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THE DESIGN AND FABRICATION OF THE PDX POLOIDAL FIELD SOLENOID UTILIZING FIBERGLASS REINFORCED EPOXY

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Summary

This paper discusses the basic design of the Poloidal Field Solenoid Coil. It will be mainly concerned with the more unique features of the Solenoid such as the copper coil windings and the design of the epoxy-glass structural support mandrels.

The center solenoid coil of the PDX machine consists of five different coil systems (OH #8, #9; NF #11; DF #7; EF Solenoid and CF #9)[1]. Three concentric fiberglass reinforced epoxy cylinder fabricated in-house will act as mandrels to support and to house the coils that will result as an integral unit.

Introduction

The center solenoid is essentially a variety package of the poloidal field coils in the PDX machine. The physical configuration is that of a large cylinder. The center support column of the machine and the nose of the TF coils are located at the center of the solenoid, with the toroidal shaped vacuum chamber around the solenoid.

The epoxy-glass cylinders or mandrels of the solenoid were designed as spacers and insulators for the coils, and they were also designed as structural supports for the upper and lower arches that support the other OH Coils in the machine and, thirdly, act as winding mandrels for the coil winding operations. The diversity of functions of the cylinders are such that the tooling equipment and fabrication procedures became a series of complicated, but interesting design problems.

Basic Configuration

The solenoid has a finished I.D. and O.D. of 45.37 inches (1.15 m) and 54.37 (1.38 m) respectively, and a length of 67.38 inches (1.71 m). Within the four and one-half inch thick wall there are three epoxy-glass laminate walls and three layers of copper coils. Viewing the section from I.D. outward to the O.D. in Fig. 3, we see that there is first an epoxy-glass laminate wall, then two layers of OH coils, an intermediate wall of epoxy-glass laminate, then one more layer of coils, and finally an outer epoxy-glass wall. The estimated weight of the composite is approximately 5300 pounds.

The Inner Mandrel

Ohmic Heating

There are two sizes of OH coils in the solenoid. The larger one is called the OH-8 and the smaller one is called the OH-9. Their dimensions are as follows:

	Radial Width (in.)	Vertical Width (in.)	Hole Diameter (in.)
OH-8	0.625	1.320	0.313
OH-9	9.625	1.050	0.313

The hole in the coils is for water cooling during operation.

The coils will have turn -to-turn eight layers of 0.00325 inch pressure sensitive Mylar tape, half-lapped, and one layer of 0.007 inch fiberglass cloth tape, half-lapped, with epoxy impregnating the glass tape. The total build-up of insulation will be approximately 0.07 inches. The insulation will be designed for a one-time test at 45 kV and an operational rating of 22 kV.

The Intermediate Mandrel

Null Field - NF #11; Diverter Field - DF #7; Equilibrium Field - EF Solenoid; Compressive Field - CF #9

All of these coils will be separately wound on the intermediate mandrel; however, since the cross-sections are different for each coil, the mandrel is machined in steps in order to obtain a uniform outer diameter at the completion of winding, as shown in Fig. 4. The insulation build-up is the same as that of the OH coils, but the dimensions are smaller. The dimensions are as follows:

	Radial Width (in.)	Vertical Width (in.)	Hole Diameter (in.)
NF-11	0.723	0.847	0.250
DF-7	0.724	0.847	0.250
EF-Sol.	0.734	0.500	0.250
CF-9	0.873	0.500	0.250

Coil Winding Operation

Inner Mandrel

All the winding mandrels are made of fiberglass reinforced epoxy; howevever, for additional support and minimum winding tooling, the steel mandrel beneath the epoxy-glass cylinder will remain through the winding operations.

The inner epoxy mandrel will be machine finished to an O.D. of 46.24 inches, except for the center collar area which is shown in Figs. 3 & 4. The mandrel was made 3/8 inches longer on each end so that the resin rich corners and ends can be machined away before final assembly.

To start the inner OH-9 windings, the starting end of the coil needs to be restrained, so it will be bolted to the end plate. This OH coil package is wound on a helix; therefore, to establish the proper helix angle a spacer is made to the proper angle to act as a vertical mandrel for the first turn. This helix angle is 0°27'42". Compression is applied in the lengthwise direction in order to pack the coils tightly against each other and to maintain the helix angle, and tension is applied to the coil as it is being wound onto the mandrel.

Axial and radial dimensions will be checked after each turn as to avoid cumulative errors. Errors can be corrected by increasing Mylar insulations on one turn or distributing the error over several turns.

At a certain point during winding, the OH-8 coil will have to make a transition into the OH-9 coil. To accomplish this, another spacer machined to the proper transition steps, is placed into the turns amidst the transition. The two different size coils are brazed together with an intermediate copper transition piece. The new spacer will enable the smaller coil to maintain the same helix angles as the larger coil.

Before the OH-9 coil makes contact with the center collar, another spacer is required to diminish the helix angle against the collar wall. Now another transition is required for the coil to reverse its winding direction. To do so, a copper transition piece is machined out to fit in the proper place and have the coil ends brazed on to continue the winding. This transitional piece also has input and output tubing connections for the cooling water to complete two separate circuits for the inner and outer layer of the OH coils. The water leads will be tugged away in a small machined out area in the center collar. The lines will be brought in for connection after intermediate mandrel has been laid-up, and aisle ways machined out for the tubings to be in. This will be clearer after the discussion in the next section.

From that transition, the OH-9 inner coil now becomes the OH-9 outer coil, but now it has a smaller helix angle due to the increase in mean diameter (0°26'47"). It meets the OH-8 outer coil at the same place as the inner groups did and turns back into the OH-8 again after the transition. Similar space as before is used for the step transition to maintain the new helix angle.

To terminate this package of coil windings, a spacer is placed against the end plate and diminishes the helix angle. To secure the coil end, it is bolted through the end plate similar to the other end at the start of the winding. The coil ends will later have special leads brazed on for bus work connections.

Since the coils will be fed and wound from one direction and the leads must extend from the ends of the solenoid, the most convenient winding configuration was the one presented. This results in a mirror image winding for the upper and lower halves of the solenoid having the horiztonal center line as the axis of symmetry. For this reason, only one-half of the solenoid coil was necessary for discussion.

Intermediate Mandrel

There are four different coil systems wound on the intermediate mandrel. Although some are significantly different in dimensions, all of them will have the same finish-wound O.D. measurements. Because of this requirement, the mandrel is machined in steps in order to achieve this dimensioning. Each of the four coil systems will have its own bus work, lead-in, and lead-out, totally independent of each other. This arrangement may pose problems for leads of the coils inboard of the NF-11's. The most compatible solution was to have the leads to travel under the coils in aisles machined into the mandrel. Each set of leads will have its own aisle to travel out of the solenoid to prevent interference to other coils and confusion with the other leads.

The coil to be wound first this time is the inner most one from the center collar and that is CF-9. It has five turns that are parallel to the horizontal midplane. Referring to Fig. 2 again, note the joggles that are necessary to maintain the required configuration. One lead is purposely lead out center-on-center so as to cause cancellation of unbalanced fields generated by the joggles. The joggles of all four coil systems will be formed on the winding line. This will eliminate the need for preformed parts and extra brazed joints.

The other coils on the intermediate mandrel will have the same basic configuration as the CF-9. Since the leads of each coil system will not share the same lead aisles, extra machining is necessary to overcome some of the physical interference difficulties.

Tooling for the Winding Operation

To form the epoxy-glass mandrels, a steel mandrel is rolled and machined along with two end plates. The steel mandrel was designed such that it will collapse and would be withdrawn from the solenoid after the completion of all coil windings and mandrel lay-ups. Slot openings were machined into the end plates for locating the leads and rib anchors. Rib anchors are stainless steel attachment lugs embedded into the intermediate mandrel to help to locate and secure the arches that support the other OH coils outside of the solenoid.

An adjustable tension unit riding on transverse rails will provide approximtely 1000 pounds of tension on a copper strand as it is being wound onto the mandrel. A series of roller mounted under the copper feed in progressive heights will maximize catenary control. On the platform that surrounds the mandrel support frame, are the saw table, brazing stand, joggle forming station, and the wet-tape winding machine.

The copper coils will have already been stretched and tape insulated prior to mounting on the tension unit. Where a braze is made, the joint has to be electrically and hydraulically tested and be within certain limits before the area is cleaned and retaped for winding.

Epoxy-Glass Cylinders

As design considerations, there are three types of forces acting on these cylinders. The first of the types are the gravity forces of the upper OH coils and the supporting arches, and the weight of the solenoid unit itself. The second type is the radial and axial forces generated from the solenoid coils and influences of other PF coils during pulses. The third source is contributed from the upper and lower OH coils as they transfer their pulse forces through the supporting arches to the solenoid.

The materials available for this particular application are broad in range. A non-metallic material was generally preferred for its dielectric properties, such as resistivity and dielectric strength and zero retentivity. Non-metals, such as reinforced plastics, are superior in strength to weight ratio, as compared to metals. Just as an example of such a weight advantage, the specific tensile strength of a heat treated alloy steel is 710,000 in. as compared to an epoxy reinforced with woven glass of 1,270,000 in. Since the weight of the solenoid is an important factor in the structural design of the lower OH arch supports, a lower weight of the solenoid is preferred.

The polyester and epoxy resins are both thermosetting materials and have been the most popular resin matrices for structures and tooling in the reinforced plastics field. Because of the high modulus and strengths of glass, fibered-glass has been the most practical and economical reinforcement for these resins. Neither one of the resin or glass is useful by itself structurally, but when properly combined, they can be stronger, tougher, and more impervious to weathering or chemicals than many of the metallic alloys.

Fabrication

It is desirable for the resin-glass compound to be the heat post-curing type because a post-curing will bring out the full mechanical and electrical properties of the resin, although the unit will only be operating in a 65°C environment. The material should not present machining problems. Neither excessive brittleness nor resiliency are good qualities for impulse loadings on the solenoid; which means the modulus of elasticity should be within a range such that the resulting strain is within tolerable limits. The axial compressional deflection must not exceed 0.030 inches.

There are several good methods to fabricate the cylinders. The first one comes to mind is the most popular and proven method of fabrication: filament winding. This method has brought great success to the aerospace industries as well as almost any manufacturer of military, structural or consumer products, ranging from rocket motor cases to golf clubs.

Using pre-pregs is the next most popular method because it is very convenient, excellent control in in ratio of glass to resin content, and least difficult in handling in-house. Pre-pregs are B-stage tapes or pre-impregnated fiberglass tapes. It is available in both the unidirectional and cross-ply configuration with varying thickness. Both the polyester and epoxy resins are available as the resin matrix for these tapes.

The third possibility for the mandrel fabrication is an old, common art, and that is the wet lay-up method. This is an extremely messy job and at times a hazardous job for someone who is sensitive to the chemistry of the resins. Epoxy resins usually cause more dermatitis problems than the polyesters.

The selected method is actually a hybrid of the previous three mentioned. It is a type of filament winding, because the glass is wound in tension onto a rotating mandrel, which, in our case, will result in a mechanically stronger structure. It is similar to a pre-preg operation because the fiberglass tape will be pre-wetted and squeegeed to control the resin-glass ratio prior to winding onto the mandrel. Finally, it is also like a wet lay-up operation, because the mixing and squeegeeing procedures remain very much the same.

This method requires a design of a simple wet-tape applicator. It takes the dry glass tape and sends it through a series of knurled rollers submersed in the resin mixture, and then through a series of teflon bars; the excess resin is forced off the tapes. This applicator can pivot on its vertical axis to vary the tape angle, and is mounted on rails that enable it to travel the length of the mandrel. It will only require one person to control the entire operation, because mounted on the applicating fixture are hand controls of the mandrel winding motor. The operator can adjust for the RPM of the mandrel in both directions as well as the on and off switching.

Selecting the Resin

Cured samples of polyester resin with fiberglass reinforcement were provided by a number of interested parties for evaluations. Probably due to the imperfections of hand lay-ups and resin control, the samples could not sustain more than 200 volts per mil of dielectric strength. The parts were also very brittle and chipped easily. When one sheet-sample was machined for tensile specimens, it delaminated in many places, and the resultant data were not accurate. The overall results for the polyester resins were a little disappointing.

Resins designed for laminating purposes generally have lower viscosities, and therefore were an important factor; however, to our surprise, it was found later that mixtures below 10,000 cps were actually too low in viscosity for our type of tape windings. The ideal viscosity was between 12,000 to 15,000 cps. The probable reasons are likely to be the tension applied on the tape during winding, and the particular weave and sizing of the fiberglass tape that enables the resin to impregnate better than expected. Another important consideration is the mechanical and electrical properties after post curing, and at high temperatures. The solenoid will operate slightly above room temperature (approx. 60°C.), and also in case of cooling failure, the mandrels can retain sound structural integrity up to 200°C. There were much greater selections in epoxy resins than polyesters for high temperature applications. Machining qualities is a very important consideration since the maximum allowable tolerance on machining is ± 10 mils. Because of resin additive or fillers, some resins will stand up to cutting and its temperatures better than others.

Different epoxy vendors suggested different approaches in formulations. Several believed in single component systems, because the tape winding operation may require more than one day of work. This type of resin already has the two reactants in the same matrix, and only requires heat to initiate the reaction. The pot-life is essentially the shelf-life of the resin system.

The main advantage of this type of system is that the resin will not gel over the period of time that the winding operation requires. This eliminates the risk of delamination due to poor adhesion between a gelled surface and a fresh coat of resin. One basic disadvantage found with using this system is that even at high viscosities, some amount of the resin tends to run to the bottom of the mandrel to create a more resin rich area. This is due to the fact that our winding is so large that the resin invariably overcomes the surface tension, and tends to travel. The solution for this problem would be to continuously turn the mandrel until the resin has gelled in the oven. The extra monitoring and tooling required were not generally favored. The samples were very brittle and chipped easily. Most single-component systems are designed for armature dipping or coating as such where a heated part can be submersed into the resin and activate the system that adheres to the part. Although eliminating the step of mixing greatly reduces the chances of error, the extra tooling and the cured physical properties did not favor the benefit of single-component resin systems.

The poly-component resin systems allows for more variations in formulations between resins, hardners, and accelerators. Many compounders use just a few basic resins and hardeners to obtain a whole slew of formulations with different physical, mechanical and electrical properties. The users are not encouraged to formulate their own concotions unless they have the chemistry knowledge or lengthy experimental time to prove long term atomic-structural stability.

Most compounders will have already mixed the accelerator into the curing agent or hardener before the user receives the components. The accelerator is sometimes used for applications where a short gel time or curing time is necessary. Some resin and hardener combinations are such that a full cure will require days without additional heating; therefore, to accommodate for the lack of facilities or limited operation time, compounders add an accelerator to expedite the polymerization. There is a limited range of quantity, however; if too much accelerator is used, properties will vary and degrade significantly in time.

There are resins and hardeners that have variable mix ratios that will result in a variety of property changes. Some are desirable, and some are not. Most compounders will not publish such flexibility range, but let the user be restricted to one fool-proof mix ratio for that system.

Very often fillers are used in the systems. Fillers are inert particles which are added into the epoxy to achieve various results or properties that pure resins may lack. The benefits derived from filler additives in epoxy are the lowering of resin cost, decreased exotherm, less shrinkage during cure, lowering of thermal coefficient of expansion, increasing viscosity, raising the heat distortion temperature, increased abrasion resistance, increased impact strength and increasing the compressive modulus; however, both tensile and compressive strengths, and elongation may be adversely affected. For severe strss applications, these adverse factors must be taken into consideration in filler additives.

Conclusion

At the writing of this paper, all the tooling for construction of the solenoid is more than 90% complete. The design and intended construction methods and materials is believed to be the most practical and economical solution for the solenoid coil structure. The technical assistance of the Coil Design group has long acquired expertise in the handling of epoxy-glass composites.

At times when the strength to weight ratio is important, only some of the titanium alloys can claim higher values, but its restivity and costs is far from that of the reinforced plastics. This type of application, using epoxy-glass, is not an extraordinary feat; however, it is an indication as more advanced materials become known that the reinforced-plastics concept will play larger roles in the future in applications where nonconductive structural materials is required.

A more thorough and detailed paper concerning the design and fabrication of the PDX solenoid will be available through Princeton University as MATT-1189.

Reference

[1]"PDX Machine Poloidal Field Coils" by P. J. Heitzenroeder and F. Dahlgren (Presented at the Sixth Symposium on Engineering Problems in Fusion Research)

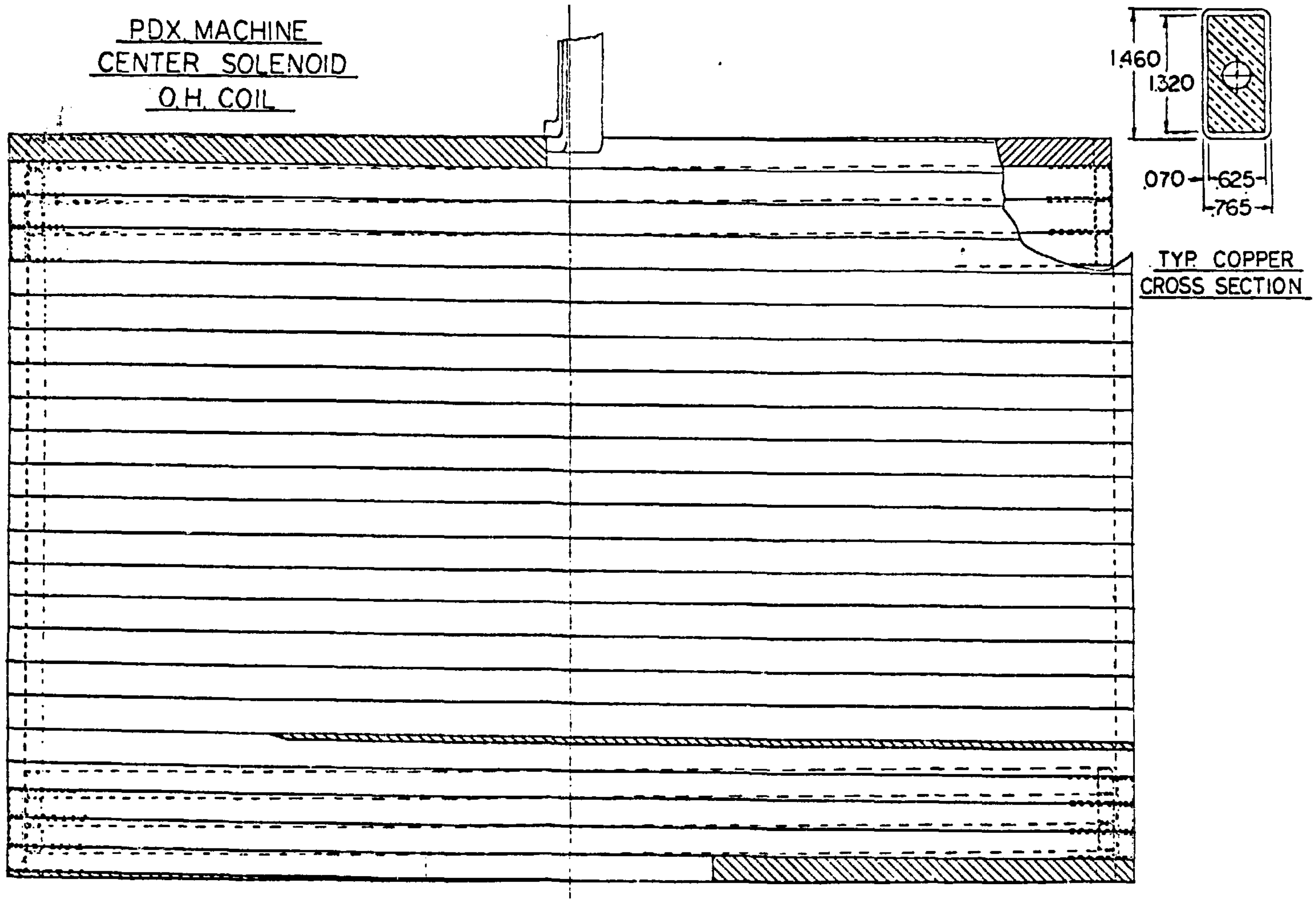

Fig. 1 Helical Winding of the Solenoid Coils

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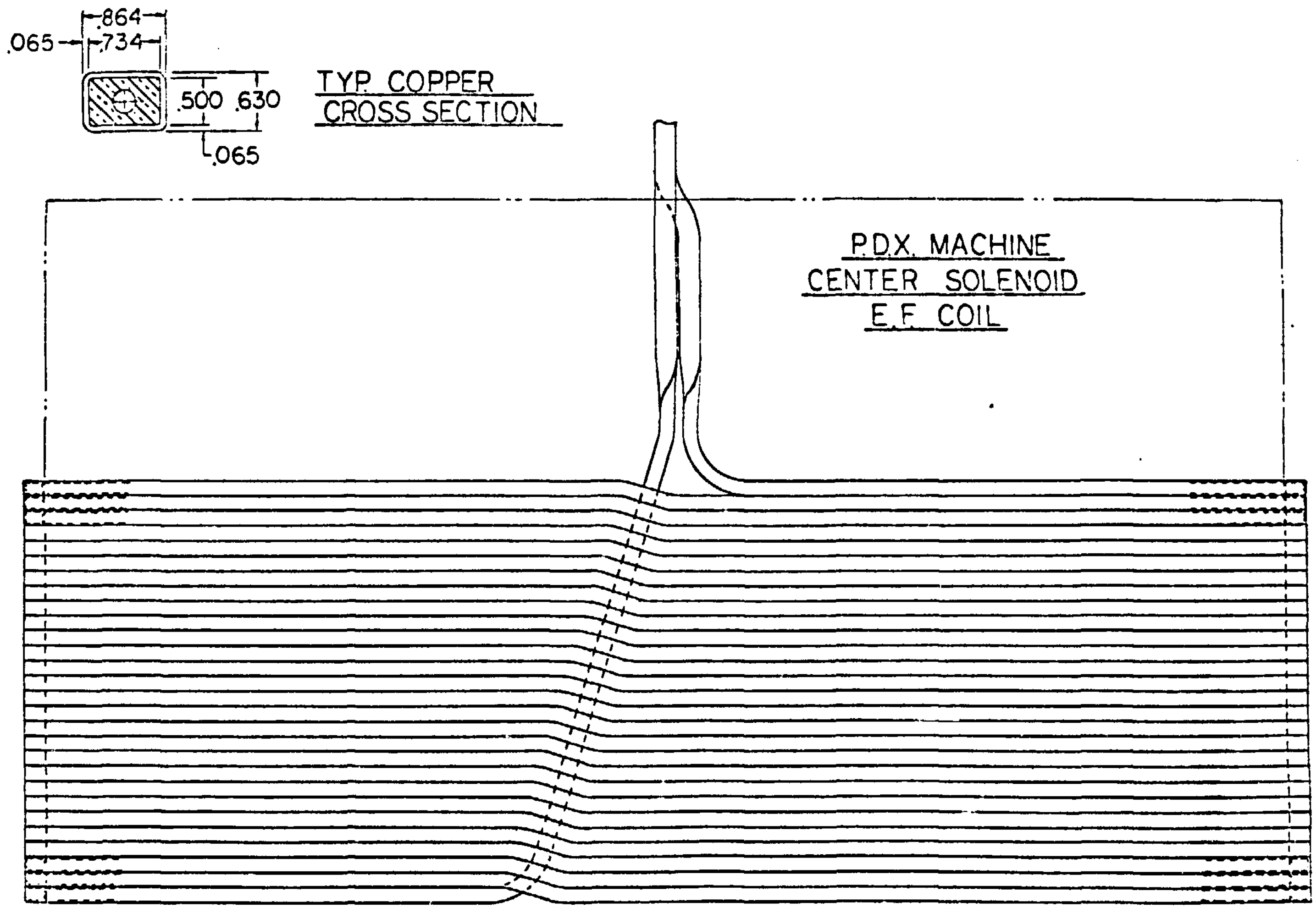

Fig. 2 Typical Coil Windings of the Solenoid
NF, DF, EF and CF Coils

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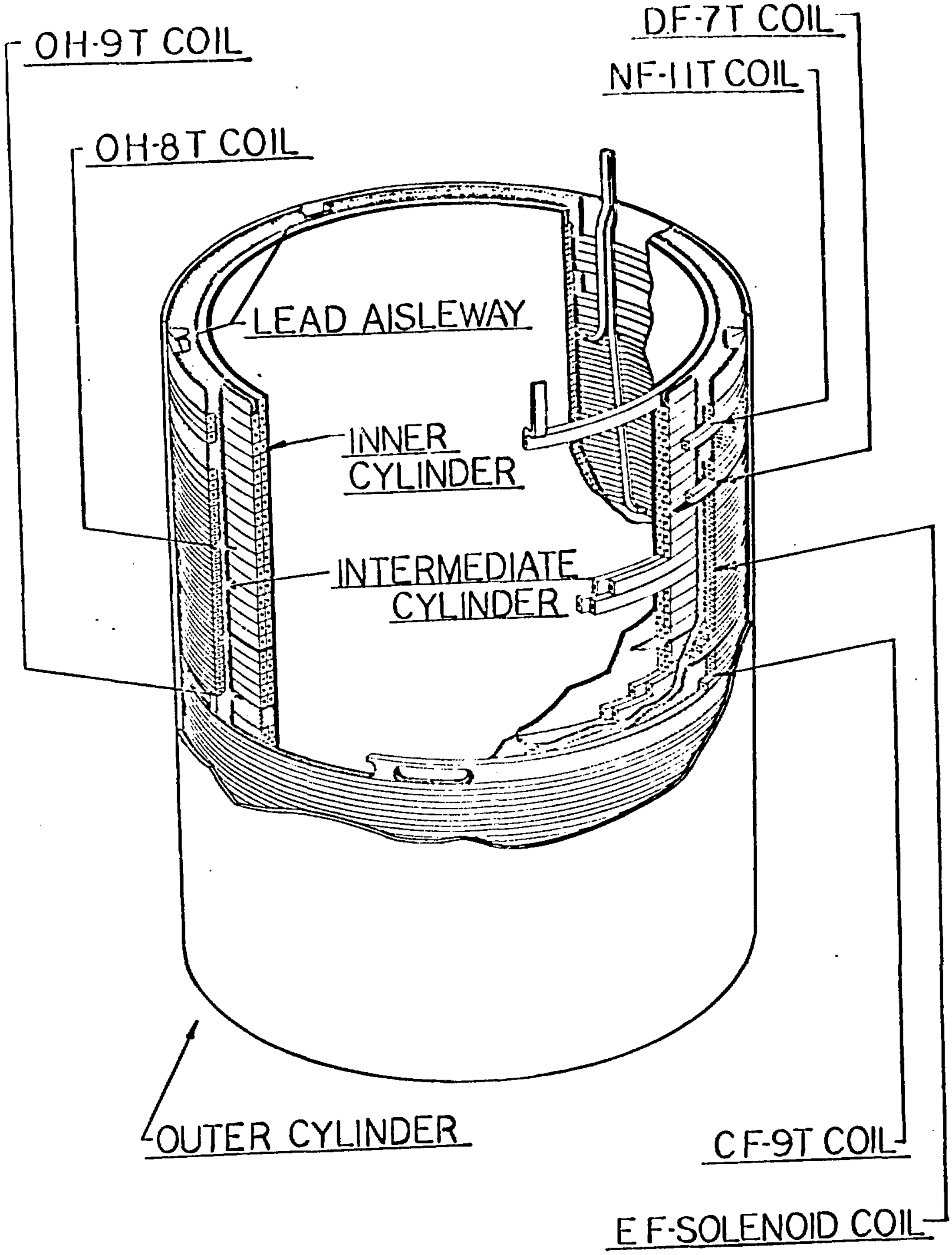

Fig. 3 The PDX Solenoid

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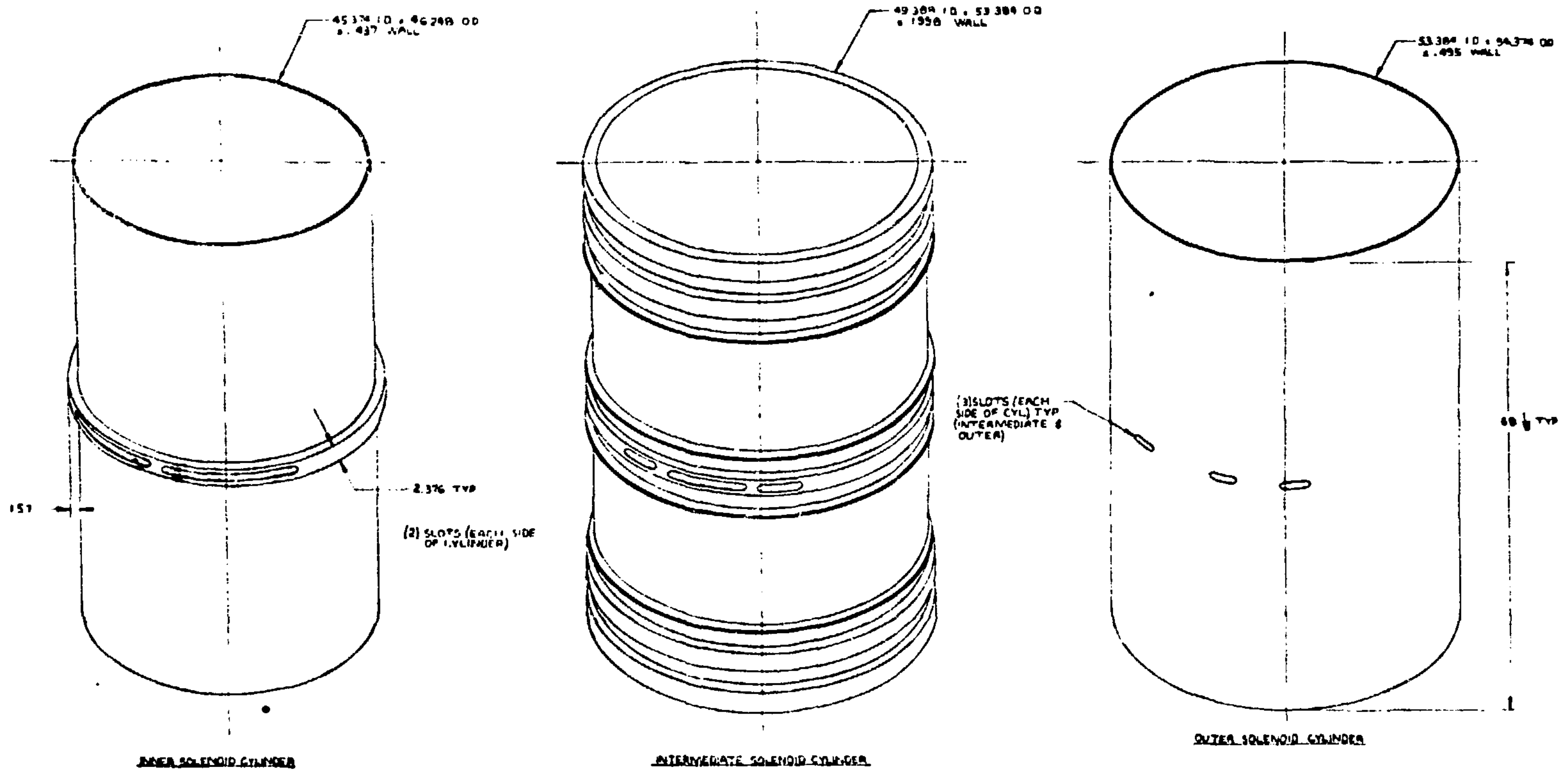

Fig. 4 The Solenoid Epoxy-glass Structural Mandrels

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COIL SYSTEMS	PEAK CURRENT I_p (kA)	$V_{max.}$ (kV)	RESISTANCE (Milliohms)	$J_{max.}$ (amp/ in^2)	ESW (sec)	REP. RATE (sec.)
OH #8 & 9-inner	22.	20.0	3.359	29,730 38,462	1.500	120
OH #8 & 9-outer	22.	20.0	3.467	29,730 38,462	1.500	120
NF #11	21.	10.0	0.585	37,770	0.028	120
DF #7	21.	1.7	0.640	37,702	1.500	120
EF Solenoid	7.	5.0	10.396	22,581	1.500	120
CF #9	21.	10.0	1.738	55,263	1.500	120

COIL SYSTEMS	PEAK COPPER TEMP (°C)	MAX ΔT PER PULSE (°C)	PEAK WATER TEMP (°C)	GPM	Cu SIZES	COPPER AREA ($in.^2$)	LENGTH OF COIL (ft.)	Cu WT. (lb.)	TURNS
OH #8 & 9-inner	49.7	19.8	46.4	2.7	(OH-8) .625x1.320x.313	0.740 - 8 0.572 - 9	280.775	3031 (both OH)	22
OH #8 & 9-outer	49.9	20.4	47.3	2.7	(OH-9) .625x1.050x.313	0.740 - 8 0.572 - 9	275.642		22
NF #11	12.5	0.5	12.4	3.95	.723x.847x.25	0.556	41.249	178	3
DF #7	36.3	27.4	34.8	3.95	.724x.847x.25	0.557	41.249	178	3
EF Solenoid	37.1	9.5	35.5	1.2	.734x.5x.25	0.310	384.992	926	28
CF #9	66.0		63.0	2.95	.873x.5x.25	0.380	68.552	202	5