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CONSTRUCTION AND ASSEMBLY OF A FOUR LAYER Nb_3Sn DIPOLE MAGNET*

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INTRODUCTION

A dipole magnet using Nb_3Sn conductor designed to produce 10 tesla in a 40 mm diameter aperture has been constructed and tested. The coils were wound in flat race tracks with ends tilted up at 10°. The finished cross section consists of an eight layer block type geometry as shown in Fig. 1. Overall magnet length was one meter.

The insulated cable was wound onto stainless steel forms to make a four layer assembly, which was placed in a vacuum furnace for a prescribed time-temperature cycle to activate the conductor. The S.S. forms were then replaced by Nema G-10 pieces of identical dimension and the 4 layer assembly was vacuum impregnated with epoxy. Two of these potted coil assemblies were instrumented and assembled around a "stepped" bore tube. A stainless steel and aluminum structure was used for compression and containment of the coils, as shown in Fig. 1.

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Conductor and Insulation

The conductor was an 11 strand Rutherford type cable compacted to approximately 80 percent. Strands were 0.068 inch diameter and contained 50 percent copper stabilizer and 72,102 filaments. The cable was annealed for 3 hours at 200°C prior to insulating and winding.

The cable was insulated in-line during the winding process. Insulation was 0.05 to 0.06 inch wide x 0.003 to 0.004 inch thick "S"glass tape which was cold cleaned after weaving and half-lap wrapped onto the cable. Cable size over insulation was 0.128 x 0.446 inch.

Winding

A winding base with a 20 inch straight section and ends sloped downward at 10° was mounted on the winding table. The S.S. pole spacers (islands) for the 4 layers of one magnet pole were attached to the base with the smallest (outermost, layer 4) island on the bottom. Layers 3 and 4 were wound of one unspliced length of conductor. The bottom most layer (No. 4) was wound first with the conductor for layer 3 carried piggyback on the winding base, with the transition between layers located in the end turn around. Two layers of 0.006 inch thick "S"glass cloth was placed between layers during winding. After winding each layer, its S.S. outer spacers (picture frames) were put into position and temporarily clamped against the windings. Conductor back tension was 95 pounds. Layers 1 and 2 were wound similarly. Layers 1, 2 and 3 had 14 turns and layer 4 had 11 turns.

The remaining sides and ends of the S.S. forms were assembled around the coils as shown in Fig. 2. From the "lightly clamped" dimension, the coils were compressed an average of 1.2 percent.

Activation

The outer turn of each layer was brought out of the S.S. activating forms and left about 4 feet long. The strand ends were melted to seal against molten tin leakage during activating. After installation in the vacuum furnace a thermocouple was installed in a drilled recess in the activating form. The activating schedule followed was an attempt to duplicate the process used in preparation of formerly tested samples and is shown in Figs. 3 and 4.

After activation, the form sides and ends were removed. This proved difficult due to galling of the S.S. studs and nuts. Various compounds were used in an attempt to prevent this, but none proved effective in this environment.

Inspection of the windings showed a gray-green coloring of the originally white glass insulation. This was non-conductive and was perhaps a combinaton of products from glass sizing residue and conductor surface changes. The glass insulation showed no visible evidence of deterioration.

Potting

To prepare the coils for epoxy impregnation, the S.S. islands and picture frames were replaced by mold released Nema G-10 pieces of identical dimensions. During this procedure, fixtures were used to enable handling the coils without straining the brittle conductor.

Prior to installing the G-10 picture frames on each coil, a NbTi lead was solder spliced to the Nb_3Sn conductor. First, the outer turn of Nb_3Sn conductor was cut off at the end of the 20 inch straight section. This 20 inch section was then pulled away slightly from its adjacent conductor until an "L" shaped piece of kapton cound be inserted behind it. This kapton piece served as a containment barrier for solder and flux during soldering. The glass insulation was then cut away and the copper conductor surface cleaned and tinned using rosin flux. A pre-tinned pair of NbTi conductors, having the same combined area and copper content as the Nb_3Sn conductor, were then clamped against the prepared Nb_3Sn conductor and the solder joint made. Joint length was 20 inches. The solder used contained 62 percent tin and 2 percent silver. The solder area was cleaned with alcohol and a glass sleeve slipped over the joint area for insulation.

With the conductor and G-10 cross section complete, aluminum potting forms were assembled around the coil package. The forms were made leak tight with rubber "O" ring seals and RTV around the conductor leads. This assembly was enclosed in a vacuum chamber and pumped and baked for 12 hours. The potting form was hot water heated. An Epon 826(50 parts) and DER 736 (50 parts) resin mix was then catalyzed with Tonox (25 parts) and evacuated. This mix was forced into the lower corner of the form using atmospheric pressure. The curing scheudule was 50°C for 5 hours, 60°C for 8 hours and 80°C for 8 hours. Approximately one quart of epoxy per casting (4 layers) was used. After a slow cool down the forms were disassembled and the potted coils were inspected and measured. The casting resulted in layers 1 and 2 becoming a rigid pair and layer 3 and 4 becoming a rigid pair.

Electrical measurements of the coils were taken before and after potting, see Table 1.

TABLE I

Electrical measurement of D10A coils at various stages of fabrication. Resistance was determined by passing 100 mA current through the coils.

Coil (Layer No.)	Resistance (Ω)	Inductance (μH)	Dissipation Factor
After Winding (uncompressed)			
Top 1,2	0.0637	111.9	0.657
Top 3,4	0.0502	191.0	0.385
Bottom 1,2	0.065	-	-
Bottom 3,4	0.050	-	-
In Potting Fixture (before potting)			
Top 1,2	0.0645	125.7	0.691
Top 3,4	0.0507	128.6	0.421
Bottom 1,2	-	-	-
Bottom 3.4	-	-	-
After Potting			
Top 1,2	0.0645	317.0	0.341
Top 3,4	0.0508	187.0	0.394
Bottom 1,2	0.062	-	-
Bottom 3,4	0.048	-	-

Instrumentation

The picture frames were taken away from the potted coil assembly for instrumentation. Four SK-13-062-350 MM strain gages were mounted to form a full bridge on a 1/4 inch thick aluminum block. One gage block wasinstalled in a slot in one G-10 picture frame of each layer. Each installed gage was then calibrated in a compression fixture.

Voltage taps were connected to the windings at each solder spliceand layer to layer transition (start and finish of each layer), 7 taps per half magnet and 15 taps total. Instrument wires were brought to the outside of the structure by soldering gage and voltage tap leads to 0.007 inch thick flexible printed circuit boards. Each potted coil pair had a circuit board .

Assembly

The potted layer pairs with instrumentation in place were assembled around the stepped S.S. bore tube structure. A 0.010 inch mylar insulator was used over the bore tube. The 0.117 inch space between potted coil pairs was filled with 2 P.C. boards and a G-10 spacer. A 0.125 inch G-10 spacer was used at the midplane.

As can be seen in Fig. 1, the structure consists of 2 1/2 inch thick S.S. side plates and 2 3/4 inch thich by 5 inch wide aluminum keeper bars on top and bottom. One inch diameter S.S. studs on 2.5 inch centers were used to provide compression vertically. Temporary assembly clamps were used to compress the windings horizontally. Tapered shims, shown in Fig. 5, were then installed which transfer this compression to the keeper bars when the assembly clamps were removed. The 10° sloped ends were accomodated using tapered filler pieces between the keeper bars and the coils, see Fig. 6.

Clamping

Poisson code results predict the coil forces due to the superposition of a 0.005 inch precompression and Lorentz forces (for 10 tesla central field) and are shown in Fig. 7.

Based on this distribution, and caution about over straining the conductor in the end turn around region, the goal of our assembly procedure was to achieve a uniform horizontal compression of 5,000 psi. The vertical and horizontal compression was increased in steps, as shown in Table II. Prior to compression of the coil cross section, the end shoes were brought up snug against the coil ends of each layer. The measured coil compression and deflection is shown in relation to assembly clamp torque in Fig. 8.

During compression, only 3 of the original pressure gages were functioning. After the magnet was tested an autopsy showed that the copper traces on the P.C. boards were cracked where they had to bend over a .030 inch radius. Figure 10 shows that the horizontal compression decreased by 2,500 psi when the assembly clamps were removed and the load transferred to the aluminum keeper bars. During cooldown and testing the pressures were not readable. After warm up, the horizontal coil compressions were at, or exceeded, 80 percent of their pre-test levels.

TABLE II

D10A Assembly clamping schedule. Predicted coil compression values are shown next to torque values.

Vertical Tie Rod Torque (ft-lbs)		Horizontal Assembly Clamp Torque (ft-lbs)
20 (183psi)		0
20		40 (320psi)
40 (366psi)		40
40		100 (800psi)
150 (1372psi)		450 (3600psi)
	Creep 12 hours at 45°C	
150		525 (4200psi)
150		600 (4800psi)
200 (1829)		600

Post Test Disassembly

The structure was disassembled and removed. Widths of individual layers were measured and agreed to +0.000, -0.007 inch of their pre-assembly dimensions, see Table III. As mentioned above, many of the P.C. board copper traces were found to be cracked. Space permitted repair by soldering a small wire to bridge the cracks without having to dismantle the assembled coil package. No damage to visable G-10 or epoxy filled portions of the coils were apparent.

TABLE III

D10A Coil widths measured over picture frames.

Layer No.	Lightly Clamped (in)	After Activation (in)	After Potting (in)	After Testing (in)
Top 1	6.935	6.907	6.900	6.900
2	6.935	6.907	6.900	6.900
3	6.931	6.909	6.905	6.899
4	6.945	6.909	6.905	6.898
Bottom 1	6.935	6.906	6.900	6.898
2	6.936	6.906	6.900	6.898
3	6.951	6.906	6.900	6.897
4	6.951	6.906	6.900	6.900

Re-Clamping

During reassembly 0.012 inch shims were added to the outer pancakes, layers 3 and 4, of both magnet halves to provide more compression in these layers during reclamping. An extra set of horizontal assembly tie rods were used to achieve greater horizontal compression. The target was to bring layer 4 up to 10,000 psi compression. The clamping schedule followed is shown in Table IV. The deflections and compressions are shown in Fig. 9. As shown, the average layer compressions decreased by 4,000 psi when the assembly clamps were removed.

TABLE IV

D10A Reassembly (second assembly) clamping schedule. Predicted coil compression values are shown next to torque values.

Vertical Tie Rod Torque (ft-lbs)	Horizontal Assembly Clamp Torque (ft-lbs)
30 (275psi)	0
30	30 (240psi)
30	100 (800psi)
100 (915psi)	100
200 (1829psi)	100
200	400 (3200psi)
200	600 (4800psi)
200	800 (6400psi)
200	1000 (8000psi)
200	1100 (8800psi)
200	1150 (9200psi)

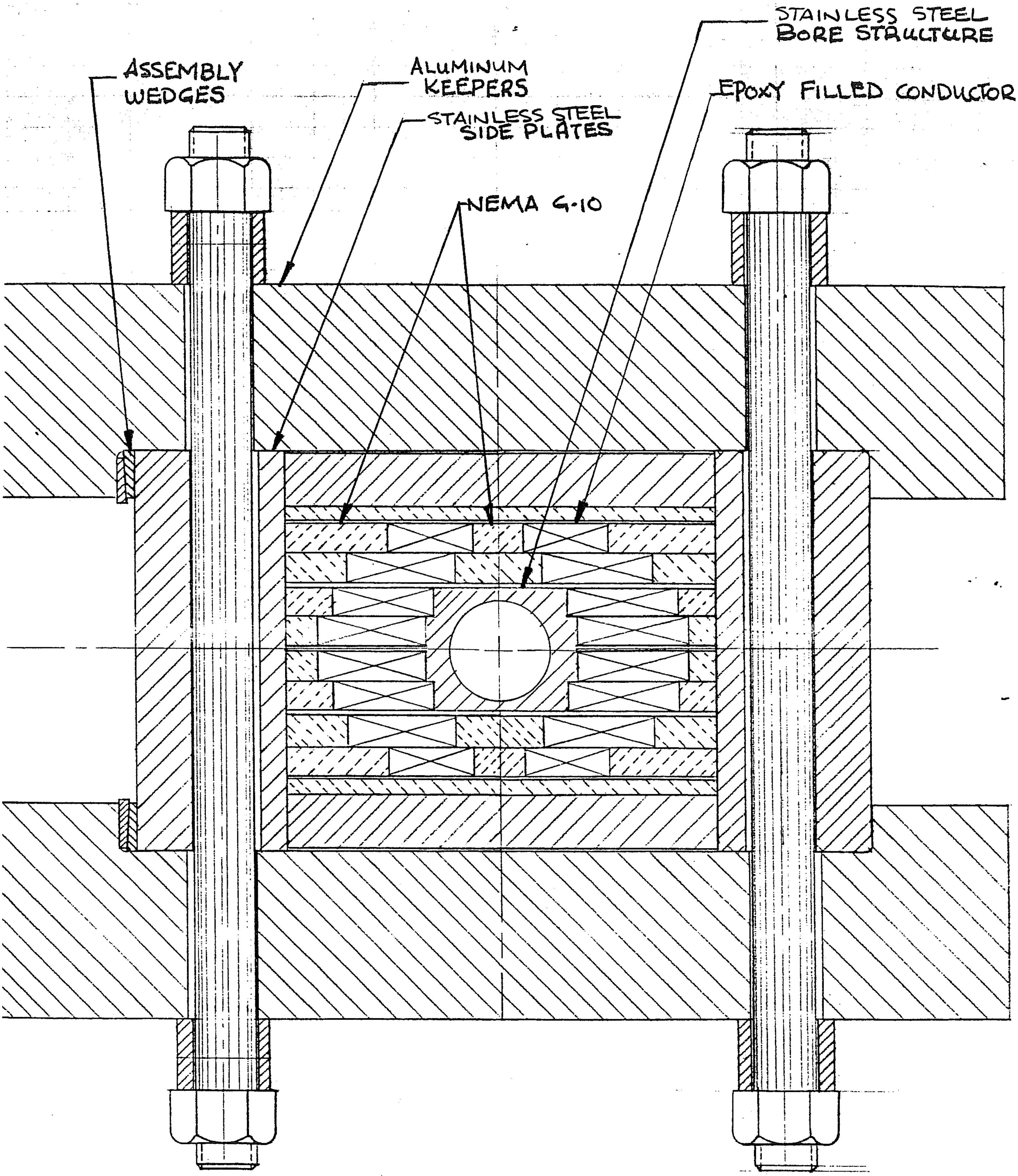
Cooldown

The compression of each layer was monitored during cooldown. The compression levels at 4 K are shown on Fig. 13.

Acknowledgement

Appreciation is expressed to the technician crew, and Roy Hannaford in particular, for the patience and TLC to see this tedious project through each stage to completion.

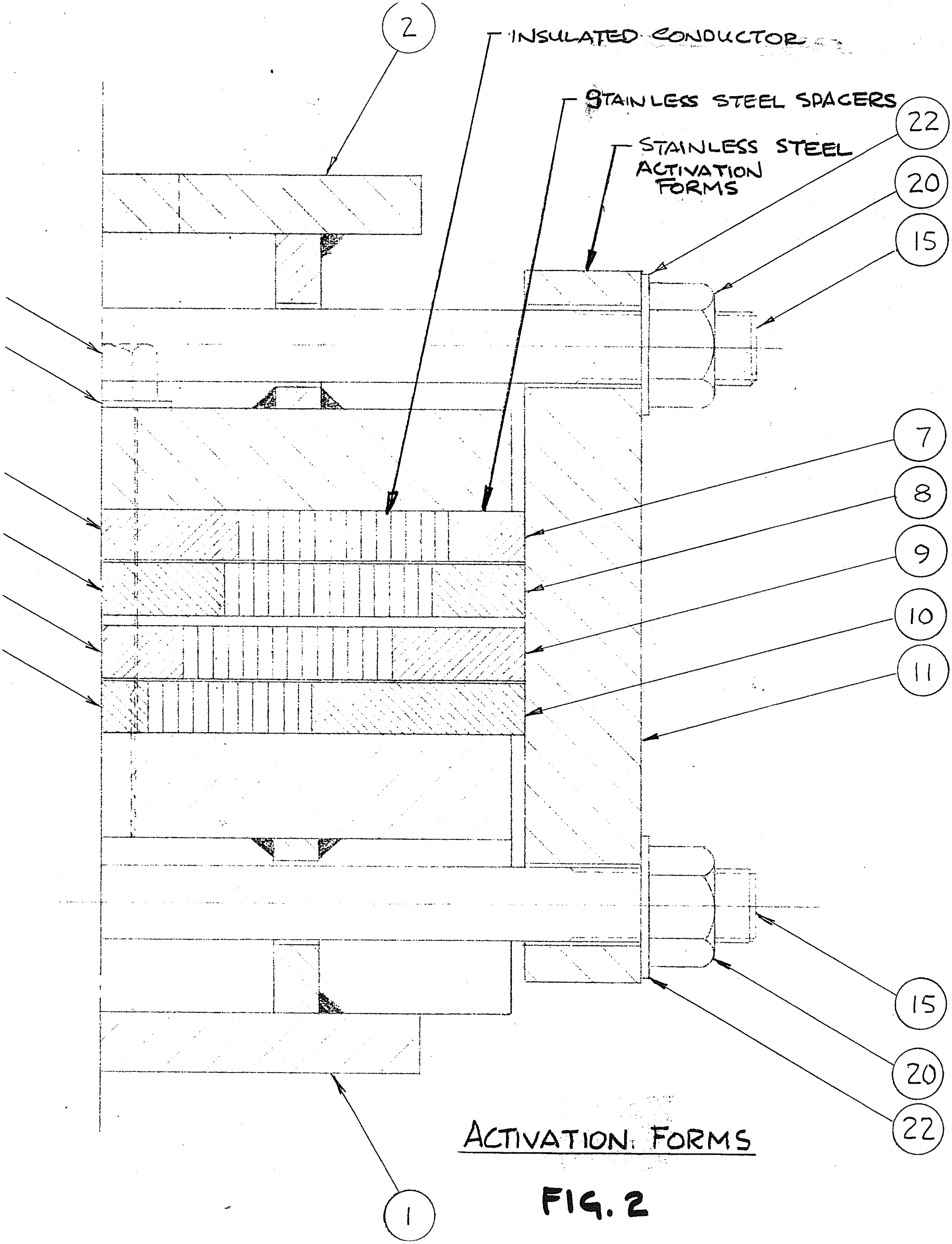
LIST OF FIGURE DESCRIPTIONS



D-10A CROSS SECTION

XBL 836-10128

FIG. 1



ACTIVATION FORMS

FIG. 2

6-20-
R.H.

REACTION SCHEDULE

D-10 A TOP Nb_3Sn

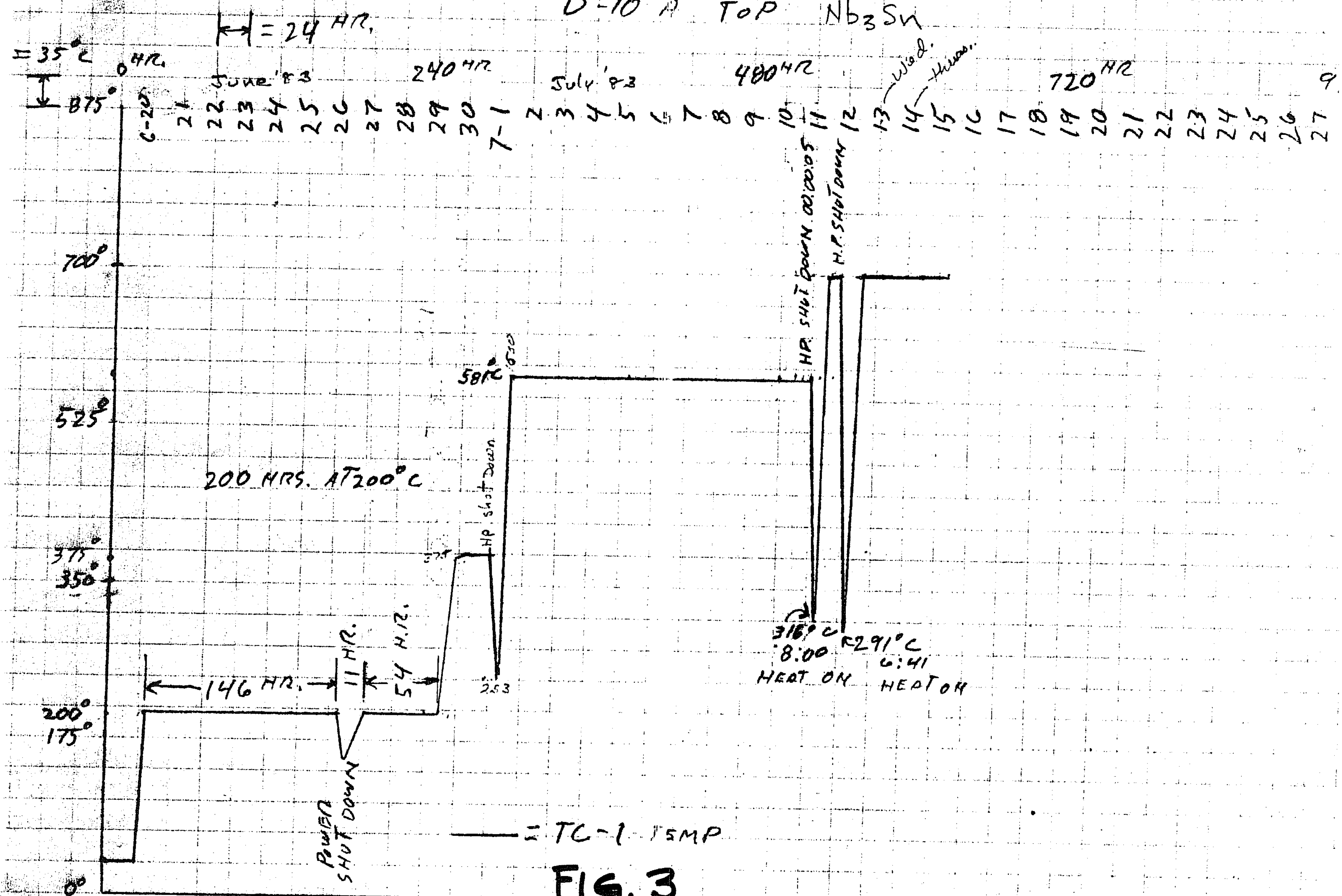


FIG. 3

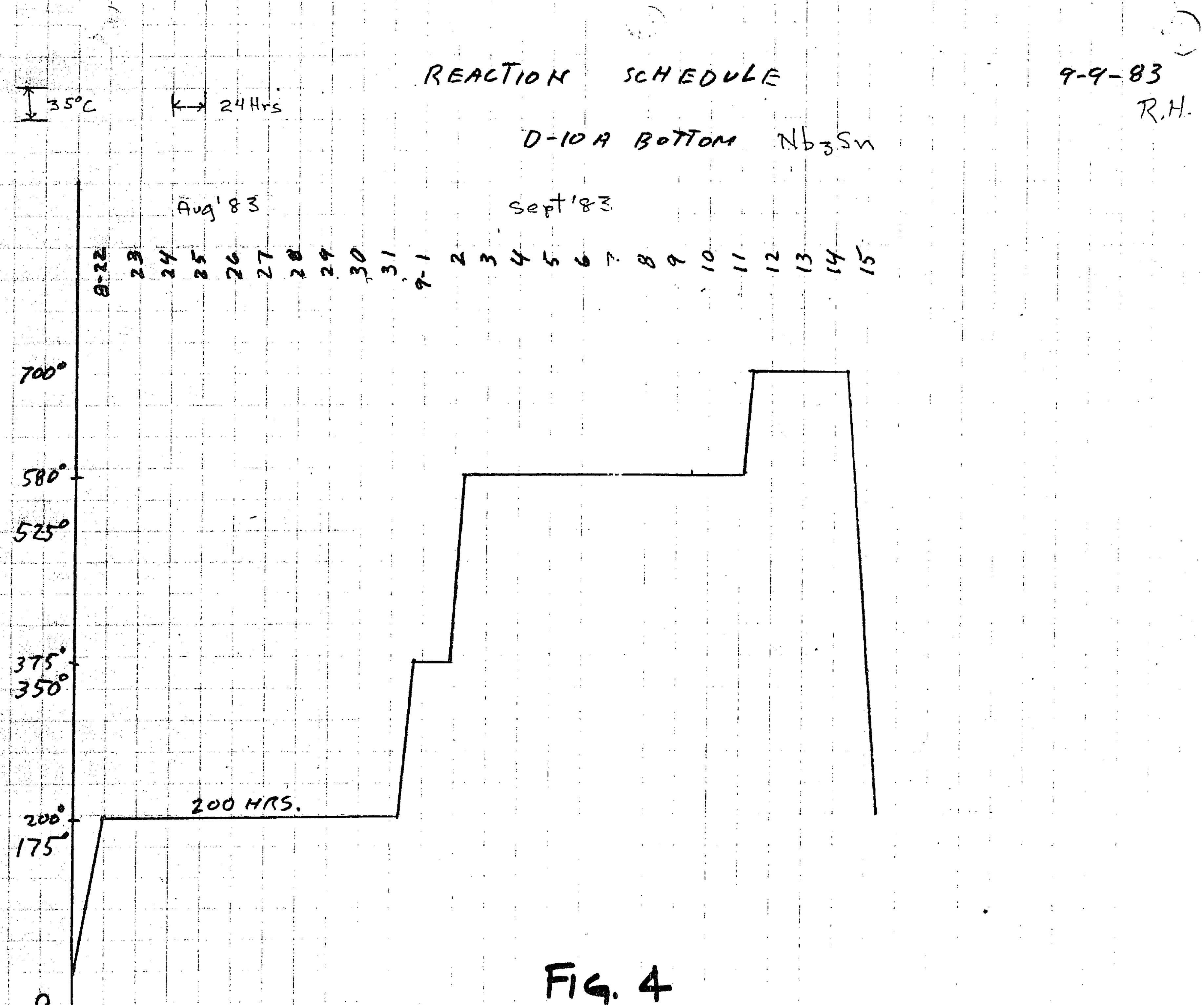
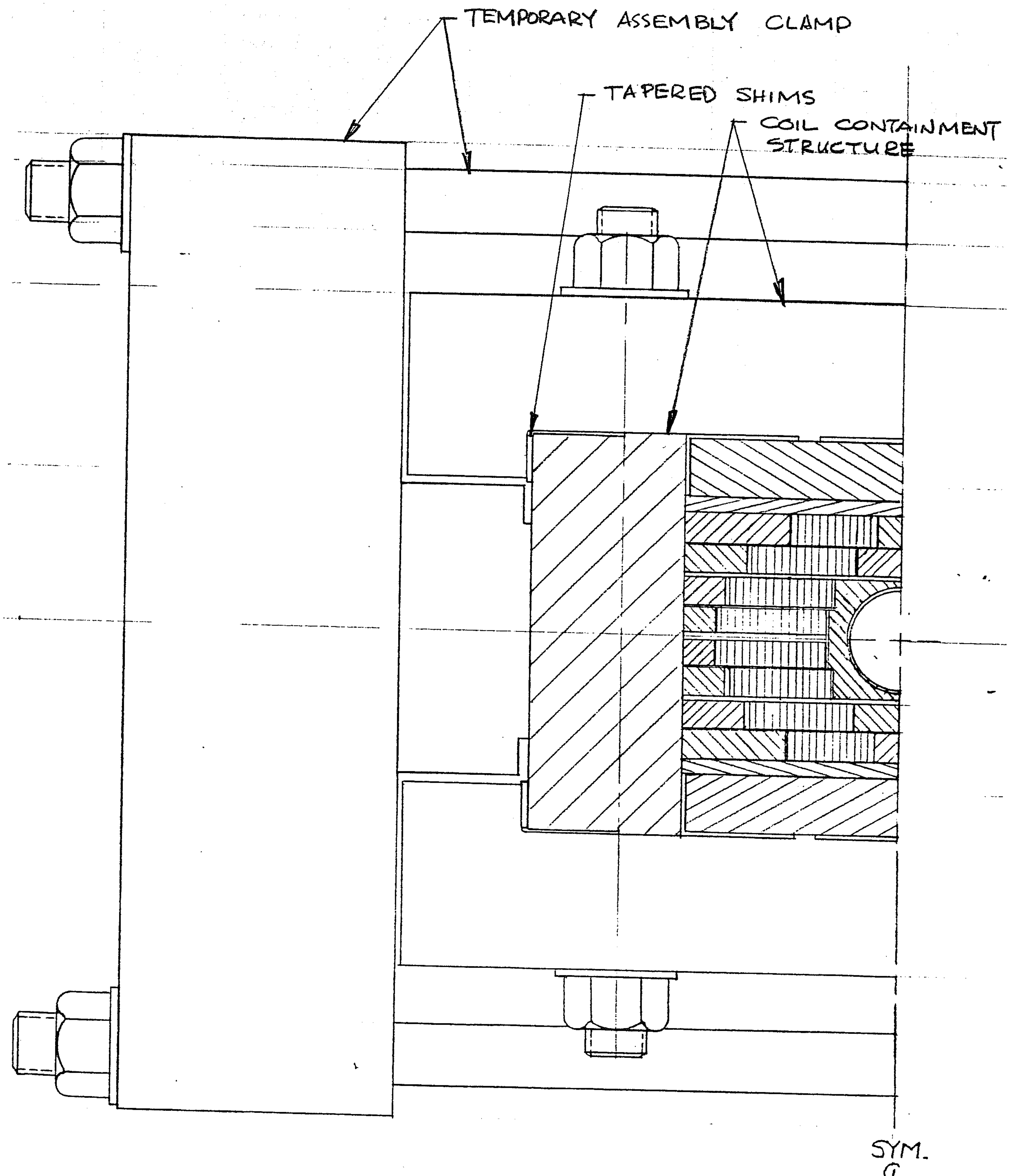
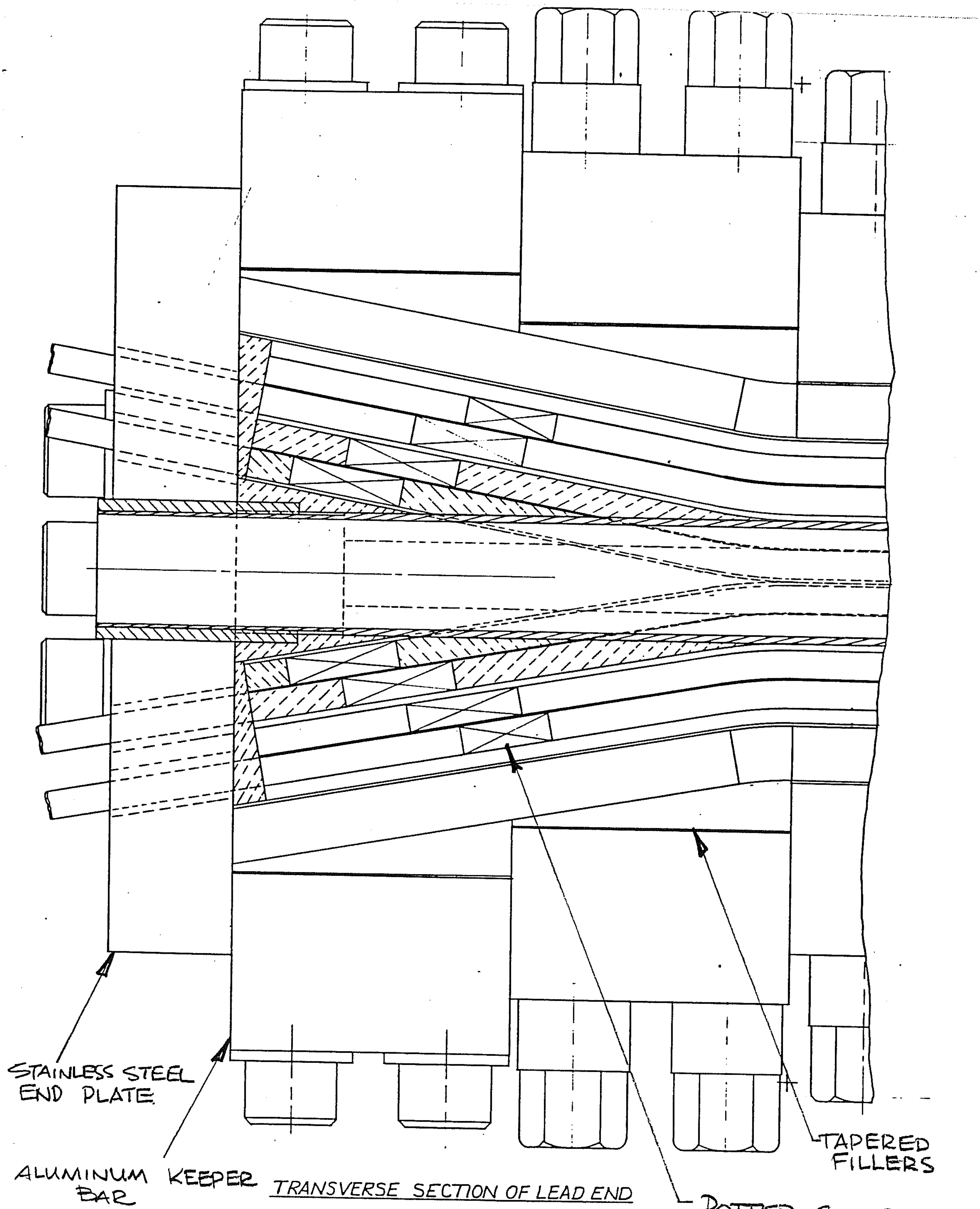

REACTION SCHEDULE
9-9-83
R.H.
35°C
24 Hrs
D-10A BOTTOM Nb_3Sn
Aug '83
Sept '83
8-22 23 24 25 26 27 28 29 30 31 9-1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
700°
580°
525°
375°
350°
200°
175°
0
200 HRS.

FIG. 4



DIOA ASSEMBLY CLAMP

FIG. 5



TRANSVERSE SECTION OF LEAD END

FIG. 6

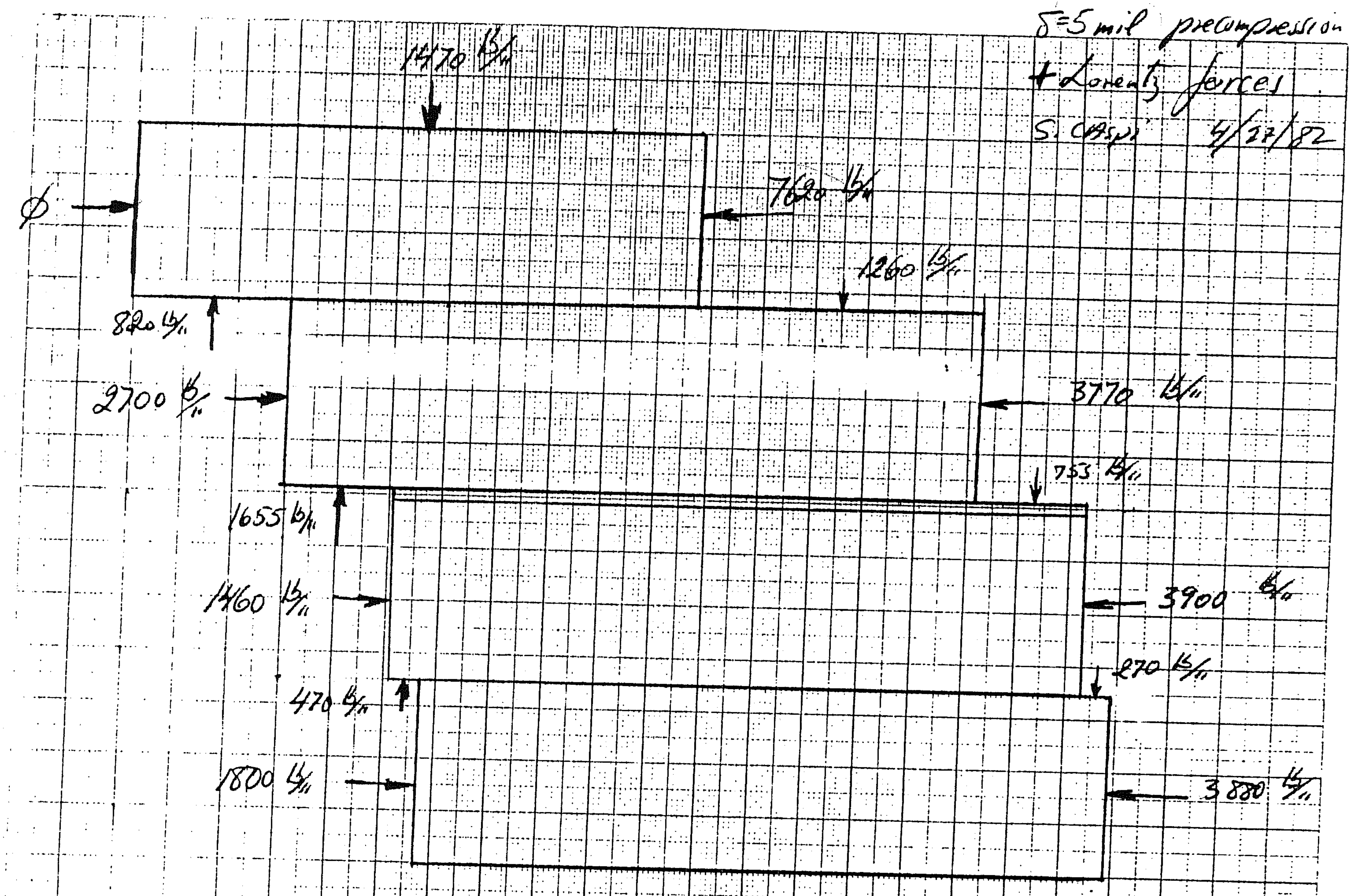
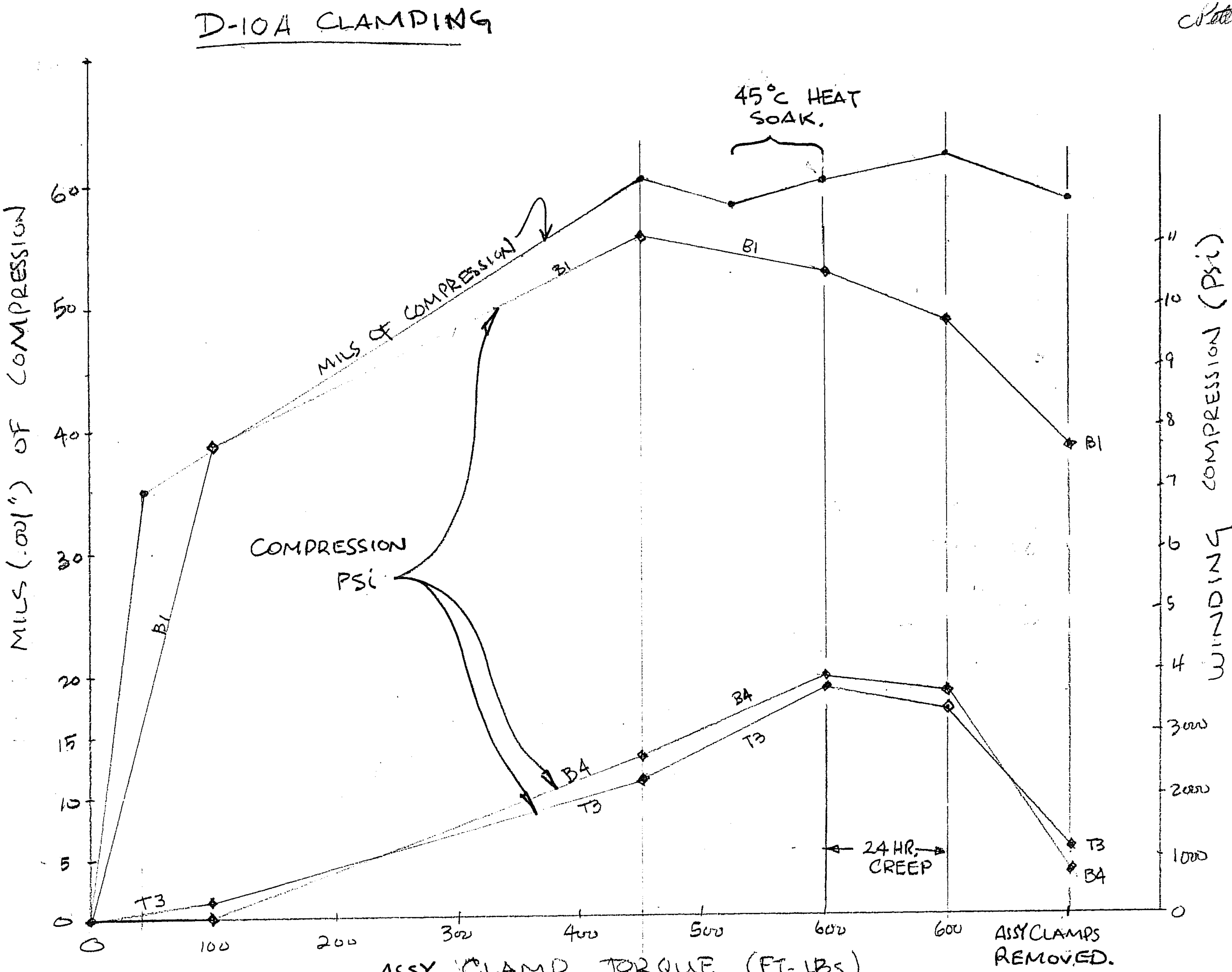
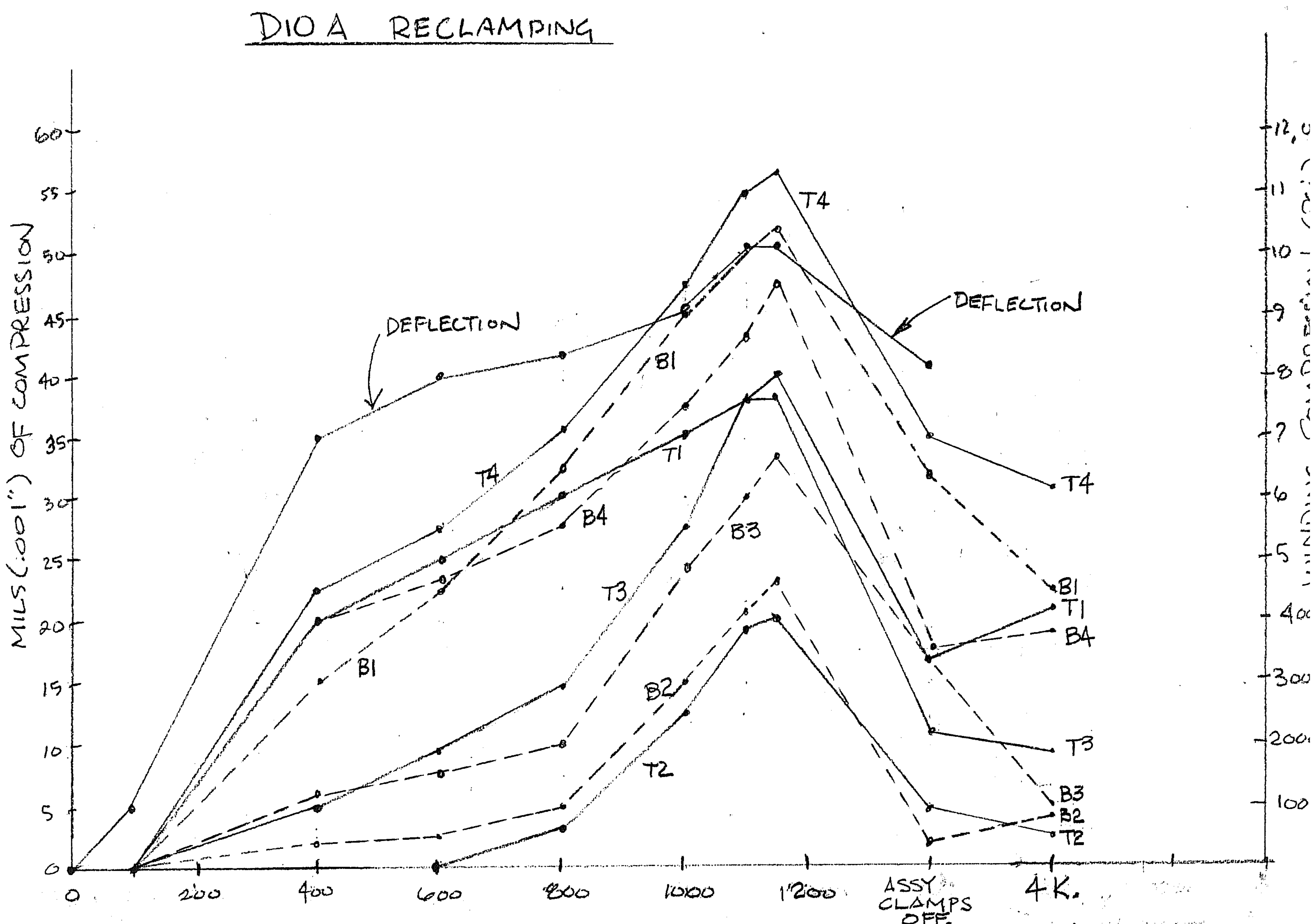


FIG. 7 Average reacting forces per unit axial length



D-10A CLAMPING
MILS (.001") OF COMPRESSION
WINDING COMPRESSION (PSI)
ASSY CLAMP TORQUE (FT-LBS)
45°C HEAT SOAK.
MILS OF COMPRESSION
COMPRESSION PSI
B1
B4
T3
24 HR. CREEP
ASSY CLAMPS REMOVED.
0
100
200
300
400
500
600
600
5
10
15
20
30
40
50
60
1000
2000
3000
4
5
6
7
8
9
10
11

FIG. 8


DIO A RECLAMPING
MILS (.001") OF COMPRESSION
60
55
50
45
40
35
30
25
20
15
10
5
0
0
200
400
600
800
1000
1200
ASSY CLAMPS OFF.
4K.
ASSY CLAMP TORQUE (FT-LBS)
DEFLECTION
DEFLECTION
T4
T4
T4
B1
B1
B1
T1
T1
B4
B4
T3
T3
B3
B3
B2
B2
T2
T2
12,0
11
10
9
8
7
6
5
400
300
200
100
FIG. 9