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Preliminary Design for the Stellarator

Part I. Field Winding
Part II. Vacuum Chamber and
Supporting Frame

AEC RESEARCH AND DEVELOPMENT REPORT

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Technical Memorandum
Number 1

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Prelimina[redacted]esign for Stellarator Field Winding

1. Assumed Specifications

In studying the field winding for a Stellarator the following specifications have been assumed as a basis for the preliminary design.

A. Magnetic flux density, 2000 Gausses.

B. Vacuum chamber, 4 inches inside diameter, glass pipe appears to be the material best suited for the vacuum chamber. This is available in several sizes with standard fittings. The 4 inch size has an overall outside diameter of 5 11/32 inches at the ends; 4 1/2 inches outside diameter for body of pipe.

C. Inside diameter of field coils, 5 1/2 inches. This gives about 1/2 inch clearance between inside of field coils and main body of pipe but only 1/16 inch clearance at ends of pipe where coil must be placed on pipe.

D. Rectangular magnet wire, 1/8 inch thick by 1 inch wide. The field winding should be made in small coils which can be easily assembled on the vacuum tube. These coils should be wound of rectangular wire with a large cross section to reduce the labor of winding the coils. This gives a high current low voltage field winding. The wire should be thin enough to bend easily and wind tightly. The width should be such that coils on the curved portion of the Stellarator will fit well. Thick coils will increase the disturbance in the magnetic field due to the connections between coils.

E. Insulation: 0.010 inches of fiberglas or asbestos. The safe temperature limit of the field is determined primarily by the insulation. Fiberglass will operate safely up to 250° C. This temperature is higher than would be convenient for the personnel but it is very desirable to avoid danger of damaging the insulation by over heating. The thinner the insulation on the copper the lower the radial temperature gradient through the coils, and the higher the space factor of the winding. An 10 mil insulation thickness will be adequate for mechanical strength of insulation.

2. Heat Dissipated from Exposed Coil Surfaces by Radiation and Free Convection.

Using data from articles by W. J. King (Mechanical Engineering, Vol. 34, Page 190, 275, 347, 410, 492 and 560) the watts, which can be dissipated per inch of axial tube length, have been calculated for several values of temperature rise above ambient. The results are given in Table 1.

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Power dissipated from surface of field winding per inch of axial length.

d = winding depth in inches
D = outside diameter of field coils in inches
q_t = watts per linear inch dissipated from surface of field coils.

Surface emissivity 0,65. See Mechanical Engineering, Vol. 54, Page 494, Table 1. This value is suitable for a copper surface but is high for bare aluminum. It may be possible to raise this value a little by a suitable paint.

Temperature rise above ambient degrees C	d=1, D=7½ q_t watts/in.	d=2, D=9½ q_t watts/in.	d=3, D=11½ q_t watts/in.	d=4, D=13½ q_t watts/in.	d=5, D=15½ q_t watts/in.	d=6, D=17½ q_t watts/in.
50	7.3	8.9	10.5	12.1	13.7	15.4
100	17.9	22.0	26.0	30.0	33.8	37.7
150	31.7	39.2	46.3	54.0	61.5	68.0
200	49.5	61.2	72.6	83.8	95.2	105.8
250	71.9	89.0	106.0	121.3	139.5	155.6

3. Aluminum and Copper Field Windings

Data for coils of aluminum and copper is given in Tables II and III

Table II
Data on Aluminum Field Coils
5 1/2 inches inside diameter

Winding depth inches	Steady State surface temperature rise degrees C	Initial heating rate degrees C per minute	Values per foot of tube length		
			Field Power kw/ft.	Wgt. of field winding in lbs/ft.	Cost of Aluminum for field dollars/ft†
1		32.	4.79	20.9	13.65
2		8.	2.76	48.2	31.60
3	340.	3.6	2.10	82.3	53.90
4	280.	2.0	1.75	122.4	80.20
5	238.	1.3	1.54	169.0	110.00
6	212.	.9	1.41	223.	145.50

†Aluminum at 66.5 cts. per pound

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Table III
Data on Copper Field Coils

5 1/2 inches inside diameter

Winding depth inches	Steady State surface temperature rise degrees C	Initial heating rate degrees C per minute	Values per foot of tube length		
			Field Power kw/ft	Wgt. of field winding in lbs/ft.	Cost of copper† for field dollars/ft.
1		15.2	3.06	69.0	31.00
2	340.	3.7	1.77	160.	72.00
3	250.	1.7	1.33	271.	122.00
4	213.	0.9	1.12	405.	182.00
5	180.	0.6	0.98	556.	250.00
6	160.	0.4	0.90	733.	329.00

†Copper at .45 cts. per lb.

From Tables II and III it is evident that the final surface temperature and initial heating rate are about equal for aluminum and copper coils if the winding depth for aluminum is 1.5 times the depth of the corresponding copper coils.

Table IV gives a comparison of aluminum and copper windings having approximately equal heating rates and final surface temperatures.

Table IV

Comparison of Aluminum and Copper Field Windings for Stellarator

5 1/2 inches inside diameter for coils assumed.

Material	d inches	Final surface temperature rise degrees C	Initial heating rate degrees C per minute	Values per foot of tube length		
				Field power kw/ft.	Weight lbs/ft.	Cost of material dollars/ft. †
Aluminum	6	212.	0.9	1.41	223.	145.50
Copper	4	213.	0.9	1.12	405.	182.00
Aluminum	4.5	256.	1.6	1.63	145.	97.00
Copper	3.0	257. °C	1.7	1.33	271.	122.00
Aluminum	3.	340.	3.6	2.10	82.3	53.90
Copper	2.	340.	3.7	1.77	160.0	72.00

† Aluminum 65.5 cts/lb; copper 45 cts/lb.

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4. Reduction of Surface Temperature by forced Convection

Cooling can be improved by forced circulation of the air over the coil surface. To estimate the improvement which might be attained in this way an air velocity of 29.4 feet per second (20 miles per hour) is assumed for computation. The steady state surface temperature as computed with forced convection is given in Table V. The surface temperature without forced convection is also included in Table V for comparison.

Table V.

Comparison of final surface temperature with and without forced convection. Inside coil diameter 5.5 inches, air velocity 29.4 feet per second.

Material	d inches	Final Temperature °C	
		Free Convection	Forced Circulation
Aluminum	4.5	256	242
Copper	3.0	257	239
Aluminum	3	340	315
Copper	2	340	314

The temperature reduction with an air velocity of 29.4 feet per second is trivial. High air velocity will require shrouds to direct the air flow. This method for improving the heat transfer to the air is ineffective.

5. Temperature Gradient Through Coils

Most of the radial temperature difference through the field winding is due to the layer of insulation between turns which has been assumed to be 10 mils on each conductor or 20 mils between turns.

Values of heat conductivity for fiberglas insulation are not available. The conductivity values for other electrical insulating materials, given in Table III, page 278, Volume 54, Mechanical Engineering, suggest a value of 2. b.t.u. per hour, per square foot per degree F per inch, as reasonable.

Using this assumed value of the conductivity for fiberglas insulation a temperature difference between the outer and inner surface of a coil, for steady state temperature conditions, has been computed. Values obtained for coils with 5 1/2 inches inside diameter are given in Table VI.

Table VI

Temperature difference between inner and outer coil surfaces due to insulation between turns, for steady state conditions. Inside coil diameter 5 1/2 inches.

d inches	Aluminum coil temperature difference degrees C	Copper coil temperature difference Degrees C
1	75.	49.2
2	77.	49.2
3	75.	47.6
4	73.	46.2
5	69.4	44.7
6	68.3	44.3

The temperature drop through a coil is approximately independent of the depth of the winding. A corresponding effect is encountered in other electrical machines. The "hot spot" temperature increment for copper is only 2/3 the corresponding value for aluminum as given in Table VI. This is the result of a smaller power loss for copper.

The temperature drop through the metal whether aluminum or copper is very small and has been neglected. The temperature gradient due to insulation between turns is however, considerable and some means for reducing this should be employed if the field is to be designed for continuous operation. A reduction of this gradient through the coils would also be desirable for intermittent operation as this would decrease the off time required for cooling.

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6. Copper Fins for Reducing Surface Temperature and Temperature Gradient Through Coils due to Low Heat Conductivity of Insulation.

Copper fins extending beyond the surface of the coils may be used to reduce the surface temperature by increasing the active surface for heat dissipation. These fins will also reduce the temperature gradient through the coil by providing a radial path of high conductivity.

Fins may be installed conveniently at the center of each coil as shown in Figure 1. (Fins between coils would obstruct the connection between coils.) If the fins extend 1 inch beyond the surface of the coil they will more than double the active area for heat dissipation. Table VII gives steady state surface temperatures with and without copper cooling fins. A fin 1/8 inch thick extending 1 inch beyond the coil surface has been assumed for computation.

Table VII

Steady State Surface Temperatures of Winding With and Without Fins

Inside coil diameter 5 1/2 inches

d inches	Aluminum Coils		Copper Coils	
	Without fins surface temperature °C	1/8 in. Copper fins surface temp. °C	Without fins surface temperature °C	1/8 in. fins surface temperature °C
1				343
2		283	345	217
3	340	216	250	166
4	280	179	213	133
4 1/2	255	161		

The temperature difference radially across the copper fins will not exceed 10 degrees C. when the fin is conducting its share of the heat to be dissipated to the outside air.

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7. Conclusions Concerning Material, Winding Depth and Cooling Fins

It is evident from Table IV that, for equal initial heating rates and final surface temperatures an aluminum field winding is cheaper and lighter per foot than a copper winding but the winding depth for aluminum must be 50 per cent greater. This greater winding depth will increase the radius of curvature and length of the Stellarator, which may over come the per foot advantage in weight and cost for aluminum fields.

A copper field winding will have the following advantages:

1. Shorter stellarator tube.
2. Lower hot spot temperature rise inside the winding.
3. Lower power for field excitation.
4. Fewer turns and smaller outside diameter for same initial heating rate and final surface temperature.

Copper therefore appears to be the best material for the field winding.

A copper winding, having a depth of only 2 inches, appears suitable for continuous operation if a surface temperature around 250 degrees C is permissible and fins are provided to improve cooling (see Table VII). This depth of winding would also have an initial heating rate of about 4 degrees C per minute (see Table III). This would give several minutes of operation without reaching an undesirable temperature if the coil were initially at room temperature.

Cooling fins should be installed even though continuous operation is not required. These will be very effective in reducing the "hot spot" temperature inside the winding and in increasing the rate of cooling.

If continuous operation should be required water cooling should be provided by water tubes installed on the cooling fins. These will not be considered for the present because continuous operation seems unnecessary with the low initial heating rate.

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8. Coils for Straight Section of Stellarator Field

The field winding should be formed of short unit coils which can be assembled readily on the vacuum tube. Both start and finish for a unit coil should be on the outside to facilitate connecting the coils after they are assembled on the vacuum tube. This is possible by winding double coils one half coil wound clockwise the other counter clockwise.

Allowing for four layers of 10 mil insulation on two one inch wide copper wires with a 1/8 inch cooling fin in the center gives a minimum coil-thickness of 2.165 inches for a double or unit coil. If coil forms having an axial length of 2 1/6 inches are used the coil forms would not extend beyond the winding and the coils could be in close contact when stacked on the Stellarator tube. This would give uniform ampere turns per unit length for the straight sections of the stellarator tube. The coil forms probably should be of brass tubing 5 1/2 inches inside diameter and 1/16 inch wall thickness. A magnetic coil form might be desirable to reduce the field ripple due to irregularities in the field winding. This magnetic shield would also tend to reduce disturbances at the ports where there must be a gap in the field winding.

Starting with a coil form the first half coil will be wound as shown in Figure 2. The starting end of the first half-coil which is next to the coil form is displaced axially as shown by the dotted lines in Figure 2 to form the connection to the second half coil. Whent the first half coil is completed the wire must be cut and the free end fastened to prevent unwinding. The cooling fin is then placed in the center of the coil form adjacent to the first half coil as shown in Figure 2. The wire for the second half coil is then brazed to the start of the first half coil and the second half coil is wound in a direction

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opposite to that of the first half coil. The finished coil will then have both ends on the outside and unit coils may be conveniently connected in series after the coils are installed in the vacuum tube.

9. Tapered Coils for Curved Sections of Tube.

A tapered coil, which is thicker on one side, may be formed by spreading one side of the coil as shown in Figure 3. On the thin side the wire is wound with a full over lap. The other side is made thicker by shifting alternate turns right and left which gives less over lap of adjacent turns. A minimum lap of 1/4 inch is necessary to give mechanical strength to the coil. This will result in a unit coil 1 1/2 inches thicker on the thick side as shown in Figure 3.

10. Winding Depth for the Curved Section of Stellarator

A series connection of all unit field coils will permit the simplest power supply for the field. This arrangement will be assumed for the preliminary design.

The winding depth should be increased on the curved section because the tapered coils have a greater effective thickness than those for the straight section. If the field strength in the vacuum tube, for the longest flux path is to be constant at 2000 gauss the winding depth must be increased in proportion to the coil thickness at a distance 2 inches from the axis toward the thick side of the tapered coils. This requires a winding depth of 3 inches on the tapered section of the Stellarator as shown in Figure 4.

The winding depth must vary by steps corresponding to the thickness of one turn and this may make it desirable to use a separate power supply for exciting the curved section. It will still be desirable to increase the winding depth in the curved section in proportion to the effective axial length of the tapered coils to maintain the current density in the copper approximately constant. This constant current density in the copper gives a uniform initial rate of heating for the copper which is desirable if the Stellarator is to be operated on an intermittent basis.

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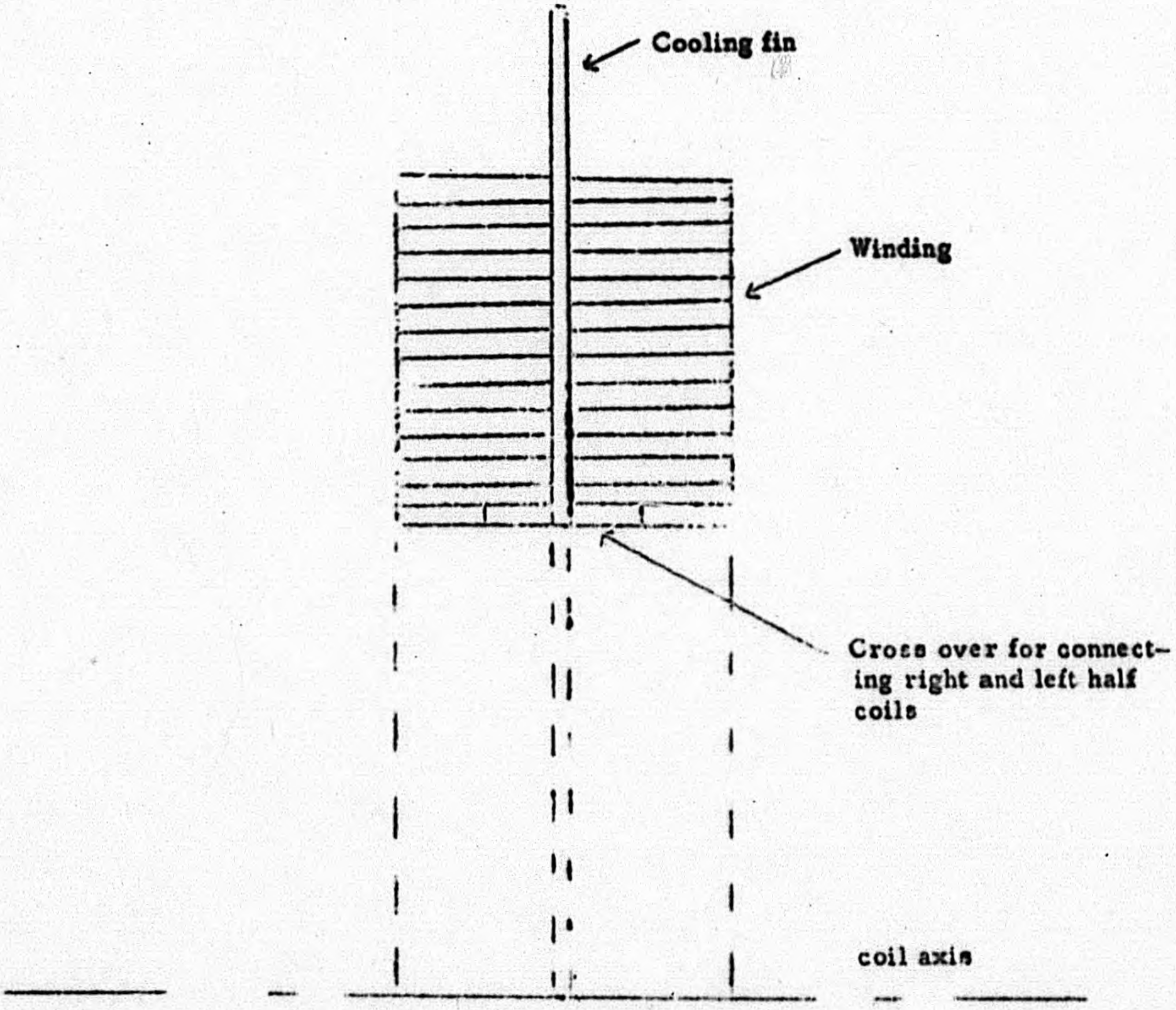

Figure 1. Unit coil with cooling fin in center. Sectional view. Upper half coil. Full scale.

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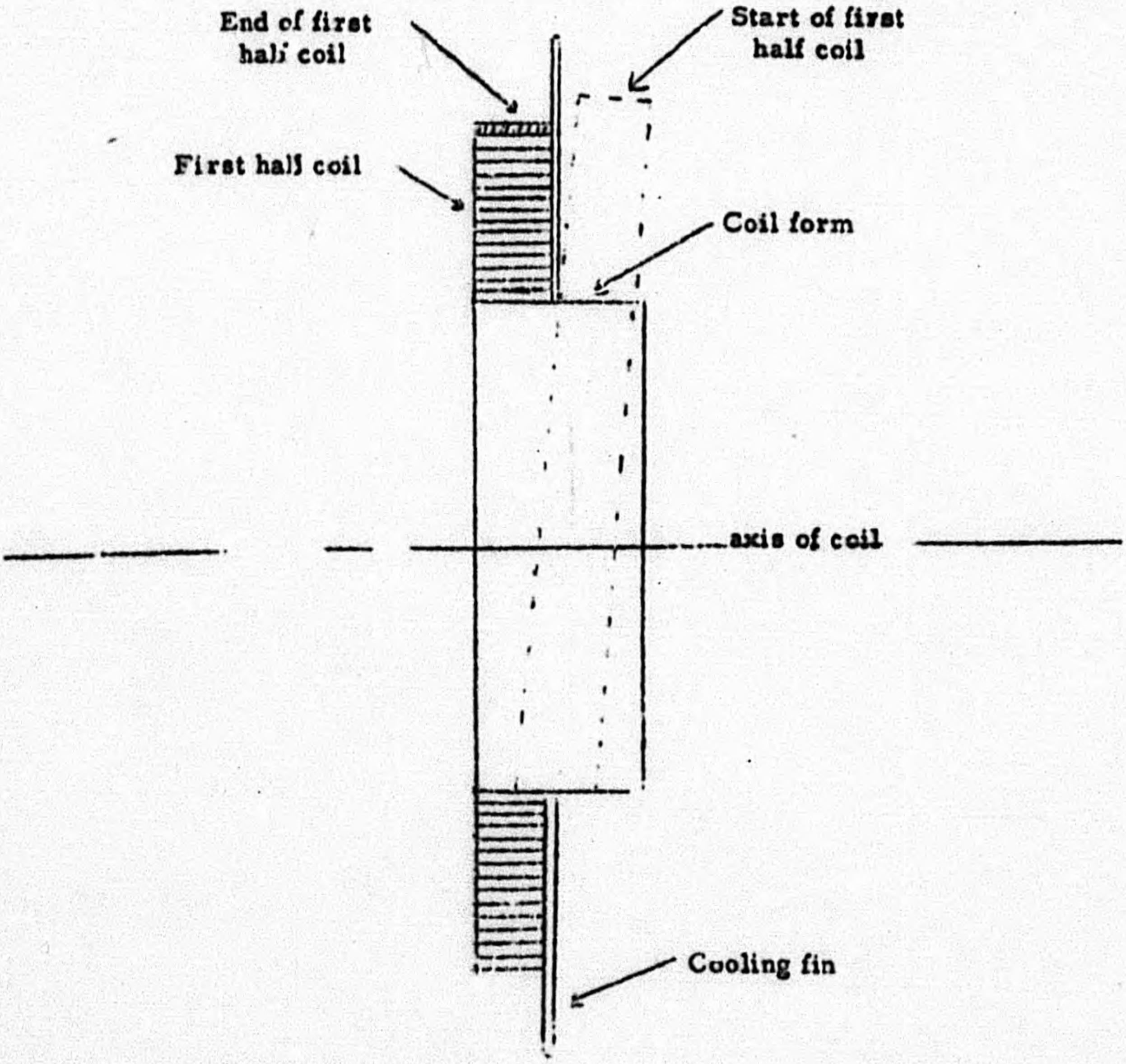

Figure 2. Unit coil for straight section. First half coil completed and cooling fin installed at center of unit coil.

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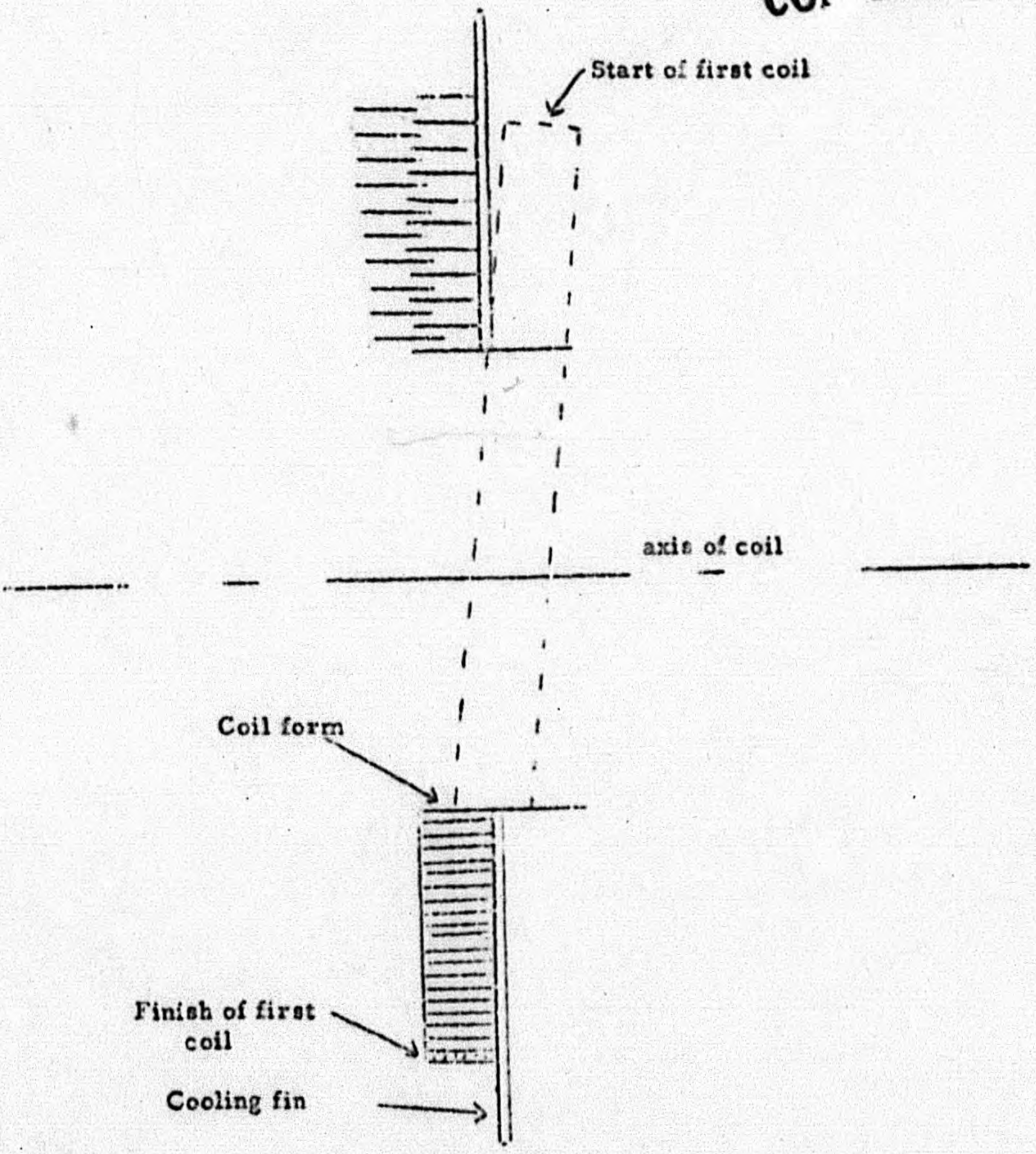

Figure 3. Unit coil for curved section. First half coil completed and cooling fin installed at center of unit coil.

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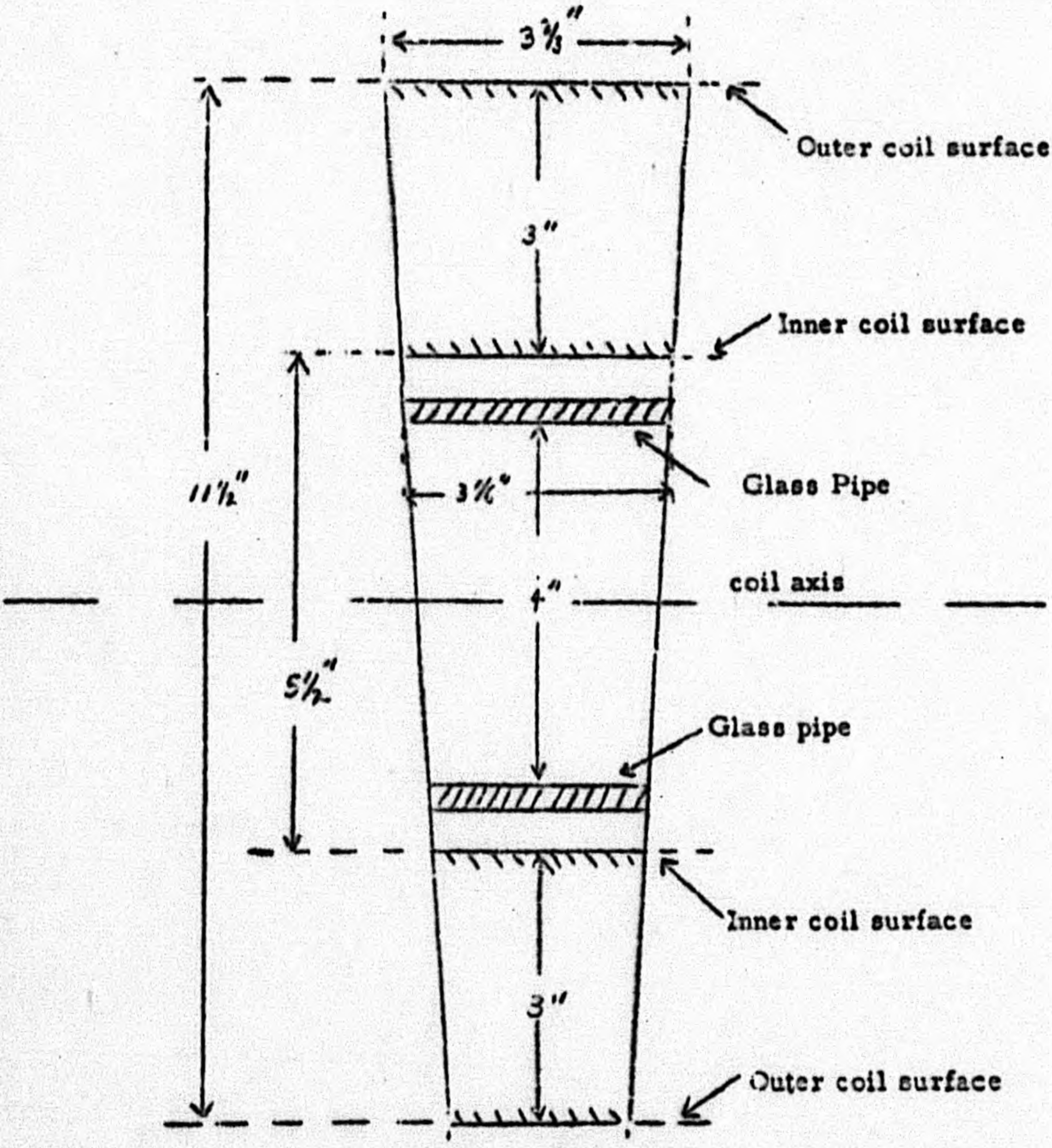

Figure 4. Dimensions of Tapered Coils.

11. Vacuum Chamber and Supporting Frame

Radius of curvature, for Stellarator tube.

A preliminary design of the field winding for a 2000 gauss Stellarator led to the tentative conclusion that the winding depth, with copper field coils, should be 2 inches on the straight section of the Stellarator tube or 3 inches for coils on the curved section.

Irregularities in the magnetic field will be minimized when the m.m.f. of the field coils approaches a uniform current sheath as closely as possible. On the curved section this condition requires that the tapered coils should fill the winding space on both the inside and outside of the tube. The radius of curvature of the Stellarator tube is therefore determined by the taper of the field coils to be used in the curved section.

Table 8 gives the radius of curvature for Stellarator tubes of pyrex glass pipe having standard diameters of 2 inches or more. The radius of curvature is based on a tapered coil formed of wire 1 inch wide as shown in Figure 4, Section 9 of the Preliminary Design for the Stellarator Field Winding.

Table 8

Radius of Curvature for Stellarator
tubes of standard diameters.

Diameter of Stellarator tube inches	Winding depth inches	Diameter of coil inches		Radius of Curvature of vacuum chamber inches
		Inside	Outside	
2	3	3.0	9.	17.
3	3	4.0	10.	19.
4	3	5.5	11.5	22.5
6	3	8.0	14.	27.5

12. Component parts for Stellarator Tube

The Stellarator tube should have a minimum number of joints for convenience of assembly and to reduce discontinuities in the field winding. The pumping ports should be approximately equidistant around the tube. Four pumping stations will probably be needed. A standard tee fitting of pyrex glass may be used for a pumping port. If a station for pumping and experimentation are to be combined a "cross" fitting may be employed.

Two tube designs will be considered, one having 10 joints and no straight section of tube except that included in the fittings and swing bends. This design, which is shown in Figure 5, has a minimum length and requires pipe bends totaling 300 degrees of curved section for each end of the Stellarator. This will be referred to as the 300 degree design.

The second design will require only 240 degrees of curved section for each end but will have a section of straight tube on either side between the curved end sections. This design which will be described as the 240 degree design, is shown in Figure 6.

The parts required for a Stellarator vacuum tube are given in Table 9. It should be noted that both the 300 degree and the 240 degree design have a number of parts in common.

Table 9.

Parts for Stellarator Vacuum Tube

Item	Description	Number of Parts	
		300 degree design	240degree design
a	180 degree bends, 10 inch straight section at ends	2	2
b	60 degree bends, 10 inch straight section at ends	4	
c	30 degree bends, 10 inch straight section at ends		4
d	Straight sections		2

(Continued on next page)

Table 9. (Continued)
Parts for Stellarator Vacuum Tube

Item	Description	Number of Parts 300 degree design	 240 degree design
e	Tees or crosses	4	4
f	Teflon gaskets	10	12
g	Metal flanges and asbestos inserts	20	24

13. Comparison of 240 and 300 degree designs.

A summary of data for the 240 and 300 degree designs having a vacuum tube of 4 inch pyrex pipe is given in Table 10. The radius of curvature for the curved section is 22.5 inches.

Table 10.
Data for 240 and 300 degree Stellarator with 4 inch vacuum tube and a 22.5 inch radius of curvature

Item	Description	300 degree design	240 degree design	
a	Length of curved portion of tube	20	16	ft.
b	Length of straight parts of tube	15	24	ft.
c	Total length	35	40	ft.
d	Total weight of copper	7820	8180	lbs.
e	Total dc power for exciting field	86.5	90.4	kw.
f	Total voltage with series coils	302.	310.	volts
g	Resistance of field with series coils	1.06	1.11	ohms.
h	Number of unit coils for curved section	110	88.	
i	Number of unit coils for straight section	48	104.	
j	Total winding induction with series coils	0.107	.118	
k	Time const. of field with series coils	0.1	0.1	sec.
l	Distance between pumping ports around ends	106.	102.	inches
m	Distance between pumping ports along center section	106	136	inches

The 240 degree design requires very little more material but includes two 58 inch straight sections of pipe. This may be desirable for experimental purposes. The 240 degree design is therefore preferred. If a longer straight section is required this may be accommodated by replacing the 4 – 30 degree bends by sections having a shorter arc.

14. Support for Stellarator vacuum chamber.

The Stellarator vacuum tube must be supported inside the field coils in a position concentric with these coils. This may be accomplished by using spacers, of a suitable thickness, to separate the pyrex tube from the coil forms. This arrangement is shown in Figure 7. The spacers which should be curved to fit the wall of the pyrex pipe, should be 1/2 inch thick for the 4 inch tube. These spacers may be made of any non-magnetic material which will resist an operating temperature of 250 degrees C. The spacers would be placed beneath the vacuum tube at intervals of about one foot. Where the tube slopes the spacers should be fastened to the coil forms to keep them in place. If the space between the coil forms and the pyrex pipe is used for a winding to produce an accelerating electric field, this winding may also serve as the spacer between the pyrex pipe and the coil forms.

15. Support for field coils.

The field coils, which support the vacuum chamber, must themselves, be supported to conform with the shape of the Stellarator tube. The field coil supports must be adjustable in three dimensions to permit the coils to be accurately centered on the axis of the vacuum tube and mounted close together. It is also necessary, in supporting the field coils, that they be electrically isolated to avoid concentrating the electrical stress on two layers of insulation. Insulating supports of micalex will give the necessary insulation and permit a high operating temperature.

A possible structure for supporting the field coils, which provides the necessary insulation and freedom of adjustment, is shown in Figure 8. This figure shows the micalex blocks for supporting and insulating the coils. These blocks may be in contact with the cooling fins of the coils as shown. Figure 9 gives a detail of a clamping arrangement for holding the micalex blocks.

The frame shown in Figure 8, for supporting and adjusting the coils, may be made of angle iron. It will probably be desirable to build this frame in four sections. One section at each end will support the 180 degree bends and another section to support each of the horizontal portions of the Stellarator. Figure 10 shows a detail of adjusting screws for leveling and aligning the sections of the supporting frame so the vacuum chamber could be aligned for sealing by clamps.

Pumping ports would come at the junctions between the supporting frames. The several sections of the supporting frames may be constructed at any convenient location in the laboratory and after the vacuum tube is installed and the field coils assembled, the sections may be moved on lift trucks to the place where the four sections are to be joined to form a Stellarator.

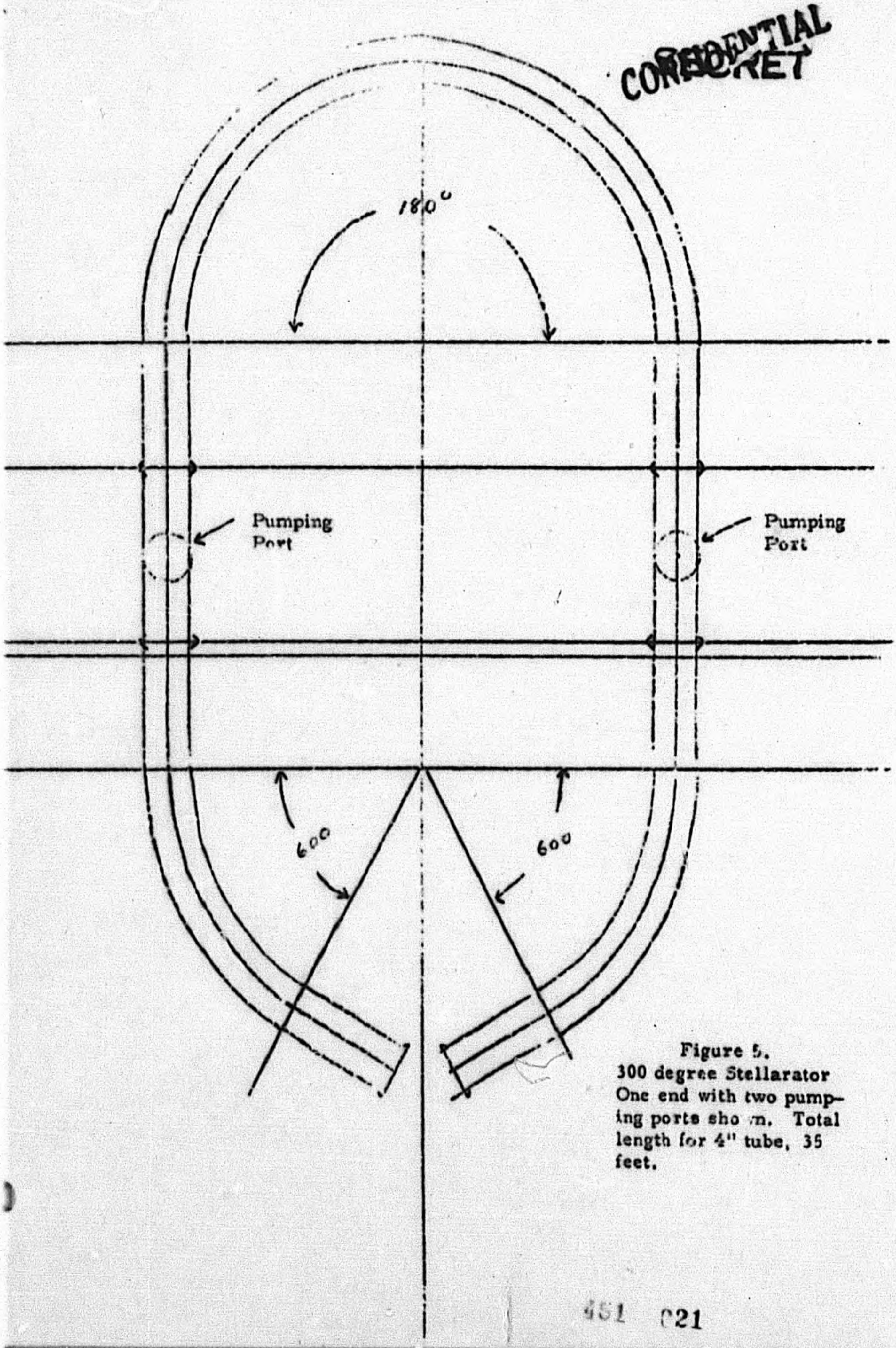

Figure 5.
300 degree Stellarator
One end with two pumping ports shown. Total length for 4" tube, 35 feet.

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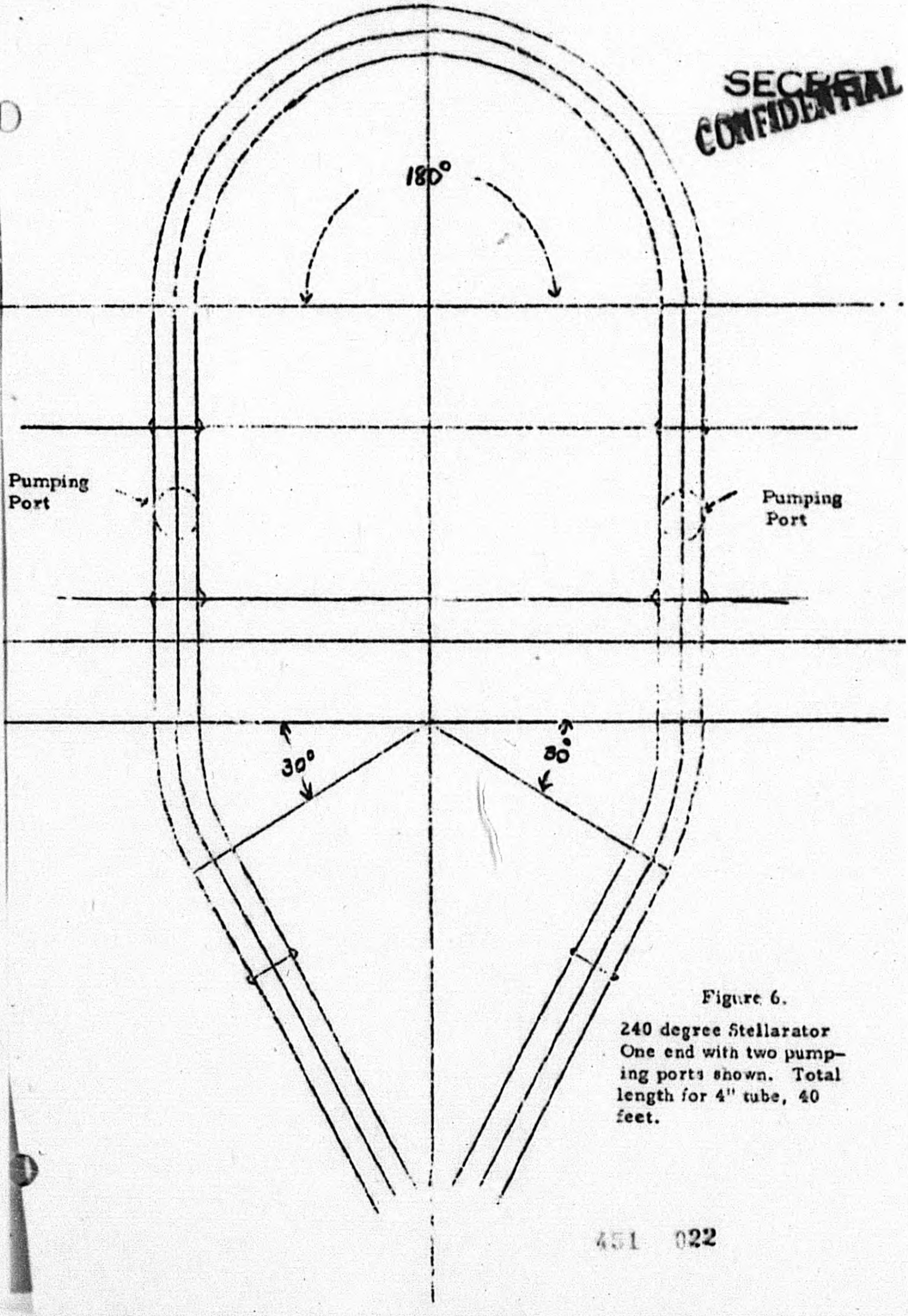

Figure 6.

240 degree Stellarator One end with two pumping ports shown. Total length for 4" tube, 40 feet.

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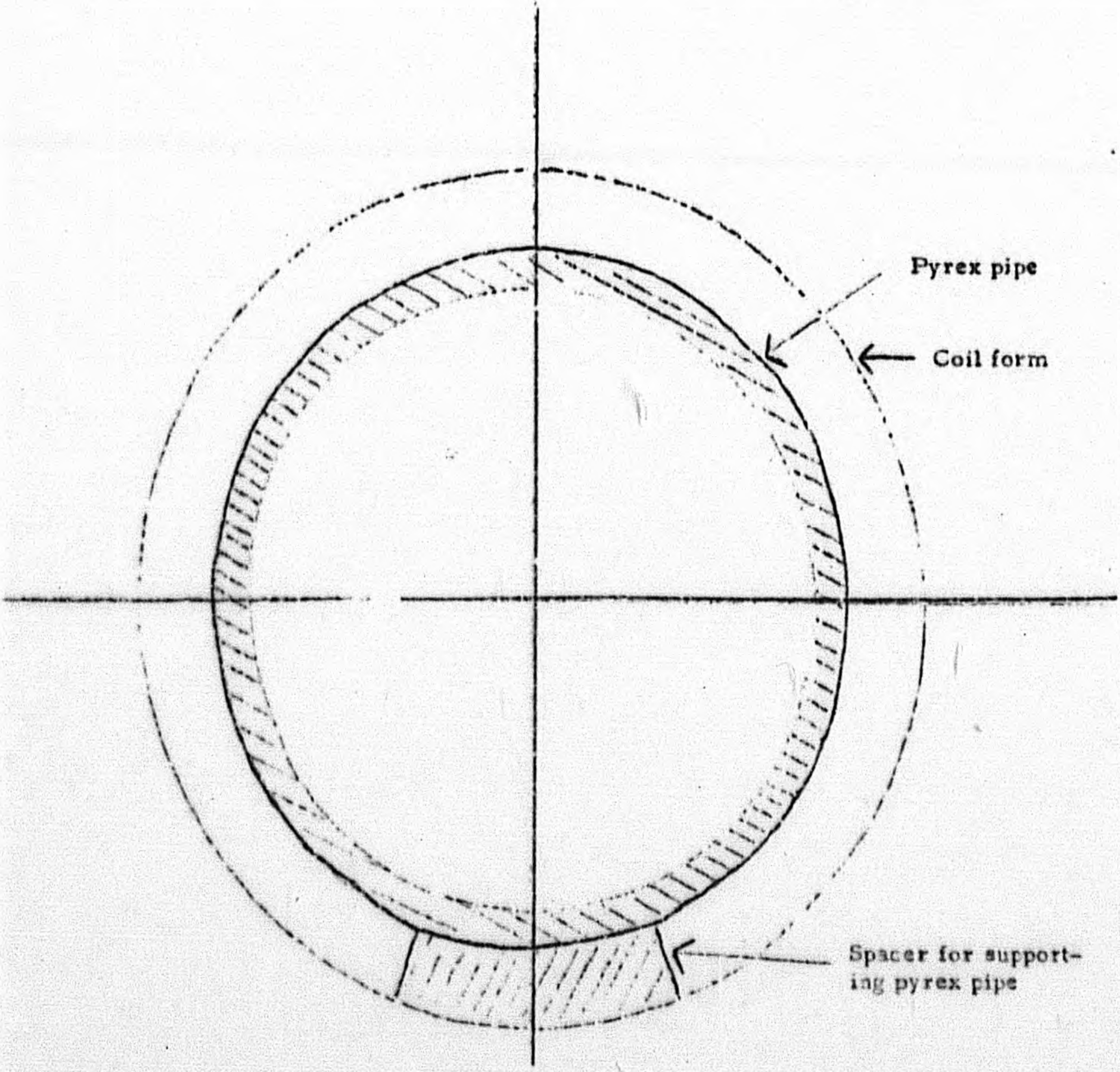

Figure 7.

Spacer for supporting vacuum tube inside coil form.

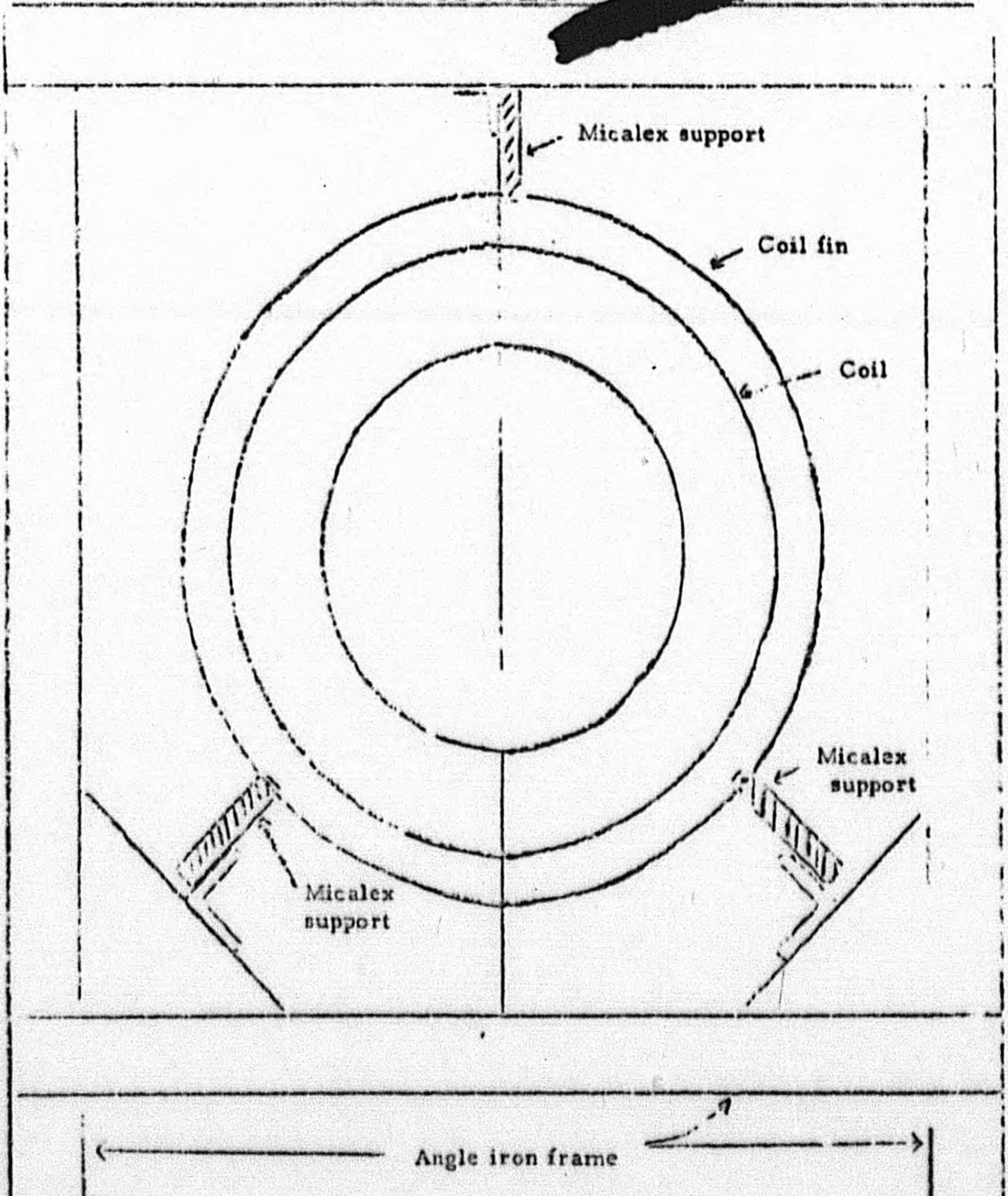

Figure 8.

Frame for insulated support
of field coils.

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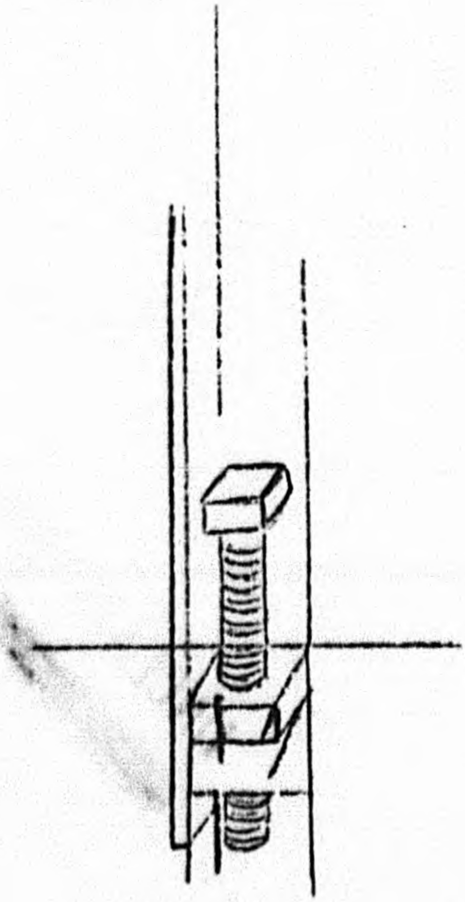

Figure 10. Leveling screw for angle iron frame

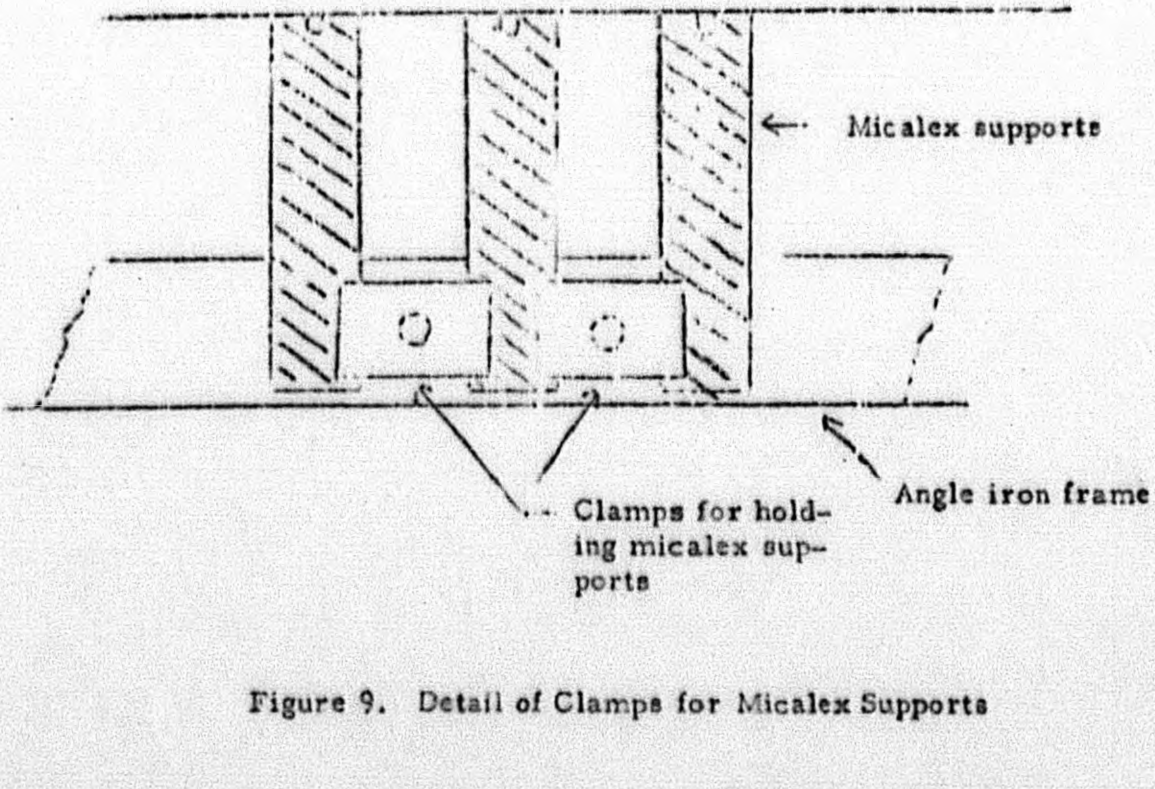

Figure 9. Detail of Clamps for Micalex Supports