REPAIR OF ZGS RING MAGNET COIL DAMAGED CONDUCTOR SECTIONS*

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Abstract

Two magnet coils of the Argonne National Laboratory's Zero Gradient Synchrotron suffered serious mechanical damage to conductor and insulation as the result of electrical shorting. The nature of the coils and the extent of damage are described. Methods of conductor repair considered are enumerated along with their corresponding advantages and disadvantages. The aspects of conductor repair; i. e., preparation, brazing, clean-up, etc., are presented along with test data generated by several feasibility studies. The actual repair of the conductor section with the use of fixturing which employs, as an advantage, the thermal expansion of the metal due to braze heating is presented in detail.

I Introduction

The ZGS Ring Magnet is an annular shaped magnet arranged in eight sections (octants) around the circumference of a 61 m diameter circle. The magnet gap is rectangular in cross section with coils on each of the short sides. A rectangular steel frame surrounds the coil assembly.

The magnet is pulsed from 0 to 10,000 A and can produce a maximum magnetic field of 21,000 G. The total voltage drop across the coil is 1500 V. The maximum normal turn-to-turn voltage is 50 V, while the normal layer-to-layer voltage is 400 V. However, under certain fault conditions voltage spikes occur resulting in peak potentials several times those mentioned above.

Figure 1 shows the octant coil and Figure 2 shows the cross section of the outer side coil. The conductor in the inner and outer side coil are continuous bars of copper with a central water cooling hole. At the coil ends half of the conductors are bent vertically upward and the other half are bent vertically downward. Brazed to these vertical conductors are horizontal conductors which complete the electrical circuit by connecting the conductors in a series circuit. Some of the other physical properties of the ring magnet are shown on Figure 1.

On April 21, 1970, the coil of the ZGS Octant No. 2 failed. It was subsequently replaced by an existing spare coil. On January 9, 1971, the coil of the ZGS Octant No. 3 failed. In both cases the coil failure was an electrical short from an outside bottom turn of the outer side coil to the outer turn in the next layer above it. The heat, generated by the short, melted copper in both turns. In the case of the Octant No. 2 coil, significant damage to the two adjacent turns resulted. Coils No. 2 and No. 3 had undergone 41 million and 45 million pulses, respectively, since ZGS startup.

On the Octant No. 3 coil, two conductors; i. e., turns 16 and 24 in the outer row, suffered major damage with copper conductor material completely melted over a distance of approximately 15 cm.

On the Octant No. 2 coil, five conductors: i.e., turns 1, 8 and 16 in the outer row and 1A and 9 in the second row, suffered major damage. Copper was melted in a section approximately 15 cm long but due to the greater number of conductors involved more total damage resulted. In both cases, the molten copper was forced down through the cooling water holes of the various turns by the steam pressure created during the failure. The maximum distance the molten copper traveled through the cooling water hole was approximately 305 mm before it solidified.

On both Octant No. 3 and Octant No. 2 coils, major damage occurred to the turn and layer insulation in the immediate area of the fault. Insulation adjacent to the fault was not visibly affected. However, due to the greater amount of heat generated by Octant No. 2 coil failure, the insulation damage in this coil was far more extensive.

Table I presents the pertinent information for these two failures in tabular form.

II Methods of Conductor Repair

The various methods considered for coil repair were evaluated on the basis of cost, time

* Work performed under the auspices of the U. S. Atomic Energy Commission.
**Presently employed by National Accelerator Laboratory, Batavia, Illinois.

and probability for success. Additional factors considered were: Will the method allow for complete inspection of damaged insulation? Will additional insulation be damaged during repair? Will successful reinsulation be possible? How reliable will the joint be?

Replace Entire Turn

The coil conductor, as mentioned previously, runs from one end of the coil to the other end where it is then brazed to the crossover conductors. A method considered was to strip the outer wrap insulation, the anchor plates, the inner wrap insulation and other turn insulation as required, from the entire side coil in order to remove the damaged turns and replace with new conductor.

Advantages of this method are: 1.) No joint in the cooling water circuit. 2.) No brazing in an area where insulation is minimal. 3.) No thermal expansion problems.[1] 4.) Complete access to damaged insulation.

Disadvantages of this method are: 1.) Extremely time consuming and expensive stripping of all the insulation from the side coil. 2.) Chances of damaging good insulation while stripping would be great, and thus reinsulation might be more difficult. 3.) Reinsulation would be very time consuming. 4.) Insulation in the transition section was hand fitted and thus would present great problems.

Replace Partial Turn to One End

A second possibility considered was to strip the side coil to one end only. The damaged conductor would then be unbrazed from the crossover conductors and removed. New conductor would be formed, spliced to the rest of the turn and rebrazed to the crossover conductor.

Advantages of this method are: 1.) One joint in the cooling water circuit. 2.) No thermal expansion problem while making the joint since the conductor is free at one end. 3.) Insulation is accessible for repair. 4.) Splice in the conductor to be made while the conductor is pulled away from the insulation. Thus, insulation would be protected from damage.

Disadvantages of this method are: 1.) Stripping of the insulation would still be quite time consuming and chances of damage still great. 2.) Stripping of insulation in the transition section would still be required on one end. 3.) Reinsulation would be time consuming.

Replace Partial Turn with Internal Splice

The third possibility considered was to replace the damaged section of the conductor with a short ($\sim$1.0 m) splice, and inserting it in the damaged turn by making two joints.

Advantages of this method are: 1.) The least amount of insulation removal. 2.) No insulation to be stripped in the transition section. 3.) Reinsulation would be simpler.

Disadvantages of this method are: 1.) Two joints required in the cooling water circuit. 2.) Brazing to be done near by to the insulation. 3.) Thermal expansion during brazing would be a problem since both ends of the conductor are restrained.

The last alternative considered; i.e., internal splicing of the short section of conductor to replace the damaged section, was selected. The primary factor affecting the selection was that it was felt that the stripping of undamaged insulation should be minimized so as to avoid other possible complications. Also, it was considered desirable to avoid the transition area because of the reinsulation problems anticipated for that area. These advantages were considered sufficiently important so as to outweigh the disadvantages of having two joints in the water cooling loop as well as the difficulty of making a brazed joint between two fixed ends of conductors.

III Brazed Joint Design

Based on earlier experiences combined with the preparation and evaluation of several test sections of various joint designs considered, the decision was made to use a silver brazed butt-ferrule type joint. The joint geometry, and the conductor parameters are shown in Figure 3.

Although the conductor dimensions varied slightly from joint to joint, the clearances were held constant by machining the ferrule to suit each joint made during testing and in the actual coil repair.

Silver solder rings, 0.13 mm thick by 6.35 mm wide, were placed in the recessed areas of the ferrule. The raised portion of the ferrule provided a centering of the two conductors to be joined. The 0.13 mm silver solder wafer placed between the butted conductor ends was cut to extend 1.59 mm past each side of the conductor.

The silver solder used was American Platinum Works (APW) No. 355 having a composition of: 56% Ag, 22% Cu, 17% Zn and 5% Sn. White 1200 silver brazing flux* was liberally applied by brush to the joint before assembly of the parts. Standard oxygen-acetylene torch heating was used to complete the joint.

A total of 42 test joints were made. Each test joint was mechanically and electrically tested. Representative braze joint factors were an ultimate strength of 1406 kg/cm^2 vs 2109 kg/cm^2 for regular annealed conductor and an increase in resistance of .045 x 10^{-6} ohms across the joint. The test joints were also checked for leaks with a helium mass spectrometer and hydrostatically tested at 25 kg/cm^2 for five minutes.

IV Coil Preparation Prior to Field Splicing

In preparation for the field splicing of the replacement length of conductor; i.e., splice bar, the damaged coil was stripped as shown in Figure 4. The 3.2 mm thick ground insulation was stripped over a 482.6 cm length so that four of the 109.2 cm long by 18 mm thick stainless steel anchor plate sections could be removed.

Sections of the damaged turns were then saw cut out of the coil. The turns to be repaired were freed from the coil back to an end clamp location by driving phenolic wedges behind the turn. The end clamps were then installed and the exposed conductors securely clamped to prevent loosening of the turns past the stripped area of the coil.

Facing and counterboring of the conductor ends was done using the tooling shown in Figure 5. After the ends were machined, the turns were clamped into position against the coil and the required splice bar length was determined. The actual splice bar was made 2.3 mm longer than required to allow for adjusting the bar length for the second joint operation.

The ends of the splice bar were faced and counterbored and surfaces of the bar which were to be adjacent to other coil turns were relieved 0.25 mm to allow for Kapton "H" film** insulation during reinsulation. After completion of machining, the bar was formed to the required radius of the coil.

V First Joint

The first joint for the splice bar was made at the turn end closest to the end clamp. A 25.4 mm diameter phenolic ball was inserted behind the turn to be brazed. Inserting the ball 83.8 cm from the turn end towards the end clamp positioned the joint 55 mm out from the coil surface. Strain gauges mounted on the turn face adjacent to the end clamp allowed a determination that the bending stresses were well below the yield point stress for the conductor.

The ends to be joined were inserted into a spring-loaded brazing fixture shown in Figure 6. The design was such that during brazing the fixture would slide on its support plate to allow for the 3.2 mm expansion due to heating the joint to brazing temperature; i.e., approximately 650°C. The spring-loaded jaw maintained a compressive force of 27 kg between the joint faces. Water-cooled chills were placed adjacent to the fixture to prevent heat from traveling along the conductor.

The existing coil insulation was protected during the brazing operation by placing a 0.8 mm thick water-cooled copper sheet between the coil and the brazing fixture. This was followed by packing wet asbestos over the copper sheet. The actual brazing of the joint is shown in Figure 7.

Upon completion of brazing, the joint was cooled and cleaned up by hand filing and polishing with emery paper. During this time, a shield was placed over the existing coil to prevent filings from entering the insulation. After cleanup, the joint was helium mass spectrometer tested, and the increase in electrical resistance across the joint was measured.

VI The Second Joint

The second, and final, joint was made between the remaining coil end and the splice bar end approximately midway between the two end clamps. The conductors were machined to the same dimensions as the coil ends of the first joint.

The joint also experiences a 3 mm thermal expansion during brazing. However, since it was the final joint in the repair, it was constrained between the end clamps with no open end to allow for free thermal expansion. If the thermal growth was not absorbed in some manner, the resulting compressive forces would have ripped the coil insulation beyond the end clamps. It was considered that a joined conductor, acting as a deflected column, could buckle elastically laterally away from the coil assembly and would be long enough then, in that geometry, to accommodate the thermal growth with smaller

* Manufactured by Handy and Harmon Company.
**Manufactured by E. I. DuPont De Nemours and Company, Inc.

compressive loading on the coil or column end clamps. In fact, the loading on the joint and end clamps could be controlled if the lateral deflection of the coil was also controlled by an additional variable lateral force.

Based on the above-mentioned scheme, a fixture was utilized which contained the free ends of the coil parallel to each other and the coil assembly, but at about 7.5 cm out from the main coil assembly (see Figure 8). This resulted in a "S" shaped bend in each coil from end clamp to fixture where the yield strength of the outer coil fibers was approached but not exceeded. The free ends to be joined were the desired 3 mm apart in this position (see Figure 9). The coil ends were previously machined flat and parallel with 0.10 mm gap between ends as they nested unjoined in the coil assembly.

The same type of brazed joint as the first joint was then made except that the fixture was employed to feed the joint and coil back towards the assembly as it cooled. Approximately 200 kg compression on the joint was maintained during cooling.

The joined coil was held out from the coil assembly about 3.2 cm by means of heaters to allow fixture removal, dressing and cleaning of the joint, and insulation fitting (see Figure 10). Finally, the coil was allowed to fully cool and thereby pull into its place in the assembly with the aid of about 100 kg tension resulting from the original 0.10 mm open joint gap having been reduced to about 0.02 mm silver braze thickness.

VII Results

Completed joints (see Figure 11) were inspected visually as well as electrically and hydraulically. Outward appearance compared favorably with test joints previously tensile tested to 2/3 of the strength of an unjoined conductor. Electrical resistance across the actual joints increased less than 4% of the actual resistance of an unjoined conductor section (see Figure 12). The joints were also checked for water leaks by helium mass spectrometer followed by a hydrostatic test as previously mentioned.

However, the important result is that the coil has functioned properly over a years duration or over five million pulses to date.

VIII Acknowledgments

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References

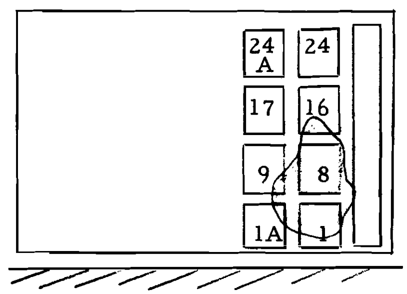
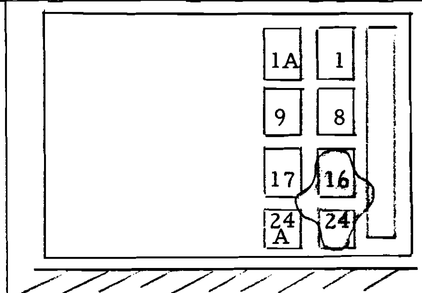
1. C. Bally, J. Bywater, R. Niemann, "Investigation of the Bowing of a Section of ZGS Ring Magnet Conductor Subjected to Localized Heating", Argonne National Laboratory, Engineering Note No. 30C.37, March 31, 1971.

* Former employee.

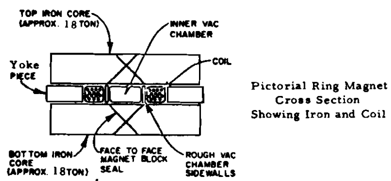
Table I - Tabulation of Facts - Octants 2 and 3 Coil Failures

Facts	Octant 2 Coil	Octant 3 Coil
a. Fault location	Outer row of conductors of the outer side coil along the radius portion of the conductors - approximately . 9 m from the radial line transition point of conductor radius to straight length.	Outer row of conductors of the outer side coil along the radius portion of the conductors - approximately 1. 9 m from the radial line transition point of conductor radius to straight length.
b. Number of conductors involved	Major damage to five conductors (turns 1, 8 and 16 in outer row and 1A and 9 in second row).	Major damage to two conductors (turns 16 and 24 in outer row).
c. Layer-layer voltage between conductors involved in failure	400 V.	400 V.
d. Insulation damage	Major damage occurred to the turn and layer insulation in the immediate area of the fault. Insulation adjacent to the fault was not visibly affected (pictures available).	Major damage occurred to the turn and layer insulation in the immediate area of the fault. Insulation adjacent to the fault was not visibly affected (pictures available).
e. Amount and location of hole plugging caused by molten copper forced through the cooling hole	Turn 1 was plugged at both upturned ends. Turn 8 was plugged at the short straight section (SSS) end a distance of 12. 192 m from the fault.	Turn 16 was blocked in the crossover tubing at the long straight section (LSS) end. Turn 24 was blocked at the short straight section end 10. 06 m from the fault.
f. Anchor plate to coil bonding	Approximately 20% - 25% of the anchor plate surface shows evidence of resin bonding. These plates were easily removed from the coil once the ground wrap was cut and screws removed.	Very little evidence of resin bonding could be detected on the four (4) anchor plates removed for coil repair. These plates were very easily removed from the coil.
g. Insulation removal	Ground insulation on inside, top and bottom surfaces had to be forceably pried off - good bonding was apparent. Ground insulation on anchor plate was also well bonded except for the radius corners.	Ground insulation on inside, top and bottom surfaces had to be forceably pried off - good bonding was apparent. Ground insulation on anchor plates was also well bonded except for radius corners. Anchor plate-to-coil insulation was well bonded except in the fault area where steam pressure had forced some sections loose.
h. Indication of mechanical insulation failure	None noted.	None noted.

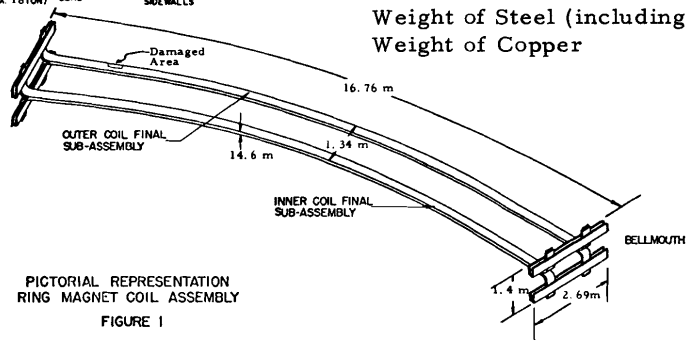
Table I - Tabulation of Facts - Octants 2 and 3 Coil Failures (continued)

Facts	Octant 2 Coil	Octant 3 Coil
i. Number and location of missing anchor bolts	One upper rod of outer yoke 2. 2S block was missing. This is not in the fault area.	Block 31 on outer radius had one anchor rod missing. This position is at fault and was observed missing by F. Brumwell on octant disassembly.
j. Relationship between anchor rod hole and fault	Area of fault which reached anchor plate was 6 cm from closest anchor rod hole.	Area of fault which reached anchor plate was 5 cm from closest rod hole.
k. Relationship between anchor plate joint and fault	Center of fault occurred 22 cm from a joint.	Center of fault occurred 45 cm from a joint.
l. Fault cross section	 Lower Magnet Pole	 Lower Magnet Pole

Number of Magnets	8
Arc Length of Each	16. 32 m
Height of Pole Pieces	0. 28 m
Width of Pole Pieces	2. 60 m
Width of Yoke Pieces	0. 65 m
Width Between Yokes	1. 365 m
Width of Copper Coil	0. 20 m
Height of Gap	0. 146 m
Height Inside of Vacuum Chamber	0. 133 m
Width Inside of Vacuum Chamber	0. 812 m
Length of Long Straight Section	6. 06 m
Length of Short Straight Section	4. 23 m
Weight of Steel (including edge iron)	4, 342 tons (metric)
Weight of Copper	61. 7 tons (metric)



Pictorial Ring Magnet Cross Section Showing Iron and Coil



PICTORIAL REPRESENTATION
RING MAGNET COIL ASSEMBLY
FIGURE 1

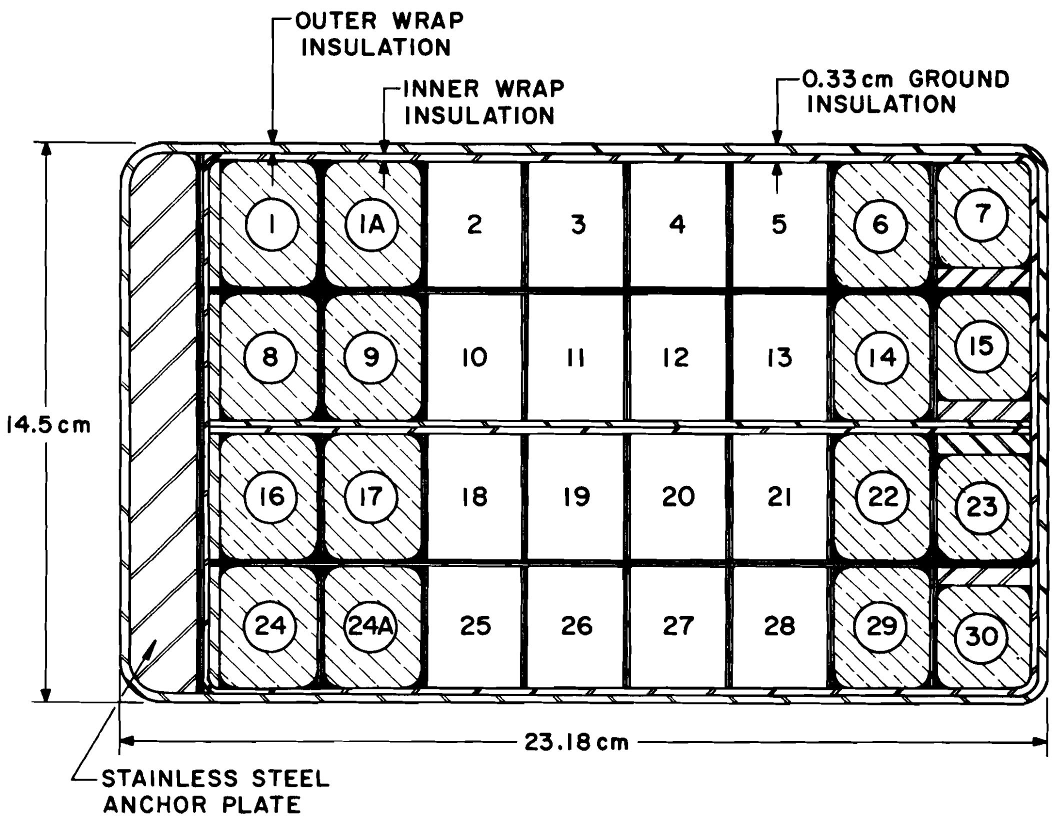
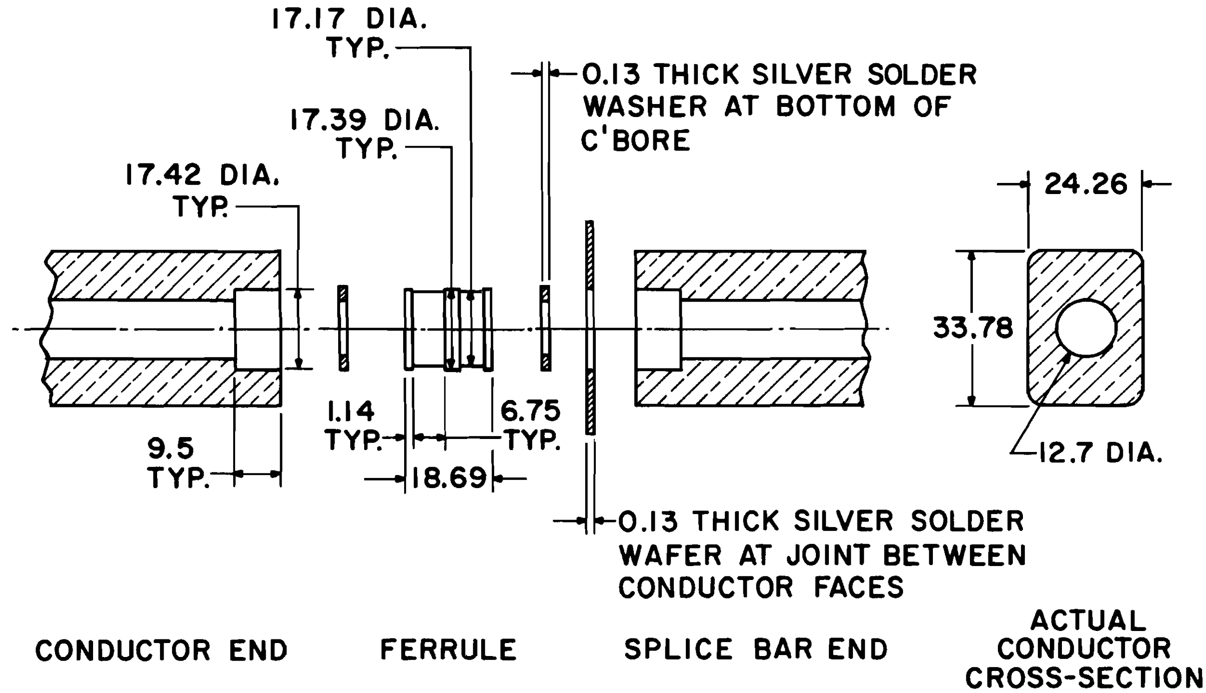


FIG. 2. OUTER SIDE COIL



ALL DIMENSIONS IN mm

FIG. 3. BRAZED JOINT GEOMETRY

All dimensions are in cm except as noted.

Octant No. 2 coil is shown.

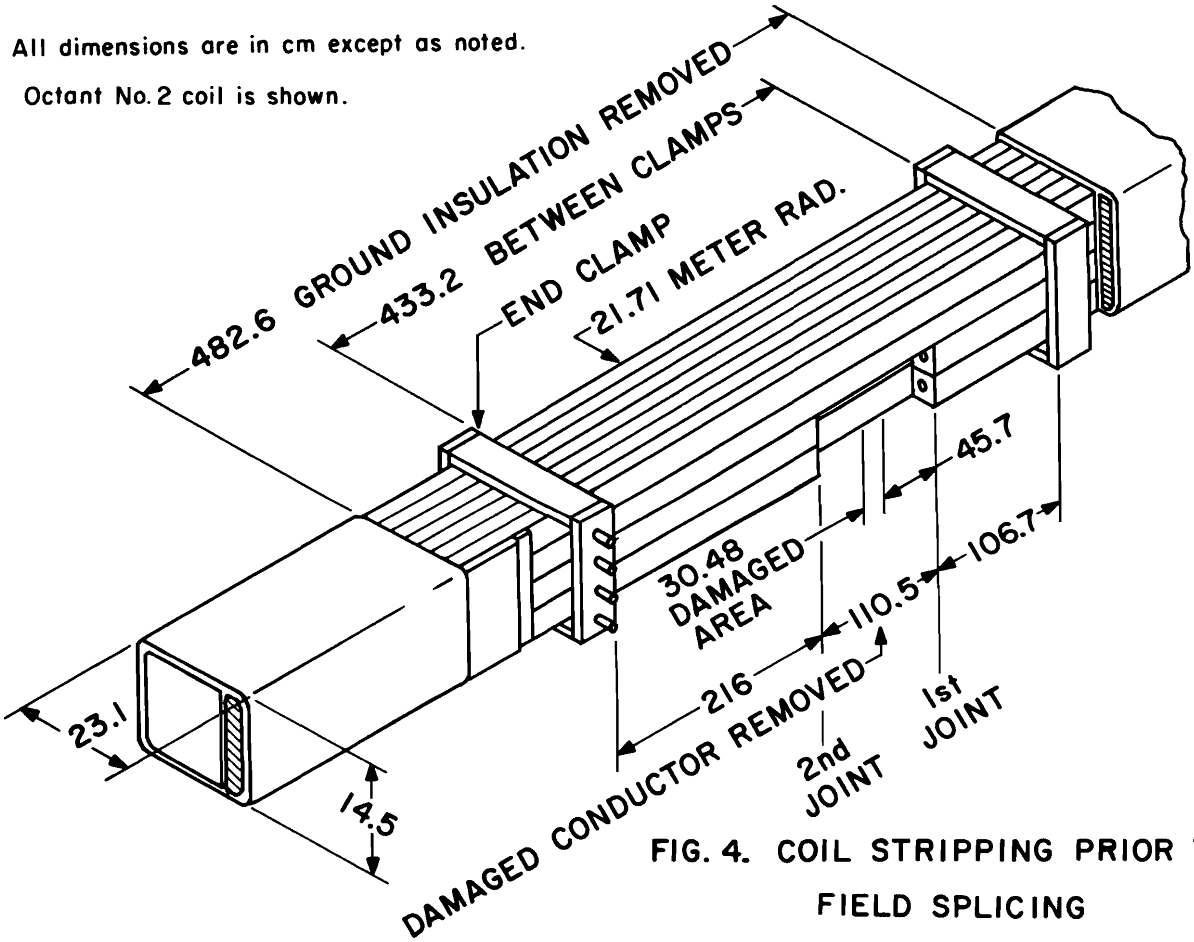


FIG. 4. COIL STRIPPING PRIOR TO FIELD SPLICING

Figure 5 Conductor End Preparation

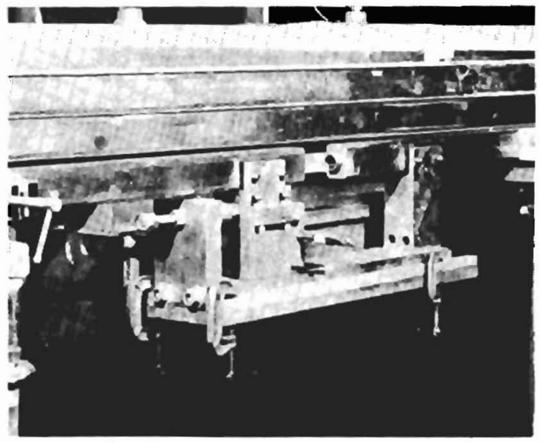


Figure 6 Spring Load Braze Fixture for First Joint

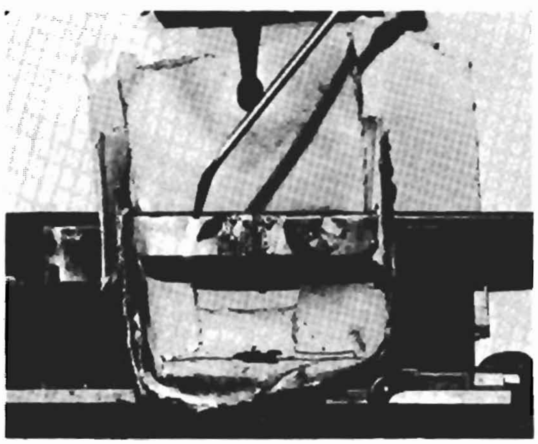


Figure 7 Actual First Joint Brazing

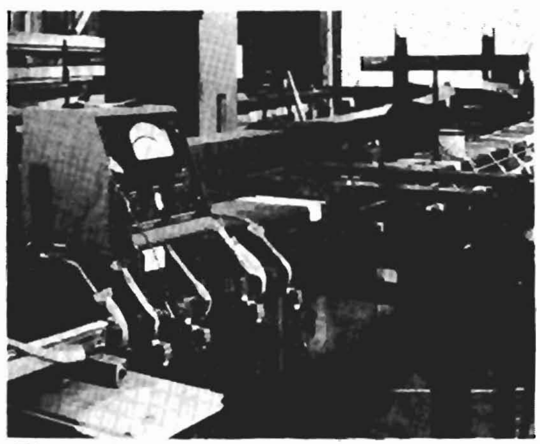


Figure 8 Second Joint Fixture

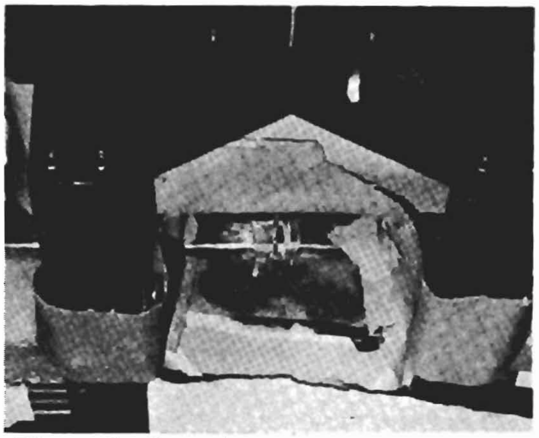


Figure 9 Second Joint End Spacing Prior to Brazing

Figure 10 Typical Joint Cleanup

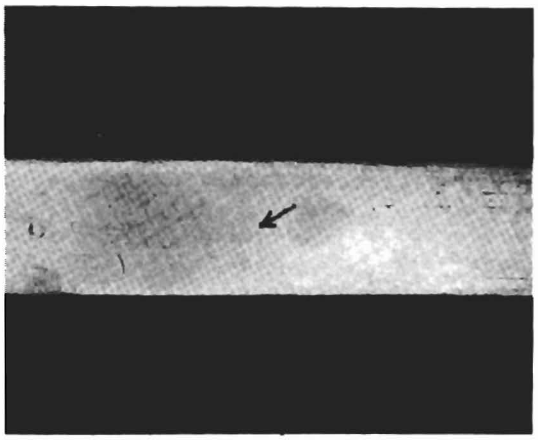


Figure 11 Completed Joint

Figure 12 Resistance Check Across Completed Joint