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DEALS - A Maintainable Superconducting Magnet System for Tokamak Fusion Reactors*

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Abstract

The feasibility of demountable superconducting magnet systems has been examined in a design study of a DEALS [Demountable Externally Anchored Low Stress] TF magnet for an HFITR [High Field Ignition Test Reactor] Tokamak device. All parts of the system appear feasible, including the demountable superconducting joints. Measurements on small scale prototype joints indicate that movable pressure contact joints exhibit acceptable electrical, mechanical, and cryogenic performance. Such joints permit a relatively simple support structure and are readily demountable. Assembly and disassembly sequences are described whereby any failed portion of the magnet, or any part of the reactor inside the TF coils can be removed and replaced if necessary.

Introduction

In the search for inexhaustible energy sources, nuclear fusion energy has received much attention in the past decades. Of the various confinement approaches, the Tokamak is by far the most developed fusion concept. The recent achievements in plasma research at major U.S. fusion laboratories promise demonstration of the scientific feasibility of magnetic fusion within the next few years.

In our view the present route towards the design and construction of superconducting magnets for Tokamak reactors, although probably satisfactory for experiemental devices, will not be acceptable for commercial fusion power plants. One may accept a certain measure of reliability risk and non-maintainability for a one of a kind, short lifetime fusion device, but extremely reliable, maintainable systems will be required for commercial plants.

The DEALS magnet approach(1) has been proposed as a way to increase the reliability and maintainability of magnetic fusion reactors. The DEALS [Demountable Externally Anchored Low Stress] magnet system uses demountable superconducting joints, so that if any portion of the magnet fails, it can be replaced relatively rapidly. In addition, the conductor/support structure assembly is arranged so that the conductors transfer the magnetic forces on them to an external reinforcement structure. The load transfer device and demountable joints are designed so that the reinforcement structure operates at relatively high tensile stress/strain levels, while the conductors operate at relatively low compressive strain levels. This concept has been investigated during the past two years by a joint Brookhaven National Laboratory-Grumman Aerospace Corporation study team. A design study(2) of a High Field Ignition Test Reactor has been carried out, with preliminary experiments on small scale demountable joints. Our conclusion is that demountable superconducting magnet systems appear feasible for Tokamak fusion reactors. Extensive development work is required, however, before practical large magnet systems can be designed and constructed. The most important need appears to be for further experiments on the mechanical and electrical properties of relatively large scale prototype superconducting demountable joints to establish a data base for design and construction. The balance of this paper describes the latest design approaches for the DEALS magnet concept as well as the results of experiments on movable pressure contact superconducting joints. We would like to point out that these latest design efforts, although they represent improvements over earlier concepts, should not be regarded as the final optimum approach for a demountable magnet. Improvements will undoubtedly continue to be made.

The Concept of a Maintainable, Demountable, Superconducting Magnet System

The Tokamak fusion reactor is a very complex system with TF magnet, poloidal coils, plasma chamber, etc., all interlocked together. If any component of this system fails, it will be almost impossible to service or to repair it without making a major disassembly of the highly radioactive reactor. At a minimum, there will be a prolonged plant shutdown of many months, and it may not be feasible at all. In this event the capital investment in the reactor will be lost.

In the DEALS magnet concept, TF magnet coils are formed from removable coil segments. These segments can be mass produced at a central facility and then shipped to power plant construction sites for joining.

Figure 1 shows a cross sectional view of a typical DEALS conductor assembly inside a coil case. The conductors are wide (83 cm), thin (0.8 cm) plates of copper with a transposed superconducting braid at the midplane. [The conductor is formed by soldering the superconducting braid between two copper plates.] Coolant grooves are arranged on the conductor surfaces for heat transfer to a liquid helium bath. The conductors are cryostable, with maximum heat fluxes in the range of 0.3 to 0.4 W/cm^2 when all the current flows in the copper stabilizer. The conductors in each coil segment are typically several meters long. At the ends one-half of the copper stabilizer is milled away to form a region where the demountable joint will be made when coil segments are put together to form the complete coil. [The current passes from a given conductor to the next by transfer through the overlapping joint area, which is on the order of 3 to 4 x 10^3 cm^2 in area.] The joint can be of the soldered type, or more desirably, of the movable pressure contact type described in the next section. The conductors are arranged so that the completed assembly forms a multi-turn coil with the turns in series. Conductors are insulated from each other and from the coil case by ceramic or epoxy-fiberglass plates (Figure 1). Since the coil is formed without winding by simply putting prefabricated segments of the type shown in Figure 1 together, it is feasible to use ceramic insulators. Ceramics appear to be probably necessary for fusion magnets because organic insulators will be damaged by radiation, and will degrade He dielectric strength by release of radiolytic H_2.

The segmented coil approach is a key feature of DEALS magnet design and has important benefits in terms of accessibility and maintainability for Tokamak reactors. Figure 2 illustrates how all parts of the TF magnet and associated reactor system can be accessed and maintained. The assembly sequence gives insight as to how the DEALS magnet benefits reactor maintainability and accessibility. (Refer to Figure 2.)

Sequence 1

The center tension post is first lowered into place and embedded in the concrete foundation. It consists of 16 wedge shaped pieces strapped together to form the tension post with electrical insulating material between adjacent sections to reduce eddy currents. The tension post can be lowered into place as one section, or each of its 16 components lowered into place separately if it is necessary to reduce the maximum load on the overhead crane. The lower collar and the insulator ring are then lowered into a temporary location in the basement and the lower poloidal field coils and lower torque plate/insulator blocks are seated above the lower collar. This entire assembly is later repositioned during the third step in the assembly sequence.

Sequence 2

The bucking column and inner torque ring assembly next is lowered into its final position. The equilibrium field and ohmic heating coil ring assembly is then placed between the bucking column and the tension post.

The inboard vertical, and lower torque support structures are assembled and each of the 16 vertical inboard magnet legs is then inserted into its channel and locked into place as shown above.

Sequence 3

Each of the 16 lower inboard magnet legs is installed in place and the mating finger joints of the magnet segments are connected. The helium and vacuum dewars are then connected. At this point the lower outboard poloidal field coils are installed, followed by the lower outboard torque support structure. Each of the 16 lower outboard magnet legs is then positioned and the mating finger joints connected. The lower collar assembly is now raised (from its temporary position) to its final position and locked into place by the lower retaining ring followed by the vacuum vessel, which can be preassembled and tested off-line if desired.

Sequence 4

At this stage the vacuum vessel shielding is installed and the outboard vertical torque support structure is erected. Each of the 16 outboard vertical magnet legs can now be placed in position and the mating finger joints connected.

Sequence 5

The fifth stage in the assembly procedure involves the installation of the upper outboard and upper inboard torque support structure. Each of the 16 upper outboard magnet legs is put in place and the mating finger joints are connected. This sequence is followed by lowering each of the 16 upper inboard magnet legs into place. Since these are the last of the magnet legs to be installed, mating finger joint connections are required at both ends of the magnet leg. The last step in sequence 5 is then to place the upper torque plate and insulator blocks in the assembly.

Sequence 6

The upper poloidal field coils, upper insulator ring and upper collar are now lowered into position. The upper collar assembly is then locked into place by the upper retaining ring. (This sequence mirrors the lower collar assembly in sequence 3.)

The outboard insulator blocks are installed at this point and each of the 16 outboard structural support assemblies is wheeled into place along tracks. After each of these assemblies is properly aligned, the assembly sequence is finally completed by inserting the upper and lower pins as shown above.

The Low Temperature Movable Joint Approach

Various types of conductor joints have been used in magnet coil applications, including both soldered and pressure contact joints. Both types have been successfully used in room temperature copper and low temperature superconducting coils. However, these joints are usually held rigidly together by bolts, reinforcement and structure supports. Low temperature superconducting movable joints have been investigated at LASL(3) and MIT(4).

A soldered type of demountable superconducting movable joint was proposed in the first DEALS studies (1), while feasible in principle, soldered joints will require an actively controlled type (e.g., hydraulic pistons) of load transfer device between the coil segments and the external reinforcement structure. A movable pressure contact type of joint is now favored as the best approach, and forms the basis for the HFITR DEALS design(2) and the assembly sequence shown in Figure 2. The overlapping regions at the ends of adjacent conductor plates are pressed together with a modest clamping pressure to establish good electrical contact, but are free to move slightly ($\sim$ 1 cm) relative to each other. This eliminates the need for actively controlled load transfer devices between conductors and the external reinforcement structure. Instead, simple passive low thermal conductivity epoxy-fiberglass blocks can be used; the movable superconducting joints then permit the conductors to move to accommodate differential thermal and mechanical movements between conductors and the reinforcement structure. The heat leak through the passive support blocks is quite low, and permit the use of an external warm reinforcement structure. [Such a structure should be substantially cheaper than a cold reinforcement structure.]

Current transfers from one conductor to the next across the flat overlapping joint regions. The joint surfaces must provide adequately low electrical resistance and permit small, slow motions without degrading either mechanical or electrical properties.

Experiments on properties of movable pressure contact joints are described in the following section. Two design approaches have been developed for applying pressure on movable pressure contact-type joints, and these are described in the remainder of this section. It should be remembered that no tensile loads are carried by conductors (other than those due to frictional forces associated with joint surfaces, which are small), and that magnetic forces are transferred to the external reinforcement structure. Relative joint movement is allowed during the following conditions:

i) during cooldown or warmup while clamping pressure is not required;

ii) under controlled clamping pressure to achieve tolerable contact resistance when the magnet is energized or discharged in normal operation;

iii) during a quench or emergency shutdown situation that requires quick release of the clamping pressure.

The first design approach shown in Figure 3 is a self-activating clamping and/or declamping mechanism which takes advantage of both the Lorentz force which pushes the magnet coil segment outward and the support structure element acting as an elastic constraint which continues the magnet coil and pushes it inward. The ramp mechanism (which might be curved for a desirable controlled clamping pressure) is designed to utilize both the outward Lorentz force for clamping the joint and the inward hoop force from the structure for declamping the joint. This will satisfy the requirements mentioned above in ii) and iii). The movable part of the ramp mechanism is designed to develop the initially required joint pressure. This can be adjusted on each individual joint after cooldown but before the magnet is energized.

The second design approach is shown in Figure 4 and acts in a similar way to the first design except that it is sensor activated. The activator cylinders will operate in the direction (based on the signal) that either exerts or releases pressure on the joint. This is a simple screw thread mechanism.

In the magnet start-up sequence, an initial preloading of the joints is applied through the adjustable movable ramp mechanism to ensure sufficient contact area and a low enough resistance to permit the magnet to be energized. The current is then built up to operational level and the I^2R losses are monitored to ensure that they are within bounds. As the current increases, the electromagnetic forces on the conductors and joints increase and the conductors are permited to move slightly in the contact region to allow the conductor and joint stress to be transferred to the external support system. This is accomplished automatically by the ramp design which will exert increasing clamping pressure on the joint when the coil moves radially outward, taking into account the requirement of the tolerable contact resistance and degree of joint movement at every stage of the charging process. During discharge of the coil under normal or emergency conditions, the joint clamping pressure will be released in the first design by the hoop force in the structure when the coils are pushed inward, or in the second design by the sensor-activated screw mechanism.

Preliminary Experimental Results

Since the movable joint is very desirable for demountable superconducting magnets, it is important to demonstrate the feasibility of this joint concept. A small experimental test rig shown schematically in Figure 5 was set up to obtain information on some fundamental parameters concerning this type of joint. The various components designed for these test purposes can be identified in the actual equipment shown in Figure 6. Experimental measurements were made on a set of small sample movable joints (4.74 cm^2 contact area) shown at the bottom of Figure 6 to determine:

1. Electrical resistivity as a function of surface type and contact pressure.
2. Friction coefficient as a function of surface type and contact pressure.
3. Effects of surface motion on joint electrical and mechanical properties.

This simple experimental set up (Figure 6) permits testing the joint at various pressures and current densities, using small areas of contact surface which can be changed as desired, either by changing the contact size or material type. Surface conditions between the contacting surfaces can also be changed.

During a given contact test, electrical resistivity and friction coefficient were measured both statically and dynamically (i.e., when the upper and lower contact surfaces moved relative to each other), as a function of contact pressure. First, contact pressure was monotonically increased from the low end of the range to the upper, with measurements taken at a number of intermediate loading conditions. Measurements were then taken as a function of monotonically decreasing contact pressure, followed by another set of measurements under increasing pressure conditions.

Several additional observations can be derived from these experiments. First, the resistance of the joint is essentially the same whether or not the joint surfaces are moving relative to each other. This indicates that the DEALS joints should be able to move during operation without adversely affecting performance, particularly since the rates of relative motion for the DEALS application will be very small compared to the rates in the experiments.

Second, although joint resistance decreases with increasing contact pressure, it remains relatively low at low contact pressures, i.e., several hundred psi (∿2-3 MPa), particularly for the indium coated joints. This indicates that although moderate clamping pressures [e.g., ∿600 psi (40 MPa)] may be desirable during the steady state, fully energized period to keep joint resistance low, reduced clamping pressures [e.g., ∿300 psi (20 MPa)] during the period of magnet energization or discharge should not result in any significant heating problems.

Third, the joint resistance is much greater (one to two orders of magnitude, depending on pressure and surface type) than the resistance of a perfect joint with no interfacial resistance. The reason for this is not certain and needs further study. It may relate to imperfect contact between surfaces, or to some thin poorly conducting film on the surfaces. It is clear that the softer surfaces (joints), i.e., those with indium coatings, have lower resistances than those with hard surfaces [the thickness of gold on the gold plated copper surfaces is too small to affect their mechanical conformity]. No galling was observed on the thin indium and gold coated surfaces, even when high contact pressures [i.e., ~1000 psi (70 MPa)] were applied. It appears likely that softer surfaces, or a combination of a soft and hard surface will be more desirable for joints than hard surfaces.

Joint resistances were derived from current and voltage measurements on the joint. The voltage measurement was compared with the voltage across a calibrated standard resistance at the same temperature. A calibrated load cell was used to measure contact pressure on the joint. The friction coefficient was then derived from the contact pressure and the applied torque as the joint was moved.

Four types of contact surfaces were tested:

1. Thick indium (~20 mil) coated copper surfaces.
2. Thin indium (~3 mil) coated surfaces.
3. Thin gold plated copper surfaces.
4. Bare copper surfaces.

Figure 7a shows the measured resistances for the two indium surfaces, and 7b, the measured joint resistances for the gold plated copper surfaces. Results for the bare copper surfaces are not shown; typically, resistances for the bare copper joint were a factor of two to three higher than those for gold plated copper joints.

The thin indium surfaces give the lowest joint resistance. If the measured value for this surface is used to calculate I^2R joint heating for the DEALS HFITR magnet system, the total heating is approximately ten times greater than the value projected in the study. The study value was estimated to be 1 kW at 4°k, which with a refrigeration factor of 326 kW(e)/kW (4°k), required a refrigeration input power of 0.32 MW(e). Using the experimental electrical resistance values found for thin indium coated copper surfaces, total joint heating for the complete TF system would be 10 kW at 4°k or 3.2 MW(e) for the refrigeration power input. Adding in the additional refrigeration for the other thermal inputs (current leads, passive support blocks, eddy current heating, etc.) the total refrigeration power input is 4.4 MW(e). This appears to be quite acceptable. Considering that a 1000 MW(e) fusion power plant will not be much larger than HFITR, the refrigeration power input for a DEALS magnet system represents less than 0.1% of the plant output. However, in a better controlled experiment, it is likely that joint resistance can be substantially reduced by further optimization of joint surfaces.

The measurements of friction coefficient for indium (Figure 8a) and gold plated copper (Figure 8b) surfaces indicate that the friction coefficient is relatively uniform with contact pressure, and that the harder surface exhibits somewhat lower friction coefficients than the softer one ($\sim$0.4 vs 0.5). The friction coefficient for the indium surface is quite acceptable, however, in terms of a DEALS joint.

The effect of joint size on electrical and mechanical properties was not investigated. DEALS joints will have $\sim 10^3$ greater contact area than the small scale tests described here, and a future development program should examine the effect of scale. It is likely that if there is any effect, it will be related to the ability to manufacture large flat joint surfaces. The effect of magnetic field on joint-properties was not investigated, either and would have to be examined in any development program.

The results of the movable joint tests give strong indication that large scale movable joints can probably be developed. The next step toward the development of the DEALS magnet concept is to build a small prototype coil containing several turns of ~1 meter length, movable joints. Operation of such a prototype coil would demonstrate the practicality of the DEALS system on a sufficiently large scale that it could be considered as a viable alternate to the mainline wound coil approach.

Summary and Conclusions

The DEALS magnet concept has significant complications and potentially important benefits for magnetic fusion reactors. DEALS magnets are expected to be readily maintainable if failures occur, they can be demounted to improve accessibility to other reactor systems [blankets, beam lines, etc.]; their capability to operate at low conductor stress should improve reliability; magnet components can be made,produced and assembled at the construction site with minimum field work, elimination of winding stress allows the use of brittle superconductors and insulators; high current conductors can be employed for rapid energy extraction capability; and pulsed field losses are low, even for heavily stabilized conductors.

Design studies indicate that: adequate structural support should be readily achieved, practical conductors appear fabricable, cryostable operation is feasible, and estimated refrigeration requirements are reasonable. The primary technical issue for the DEALS concept appears to be the electrical and mechanical feasibility of the demountable superconducting joint. Design studies of an attractive joint option, the movable pressure contact type, have been carried out, along with experimental measurements of the electrical and mechanical properties of small scale movable joints. This type of joint allows current to be carried while overlapping joint surfaces move slightly to accommodate differential thermal and mechanical movements in the conductor/support structure assembly. Mechanisms for applying moderate, adjustable clamping pressures to multi-turn joints have been devised. Experiments indicate that the electrical resistivity of such joints is not affected by relative motion of the surfaces, that joint I^2R heating is sufficiently low to yield practical refrigeration requirements, that frictional coefficients are reassurably low, and that joint surfaces are not adversely affected by the applied clamping pressures and relative motion.

On the basis of the studies and experiments, it is concluded that the DEALS concept appears feasible. More work should be carried out, including tests of larger joints, to develop the engineering base for the design and construction of large scale systems.

Acknowledgment

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3. J. Lindsay, D. H. Whitaker, LASL - private communication.

4. Y. Iwasa, MIT - private communication.

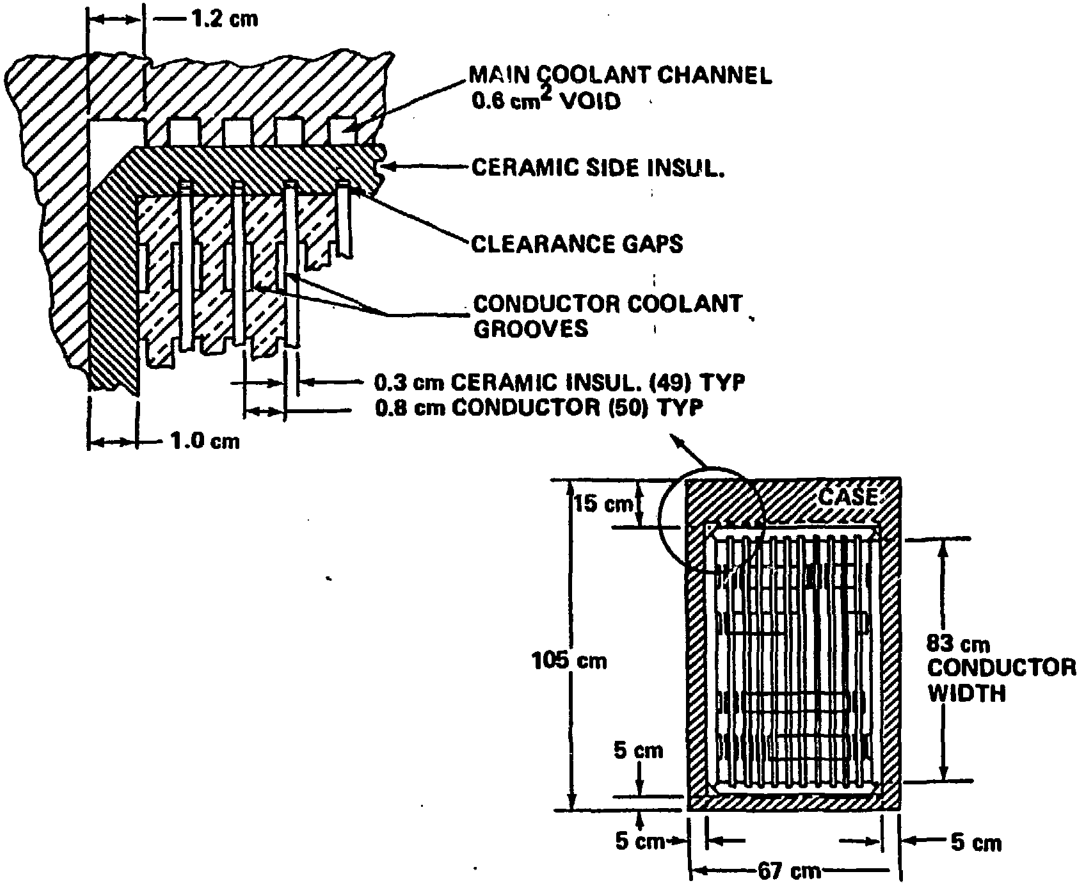


Fig. 1. Coil Case Design.

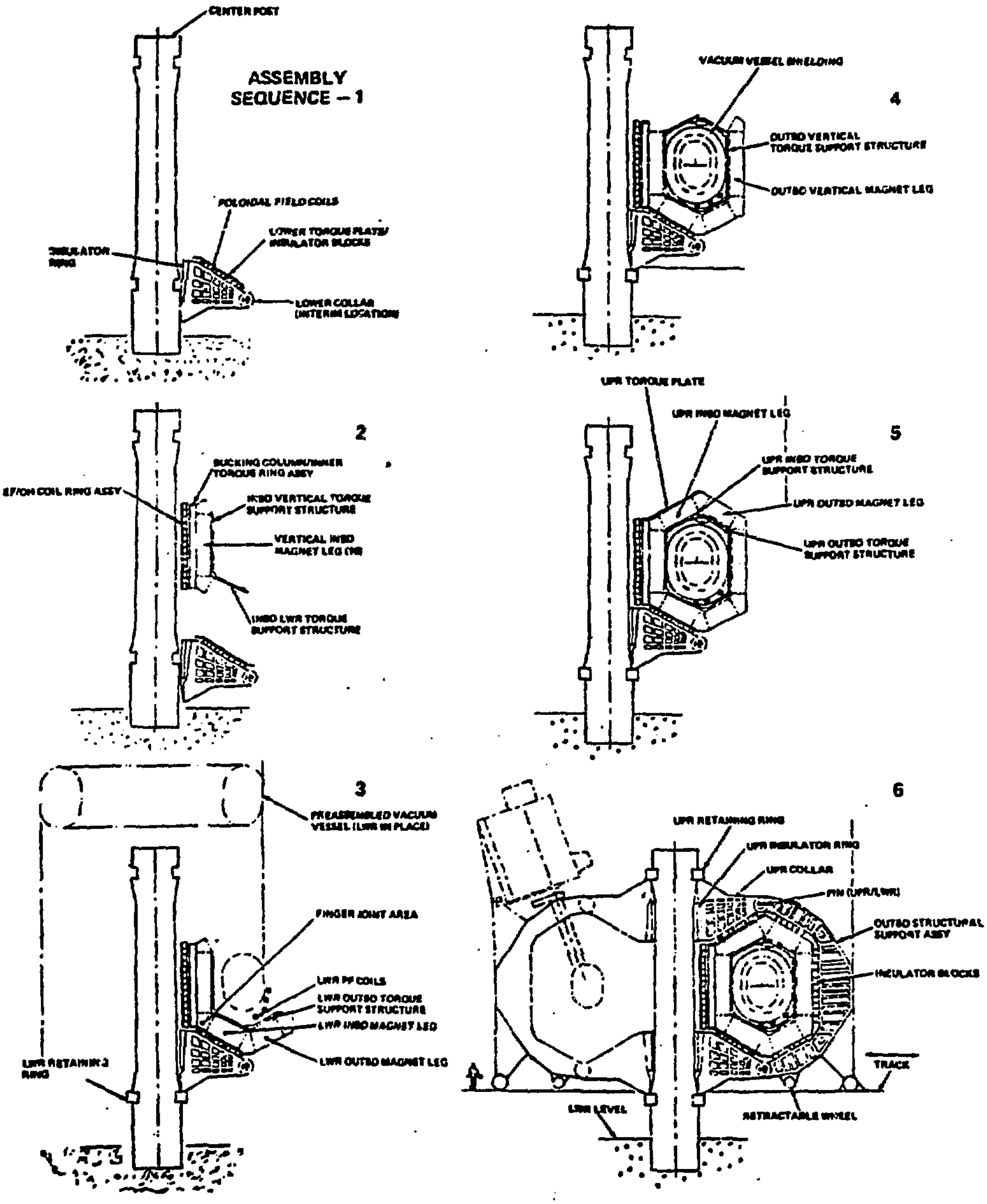


Fig. 2. Total Assembly Sequence 1 to 6.

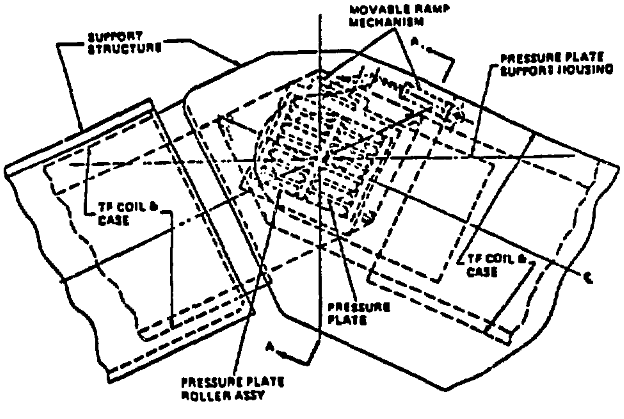


Fig. 3a. Conceptual Joint Design (Baseline).

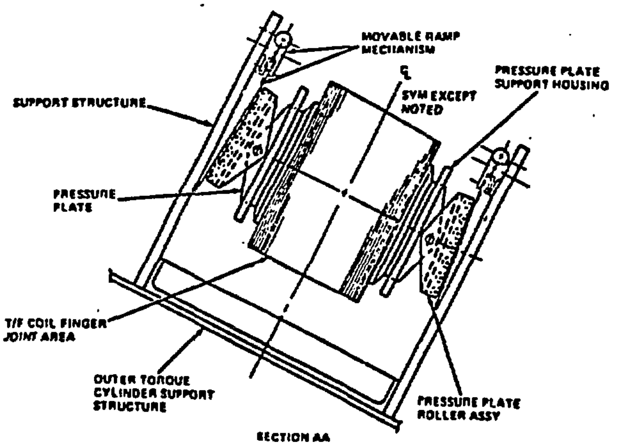


Fig. 3b. Conceptual Joint Design (Baseline).

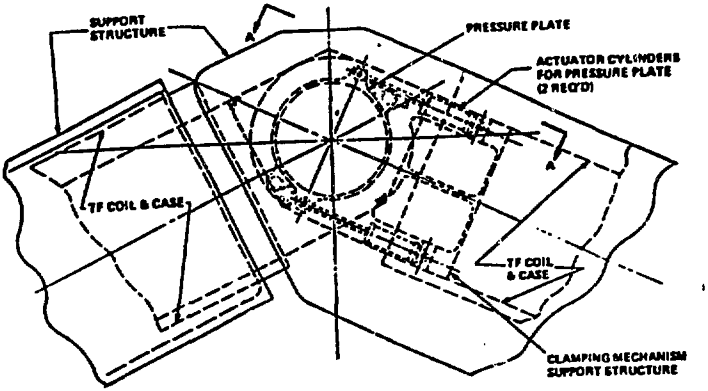


Fig. 4a. Alternate Conceptual Joint Design.

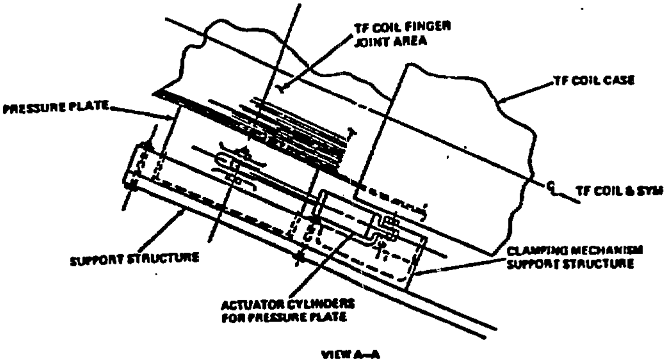


Fig. 4b. Alternate Conceptual Join Design.

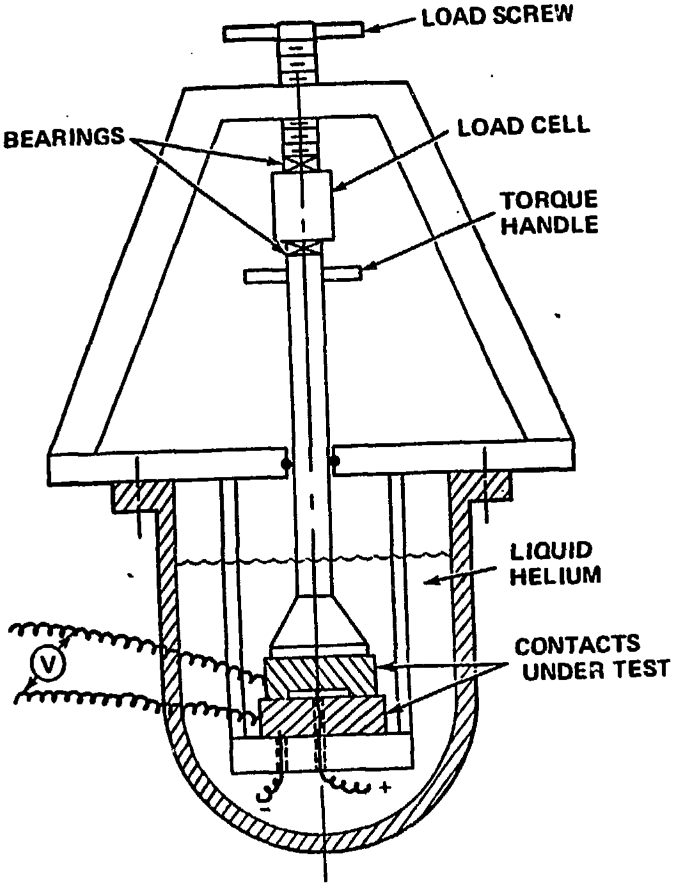


Fig. 5. Test Rig for Simulating Movable Contacts.

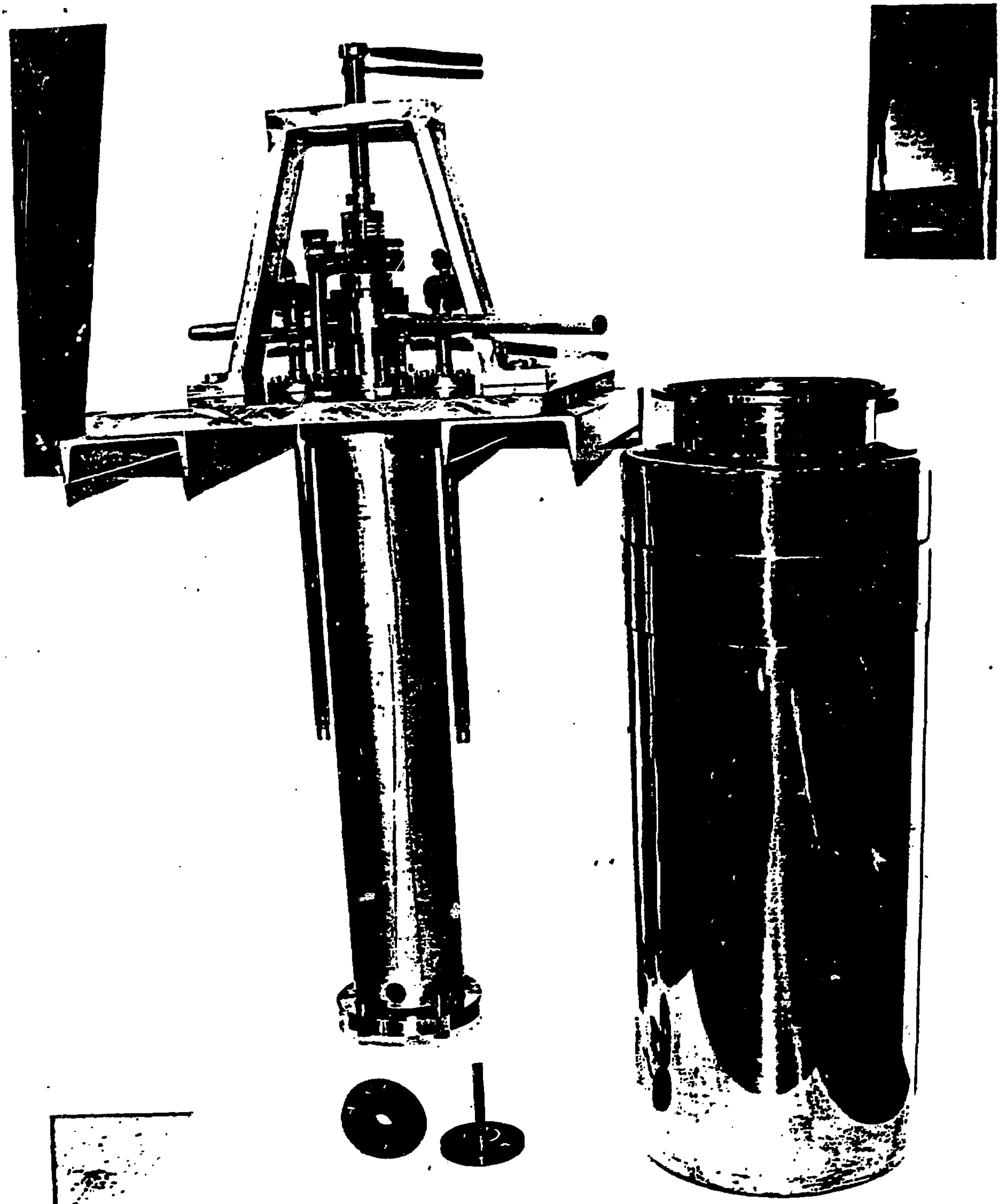


Fig. 6. Experimental Set Up and Sample Movable Joint.

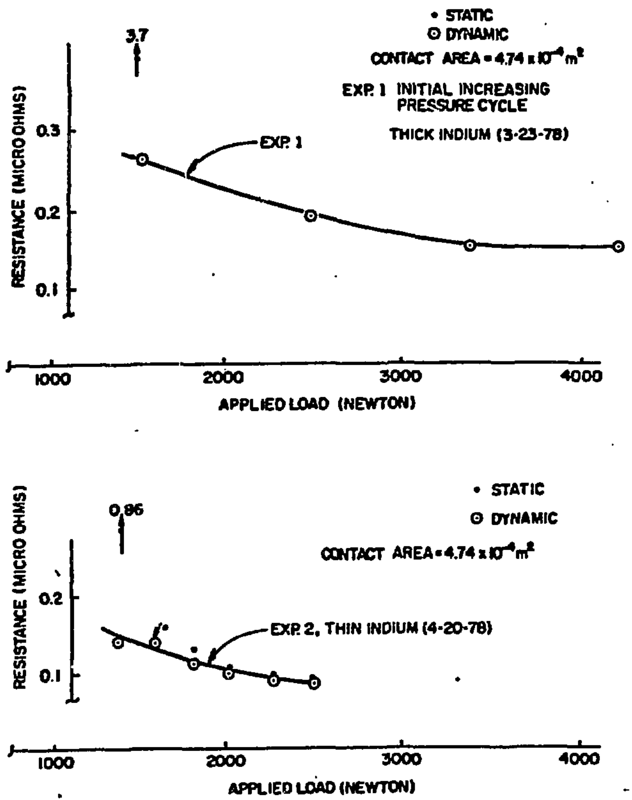

• STATIC
⊙ DYNAMIC
CONTACT AREA = 4.74 x 10^-4 m^2
EXP. 1 INITIAL INCREASING PRESSURE CYCLE
THICK INDIUM (3-23-78)
3.7
EXP. 1
RESISTANCE (MICRO OHMS)
0.3
0.2
0.1
1000
2000
3000
4000
APPLIED LOAD (NEWTON)
• STATIC
⊙ DYNAMIC
CONTACT AREA = 4.74 x 10^-4 m^2
0.86
EXP. 2, THIN INDIUM (4-20-78)
RESISTANCE (MICRO OHMS)
0.2
0.1
1000
2000
3000
4000
APPLIED LOAD (NEWTON)

Fig. 7a.

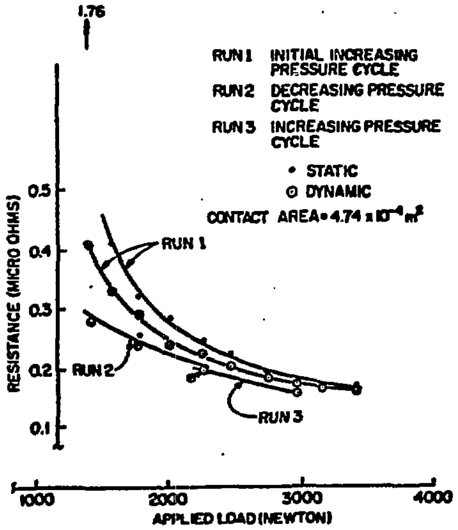
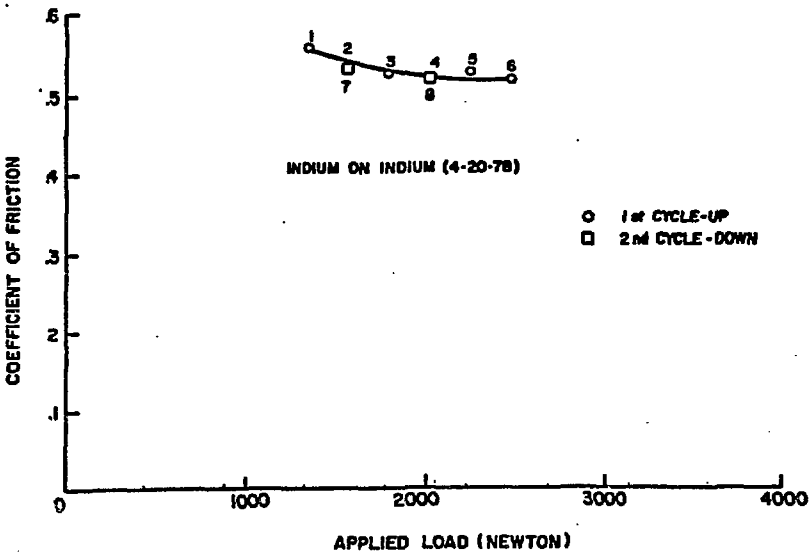

1.76
RUN 1 INITIAL INCREASING PRESSURE CYCLE
RUN 2 DECREASING PRESSURE CYCLE
RUN 3 INCREASING PRESSURE CYCLE
• STATIC
⊙ DYNAMIC
CONTACT AREA = 4.74 x 10^-4 m^2
RUN 1
RUN 2
RUN 3
RESISTANCE (MICRO OHMS)
0.5
0.4
0.3
0.2
0.1
1000
2000
3000
4000
APPLIED LOAD (NEWTON)

Fig. 7b.


.6
.5
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0
COEFFICIENT OF FRICTION
1
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7
8
INDIUM ON INDIUM (4-20-78)
○ 1st CYCLE-UP
□ 2nd CYCLE-DOWN
1000
2000
3000
4000
APPLIED LOAD (NEWTON)

Fig. 8a.

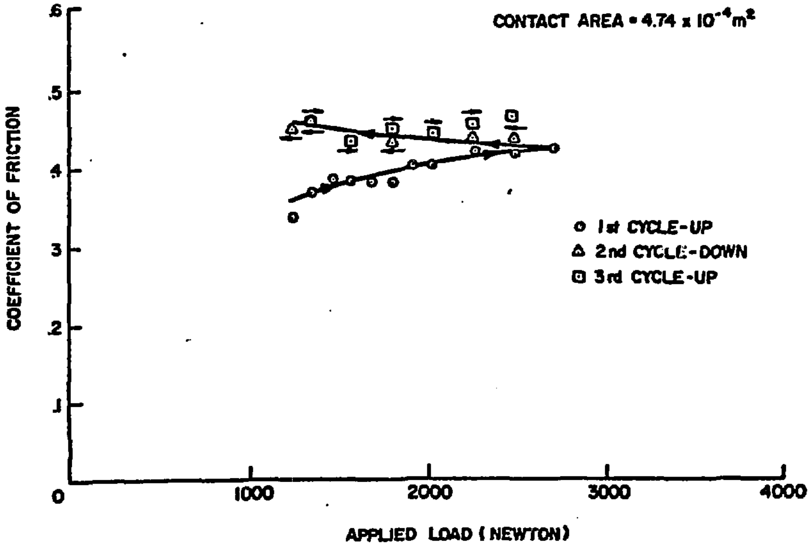
CONTACT AREA = 4.74 x 10^-4 m^2
.6
.5
.4
.3
.2
.1
0
COEFFICIENT OF FRICTION
○ 1st CYCLE-UP
△ 2nd CYCLE-DOWN
□ 3rd CYCLE-UP
1000
2000
3000
4000
APPLIED LOAD (NEWTON)

Fig. 8b.