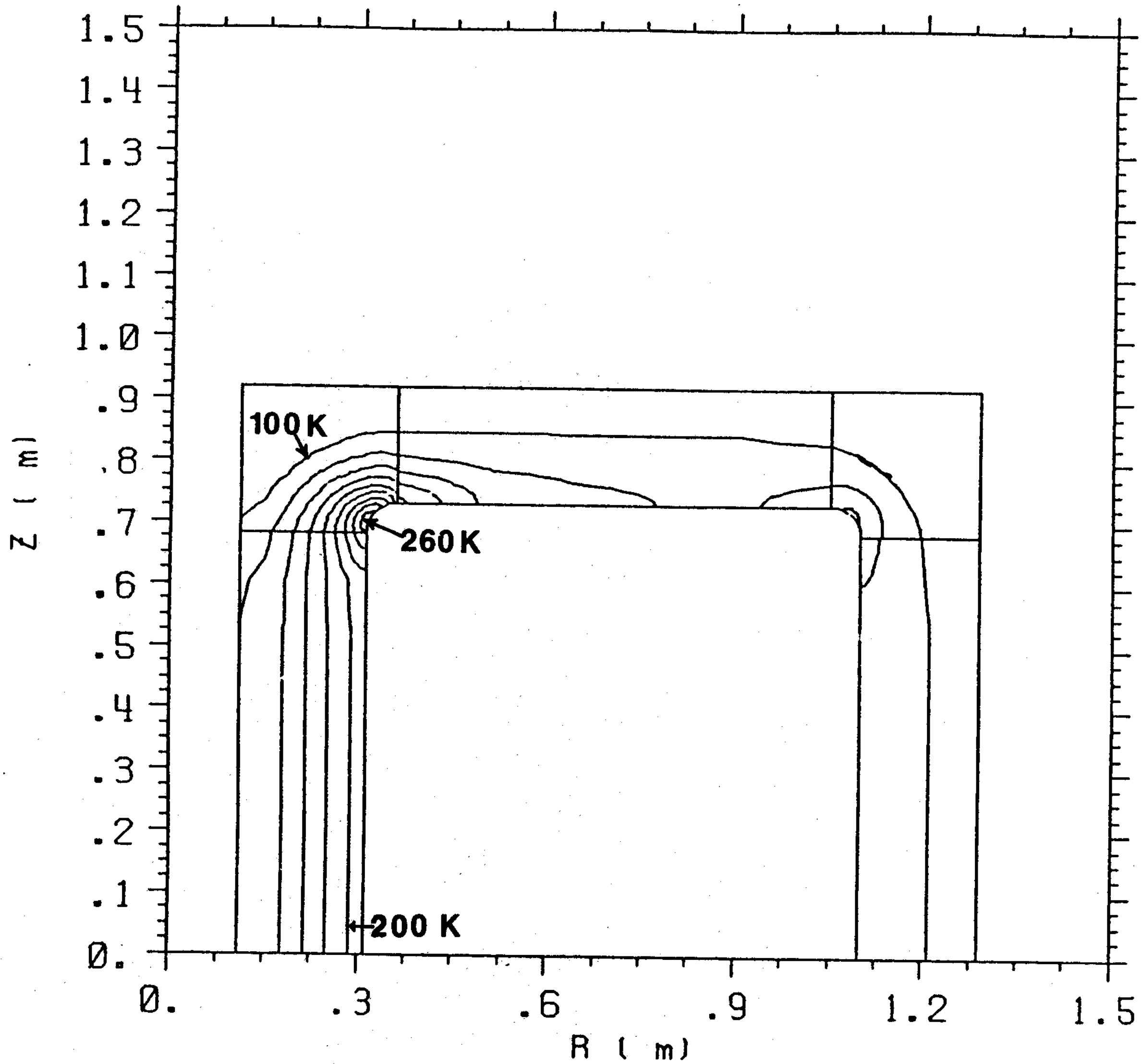

Fig. 3. TF magnet temperature contours.

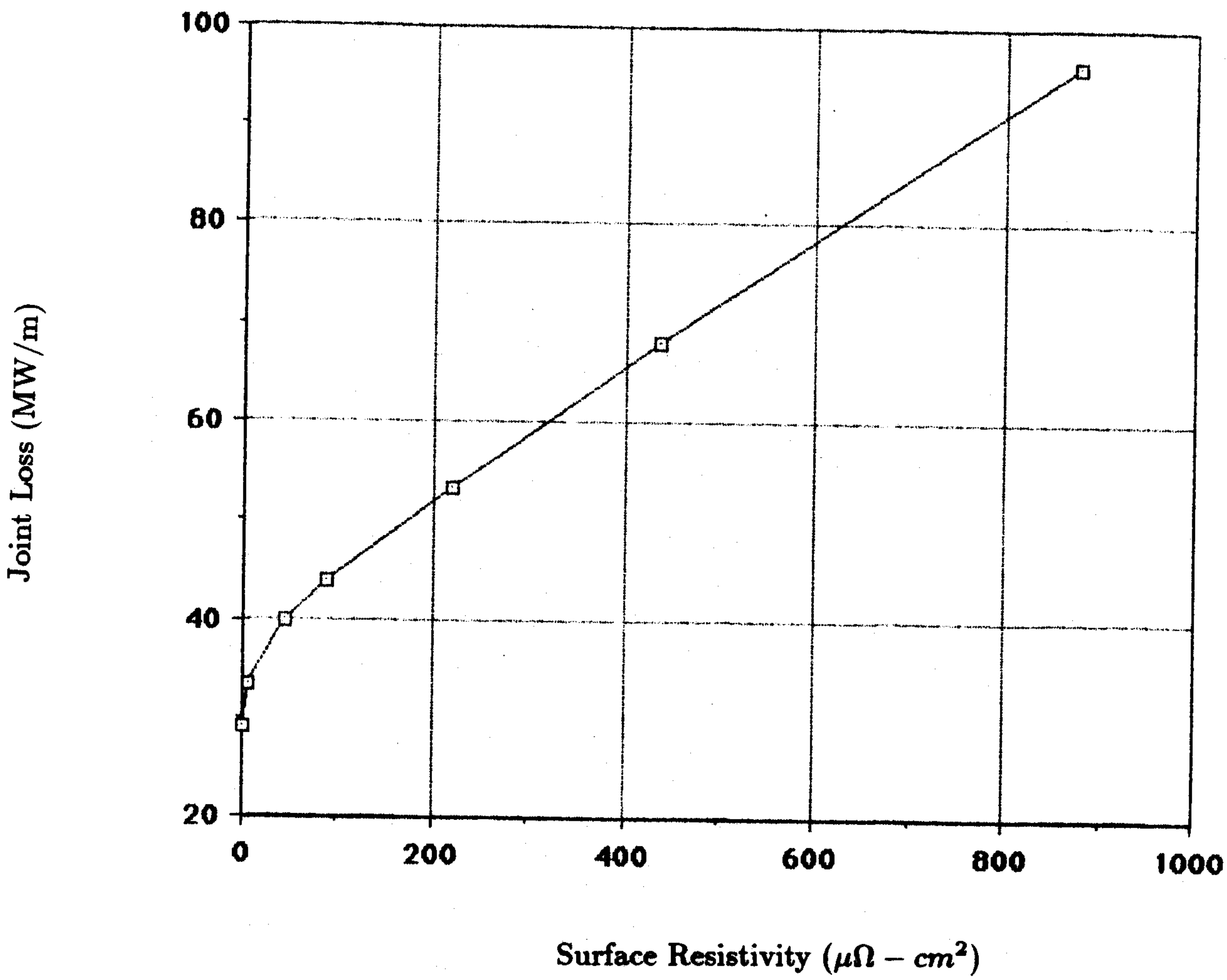

Fig. 4. Specific joint loss (MW) vs. joint surface resistivity ($\mu\Omega$ - m^2).

Table III
TF Joint Requirements

Parameter	Description	Value
I_{cond}, (kA)	joint current	267
A_{joint}, (cm^2)	total joint area	252
A_{entry}, (cm^2)	total cross section into joint	14.5
$J_{joint,av}$, (kA/cm^2)	average current density through joint	1.06
$J_{joint,peak}$, (kA/cm^2)	peak current density through joint	15
$J_{cond,av}$, (kA/cm^2)	average current density into joint	18.4
$J_{cond,peak}$, (kA/cm^2)	peak current density into joint	60

Table IV
Small Scale Joint Resistivity Test Results

Surface Types	No. Cycles	p (psi)	$\rho_{surface}$ (300 K) ($\mu\Omega$ - cm^2	$\rho_{surface}$ (80 K) $\mu\Omega$ - cm^2
Ag vs. Ag	static	178	7.3	2.2
Ag vs. Ag	3,000	100		60
Mo vs. Ag	1,500	500		40
BeCu Multilams	static	57 (GA: 65.6)	202 (GA: 50)	160
40 % Ag-60 % W vs. Ag	static	250		13
"	13,000	250		5.2
Ag vs. Ag with Penetrox A	static	200	16	48
"	10,000	200	5.6	

degradation of surface resistance after a few thousand cycles. A variety of tests on Mo vs. Ag indicate that it is limited to a surface resistivity of no better than 30-40 $\mu\Omega$ - cm^2. This is marginal with respect to C-Mod's joint specifications, but is nondominant when compared with current constriction. The superb performance of 40 % Ag - 60 % W vs. Ag, approaching the static resistivity of pure silver with no degradation in 10,000 cycles seemed to make it the surface preparation of choice. However, the results of the small scale tests have not yet been duplicated on the full-scale joints.

A more conservative approach to concerns that the small-scale test is not a complete simulation of mechanical wear is to use a lubricant at the joint. Two lubricants have been tested, Krytox and Penetrox. Krytox had been used successfully in the Westinghouse joint concept tested at Princeton for CIT. However, in small-scale tests at M.I.T. the performance of Penetrox A was far superior, both in the absolute value of surface resistivity, repeatability, and avoidance of a tendency to clump at cryogenic temperatures. Again, the results of the small- scale tests have not yet been duplicated on the full-scale joints. The major concern is whether the joint is achieving adequate contact area over a broad surface.

Full-Scale Joint Tests

A full-scale segment of a set of joints in the inner corner has been constructed, consisting of 7 lower arms and 7 tapered partial-length inner cylinder turns. This corresponds to one coil in the originally proposed Alcator C-Mod machine. The stack of horizontal plates for the lap joint test is shown in Figure 5, illustrating the bends and tapers needed in the joint region. A top view of the assembled joint is shown in Figure 6. The joints are spring-plate loaded to 275 psi. Both mechanical and electrical tests have been carried out on different joint concepts. The two different topologies that have been tested are a lap joint and mortise-and-tenon joint. Either concept may be acceptable, but the mortise-and-tenon is favored because of the increased contact surface and the absence of a net out-of-plane force, due to the current transfer. In the mechanical tests, a motor-driven jack screw drives the horizontal arms over a cyclical vertical travel of 5 mm, corresponding to the predicted displacement of the arms. The test frame and assembly for the mechanical tests are shown in Figure 7. One turn of the seven-turn assembly has also been run up to 150 kA for a one second pulse. Mechanical and electrical tests have also been performed simultaneously. Full mechanical and electrical qualification of a joint concept has not yet been achieved.

Bond Development

A bond between high-conductivity copper and a high-strength material, such as Inconel 718, can produce a better combination of structural, electrical and thermal properties than any individual copper alloy. This technique has also been adopted for the Compact Ignition Tokamak, in order to minimize the size of an ignition experiment. Both projects are experimenting with explosive bonding, a new technique for fabricating high-strength composites.

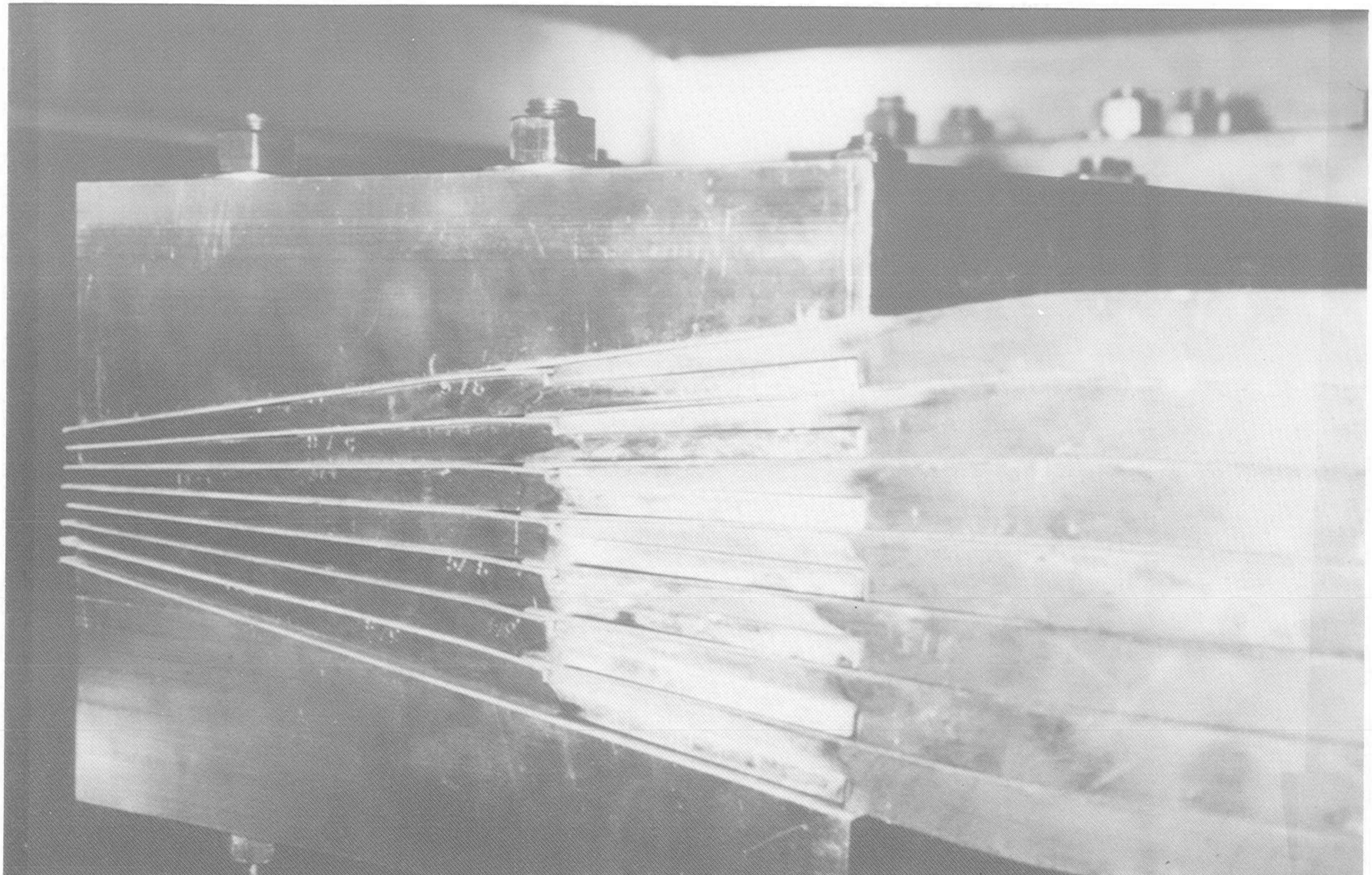

Fig. 5. Plate stack for full-scale joint test assembly.

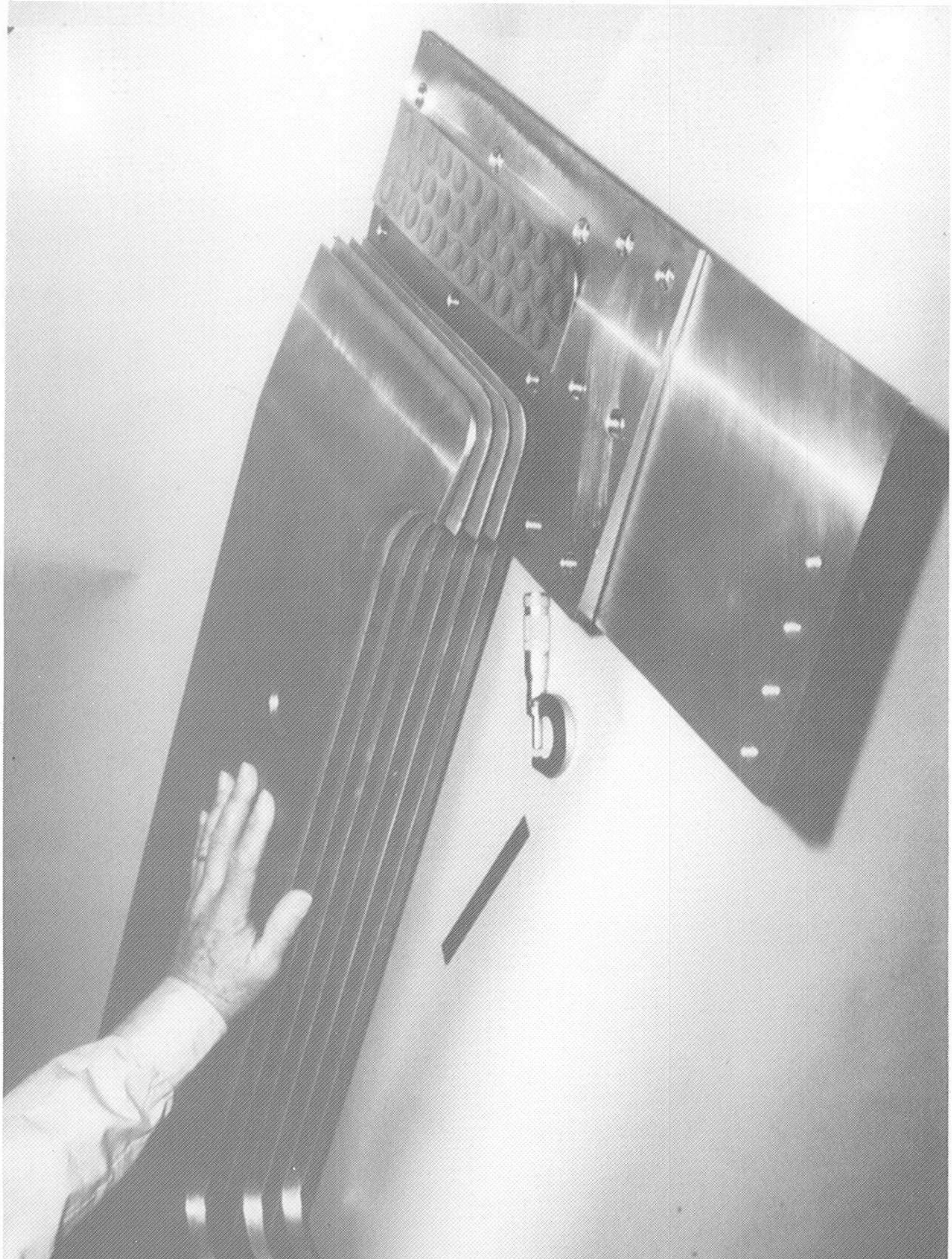

Fig. 6. Top view of assembled lap joint.

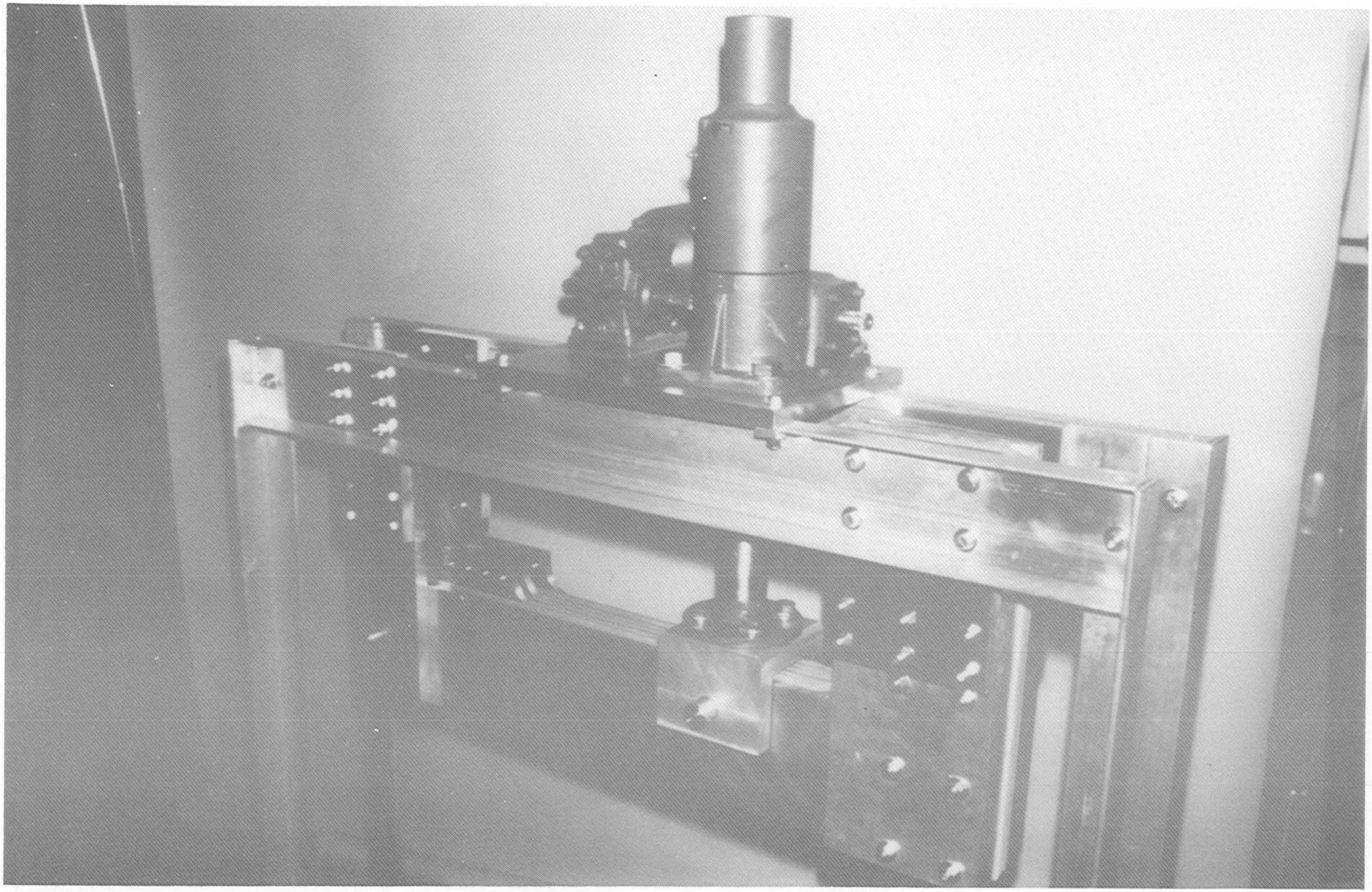

Fig. 7. Test frame and assembly for full-scale joint tests.

Alcator C-Mod is designed to remain within allowable stress limits up to a central field of 10 T. This requires the addition of 20 % Inconel 718 to a composite which also includes 80 % OFE copper and 30 mil fiberglass-epoxy insulating sheets. The present thicknesses of the sheets in the inside TF leg are shown in Table V. Inplane stresses have been calculated, as shown in Table VI. Since the average Tresca stress in the inner cylinder is above the yield of copper, the addition of a reinforcing material is necessary. The stresses show the need for about 20 % steel.

Bond Structural Behavior

Lorentz loads on the magnet are generated in the copper and must be transferred to the reinforcement through the bond. Two bonded materials in tension have equal strain and therefore share the load according to the ratios of the Young's modulus of the materials. It has not been generally understood, until recently, that two bonded materials in compression will also have equal strain if the aspect ratio of the two structures being compressed together is sufficiently large, because extrusion of the softer material is prevented by shear at the interface. A theoretical justification of this design approach, along with test results on stacks of copper-Inconel samples in compression have been reported by Becker.[5] Since the minimum aspect ratio of the composite plates is greater than 10, the high aspect ratio approximation applies and the inner cylinder would not be expected to fail, even if the the copper plates were in yield.

Bond Fabrication

High quality explosive bonds in plates with sizes typical of TF inner legs have been achieved previously in copper-Inconel composites. High quality bonds with low surface ripple were developed as part of the CIT R&D program. Mechanical tests on the CIT bonded plates indicated that the high aspect ratio approximations for composite strength were accurate. The plates for CIT have twice the thickness of those for Alcator C-Mod and twice the fraction of reinforcement. Since explosive bonds are believed to be more difficult to achieve for thin reinforcements, the bond for Alcator C-Mod has proven to be more difficult for the original explosive fabricator. A second fabricator has succeeded in achieving an explosive bond with the specified thicknesses of copper and reinforcement, and has been asked to demonstrate a bond on a full-width plate sandwich.

Conclusions

The joint and bond development programs for Alcator C-Mod have not been completed, but several important milestones of the program have been achieved:

- Joint surface preparations, with and without lubricant, have been developed with adequate electrical and mechanical properties in small sample tests.

- A full-scale joint test stand has been constructed, along with full-scale details of

Table V
Bonded Plate Dimensions - TF Inside Leg

Parameter	Description	Value
R_i, (mm)	smaller radius, inner leg	108
R_o, (mm)	larger radius, inner leg	310
t_{ss}, (mm)	reinforcement thickness	2.2
t_{ins}, (mm)	insulation thickness	0.76
$t_{i,cond}$, (mm)	least conductor thickness	5.76
$t_{o,cu}$, (mm)	greatest conductor thickness	16.2
f_{ss}	reinforcement fraction in metal	0.2

Table VI
In-plane Stresses in the TF Central Cylinder at 10 T

Stresses (MPa)	Description	Value
$\sigma_{\theta,av}$	average toroidal stress	-325
$\sigma_{z,av}$	average tensile stress	45
$\sigma_{Tresca,av}$	average Tresca stress	370
$\sigma_{Y,Cu}$	OFE copper yield stress, RT	308
$\sigma_{Y,Inc}$	Inconel 718 yield stress, RT	1,218
σ_{cu-ss}	laminate yield, 20% Cu, 80% Inconel	463
SF	Average Tresca/ allowable stress	0.94

two candidate joint concepts. The stand has been cooled to liquid nitrogen temperature, joints have been operated up to full joint current density and plate stacks have been mechanically cycled at design values of joint pressure and vertical displacement.

- Analysis tools have been developed that predict the structural, electrical and thermal adequacy of the sliding joints.

- A bonded composite has been designed that is predicted to be structurally adequate at high fields. Small sample composite stack tests have confirmed bond behavior in compression.

- A low ripple bond has been achieved on a small composite bar with the design thicknesses of copper and reinforcement.

Acknowledgments

We would like to thank E. Thibeault and the M.I.T. Reactor machine shop for the fabrication of the bent plates for the full-scale joint tests, and A.M. Dawson for the preparation of this manuscript.

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