LOW VOLTAGE DC TO DC CONVERTER-REGULATOR WITH MINIMUM EXTERNAL MAGNETIC FIELD DISTURBANCE

REPORT NO. 3

Contract Number NAS 5-3899
National Aeronautics and Space Administration
Third Quarterly Progress Report

1 December 1964 to 28 February 1965

Goddard Space Flight Center
Greenbelt, Maryland

Submitted by
Honeywell Inc.
Ordnance Division
Hopkins, Minnesota

Honeywell
ORDNANCE
A DIVISION OF THE
MILITARY PRODUCTS GROUP

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THE OBJECT of this contract is to design and develop a low voltage dc to high voltage dc converter-regulator with minimum external magnetic field disturbance. This device will efficiently convert the inherently low voltages of newly developed energy sources to useful higher regulated voltages and provide more reliable power systems for space applications which also have a requirement for minimum external magnetic field disturbance.

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1

PURPOSE

THE PURPOSE of this contract is to design and to develop an efficient, reliable, and lightweight, transistor low voltage dc to high voltage dc converter with minimum external magnetic field disturbance for space applications. The converter will be designed to convert the output of fuel cells, thermionic diodes, thermoelectric generators, solar cells, and high performance single cell electrochemical batteries to a regulated 28 volt dc output.

The program includes circuit optimization and new design efforts to reduce external magnetic field disturbance, size, and weight. Effort will be directed toward construction of a model and magnetic field measurements to verify that the design has been optimized to meet the performance requirements and design goals.

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SUMMARY

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DURING THE third quarter, the dual section bucking choke coil was fabricated and assembled into the low input voltage converter-regulator. A preliminary mapping of the magnetic field disturbance at a radius of 2.5 inches from the device axis indicated that the external magnetic field disturbance around the coaxial converter section was satisfactory. However, the magnetic field disturbance around the choke coil was much higher. Performance tests also showed that the choke coil had excessive eddy current losses. Author

The higher magnetic field disturbance around the choke coil is probably caused by construction defects and differences in the magnetic dipole due to each choke coil section. Distributed air gaps, the fringing of flux at external seams, and the use of unannealed mu-metal probably contributes to the high magnetic disturbance. The excessive eddy current losses were caused by ineffective lamination of the choke coil core. This ineffective lamination resulted from the use of mu-metal which did not have an insulated coating on its surface and lamination of the end bells and center section in an improper direction.

Because of these difficulties in the choke coil, it is necessary to correct the choke coil deficiencies before more exacting magnetic field measurements are made at the magnetic observatory. A new choke coil will be fabricated during the next quarter and the complete device will be tested at the magnetic observatory. The fact that the present tests were conducted in the earth's ambient magnetic field diminished the accuracy of the preliminary measurements and prevented measurements at the specified 18 inch distance. However, these preliminary measurements were useful in establishing that the coaxial low input voltage converter section of this device produces very little magnetic disturbance and appears satisfactory. These tests also pin pointed the magnetic disturbance of the choke coil and established that it must be improved to meet the magnetic requirements.

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CONFERENCES

NO FORMAL conferences were held during this period although several phone conversations were held between Mr. J. T. Lingle, Honeywell project engineer, and Mr. E. Pascuitti, NASA-Goddard Space Flight Center technical representative. It is anticipated that the next conference will be held in conjunction with the trip to the magnetic observatory where the device's external magnetic disturbance will be measured.

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PROJECT DETAILS

A. PRELIMINARY MAGNETIC FIELD DISTURBANCE MEASUREMENTS

PRELIMINARY MAGNETIC field measurements have been made on the coaxial low input voltage Converter-Regulator, shown on Figure 1, to determine if major deficiencies exist which must be corrected in the design before more exacting tests are conducted at the magnetic observatory. These preliminary tests were conducted by rotating the magnetic probe around various stations of the low input voltage converter-regulator and measuring the difference between magnetic fields when the converter is powering a 51 watt load and when it is de-energized. By placing the probe 2-1/2 inches from the converter instead of 18 inches away, sufficient signal can be picked up in the earth's ambient field to provide useful data. This data represents magnetic disturbance caused by the operation of the low input voltage converter-regulator and does not represent disturbance due to any residual magnetic moments. Since the sensitivity of the recording instrument was 0.05 milligauss and the measurements were taken in a 500 milligauss ambient, the accuracy of the measurements was less than desired. However, the difference in magnetic disturbance could be measured and plotted to provide significant data. These measurements showed that the external magnetic disturbance around the coaxial converter section was relatively low, but that the magnetic disturbance around the regulator section was considerably higher. The high disturbance in the regulator section was traced to the choke coil.

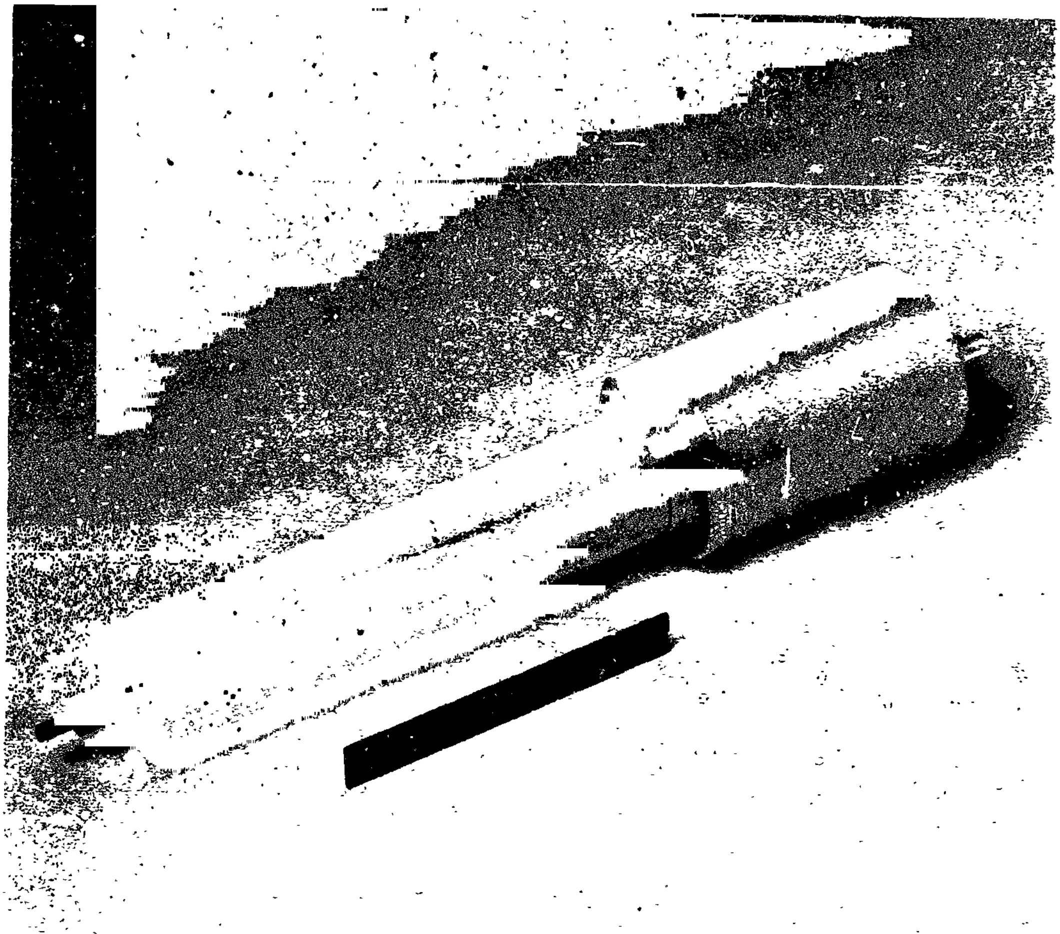
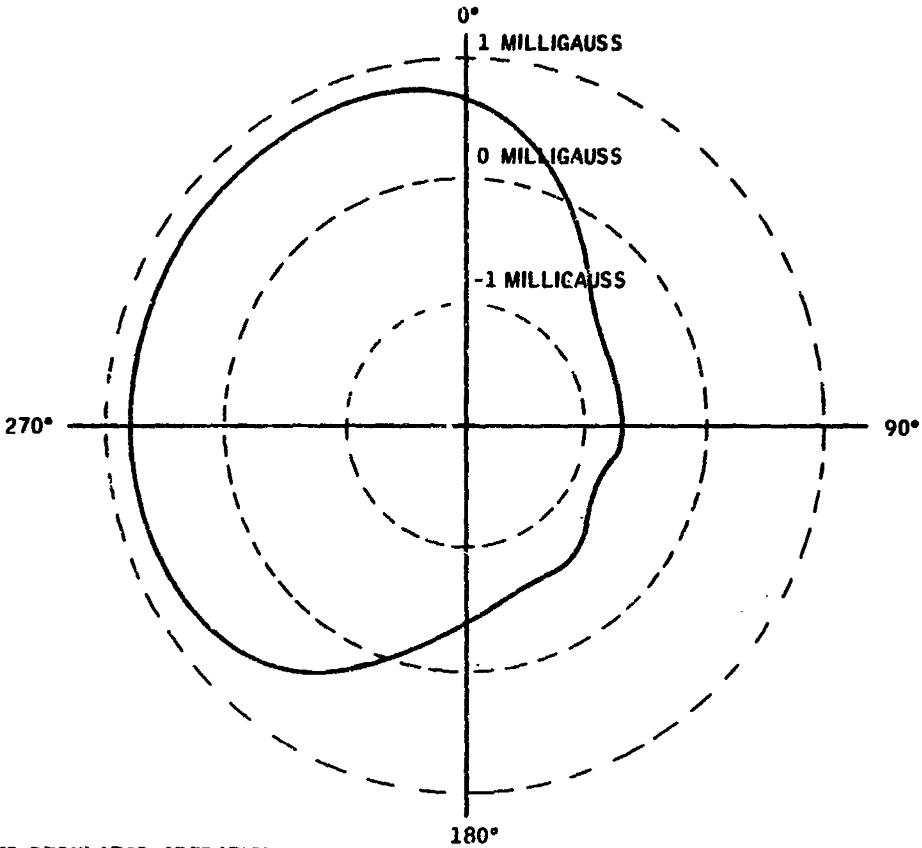


Figure 1 - COAXIAL LOW INPUT VOLTAGE CONVERTER-REGULATOR MODEL

Figures 2, 3, and 4 show the plot of magnetic disturbance around the low input voltage converter-regulator section at the coaxial input, the center, and the end joining the regulator respectively. Note (Figure 2) that the maximum magnetic disturbance varied between +0. 8 and -0. 8 milligauss as the probe was rotated about the device. The magnetic field plot for the center of the converter section on Figure 3 shows that the magnetic disturbance varied between +0. 6 and -0. 6 milligauss. Figure 4 shows that the magnetic field disturbance of the converter end where it joins the regulator section varies between -0. 5 and +0. 4 milligauss.

Examination of the eccentricity of the flux plot about the zero circle in Figures 2, 3, and 4 shows that they are all eccentric in the same direction. Because of this it is highly probable that the magnetic disturbance measured is caused by eccentricity in coaxial conductors which carry the high primary current. This is discussed under B below and in Appendix A.

The magnetic field map at the regulator end of the device shown on Figure 5 has a higher level of disturbance between -0. 9 and +2. 4 milligauss. It was also noted that a higher level of disturbance occurred around the center of the regulator section in a direction parallel to the device axis. The magnetic disturbance around the center of the regulator in this direction, shown in Figure 6, varies between 4 and 7. 5 milligauss. It was discovered that the choke coil was the primary cause of magnetic disturbance in the regulator section. Separate magnetic field disturbance measurcments were made on the choke coil.



CONVERTER-REGULATOR OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

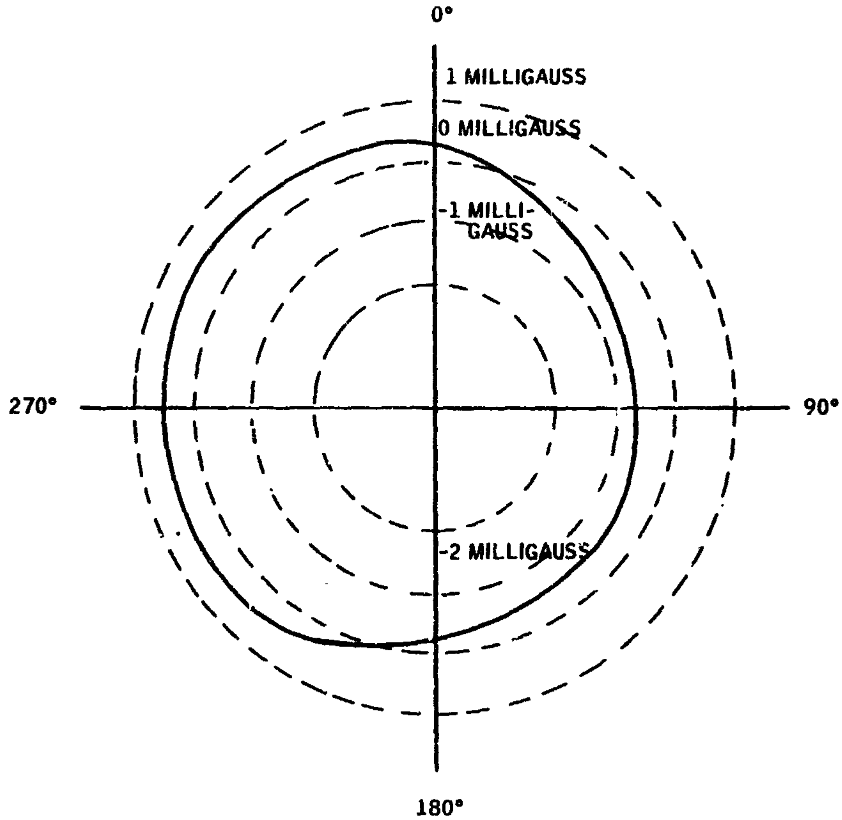
V_{OUT} = 28 VOLTS

MAGNETIC PROBE ORIENTATION

RADIAL: TANGENT TO CONVERTER SURFACE 2.5 INCHES FROM THE CONVERTER AXIS.

LONGITUDINAL: AT INPUT TO CONVERTER SECTION.

Figure 2 - MAGNETIC DISTURBANCE AROUND THE CONVERTER INPUT END



CONVERTER-REGULATOR OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

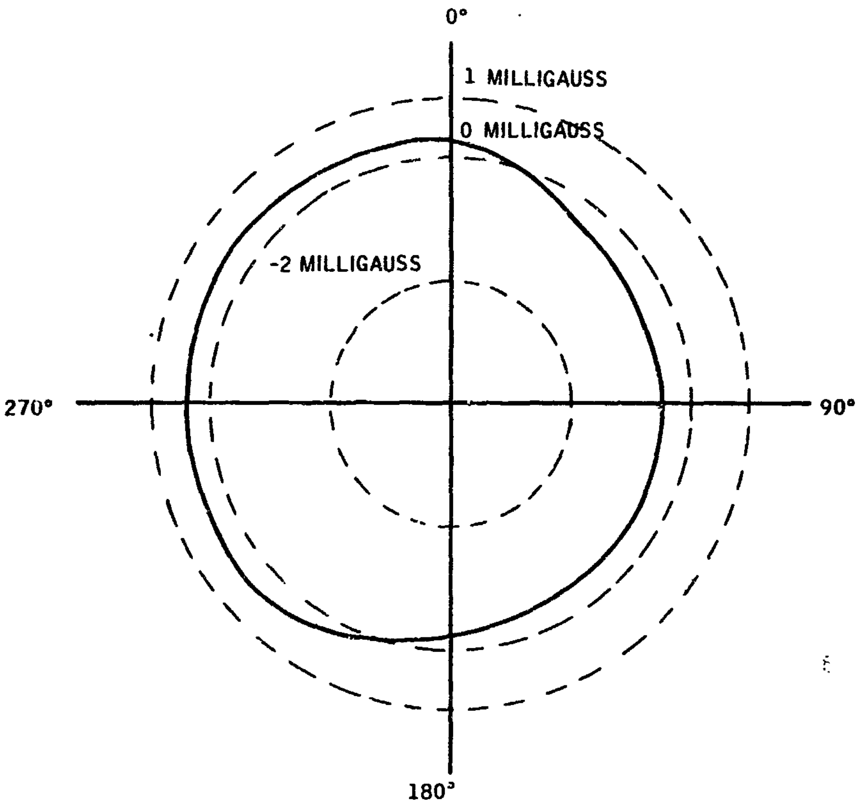
V_{OUT} = 28 VOLTS

MAGNETIC PROBE ORIENTATION

RADIAL: TANGENT TO CONVERTER SURFACE 2.5 INCHES FROM THE CONVERTER AXIS.

LONGITUDINAL: AT CENTER OF CONVERTER SECTION.

Figure 3 - MAGNETIC DISTURBANCE AROUND THE CENTER OF THE CONVERTER SECTION



CONVERTER-REGULATOR OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

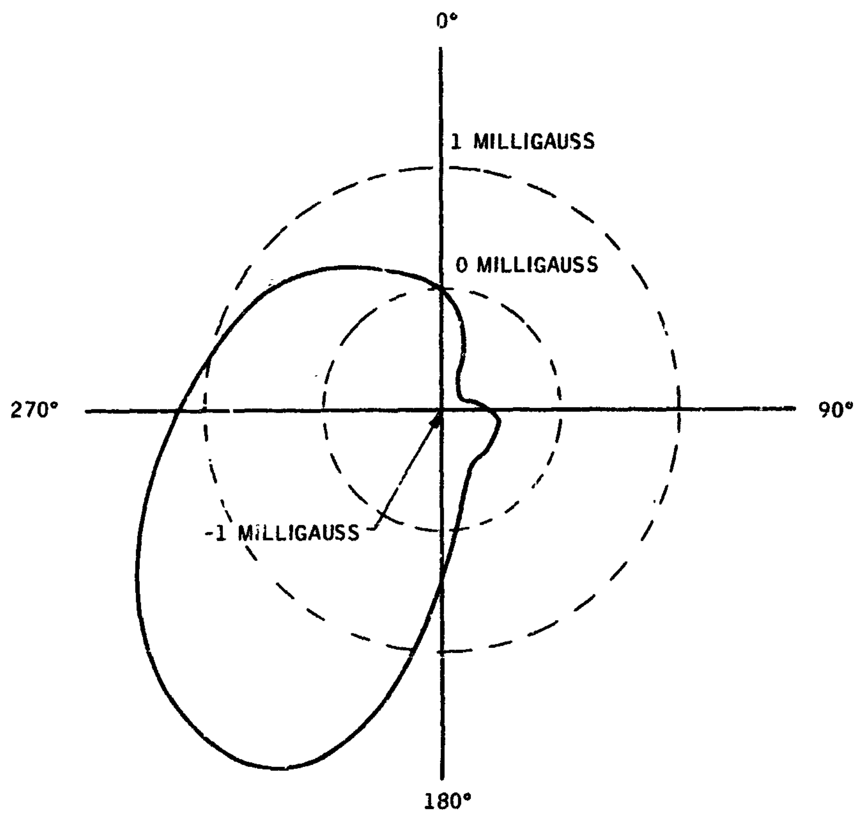
V_{OUT} = 28 VOLTS

MAGNETIC PROBE ORIENTATION

RADIAL: TANGENT TO CONVERTER SURFACE 2.5 INCHES FROM THE CONVERTER AXIS.

LONGITUDINAL: AT JUNCTION BETWEEN CONVERTER SECTION AND REGULATOR SECTION

Figure 4 - MAGNETIC DISTURBANCE AROUND THE JUNCTION OF THE CONVERTER AND REGULATOR SECTIONS



CONVERTER-REGULATOR OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

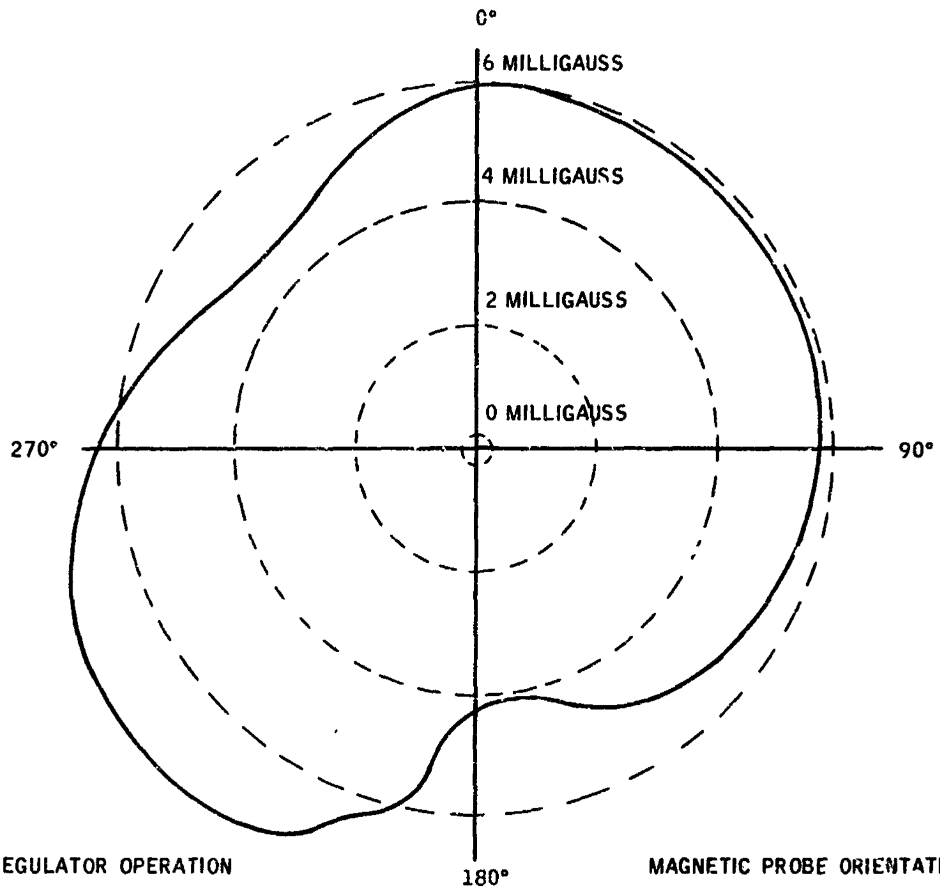
V_{OUT} = 28 VOLTS

MAGNETIC PROBE ORIENTATION

RADIAL: TANGENT TO REGULATOR SURFACE 2.5 INCHES FROM THE REGULATOR AXIS.

LONGITUDINAL: AT OUTPUT END OF REGULATOR.

Figure 5 - MAGNETIC DISTURBANCE AROUND THE CONVERTER-REGULATOR OUTPUT END



CONVERTER-REGULATOR OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

V_{OUT} = 28 VOLTS

MAGNETIC PROBE ORIENTATION

RADIAL: TANGENT TO REGULATOR SURFACE 2.5 INCHES FROM THE REGULATOR AXIS.

LONGITUDINAL: AT CENTER OF REGULATOR SECTION.

Figure 6 - MAGNETIC DISTURBANCE AROUND THE CENTER OF THE REGULATOR SECTION

Figure 7 shows the magnetic field around the choke coil parallel to the choke coil axis. Note that the field was relatively uniform at about 8.5 milligauss. The flux in this direction is caused by incomplete magnetomotive force cancellation in the two bucking sections which results in a magnetic dipole. This effect can be caused by individual differences in the fabrication and in the distributed air-gaps. A plot of flux at three stations around the choke coil perpendicular to its axis (Figures 8, 9, and 10) shows that the field is relatively uniform and is lower at the ends. The disturbance around the end where the wires exit, the center, and the other end is 1.8 to 3.4, 3.3 to 4.9, and -0.2 to +0.6 milligauss respectively. Additional flux plots around other axis of the choke shown in Figures 11 and 12 indicate that the greatest disturbance is at the ends of the choke as would be expected. Also the disturbance at the ends is relatively high (20 milligauss). Some of the flux that leaks from the enclosed coils may pass through the stainless steel screw used to hold the choke coil together. Other flux no doubt escapes along the seams. When a 6 mil end cover was placed over each end, the disturbance was reduced as indicated in Figure 12.

It can be concluded from the preliminary magnetic field measurements that the construction of the preliminary choke coil is not satisfactory. The following action should be taken to improve this:

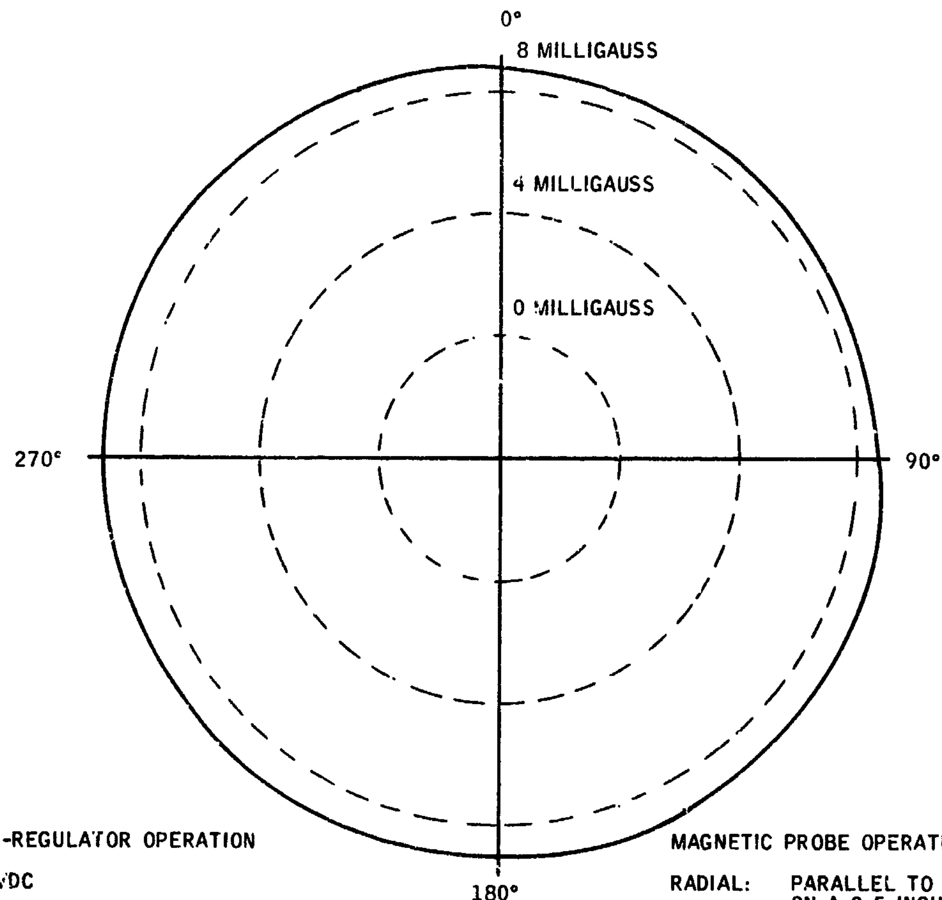
1. Use tighter fits between mating parts to eliminate distributed air-gaps that cause the flux to fringe outside the mu-metal path.

2. Make the parts to closer tolerances to minimize distributed air gaps and individual differences between the dual bucking sections.

3. Use overlapping joints at the seams to minimize flux leakage.

4. Place the completed choke in a shield can with a small non-magnetic spacer between the choke and the can to maintain a uniform spacing.

5. Anneal the mu-metal parts to provide maximum permeability.



CONVERTER-REGULATOR OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

V_{OUT} = 28 VOLTS

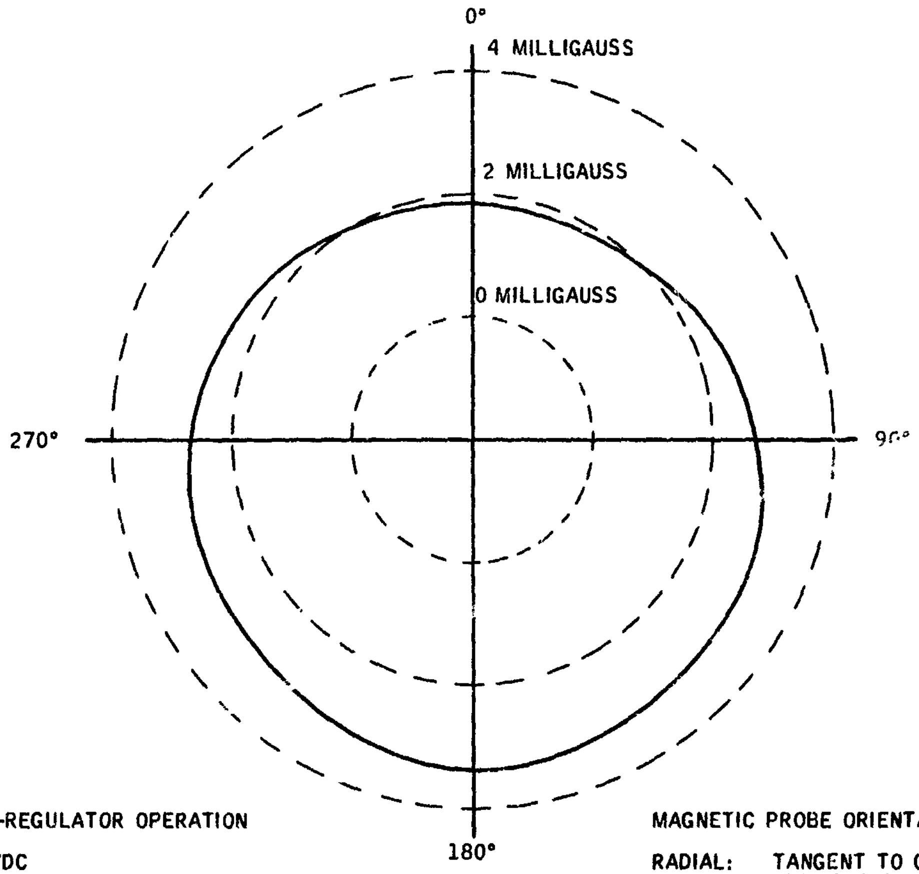
CHOKE CURRENT = 1.82 AMPERES

MAGNETIC PROBE OPERATION:

RADIAL: PARALLEL TO CHOKE AXIS ON A 2.5 INCH RADIUS FROM THE CHOKE AXIS.

LONGITUDINAL: AT CENTER OF CHOKE.

Figure 7 - MAGNETIC DISTURBANCE PARALLEL TO THE CHOKE AXIS AROUND THE CENTER OF THE CHOKE



CONVERTER-REGULATOR OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

V_{OUT} = 28 VOLTS

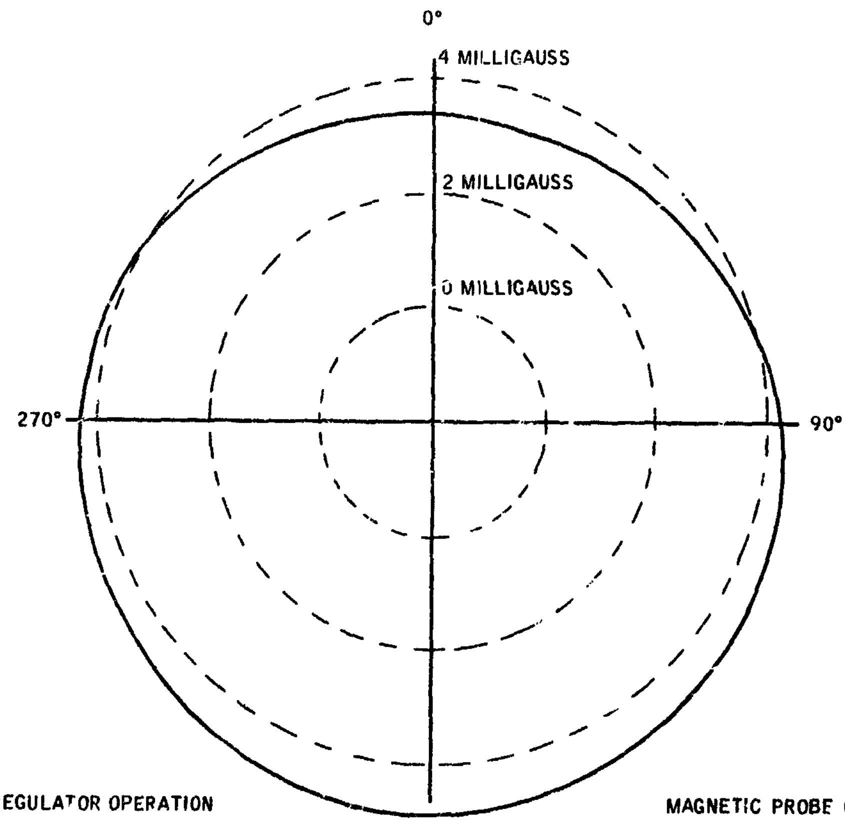
CHOKE CURRENT = 1.82 AMPERES

MAGNETIC PROBE ORIENTATION

RADIAL: TANGENT TO CHOKE CYLINDRICAL SURFACE ON A 2.5 INCH RADIUS FROM THE CHOKE AXIS.

LONGITUDINAL: AT LEADWIRE END OF CHOKE.

Figure 8 - MAGNETIC DISTURBANCE PERPENDICULAR TO THE CHOKE AXIS AROUND THE LEAD WIRE END



CONVERTER-REGULATOR OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

V_{OUT} = 28 VOLTS

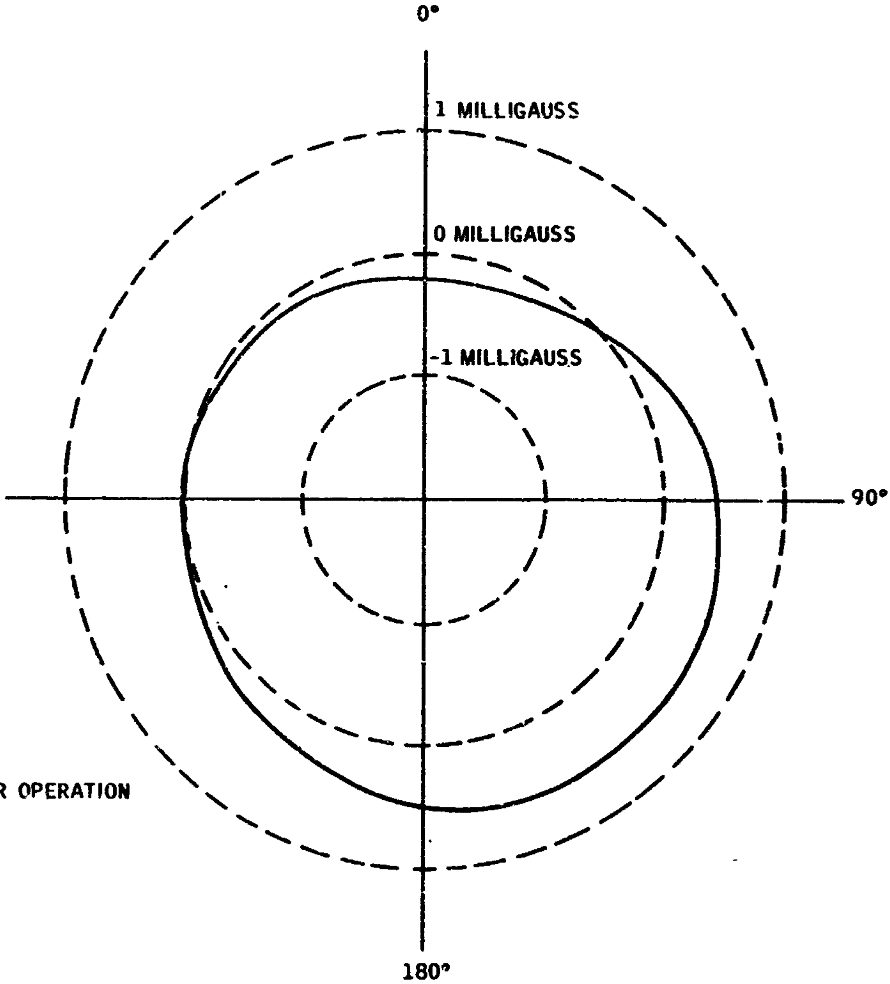
CHOKE CURRENT = 1.82 AMPERES

MAGNETIC PROBE ORIENTATION

RADIAL: TANGENT TO CHOKE CYLINDRICAL SURFACE ON A 2.5 INCH RADIUS FROM THE CHOKE AXIS.

LONGITUDINAL: AT CENTER OF CHOKE.

Figure 9 - MAGNETIC DISTURBANCE PERPENDICULAR TO THE CHOKE AXIS AROUND THE CHOKE CENTER



CONVERTER-REGULATOR OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

V_{OUT} = 28 VOLTS

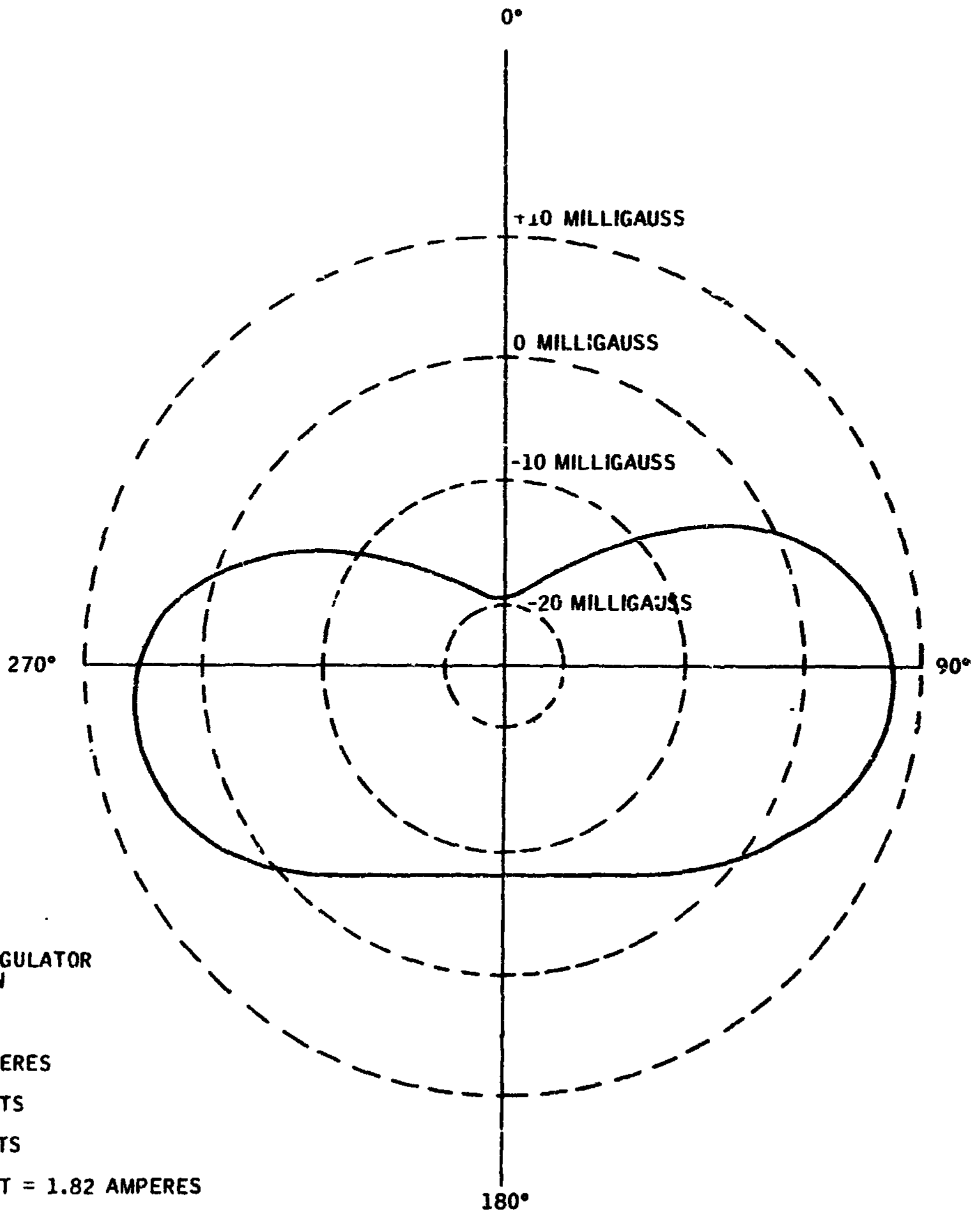
CHOKE CURRENT = 1.82 AMPERES

MAGNETIC PROBE ORIENTATION

RADIAL: TANGENT TO CHOKE CYLINDRICAL SURFACE ON A 2.5 INCH RADIUS FROM THE CHOKE AXIS.

LONGITUDINAL: AT END OF CHOKE THAT DOES NOT HAVE LEAD WIRES.

Figure 10 - MAGNETIC DISTURBANCE PERPENDICULAR TO THE CHOKE AXIS AROUND THE END



CONVERTER-REGULATOR
OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

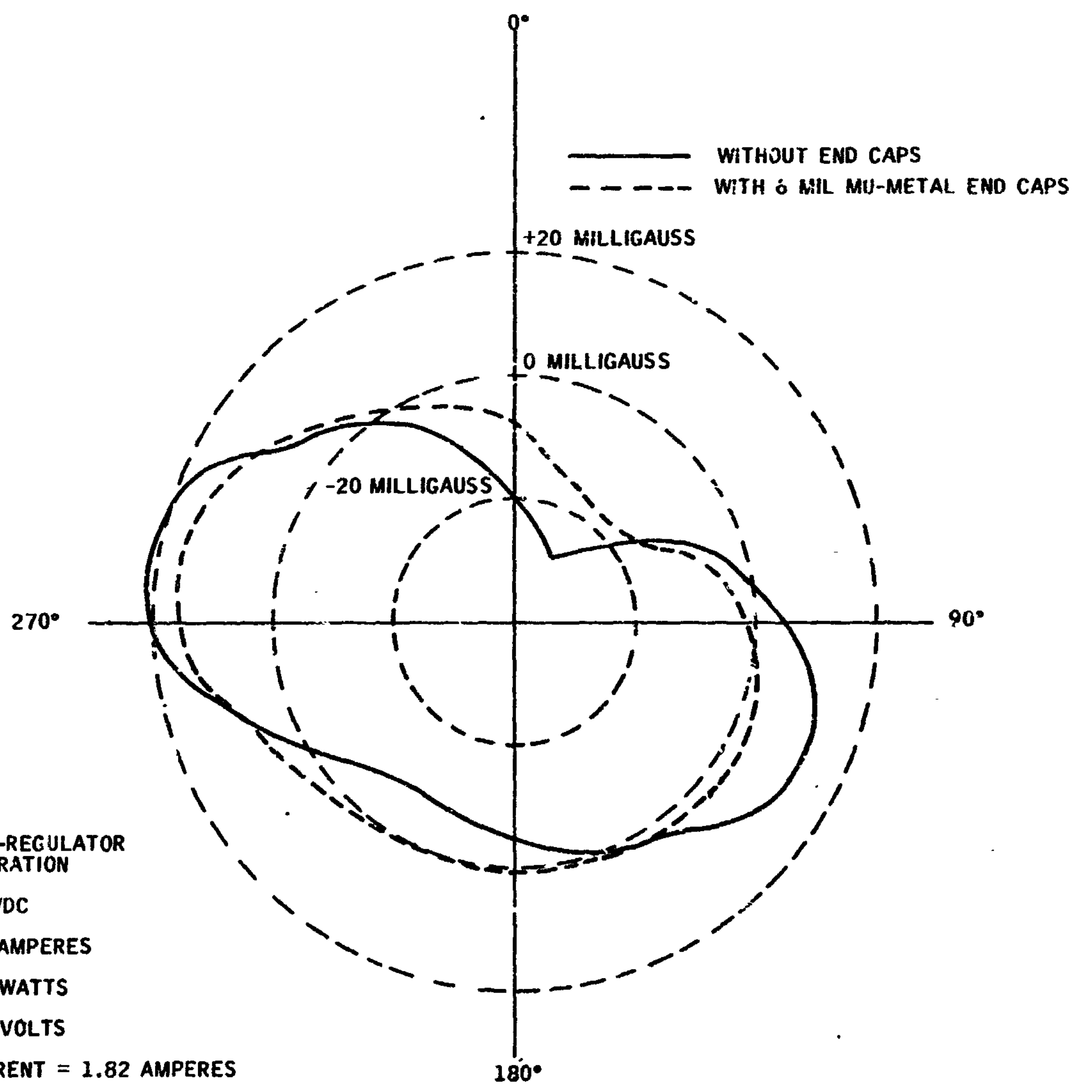
V_{OUT} = 28 VOLTS

CHOKE CURRENT = 1.82 AMPERES

MAGNETIC PROBE ORIENTATION

RADIAL: PERPENDICULAR TO THE AXIS OF CHOKE. CHOKE IS ROTATED ABOUT AN AXIS PERPENDICULAR TO ITS OWN.. PROBE IS PARALLEL TO AXIS OF ROTATION AT A 2.5 INCH RADIUS FROM THE AXIS OF ROTATION. PLANE OF LOCUS OF CHOKE AXIS PASSES THROUGH CENTER OF PROBE.

Figure 11 - MAGNETIC DISTURBANCE PARALLEL TO THE AXIS OF ROTATION WHEN THE CHOKE IS ROTATED ABOUT A PERPENDICULAR AXIS



CONVERTER-REGULATOR
OPERATION

V_{IN} = 0.8 VDC

I_{IN} = 83.4 AMPERES

P_{OUT} = 51 WATTS

V_{OUT} = 28 VOLTS

CHOKE CURRENT = 1.82 AMPERES

MAGNETIC PROBE ORIENTATION

RADIAL: PARALLEL TO LOCUS OF CHOKE AXIS PLANE. CHOKE IS ROTATED ABOUT AN AXIS PERPENDICULAR TO ITS OWN. PROBE IS PERPENDICULAR TO THE AXIS OF ROTATION.

Figure 12 - MAGNETIC DISTURBANCE PERPENDICULAR TO THE AXIS OF ROTATION WHEN THE CHOKE IS ROTATED ABOUT A PERPENDICULAR AXIS

B. MAGNETIC DISTURBANCE AT AN EIGHTEEN INCH RADIUS

The distribution of the magnetic disturbance at a radius of 2.5 inches from the axis of the Low Input Voltage Converter is shown on Figure 13. The magnetic disturbance along the converter section is less than one milligauss at this radius. It might be possible to extrapolate this data and calculate the magnetic disturbance at a distance of 18 inches from the converter axis. This may be somewhat difficult, however, because the exact cause of this particular disturbance is not known and the accuracy of the readings may not be sufficient to obtain significant data at a distance of 18 inches. If this magnetic disturbance is caused by eccentricity in the coaxial conductors, then the magnetic disturbance would be a function of the following:

$$B = f\left[\frac{1}{R}, \left(\frac{1}{R} - \frac{1}{R+X}\right)\right] \quad (1)$$

Where:

B	=	The magnetic disturbance flux density
R	=	The radius from the converter axis
X	=	The eccentricity
f	=	Denotes function.

This relationship shows that the magnetic disturbance and the effect of the eccentricity will decrease as the radius R increases. Thus, at a distance 18 inches out, the radius R will be greatly increased and hence the effect of the small eccentricity will be decreased considerably. The magnetic disturbance measurements made at a distance of 2.5 inches has provided readings which are approximately 50 times the specification at a distance of 18 inches. If the magnetic disturbance is caused by eccentricity in the coaxial conductors, then it can be seen from this relationship that the effect of this eccentricity will be much less at a distance of 18 inches. For example, if the primary current into the low input voltage converter is 83.4 amperes

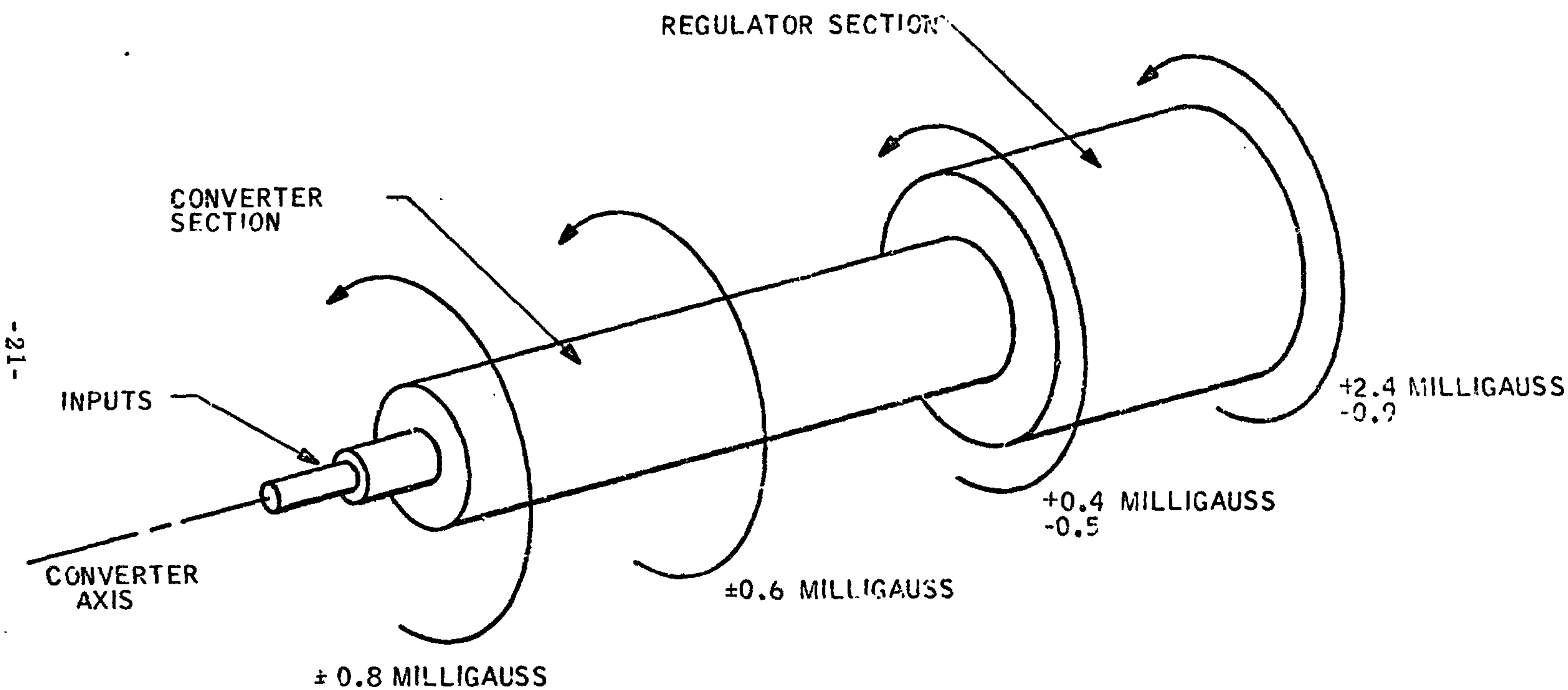


Figure 13 - MAGNETIC DISTURBANCE AROUND THE CONVERTER-REGULATOR

and if the construction were not coaxial, the field produced by a single primary conductor at a distance of 2.5 inches would be 2.341 gauss. However, coaxial construction is used, therefore each conductor produces a field of approximately 2.341 gauss and the two opposing fields cancel. A small eccentricity prevents complete cancellation. Therefore, the eccentricity is producing a net field of approximately 1 milligauss because of incomplete cancellation of fields on the order of 2.658 gauss. This represents a difference of one part in 2,341 as far as the cancellation effect at a distance of 2.5 inches is concerned. It can be seen from equation (1) that if the measurements were made at a distance of 18 inches, then the value of R would be increased by a factor of 7.2. This would result in a very substantial decrease in the value of $\left[\frac{1}{R} - \frac{1}{R+X}\right]$.

Calculations shown in Appendix A determine that a 0.000855 inch eccentricity would produce the measured 0.8 milligauss field at a 2.5 inch radius. Using this value for eccentricity, it is shown that the magnetic disturbance at 18 inches, due to the coaxial low input voltage converter section, should be about 0.89 gamma at 51 watts output. This is within the 2.0 gamma specification requirement. This of course will have to be verified when more exacting tests are conducted at the magnetic observatory.

C. CHOKE COIL EXTERNAL MAGNETIC DISTURBANCE

The magnetic disturbance around the choke coil is shown in Figure 14. Notice that the disturbance around the choke coil in a direction perpendicular to its axis is relatively low (under one milligauss at a distance of 2.5 inches). However, the disturbance in a direction parallel to the axis of the choke is quite high and uniform at approximately 8.5 milligauss at a distance of 2.5 inches from the choke axis. This shows that the main disturbance is caused by a magnetic dipole effect. This disturbance may be caused by one of the two bucking choke coil sections having a stronger magnetic dipole than the other. It might also be caused by leakages through distributed air gaps at the external seams.

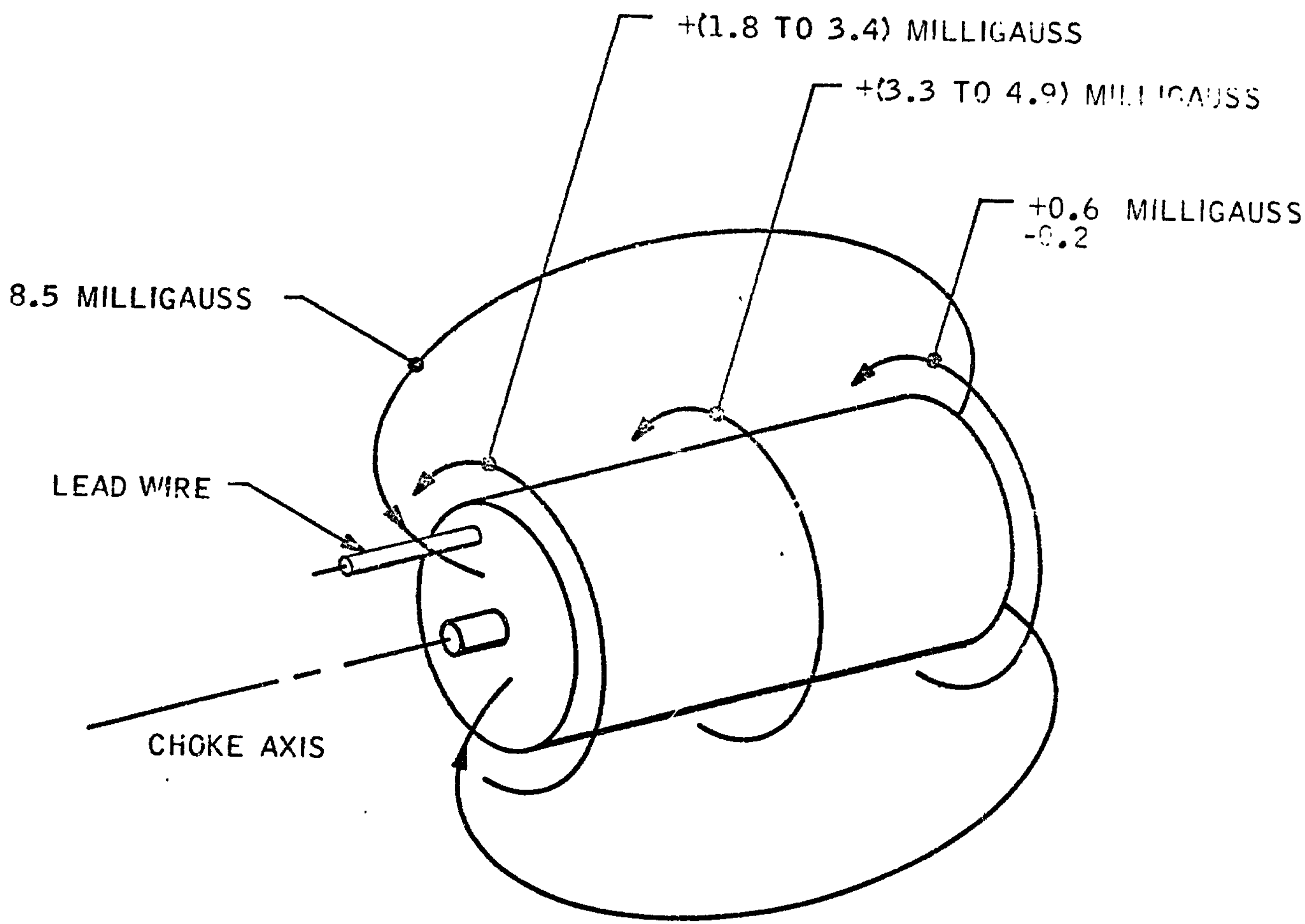


Figure 14 - MAGNETIC DISTURBANCE AROUND THE CHOKE COIL

The magnetic field disturbance at an 18 inch distance from the choke coil has been calculated in Appendix B. These calculations show that the magnetic disturbance perpendicular to the choke axis is 2.28 gamma or about 14% above the 2 gamma specification requirement. The magnetic disturbance 18 inches from the choke center along the choke axis is 4.56 gamma which is over twice the specification requirement. These interpolated results show that the magnetic disturbance is greater than desired. However, the results are reasonably close for the first attempt and this verifies that the basic design approach is correct. Because the construction of the preliminary choke is unsatisfactory, it is necessary to improve this device to meet the requirements. The next choke should provide satisfactory results and should be measured more accurately for magnetic disturbance at the magnetic observatory.

D. CONSTRUCTION OF THE DUAL CHOKE COIL

Figure 15 shows a cross sectional view of the dual choke coil arranged with two bucking halves. The ends and the center section of this choke coil were fabricated from disks of 6 mil mu-metal. All of the disks were made the same size to reduce the fabrication costs. The weight of the device could have been decreased if the ends and center section were fabricated from different sized disks staggered to provide a tapered radial cross section with decreased thickness at the periphery. This would maintain uniform cross-sectional area throughout the magnetic path. Although this would have decreased the weight, it would have increased the fabrication costs considerably. Hence the simpler approach, using only one disk size, was chosen on this preliminary model. The central part of the core B1, B2 was fabricated by wrapping a strip of 4 mil mu-metal around a mandrel and building up a laminated spiral cylinder. The two end bells, A1, A2, center disk C, and the two center cores B1, B2, form two spools around which two coils, D1, D2, are wound upon two bobbins E1, E2. Over this assembly, a two inch strip of 4 mil metal is wrapped to form the outer cylindrical case, F. Two end caps, G1, G2, are placed over each end and a stainless steel screw H with a stainless steel nut J is passed through a hole in the center of disks A1, A2,

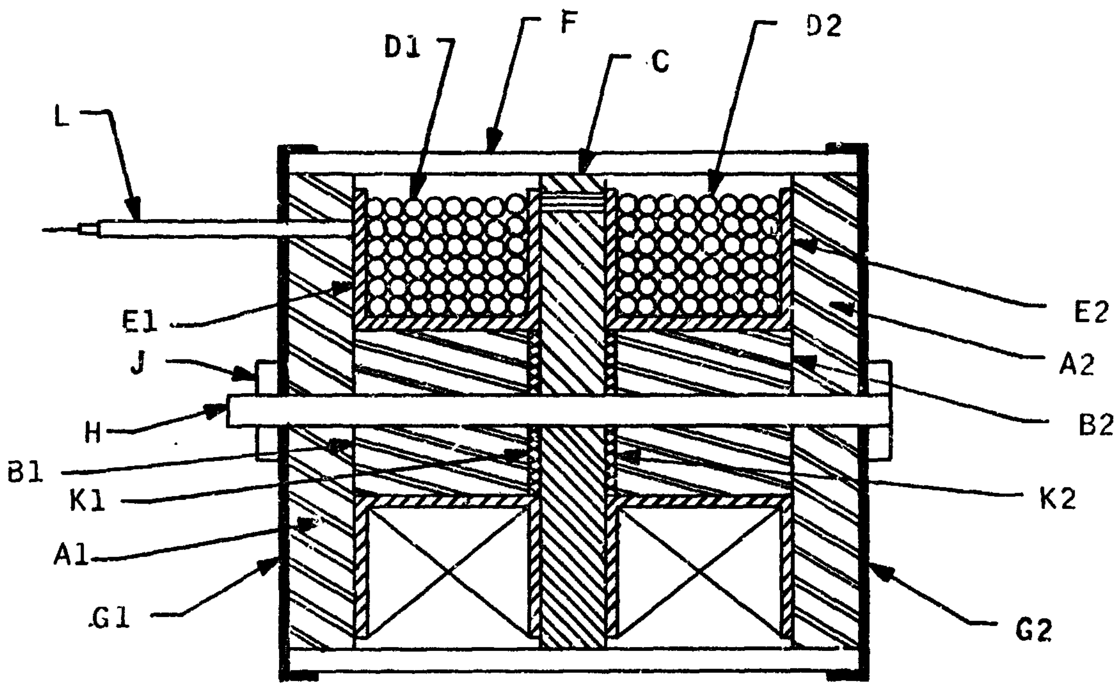


Figure 15 - DUAL CHOKE COIL CONSTRUCTION

center section C and center cores B1, B2 to hold the entire assembly together. Two air gaps, K1 and K2 are located between the center cores B1, B2 and the center disk C. The two coils, D1 and D2, are wound so that the current passes through one in the clockwise direction and through the other in the counterclockwise direction.

This produces the two bucking magnetic fields, so that the external magnetic disturbance from each choke coil section opposes the other and tends to cancel the magnetic disturbance in the space outside the choke coil. The input and output leads of this choke coil exit through a coaxial cable to minimize magnetic field disturbance.

This type of construction is advantageous because all of the flux which the coils produce either passes through the iron or is enclosed by the iron because the coils themselves are totally enclosed in the iron core. The air gaps K1 and K2, are also totally enclosed within the iron core, A-B-C-F, and hence the extremely high magnetic fields and fringing flux present at the air gaps will not escape from the device because it is totally enclosed within the iron sheath. Thus, these construction principles should provide a choke coil having minimum external magnetic field disturbance. However, the measured magnetic field disturbance was larger than anticipated. This high field disturbance is caused by the fringing of flux at the end bell seams, possible escape of flux through the stainless steel screw, and unbalance between bucking sections caused by either more turns of wire on one coil than on the other or by differences in the distributed air gaps between the two choke coil sections.

E. MAGNETIC DISTURBANCE FROM A CONVENTIONAL CHOKE COIL

Preliminary magnetic field measurements were made with a conventional choke coil connected into the low input voltage converter-regulator circuit. This conventional (C-core type) choke coil produced a magnetic disturbance of 1.5 gauss at a radius of 2.5 inches from the center axis of its coil. By comparison, the first dual section bucking choke coil produced a magnetic disturbance between 8.5 milligauss and 20 milligauss at the same radius and 1.82 ampere load. Thus, the dual section choke coil with enclosed coils, enclosed air gaps; and bucking external fields produced only 1% of the magnetic disturbance that a conventional choke coil produces. We anticipate that the next dual section choke coil will have much lower external magnetic disturbance because greater effort will be directed towards maintaining uniformity and close tolerances during fabrication.

F. CHOKE COIL PROBLEMS

Difficulties noted during the fabrication and checkout of the dual section choke coil are as follows:

1. High eddy current loss was caused by:

   The passage of flux through the end bell disk perpendicular to the direction of lamination.

   The use of mu-metal which did not have any inter larnminer insulation on it.

2. Somewhat loose fit of the mating parts which caused distributed air gaps throughout the device and resulted in small air gaps at the external seams which increased the external magnetic disturbance.

3. The use of unannealed mu-metal (not annealed after cold working).

4. Lack of tapered or conical construction of the end bells and center section increased the choke coil weight.

Because of the above deficiencies, another choke coil will be fabricated. The new choke coil will use mu-metal which has an inter-laminar insulation on each side and the end bell laminations will be further subdivided to reduce eddy current losses and remove the tendency of the disk laminations to place a short circuit on the enclosed magnetic flux. These changes will be made before the device is tested at the magnetic observatory. The changes are discussed in greater detail below.

G. EDDY CURRENT EFFECTS AT THE CHOKE COIL END BELLS

Examination of the choke coil construction and magnetic paths shows that the highest eddy current concentration will occur in the end bell disks because the direction of flux is perpendicular to the laminations. This is shown in Figures 15 and 16. Since the eddy currents generated are also perpendicular to the flux lines, the laminations do not break up the current paths and circular eddy currents can flow around the disk as indicated in Figure 16. The alternating flux induces voltages around circular paths in the disk lamir ·· n proportional to the amount of flux enclosed in a given concentric circu... path. The maximum induced voltage (E_p) occurs around the circle that encloses the total flux and this voltage is equal to the voltage per turn impressed across the choke coil winding. The conductive path through the disk lamination thus places a shorted turn on the choke coil. The total eddy current flowing through the disk is then:

$$I_e = \int_0^{R_p} \frac{E(x)}{R(x)} \, dx$$

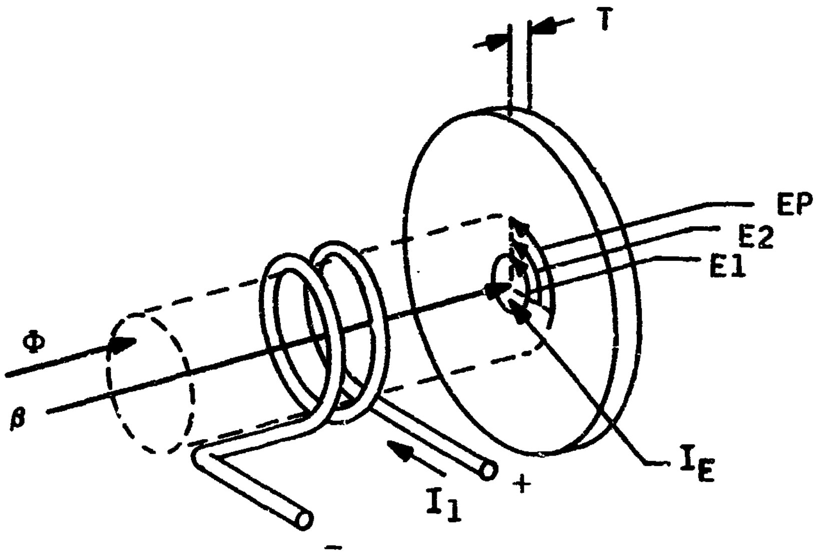


Figure 16 - CHOKE END BELL EDDY CURRENTS

Where:

I_e	=	Total eddy current
$R(x)$	=	Resistance of loop at radius
$E(x)$	=	Voltage at corresponding radius
R_p	=	Radius at the periphery

The resistance is determined by the path length, the lamination resistivity, and the incremental area per path. Since the end bell is not laminated in a direction that will break up the eddy current paths, lamination of the material in a plane perpendicular to the direction of flux flow is ineffective. The effective thickness of the material can be considered to be the average depth of perpendicular flux penetration into the end bell. The eddy current loss (P_e) is:

$$P_e = \int_0^{R_p} \frac{E(x)^2}{R(x)} \, dx$$

H. REDUCTION OF EDDY CURRENT LOSSES

Figure 17 shows methods which can be used to break up the end bell eddy current paths thereby reducing the eddy current losses there.

Figure 17a shows that complete concentric circular paths exist in the undivided disk. Flux passes through some of the disks, comprising the end bell, perpendicular to the disk surface. The complete circular paths linking the greatest change in this perpendicular flux then have the highest voltage induced in them. If the area enclosed by the path is decreased, the voltage induced in that path is also decreased. One may observe that for the same path width, the resistance of the decreased path will also be less.

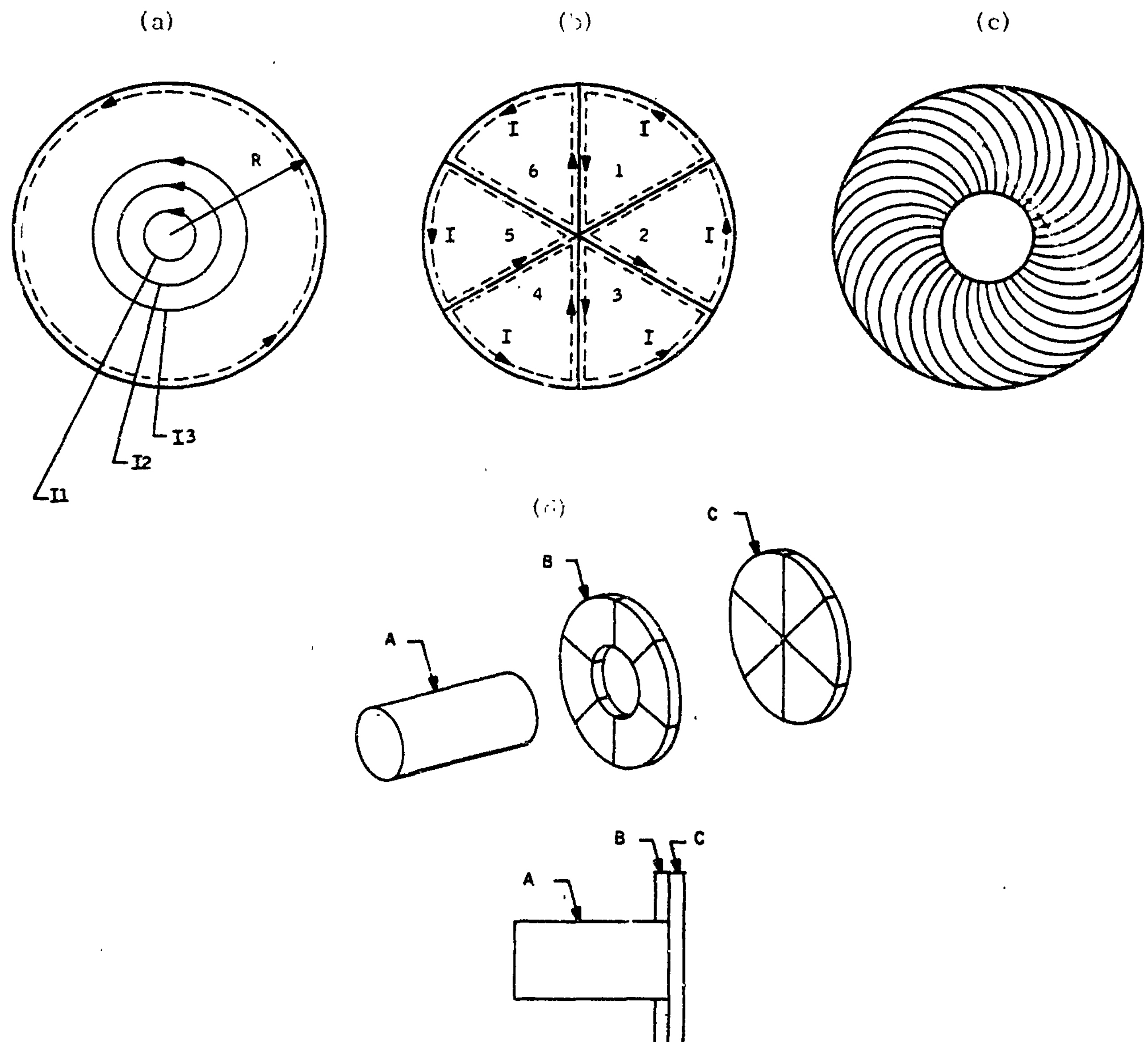


Figure 17 - METHODS OF REDUCING EDDY CURRENTS

The significant point is, however, that by increasing the total length of the insulated boundaries enclosing a specific change in flux, the voltage to resistance ratio is decreased and the eddy current power loss is also decreased.

Figure 17 further illustrates the reduction in eddy current power loss. Although the disc indicated in Figure 17b is divided into six sections, the following approach to eddy current power loss will assume n sections to provide a more general discussion. The resistance for the path around the periphery of the uncut disc (Figure 17) is equal to

$$R = \rho \frac{\ell}{A} = \rho \frac{2\pi r}{A} = K\, 2\pi r$$

Where

r = radius to path

ρ = resistivity

A = cross sectional area of the conducting path.

By comparison, the resistance around the periphery of each section of Figure 17 is equal to

$$R' = K \left(2 + \frac{2\pi}{n}\right) r$$

assuming the same path cross sectional area. The voltage (E') induced in each section of the cut disc will be 1/n of the voltage (E) induced in the total uncut disc. Thus the power loss in the path of the periphery of each section will be equal to

$$P_n' = \frac{(E/n)^2}{K \left(2 + \frac{2\pi}{n}\right) r} .$$

The sum of the power loss at the periphery for all n sections will thus be

$$P' = n\,P'_n = \frac{n\,(E/n)^2}{K\,(2 + \frac{2\pi}{n})\,r}\,.$$

The corresponding pcwer loss in the uncut disk will be equal to

$$P = \frac{E^2}{K2\,\pi r}\,.$$

Taking the ratio of these powers

$$\frac{P}{P'} = \frac{\dfrac{E^2}{K2\pi r}}{\dfrac{n\,(E/n)^2}{K\,(2 + \frac{2\pi}{n})\,r}} = \frac{2n + 2\pi}{2\pi} = \frac{n}{\pi} + 1$$

indicates a substantial reduction in the loss with the sectioned disc.

A like result will be obtained if additional and related current paths at incremental displacements from the center are considered for the respective configurations.

Thus the power loss in the sectioned disc should be substantially less than that of the non-sectioned disc. A rigorous analysis of the eddy currents of a system becomes rather involved but it is felt that the preceding discussion is sufficient to indicate that segmenting the discs will substantially reduce the eddy current power loss in the end bell.

Another method of reducing the eddy current losses is the use of involute spiral laminations as shown on Figure 17c. This would result in a much greater eddy current reduction because the eddy paths are much more finely divided. However, this type of end bell is more difficult to construct and requires a certain geometrical relationship between the center hole diameter, the outside diameter, and the lamination thickness. Honeywell has fabricated devices from laminations of this type and has found that the spiral lamination should not extend more than 180°.

Another way to diminish the end bell eddy current loss is to recess the cylindrical core section part way into the end bell as shown on Figure 17. This arrangement will allow some of the flux to exit through the segmented donut laminations (B) parallel to the direction of lamination. This reduces the flux density of flux flowing perpendicularly into the segmented end disks (C). It is necessary to segment the donut laminations (B) to prevent a shorted turn on the choke coil.

Tests on the preliminary choke coil model have established that excessive eddy current losses were caused by the lack of an insulated coating between the laminations. Also, the end bells were not laminated in the proper direction to minimize eddy current loss.

These difficiencies will be corrected by the fabrication of another choke coil utilizing insulated laminations and design changes discussed above.

I. DEPERMING COIL

The deperming coil for use in magnetic field disturbance tests at the observatory has been designed and fabricated. This coil is approximately 4.1 inches in diameter and 41 inches long. It contains 740 turns of No. 16 wire and will be operated from a variac. Magnetic field tests have shown that the deperming coil produces a field two diameters in from each end which has less than 3% variation throughout the volume. A current of 2.69 amperes is required to produce a 25 gauss field.

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CONCLUSIONS

THE DATA obtained from the preliminary magnetic field disturbance tests on the low input voltage converter-regulator indicate that the external magnetic disturbance generated by the low input voltage converter section is satisfactory. Although the measurements obtained in the earth's high ambient magnetic field do not have the desired accuracy, they have provided valuable information. If the data taken at 2. 5 inches from the axis of the converter is interpolated out to 18 inches, the external magnetic disturbance caused by the coaxial low input voltage converter section is 0. 892 gamma which is considerably less than the 2 gamma specification requirement. Thus it can be concluded that the coaxial construction of the low input voltage converter regulator results in a substantial decrease in the external magnetic field disturbance. Hence, this design approach is very desirable for low input voltage converter-regulators which have a requirement of minimum external magnetic field disturbance. Besides minimizing the external magnetic field disturbance, coaxial construction also minimizes the inductance of the converter primary section and this reduces the generation of voltage spikes at the power transistor collector emitter junctions. The reduction of voltage spikes by coaxial construction greatly decreases the switching losses in the oscillator power transistors because the instantanious voltage current product is reduced during switching. This allows efficient operation at higher operating frequencies where weight reduction can be achieved. Thus, all performance tests and magnetic disturbance tests have indicated that the coaxial construction has resulted in significant improvements in the device performance and it appears that a very satisfactory converter can be fabricated using this technique.

The preliminary external magnetic field disturbance measurements have shown that the dual section bucking choke coil has a higher magnetic field disturbance than originally estimated.

Tests have shown that the external magnetic field disturbance produced by the first dual section choke coil was about 1% of that produced by a conventional choke coil. Calculations indicated that the magnetic disturbance due to the dual section choke coil would be about 4.56 gamma for the worst case at an 18 inch distance. This is more than twice the 2 gamma specification requirement.

Performance tests have also shown that this choke coil has excessive eddy current losses. Thus, the preliminary tests have shown that the design of the dual section bucking choke coil must be improved. This will be done by redesigning the end bell disk laminations and the center disk laminations to provide lamination in the direction parallel to flux flow and thereby reduce their eddy current losses. Also, metal with inter laminar insulation will be used in the construction of this device to minimize the eddy current losses and provide a choke coil of having satisfactory efficiency.

The tests conducted during this past quarter have shown that the low input voltage converter section of this device appears to be satisfactory from a performance and a magnetic field disturbance standpoint. These tests have also shown that the dual section choke coil has certain design deficiencies which must be corrected during the next quarter. The procurement of satisfactory insulated magnetic material has caused some delay in the fabrication of the new choke coil. Action is now being taken to redesign this choke coil and correct the deficiencies so that satisfactory performance tests can be made at the magnetic observatory.

The preliminary magnetic field measurements have indicated that although the converter section appears satisfactory, the choke coil requires further work. It can be concluded that the basic design approach for this choke coil does minimize magnetic disturbance; however, certain improvements must be made in the fabrication procedure to obtain the benefits that this approach can provide. These tests have pinpointed the design deficiencies and the information obtained will be useful in achieving the design goals with the deliverable model.

These conclusions are based upon magnetic disturbances calculated from preliminary measurements in the earth's strong ambient field. More accurate tests to be conducted at the Magnetic Observatory are necessary to verify that the preliminary results are accurate and to definitely establish the magnetic disturbance level.

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PROGRAM FOR THE NEXT QUARTER

DURING THE next quarter, the new choke coil will be fabricated in order to correct the deficiencies noted in the present choke coil design. This new choke coil will then be inserted in the coaxial low input voltage converter-regulator and some preliminary magnetic disturbance checks will be made. After this, magnetic disturbance tests will be scheduled at the magnetic observatory for the low input voltage converter-regulator.

During the next quarter, further effort will be directed toward weight reduction. The use of electroplated magnesium for some of the parts inside the coaxial converter section will be considered. Also, some of the structural components in the regulator section will be examined to determine where weight can be reduced further. The use of three supporting rods in place of two in the regulator section will be considered to provide greater rigidity for the mounting of regulator components.

During the next interval, the final deliverable model will be fabricated and performance tests, environmental tests, and battery charging tests will be performed on this unit.

APPENDIX A

CALCULATION OF EXTERNAL MAGNETIC DISTURBANCE AT AN 18 INCH RADIUS FROM THE COAXIAL LOW INPUT VOLTAGE CONVERTER SECTION

The magnetic disturbance has been measured at a radius of 2.5 inches from the low input voltage converter section. It will be assumed that the measured magnetic disturbance is caused by eccentricity in the coaxial primary conductors and the magnitude of eccentricity required to produce the measured field will be calculated. After this has been done, the eccentricity obtained will be used to calculate the magnetic disturbance at an 18 inch radius. To perform these calculations, the following conditions are given:

Coaxial Converter Length = 25 cm

Magnetic Disturbance at 2.5 inch or (6.35 cm) radius at longitudinal center = 0.8 milligauss

Primary current = 83.4 amperes

Determine magnetic field disturbance at a radius of 18 inches (or 45.7 cm).

The magnetic field intensity around a finite straight wire is given by:

$$B = \frac{\mu_o I}{4 \pi a} (\cos \theta_1 - \cos \theta_2) \tag{1}$$

where the symbols are defined by the following construction:

B is in webers/m^2

I is in amperes

a is in meters

$$\mu_o = 4 \times 10^{-7} \quad \frac{\text{webers}}{\text{Ampere meter}}$$

θ_1 = angle subtended by line from one end of converter to point and line through converter axis (see Figure 18).

θ_2 = angle subtended by line from opposite end of converted to point and line through converter axis.

For a distance of 6. 35 cm radial from center of converter section, $\tan \theta_1 = \frac{6.35 \text{ cm}}{12.5 \text{ cm}} = 0.508$

$$\theta_1 = 26.93°$$

$$\theta_2 = 180° - 26.93°$$

$$= 153.07°$$

$$\cos \theta_1 = 0.892$$

$$\cos \theta_2 = -0.892$$

$$\text{Then } B = \frac{4\pi \times 10^{-7} \times 83.4}{4\pi\ (0.0635)} \quad [0.892 - (-0.892)]$$

$$= \frac{83.4 \times 10^{-7}}{0.0635} \quad (1.784)$$

$$= 13.13 \times 10^{-5} \quad (1.784)$$

$$= 23.41 \times 10^{-5} \quad \text{webers}/m^2$$

$$= 23.41 \times 10^{-1} \text{ gauss}$$

$$= 2.341 \text{ gauss.}$$

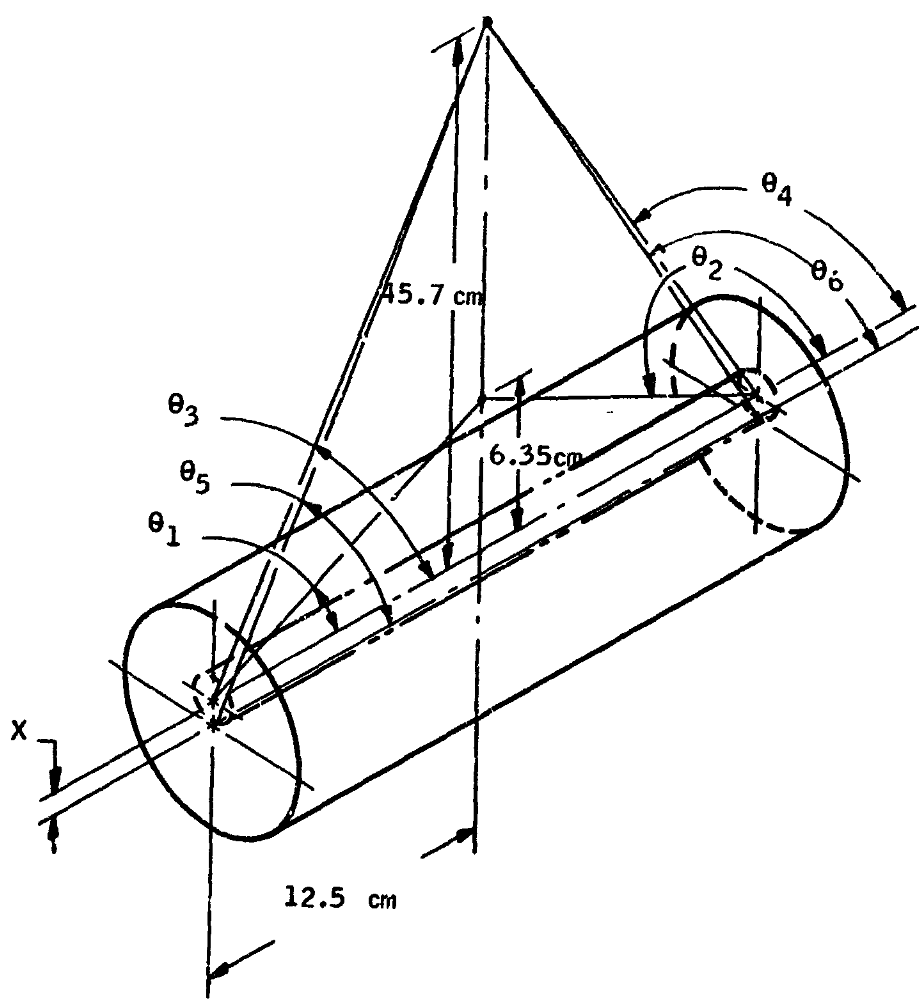

Figure 18 - GEOMETRIC CONSTRUCTION OF COAXIAL CONDUCTORS WITH SMALL ECCENTRICITY

Thus, the field due to current through one of the coaxial conductors is 2. 341 gauss at a distance of 2. 5 inches from the converter axis. The other conductor will produce an equal opposing field. However, a small eccentricity will result in incomplete magnetic field cancellation and will produce a net field of 0. 8 milli-gauss. It is now desirable to calculate this eccentricity. To simplify the calculations, it will be assumed that the value of θ_1 and θ_2 do not change due to the eccentricity. This will provide an accurate approximation because changes in the cosine function for small increments at this angle are practically insignificant.

The equation then becomes:

$$B_a - B_b = 83.4 \times 10^{-7} \left(\frac{1}{a} - \frac{1}{a + x}\right) (\cos \theta_1 - \cos \theta_2)$$

$$B_{(a-b)} = 83.4 \times 10^{-7} \frac{x}{a (a + x)} \qquad 2 \cos \theta_1$$

$$= 83.4 \times 10^{-7} \frac{x}{a (a + x)} \qquad (1.784).$$

It was previously determined that $\frac{83.4 \times 10^{-7} (1.784)}{a}$ produced field of 2. 341 gauss, therefore the equation can be written as

$$B_{a-b} = 2.341 \text{ gauss} \quad \frac{x}{a + x} \quad .$$

Measurements have shown that $B_{a-b} = 0.8 \times 10^{-3}$ gauss. Substituting this value we can solve for the eccentricity (x).

$$0.8 \times 10^{-3} = 2.341 \cdot \frac{x}{0.0635 + x}$$

$$x \; \frac{1 - 0.8 \times 10^{-3}}{2.341} = \frac{0.8 \times 10^{-3}}{2.341} (0.0635)$$

$x\ (0.999658) = 0.21700128 \times 10^{-4}$

$= 0.21707 \times 10^{-4}$ Meter

$= 0.8546 \times 10^{-3}$ Inch.

Using this value of eccentricity the magnetic field disturbance at a distance 18 inches from the converter axis can be estimated by:

$$B_p = B_c - B_d$$

Where:

B_p = Magnetic Field Disturbance at Point P.

B_c = Magnetic Field Due to Current in one Conductor at 45.7 cm Distance

B_d = Magnetic Field Due to Opposing Current in the other Conductor at (45.7 cm + x) Distance.

$$B_c = \frac{I}{a} (\cos \theta_3 - \cos \theta_4)$$

$$B_d = \frac{I}{a+x} (\cos \theta_5 - \cos \theta_6)$$

$$\cos \theta_3 = -\cos \theta_4$$

$$\cot \theta_3 = \frac{12.5}{45.7}$$

$$= 0.2735229$$

$$\cos \theta_5 = -\cos \theta_6$$

$$\text{Cot } \theta_5 = \frac{12.5}{45.7 + x}$$

$$x = 0.21707 \times 10^{-4} \text{ Meter}$$

Since $\text{Cot } \theta_3 = 0.2735229$

$$\theta_3 = 74.7025°$$

$$\text{Cot } \theta_5 = \frac{12.5}{45.70217} = 0.2735100$$

$$\theta_5 = 74.7032°$$

$$\text{Cos } \theta_3 = 0.26383096$$

$$\text{Cos } \theta_5 = 0.26381918$$

$$(\text{Cos } \theta_3 - \text{Cos } \theta_4) = 0.52766192$$

$$(\text{Cos } \theta_5 - \text{Cos } \theta_6) = 0.52763836$$

Then

$$B_c = \left(\frac{83.4 \times 10^{-7}}{0.457}\right) (0.52766192)$$

$$= \frac{44.007004128 \times 10^{-7}}{0.457}$$

$$= 96.29541 \times 10^{-7}$$

And

$$B_d = \left(\frac{83.4 \times 10^{-7}}{0.4570217}\right) (0.52763836)$$

$$= \frac{44.00504256 \times 10^{-7}}{0.457022}$$

$$= 96.28649 \times 10^{-7}$$

Then

$$B_p = B_c - B_d$$

$$= (96.29541 - 96.28649) \times 10^{-7}$$

$$= 0.000892 \times 10^{-7}$$

$$= 8.92 \times 10^{-10} \quad \text{Webers/(Meter)}^2$$

$$= 8.92 \times 10^{-6} \quad \text{Gauss}$$

$$B_p = 0.892 \text{ Gamma}$$

If we neglect the effect of the eccentricity on the Cos θ

$$B_c - B_d = \frac{(83.4 \times 10^{-7})}{0.4570000} - \frac{(83.4 \times 10^{-7})}{0.4570217} \quad (\text{Cos } \theta_3 - \text{Cos } \theta_4)$$

$$= 0.003665 \times 0.52766 \times 10^{-7} = 0.00457 \times 10^{-7} \text{ webers/meter}^2$$

$$= 0.457 \text{ Gamma}$$

Thus it can be seen that the interpolated magnetic disturbance at an 18 inch distance should be less than the 2 gamma specification requirement. We can note that the values for the Cos θ have a significant effect upon the interpolated results. Therefore for more accurate interpolation it would be necessary to consider this in the determination of eccentricity (x). These calculations and

and assumptions establish that the magnetic field disturbance is within the specification limits (as far as the coaxial converter section is concerned). Consequently, it is now desirable to conduct more accurate tests at the magnetic observatory to accurately determine the magnetic disturbance at the 18 inch distance. It will be necessary to improve the choke coil before this is accomplished. It must be noted that the above calculated results are based upon magnetic field measurements in the earth's strong ambient field. Since the measured disturbance is much less than the earth's field the accuracy of these measurements cannot be reliably established. Therefore more accurate measurements may establish results which are considerably different from these preliminary calculations.

APPENDIX B

CALCULATION OF THE EXTERNAL MAGNETIC FIELD DISTURBANCE EIGHTEEN INCHES FROM THE DUAL SECTION CHOKE.

The external magnetic disturbance measured at a distance of 2.5 inches from the choke axis will be used to calculate the inherent magnetic moment of the choke. It will be assumed that a single magnetic dipole produces this magnetic moment. The external magnetic field due to this magnetic moment will then be calculated for two positions at an 18 inch distance from the choke center. The calculations follow:

Examination of Figure 14 shows that the external magnetic field parallel to the choke axis at a distance of 2.5 inches (0.0635 meter) is 8.5 milligauss. It will be assumed that this field is caused by a single magnetic dipole of moment M. The magnitude of this magnetic moment can be found from the following equation:

$$B = \frac{\mu_o}{4\pi} \left(\frac{3\ M \cos \theta}{r4} \vec{r} - \frac{1}{r^3} \vec{M} \right) \tag{1}$$

Where the geometrical construction is as shown on page A-8 of Progress Report #1 for this contract (3899) and the symbols are as follows:

B = flux density in webers/(meter)^2

μ = Permeability of space = $4\pi \times 10^{-7}$ $\frac{\text{webers}}{\text{ampere meter}}$

$\vec{M}$ = Magnetic moment vector of dipole

$\vec{r}$ = Distance from center of the dipole to the point.

θ = Angle between $\vec{M}$ and $\vec{r}$

P_1 = a point on the choke axis at a distance r

P_3 = a point on the perpendicular with the choke axis that passes through the choke center and is at a distance r from it.

For P_1, $\theta = 0°$ and for P_3, $\theta = 90°$.

Our preliminary measurements at a point P_3' showed that for r = 0.0635 meter and θ = 90° that $B = 8.5 \times 10^{-3}$ gauss parallel to the choke axis.

or $B = 8.5 \times 10^{-7}$ webers/(meter)^2 at P_3' substituting in equation 1 gives:

$$8.5 \times 10^{-7} = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{3M \cos 90°}{(0.0635)^4} (0.0635) \angle 90° - \frac{1}{(0.0635)^3} \vec{M} \right]$$

This reduces to

$$8.5 = -\frac{\vec{M}}{(0.0635)^3}$$

$$-\vec{M} = 8.5\ (0.0635)^3$$

$$-\vec{M} = 21.764 \times 10^{-4} \text{ ampere (meters)}^2$$

$\vec{M}$ has a direction coinciding with the choke axis and is oriented 180° from the flux measured at P_3'.

We can again substitute in equation (1) to find the disturbance at 0.457 meters from the choke at P_3.

$$B = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{3\,(-21.764 \times 10^{-4})\ \mathrm{Cos}\ 90^\circ\ (.457)\quad 90^\circ}{(0.457)^4} - \frac{(-21.764 \times 10^{-4})}{(0.457)^3} \right]$$

$$B = 10^{-7} \left[- \frac{(21.764 \times 10^{-4})}{(0.457)^3} \right]$$

$$B = 2.2804 \times 10^{-9} \text{ webers/(meter)}^2$$

$$= 2.2804 \times 10^{-5} \text{ gauss}$$

$$= 2.2804 \text{ gamma at } P_3$$

Thus the magnetic disturbance on a perpendicular from the choke coil axis at a distance of 18 inches from the choke center is 2.2804 gamma. This exceeds the 2 gamma specification requirement by about 14%. The magnetic disturbance along the choke axis will be much higher however and can be calculated at 0.457 meter distance as follows:

Substituting values for P_1 in equation (1B) gives:

$$B = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{3(-21.764 \times 10^{-4})\ \mathrm{Cos}\ 0^\circ}{(0.457)^4}\ (0.457)\ \angle 0^\circ \quad \frac{(-21.764 \times 10^{-4})}{(0.457)^3} \right]$$

$$B = 10^{-7} \left[\frac{(-21,764 \times 10^{-4})}{(0.457)^3} \quad (3 - 1) \right]$$

$$B = 10^{-7} \left[\frac{2(-21.764 \times 10^{-4})}{9.544 \times 10^{-2}} \right]$$

$$B = 4.561 \times 10^{-9} \text{ webers/(meter)}^2$$

$$= 4.561 \times 10^{-5} \text{ gauss}$$

$$B = 4.561 \text{ gamma at } P_1$$

This is over twice the specification requirement and indicates that improvements should be made. Although these calculations show that the choke coil external magnetic field disturbance is too high the values obtained are reasonably close to the specification requirements. This indicates that the design approach is a step in the right direction and that further improvements discussed in the text should result in the fabrication of a satisfactory choke coil.