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Small D.C. bipolar electromagnetic design: optimization and analysis

John J. Breen

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SMALL
D.C. BIPOLAR
ELECTROMAGNET
DESIGN

OPTIMIZATION AND ANALYSIS

by

John Joseph Breen

Submitted in Partial Fulfillment
of the
Requirements for the Degree

Master of Science

Supervised by Ray C. Johnson, Ph.D.
Department of Mechanical Engineering

Rochester Institute of Technology
Rochester, New York
1984
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Approved by:

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(Thesis Advisor)

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ROCHESTER, NEW YORK
MAY, 1984
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Date: 5/8/84
I would like to take this opportunity to thank my advisor for his help and guidance through this project. The knowledge gained from his courses and its application to this project is, without question, the most useful and important segment of my graduate education. If all the curriculum required for degree work could be as practical and meaningful as the optimization techniques he presents, the worth of a graduate engineer would rise considerably.

I would also like to thank my employer and fellow workers for their support and understanding throughout this effort. Their teamwork spirit has been appreciated. The B-H testing was not a complete success, but it would not have occurred at all without the help of the personnel and use of equipment at the research labs.

Finally, and most important, I would like to thank my wife and two sons for their support and understanding throughout the graduate school period. Without their patience, the efforts could not have been completed. It is to them that I dedicate this work.
ABSTRACT

The design of electromagnets is an iterative process in which the designer arrives at a solution to his design problem through repeated design trials. This procedure can be time consuming, and the resultant configuration may or may not be the best one for the constraints imposed on it. In addition, the designer must have a reasonable knowledge of magnetics to carry out these design steps.

This paper presents the basic equations necessary for designing and analyzing a horseshoe-shaped D.C. electromagnet. With this base, two methods are developed to optimize a design for maximum holding force, subject to prespecified constraints. The first method is a graphical approach. The advantage of this method is that it presents, in a simple manner, the effects of changes in the design constraints on the final solution. The disadvantage is that the user must thoroughly understand the design equations to use it.

The second method is part of a complete computer program package, written in Basic for an Apple II+ computer. This package can be used by a designer with little or no knowledge of magnetics, the equation system, or the program. It not only designs the maximum holding force electromagnet for the constraints imposed, but also analyzes existing designs for
many of the characteristics and sensitivities needed to insure a good production coil. The graphics capabilities of the Apple microcomputer are used extensively for maximum clarity.

Holding force experiments are also presented, which are used to confirm the predicted results from the computer simulations. Good correlation is demonstrated for the configuration tested. Partial data is also presented for determining the B-H curves of various densities of sintered 50/50 nickel iron material.

The combination of the program and paper is a useful tool for an engineer faced with an electromagnet design problem. It should result in a significant reduction in the time required to arrive at an acceptable solution.
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<tr>
<td>RW</td>
<td>Random Wind factor</td>
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<tr>
<td>SA</td>
<td>Surface Area of coil</td>
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<td>Winding Width</td>
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<tr>
<td>W2</td>
<td>Wires per cm**2</td>
<td>wires/sq-cm</td>
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EQUATION SUMMARY

No. Equation

1. NC = LW * WW * RW * W2
2. Efficiency = (PI * D * D / 4) / (D * D)
3. CP = 2 * (CD + CW + (PI - 4) * R)
4. AP = CP + 2 * PI * (W + WW / 2)
5a. I1 = CD - 2 * R
5b. I2 = CW - 2 * R
6. DO = CD + 2 * (W + FW)
7. WO = C2 + 2 * (CW + W + FW)
8. LO = LW + C1 + 2 * (CW + BF)
9. PL = 2 * (LW + FW + W + C1 + C2 + 2 * (BF + CW))
10. CI = V / CR
11. CR = NC * (AP * OC)
12. NT = NC * V / NC / AP / OC
13. NT = V / AP / OC
14. B = mu * H
15. H = (0.4 * PI * (amp-turns)) / L
16. REL = L / mu / A
17. FLUX = B * A = mmf / REL
18. FLUX = mmf / REL
19a. I3 = R + G / 2
20. NT = NA + NI
21. BA = HA = 0.4 * PI * NT / (G * 2) (special case)
22. HI = 0.4 * PI * NT / PL (special case)
23. BA = BI * CA / AG
24. F = K1 * BA * BA * AG / 2 / (mu for air)
25. FT = K1 * BA * BA * AG
26. INTERPOLAR FLUX LEAKAGE = (P * h / 2) * NT * h
27. P = (C * (dTT/dt)) + (K * TT)
28. LOG((P - K * TT) / P) = -(K * t) / C
29. TT = (P / K) * (1 - exp(-(K / C) * t))
30. ST = P / K
31. TC = C / K
32. K = SM * LK
33. P = PA * SM = CI * V
34. C = 180 * WT
35. WT = 0.015385 * AP * WW * RW * LW * PI / 4
36. WP = AP + PI * WW
37. SA = M * LW * WP
37a. SM = SA / 2.54 / 2.54
38. t = -(C / K) * (LOG(P / K - 70) - LOG(P / K))
39. RE = CR * (ST + 20 + 234) / (254)
40. LH = NC * (FLUX IN WEBERS) / CI
41. LH = NC * BA * AG / 100000 / CI
42. CW = CA / CD
43. FW = (DO - CD - 2 * W) / 2

xi
<table>
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<tr>
<th>No.</th>
<th>Equation</th>
<th>Page</th>
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<tr>
<td>44</td>
<td>( LW = \frac{V}{CI} / \frac{FW}{RW} / \frac{W2}{AP} / \frac{OC}{OC} )</td>
<td>37</td>
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<tr>
<td>45</td>
<td>( W2 = 1 / \frac{ID}{ID} )</td>
<td>43</td>
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<tr>
<td>46</td>
<td>( \text{(dia of #n)} = 0.324860745 \times (0.890525717)^n )</td>
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<tr>
<td>47</td>
<td>( R = k * \frac{L}{A} )</td>
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</tr>
<tr>
<td>48</td>
<td>( \text{OI} = (8.64333333E-7) / \frac{WD}{WD} )</td>
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<td>( \text{OC} = \text{OI} / 2.54 )</td>
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<td>( \text{IN} = \text{LOG} (\frac{ID}{0.324860745}) / \text{LOG} (0.890525717) )</td>
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<td>( \text{ID} = 0.324860745 \times 0.890525717 \times \text{IN} )</td>
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<td>( \text{LK} = \text{exp}(\text{PA})/(107.23*(\text{PA}+0.194)*(\text{PA}+0.194)+191.5) )</td>
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<td>53</td>
<td>( \text{FLUX} = \text{AG} * \text{HA} )</td>
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<tr>
<td>54</td>
<td>( \text{FLUX} = (\text{AG} \times 0.4 \times \pi / G) \times \text{NA} )</td>
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<td>( \text{LOG} (\text{HI}) = \text{LOG} (\text{NI}) + \text{LOG} (0.4 \times \pi / \text{PL}) )</td>
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<td>( \text{LOG} (\text{NIa}) - \text{LOG} (\text{NI1})) / (\text{LOG} (\text{NIu}) - \text{LOG} (\text{NI1})) = \frac{(\text{Fa} - \text{Fl})}{(\text{Fu} - \text{Fl})} = \frac{(\text{NAa} - \text{NA1})}{(\text{NAu} - \text{NA1})} )</td>
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<td>( \text{NIa} = \text{NT} - \text{NAa} )</td>
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<td>( \text{KK} = \text{LOG} (\text{NIa}) + \text{AA} * \text{NIa} )</td>
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<td>( \text{AA} = (\text{LOG} (\text{NIu}) - \text{LOG} (\text{NI1})) / (\text{NAu} - \text{NA1}) )</td>
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<td>60</td>
<td>( \text{d}(\text{NT}) = \text{d}(\text{NA}) )</td>
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<td>61</td>
<td>( \text{BA} = \sqrt{\frac{\text{FT}}{\text{Kl} / \text{AG}}} )</td>
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<td>62</td>
<td>( \text{d}(\text{NA}) = \text{d}(\text{NA}) \times 2 )</td>
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<td>63</td>
<td>( \text{NT} = \text{NC} * \frac{V}{\text{CR}} )</td>
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<td>( \text{d}(\text{NA}) = \text{d}(\text{NA}) * (\text{NC} / \text{CR}) )</td>
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<td>( 1000 * \text{BA} = \text{HA} = 0.4 * \pi * \text{NA} / \text{G} / 2 )</td>
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<td>( \text{G} = 0.4 * \pi * \text{NA} / \text{BA} / 2000 )</td>
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<td>( \text{d}(\text{BA}) = \text{d}(\text{NA}) * (0.4 * \pi / \text{G} / 2000) )</td>
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<td>70</td>
<td>( \text{A} * \text{WW} ** 2 + \text{B} * \text{WW} - \text{CR} / \text{RW} = 0 )</td>
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<td>( \text{A} = \pi * \text{LW} * \text{W2} * \text{OC} )</td>
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<td>70b</td>
<td>( \text{B} = (\text{CP} + 2 * \pi * \text{W}) * \text{LW} * \text{W2} * \text{OC} )</td>
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1.1 Background

The design of electromagnets is an iterative process in which the designer arrives at a solution to his design problem through repeated design trials. This procedure can be time consuming, and the resultant design may, or may not, be the best one for the constraints imposed on it. In addition, the designer must have a reasonable knowledge of magnetics to carry out these design steps.

In the product design process, several elements are typically left until the end, with the hope that there is enough room to fit them in. While it would be very nice to know the final configuration for a design before the design process begins, this is never the case. Initial layouts are made, breadboards are built, and several elements are generally left until the end for design. Typically these include springs, electrical components, and electromagnets. Part of the reason for this is that these must be engineered, while the other elements are more creative, yet straightforward. Perhaps it is because of the lengthy calculations and understanding required that these elements are put off until last. After all, it is difficult to design a spring when the travel and force requirements are not
known. It is easier to define the physical requirements and then calculate to see if a solution exists. The problem of rearranging the simpler mechanical elements can then take place to accommodate any required changes dictated by the spring design.

An electromagnet is an order of magnitude more difficult to design than a spring, and designers qualified in the art of designing them are few. Some space is set aside for the electromagnet, but the actual calculations are put off. When it comes time to design the coil and the related parameters, the general attitude can be one of wrapping some coils around a nail to see what happens. If the nail supplies enough holding force, the design is complete. If it does not, either try a bigger nail or allow more room and try again.

1.2 Purpose of the Project

While this scenario is perhaps a little overstated, it is not far from reality for most designers. In addition, the electrical engineer is well-versed in how to calculate the inductance or resistance, but not the holding force. The mechanical engineer is no more knowledgable and often must review an old text book to relearn some long forgotten concepts.

The primary objective of this project is to prove, by example, the hypothesis that for any set of design constraints, there exists a maximum holding force
configuration. From the force equation which will be developed, this will be intuitively clear. The reader will realize that in the two extreme cases, zero force will exist. At one limit, if the entire available space is filled with core, no room will be left for coils. Then no force will be developed. Similarly, if the entire volume is filled with windings, a core will not be present. Again, no force will be developed. Between these limits, varying amounts of holding force can be calculated. The question is, for a given set of constraints, how high is the potential force, and what configuration of core and windings will produce it?

The second goal of this project is to develop an easy to use algorithm and computer program for designing the configuration of the maximum holding force, D.C. horseshoe shaped electromagnet, which is subjected to a set of prespecified constraints. The constraints must include overall dimensions, selected electrical limits, and other manufacturing considerations imposed as requirements. The method of entry must be clear and concise, and the resulting information sufficient to describe the coil in enough detail to manufacture a sample. Device related attributes should also be calculated.

The highest requirement, however, must be that the user should not have to understand the magnetics involved or the details of the program which performs the calculations. The instructions required to use the developed program must be
minimal enough to encourage its use.

With these goals in mind, the equation system required for analyzing a coil of the general size and shape being considered will be developed. With this background, a preliminary optimal design method will be developed, programmed, and numerically applied to a set of design constraints. While this first method will find the best possible solution to the problem, it will not be user friendly and method transparent.

To facilitate solution of the optimal design problem, curve fitting techniques will be applied to the tabular data normally used in the calculation process. A method of digitization for magnetic B-H curves will also be developed, which is simple to understand and easy to execute.

This base of information will then be used to develop a design algorithm and a highly user friendly computer program for use on an Apple II+ computer equipped with a monitor and disk drive. The program will make heavy use of the graphics capabilities of that machine to meet the user friendly requirements of the project. The completed package will not only design the highest force coil for the given constraints, but it can also analyze an existing coil for other characteristics of interest. It will also show the sensitivity of that design to variations in voltage supply and airgap length.

In the event that incompatible specifications exist,
methods for overcoming those incompatibilities will be suggested. In addition, the design which comes closest to meeting the requirements will be shown, thereby helping the designer decide which specifications should be changed to result in an acceptable design. This eliminates the NO DESIGNS FOUND problem of many commercial design packages for other elements.

As a check on the theory, several experiments with a commercially produced electromagnet will be conducted and compared to the computer predictions. Using the overall dimensions of the coil, the optimization method will be applied to show how the original design can be improved. As much as a fifty percent improvement will be calculated using some dimensional changes suggested by the program. It will be shown that the theory and actual practice do agree quite well, and it will prove that the methods developed have merit and a basis in fact.

Several new equations for determining airgap lengths and other information about a given design will be developed and used to explain the experimental data as well as the sensitivity graphs which are part of the computer output.

Finally, an analysis will be given for the B-H characteristics of sintered 50/50 nickel iron. While the data is incomplete, the information presented can be of use to some individuals. The information is not central to the main theme of this project; and therefore, its completion is
not necessary. However, enough new information has been collected to warrant inclusion in this report.

The automated design portion of this project is an application of the P519RE optimization program developed by Dr. Ray C. Johnson. The details of that program will not be discussed in depth, but the problems peculiar to this project will. For further information, Reference 1 should be consulted.

Many of the equations, presented in what follows, were developed specifically for this project. All equations are numbered sequentially throughout the text, and an equation number appears to the right of each. To the left of the equations will appear a reference, if appropriate. Those equations which are basic to magnetics are marked with a (B). These are so common that any text or reference manual on the subject will contain them. Any equation from a specific reference will be noted. All remaining equations are the original work of this author for the project being presented.
CHAPTER II
CONVENTIONAL METHOD OF COIL ANALYSIS

2.1 Introduction

Throughout this text, the example presented in this chapter will be applied to each of the methods described. This will provide a means of making direct comparisons and reduce the need for recalculating some of the values which need to be determined. Chapter II will present an analysis of an existing design using conventional methods. It will serve as a vehicle for reviewing the basic equations and units involved. Several extra steps will be performed in an attempt to present most of the equations needed later. These equations will be required by each of the two methods of optimal design developed for this design project.

Units of measure will be in the cgs system, with the exception of holding force, which will be in ounces. The cgs system was chosen over SI units because of the sizes of parts being considered. Force is given in ounces since the intended end user has not fully converted to the metric system and, therefore, would specify force in ounces.

Figure 1, shows the locations for all the physical dimension variables used throughout this paper. It is intended as a guide only and is not to be considered an actual assembly drawing. Many drafting rules, such as double
VARIABLE LOCATIONS

SECTION A-A

FIGURE 1
dimensioning, have been violated to fit all the variables on one drawing. For the first example, all of the variables except LO, DO, WO, PL and AP will be considered as givens. In addition, number 42 copper wire with a single build layer of enamel, will be used. Unless stated otherwise, numerical values shown apply to the project example only. They are not to be taken as constants which apply to all coil computations.

2.2 Number of Turns

Normally, the number of turns would be known, rather than the physical dimensions for the wire space. To show the equations which will be used later, however, the reverse will apply. Several items are needed to calculate the number of turns. The first is, wires per square centimeter, which can be found in standard wire tables. An example of a standard wire table page, showing single build enamel insulation for wire gages 14 through 44, is presented in Appendix G. Single build enamel insulation is the only type considered for this project. All equations and concepts, with the exception of those for determining insulated wire diameter and wires per square inch, are valid for other types. Single build enamel is normal for coils in the size range being considered here. The value of wires per area for #42 wire is given as 127,551 wires/sq-in or 19,770.4 wires/sq-cm. Using geometry and common units for each of the
the variables, the number of turns, NC, which will fit in a winding area cross section, is given by equation one.

\[ NC = LW \times WW \times RW \times W2 \]  

(1)

In equation (1), NC is the number of turns, LW is the length of the winding (0.825cm), WW is the winding width (0.0609cm), W2 is the wires/sq-cm (19770.4), and RW (1) is the random wind factor. For the numerical values given, equation one gives the number of turns as NC=993.

Random wind factors are used to compensate for the inability of a coil winder to fit the exact number of turns per area specified in the tables on an actual sample. This discrepancy may be due to factors such as crossed wires, winder tension, paper separators and so forth. Since these factors are very machine dependent, throughout this paper RW will be set at a value of unity. The programs and equations presented allow a value other than one to be entered. The standard wire table values assume that the wires are touching each other, and their centerlines are arranged to fall on the corners of a square whose sides are equal to one wire diameter. Therefore, the value for wires per square centimeter is equal to the inverse of the square of the outside diameter of the wire, including insulation. In addition, the packing efficiency for any diameter D is 0.7854 as determined by equation (2).

\[ \frac{\pi \times D \times D}{4} / (D \times D) \]  

(2)

In this equation, the denominator is the area available
to each wire, expressed as the diameter squared. The numerator is the cross sectional area of one wire. PI has the value, 3.14159. This packing efficiency is achievable on a properly set up, modern winding machine. As a comparison, if the wires were set in a hexagonal packing arrangement, the packing efficiency would equal 0.907. Therefore, there is some allowance for error built into the standard wire table values.

One assumption in the equation for the number of turns is that all of the cross sectional area of the windings is assumed to be used. In practice this is not the case, since there must be an integral number of wire diameters in the winding width. Any final design must account for this by having the flange width, FW, greater than the winding width. It is up to the designer to remember this fact when carrying out a production design, especially when winding widths are only a few wire diameters thick.

2.3 Other Geometrically Determined Values

Seven items can be calculated using simple geometry. They are core perimeter, CP; average path length, AP; core area, CA; overall depth, DO; overall width, WO; overall length, LO; and iron path length, PL. The equations are presented, without discussion, for later use.

\[
CP = 2 \ast (CD + CW + (PI - 4) \ast R) \quad (3)
\]

\[
AP = CP + 2 \ast PI \ast (W + WW / 2) \quad (4)
\]
\[ CA = I_1 * I_2 + 2 * I_1 * R + 2 * I_2 * R + PI * R * R \] (5)

where: \[ I_1 = CD - 2 * R \text{ and } I_2 = CW - 2 * R \] (5a)

\[ DO = CD + 2 * (W + FW) \] (6)

\[ WO = C2 + 2 * (CW + W + FW) \] (7)

\[ LO = LW + C1 + 2 * (CW + BF) \] (8)

\[ PL = 2 * (LW + FW + W + C1 + C2 + 2 * (BF + CW)) \] (9)

For values of CD=0.295cm, CW=0.3cm, FW=0.106cm, BF=0.15cm, 
C1=0.285cm, C2=0.07cm, R=0cm and W=0.064cm the seven 
calculated items are as follows.

\[ CP = 1.19\text{cm} \quad AP = 1.791\text{cm} \quad CA = 0.0885\text{sq-cm} \]

\[ DO = 0.635\text{cm} \quad WO = 1.01\text{cm} \quad LO = 2.01\text{cm} \]

\[ PL = 4.5\text{cm} \]

The values for overall length, width and depth will be 
used repeatedly in this paper when the optimal design methods 
presented are used to find solutions which give higher 
holding forces than the production design being discussed now.

2.4 Amp Turns

The function of an electromagnet is to convert 
electrical energy into a magnetic field which can be used to 
perform some mechanical work. Before any calculations for 
the magnetics can be carried out, the values which determine 
the magnetomotive force must be known. This force is 
proportional to the current in the coil, CI in amps, times 
the number of turns, NC. It is, therefore, necessary to
calculate CI, using the fundamental electrical identity of equation (10).

\[ CI = \frac{V}{CR} \quad (10) \]

The coil resistance, CR, is found using equation (11), where the resistance of an average turn of wire is multiplied by the total number of turns.

\[ CR = NC \times (AP \times OC) \quad (11) \]

Turning to the wire tables, the ohms per centimeter, OC, is found to be 0.0544 ohms/cm for #42 wire, which is equivalent to 1.659 ohms/ft. Thus, for the values already given, the total coil resistance, CR, is equal to 96.8 ohms. For the three volt sample being considered, this results in a current requirement of 0.031 amps. Multiplying this current by the number of turns, yields a total of 30.8 amp-turns.

While these equations, which lead to total amp-turns, NT, are correct, some manipulating of them will result in a more compact form for later work. Combining equations (10) and (11) and multiplying by NC turns gives equation (12).

\[ NT = NC \times \frac{V}{NC \times AP \times OC} \quad (12) \]

Cancelling out the common NC term leaves the final form shown by equation (13).

\[ NT = \frac{V}{AP \times OC} \quad (13) \]

This shows a very important fact about total amp-turns. The value is dependent on the voltage, wire size and average (or mean) turn path length only. Number of turns will determine the coil resistance, but has no bearing on the
total number of amp-turns in the system. Thus, once the dimensions which determine Section A-A in Figure 1 have been specified, the electrical resistance and current will be (inversely) proportional to the winding length, LW.

2.5 Magnetic Concepts and Units

At this point, all of the non-magnetic equations have been presented, which are required for determining the characteristics of the example being considered. Before examining the remainder of the problem, some concepts and terms regarding magnetics should be reviewed. Only units in the cgs system of measurements will be shown, with little more than a brief explanation of the concepts. It is assumed that the reader has already been exposed to the basic equations relating to magnetics, and needs only a quick review.

When an electric current passes through a conductor, it sets up a series of closed loop paths of magnetic flux lines about it, which follow the right hand rule. These lines are measured in Maxwells. The density of that flux is represented by the letter B and its units are Maxwells per square centimeter or Gauss. This flux density is directly related to the magnetizing force, H.

\[
B = \mu_0 H
\]  

(14)

The (constant) \( \mu_0 \) is a characteristic of the material called its permeability. Magnetizing force, H, is directly
proportional to the magnetomotive force (mmf) mentioned earlier.

(B) \[ H = \frac{(0.4 \times \pi \times \text{amp-turns})}{L} \]  \hspace{1cm} (15)

In equation (15), \( L \) is the length of the material through which the flux must pass and the numerator is the mmf. Units of mmf are Gilberts and of \( H \) are Oersteds.

An additional concept, which is often presented, is that of the reluctance of the material. This is a measure of a materials' resistance to pass flux.

(B) \[ \text{REL} = \frac{L}{\mu} \times \frac{1}{A} \]  \hspace{1cm} (16)

Variable \( A \) is the cross sectional area of the material.

Combining (14), (15), and (16) yields:

(B) \[ \text{FLUX} = B \times A = \frac{\text{mmf}}{\text{REL}} \]  \hspace{1cm} (17)

(B) \[ \text{FLUX} = \frac{\text{mmf}}{\text{REL}} \]  \hspace{1cm} (18)

When trying to learn these relationships, it can be very helpful to draw an analogy between the magnetic equation system and an electrical one. Thus, the mmf can be considered analogous to the electromotive force, volts; flux to current; reluctance to resistance; flux density to current density and permeability to conductivity. Carrying the analogy one step further, when several reluctances are connected in series, they can be added together to produce an equivalent reluctance. Finally, magnetic flux, like electrical current, must be conserved. This is analogous to the Kirchoff law for current. Therefore, the sum of the flux entering a node must equal the sum of the flux leaving that
node.

Unfortunately, the total electrical analogy is good for conceptualizing the magnetic properties only. For air, the value of $\mu$ is constant. In the cgs system, that constant is conveniently equal to 1. Air, however, is not a good flux conductor, and therefore, a high permeability material like iron is required to produce a useful magnetic circuit. This is where the problem with the concept and practical calculations comes in.

2.6 D.C. Magnetization Curves

Figure 2 shows a D.C. magnetization curve for solid 50/50 Nickel Iron. This is a graphical representation of the initial relationship between $B$ and $H$ for a virgin sample of that material. As can be seen, the value of $B$ is no longer related to the magnetizing force, $H$, by a constant $\mu$, but rather $\mu$ is a function of $H$. For the bipolar electromagnet being studied, the total mmf must still be divided between the metal path and the two airgaps as the analogy to the electrical circuit suggests, but the reluctance of the metal is dependent on the applied mmf. It is this fact that makes a mathematical determination of the mmf distribution very difficult, and is the reason a graphical or an iterative approach is used to solve a magnetic problem. Additional material curves are presented in Appendix H for reference.
DC Magnetization Curve for 50/50 Nickel-Iron

Intrinsic Induction $B_i$ - Kilogausses

Magnetization Force $H$ - Oersteds

Figure 2
2.7 Fringing Effects at the Magnet Poles

With this fleeting description of the magnetic concepts, the example problem can now be completed. Before continuing, however, it is necessary to introduce one more concept called fringing. When the flux is in a high permeability material like the metal core of an electromagnet, it is reasonably well confined within that material. When the air is entered, however, the flux has a tendency to spread out slightly, thereby increasing the area over which it is spread. An approximation of this increased area can be made by adding a band equal in width to one half of the airgap around the perimeter of the core area (Ref 2). Thus the equation for the area of the airgap, AG, is given by equation (19).

\[ AG = I_1 * I_2 + 2 * I_1 * I_3 + 2 * I_2 * I_3 + \pi * I_3 * I_3 \]  

where \( I_3 = R + G / 2 \)  

Variable \( G \) is the length of one airgap. If \( G \) is set to 0.0015cm, then AG is equal to 0.0894sq-cm, for the example being considered.

2.8 Determination of Amp Turn Distribution

The next step is to determine the number of amp turns which are in the airgap, \( NA \), and the number which are in the iron, \( NI \). The two are related by equation (20).

\[ NT = NA + NI \]  

(B)
Since the relative amounts in each is unknown, an iterative approach must be used. To avoid a completely random starting point, a first guess can be arrived at by making two extreme assumptions. The first would be to assume that all the mmf is in the air. The second, that all the mmf is used in the iron. Either assumption will result in flux densities which are too high. Therefore, a value slightly lower than the smaller of the two can be used as a first trial.

If it is first assumed that all the mmf is in the air then the flux density in the air, BA, by equations (14) and (15), would be that shown by equation (21).

\[
BA = HA = 0.4 \times \pi \times NT / (G \times 2)
\]  

(21)

In this case, HA stands for the magnetizing force, H, in the air. Since \( \mu \) for air is unity in the cgs system, BA is equal to HA by equation (14). The gap, G, is multiplied by 2 because there are a total of 2 airgaps in the system whose combined length is twice G. Plugging in the appropriate values results in a flux density in the air of \( BA = 12,901 \) Gauss, for the example.

If it is now assumed that all the mmf is in the core, then the magnetizing force in the iron, HI, can be calculated.

\[
HI = 0.4 \times \pi \times NT / PL
\]  

(22)

For the values given, \( HI = 8.6 \) Oersteds. Referring to Figure 2, this would correspond to a value of slightly more than 14,000 Gauss for BI.
Since the magnitude of BA is the lower one, as a first guess, try a flux density of 12,500 Gauss. By Figure 2, this corresponds to a value of 1.2 Oersteds in the core, which, by equation (15) is 4.3 amp-turns. As was mentioned previously, flux in a magnetic circuit must be conserved at any node, as current is in an electrical circuit. Therefore, BA = FLUX / AG and BI = FLUX / CA by eqn (17) or by combining these two,

\[ BA = BI \times CA / AG \] (23)

Plugging in the previously determined values indicates that BA = 12,374 Gauss. From eqns (14) and (15) it can be found that NA would equal 29.54 amp-turns. Equation (20) then would indicate that the total amp-turns for the system with this first guess would be 33.84. The number available is only 30.8, so it can be seen that this first guess is too high.

A second guess of 11,500 Gauss in the iron would require only 29.15 total amp-turns. Interpolating between these two guesses would produce a third guess of 11,852 Gauss. Repeating the calculation process a third time yields a total required amp-turns of 30.52. This is well within the ability to accurately read the magnetization curve, and therefore, the final answer would be given by the following.

\[ NA = 2.51 \text{amp-turns} \quad NI = 28.01 \text{amp-turns} \]
\[ BI = 11,852 \text{Gauss} \quad BA = 11,733 \text{Gauss} \]
2.9 Holding Force

Now, to calculate the primary item of interest. The equation for holding force per airgap is given as by equation (24).

(B) \[ F = K_l \times B_A \times B_A \times A_G / 2 / (\mu \text{ for air}) \] \hspace{1cm} (24)

For the example being considered, \( \mu \) is equal to 1, and there are two airgaps. Therefore, the total force will be twice that specified for each airgap in equation (24). \( K_l \) is a constant which is dependent on the units used. Since this project is mixing the cgs units with force in ounces, the value of \( K_l \) becomes 2.8696831. Combining these facts with equation (24) produces a total force, \( F_T \), for a bipolar electromagnet given by equation (25).

\[ F_T = K_l \times B_A \times B_A \times A_G \] \hspace{1cm} (25)

Plugging the appropriate values of \( B_A \) in kilogausses and \( A_G \) in sq-cm into the equation gives

\[ F_T = 35.32 \text{ ounces} \]

for the example being considered.

2.10 Flux Leakage or Loss

This answer is not entirely correct. In addition to fringing effects which have been accounted for, there are losses of flux through various leakage paths. One set of these paths is directly between the two poles of the magnet. The leakage here is zero at the base (yoke) of the core and increases linearly along the length of the poles.
Integrating along the length reveals that the total leakage between the two poles is given as by equation (26), (Ref 3).

\[
\text{INTERPOLAR FLUX LEAKAGE} = \left( \frac{p \times h}{2} \right) \times NT \times h \quad (26)
\]

(R3)  

Here, \( p \) is the direct leakage permeance between the pole cores per inch of axial length and \( h \) is the total length of each pole. In addition to this leakage between the poles, there are a complex set of leakage paths between the armature and the length of the poles which protrude beyond the bobbin. Due to the dependence of these leakages on geometry of the parts and other factors, the calculation of the total flux leakage becomes a non trivial task. The reader is referred to articles 46, 54 and 55 of the text by Roters for a more detailed explanation. For the scope of this project, the flux loss will be assumed to be equal to a constant 20\% for any design. This leaves 80\% of the calculated flux for doing useful work at the airgap.

It must be remembered that when calculating the amount of flux the core can carry, that the base (yoke) is passing all of the flux calculated. It will saturate first, and is, therefore, the limiting factor. The 80\% factor must apply only when calculating force, and since the force is proportional to the square of the flux density, only 64\% of the calculated, no leakage force will be available.

Applying the 64\% factor to the previously calculated \( FT \) leaves a total expected force for the example of:

\[
FT = 22.6 \text{ ounces}
\]
It can be seen that these losses are a significant factor, and cannot be ignored.

One possible improvement to the design suggested by this discussion would be to have tapered poles, with a large cross section at the base to carry the higher level of flux. This would result in a tapered bobbin, which would be difficult to wind in actual practice, and also cause other manufacturing problems. Since the aim of this project is to provide a simple means of designing practical electromagnets, the task of investigating this possibility will be left to some other inquisitive mind. Many of the equations presented here and in other texts would not apply in this case and a return to the fundamental equations and concepts would be required.

2.11 Thermal Considerations

Now that the coil has been analyzed for holding force and other parameters, it would be easy to conclude that the job is done. Unfortunately, factors other than holding force and physical dimensions can make an otherwise acceptable design incompatible with its intended function.

Frequently, heating is the predominant problem with an electromagnet design. A more detailed explanation of the discussion which follows may be found in Reference 4. Of particular use are the graphs and charts for the various constants. These are highly dependent on certain assumptions
which need to be made. If the assumptions made for this project do not meet the situation dictated by a particular application, the designer must refer to the reference for guidance in changing the equations presented here. All equations shown in section 2.11 are from this same reference unless otherwise stated.

When an electromagnet is energized, the power input may be used to do some work. Once the system is in equilibrium, all of the energy must be dissipated as heat. Some of this heat will be stored in the coil and those elements which are in good thermal contact with the windings. The amount stored will be related to the thermal capacity, \( C \), of each of those components. The remaining heat will be dissipated into the surrounding air. The rate at which this dissipation occurs is dependent on the temperature difference between the coil and the air and on the heat dissipation capacity, \( K \). The units of power, \( P \), are watts, of \( C \) are joules/deg-C, and of \( K \) are watts per degree-C. They are related at any instant in time by equation (27), in which \( TT \) is the difference between the average coil temperature and the surrounding air in degrees centigrade.

\[
(P4) \quad P = (C \ast (dT/dt)) + (K \ast TT) \quad \text{(27)}
\]

The term \( K \ast TT \) is that part of the total power dissipated by the coil while the \( C \ast (dT/dt) \) term is that absorbed by the thermal capacity.

If the equation is rearranged and integrated, and the
initial condition of $TT = 0$ at $t = 0$ inserted, the resulting equation (28) is found.

\[ \text{LOG} \left( \frac{P - K \cdot TT}{P} \right) = -\frac{(K \cdot t)}{C} \quad (28) \]

Taking the antilogarithm of both sides gives the desired form of the equation.

\[ TT = \frac{P}{K} \cdot (1 - \exp(-\frac{(K / C) \cdot t})) \quad (29) \]

An engineer will immediately deduce several pieces of information from equation (29). The first is, when $t$ is very large, $TT$ will reach a steady state temperature, $ST$.

\[ ST = \frac{P}{K} \quad (30) \]

$ST$ is the final temperature difference between the coil and the surrounding air in degrees C. Because the equation is of an exponential form in $t$, the temperature rise will have a time constant of

\[ TC = \frac{C}{K} \quad (31) \]

$TC$ is the value of one time constant in seconds.

While these equations are correct, the values of the constants are dependent on the geometry of the bobbin and core. To remove this dependence, another factor called the heat dissipation coefficient, $LK$ is introduced. This is the watts which can be dissipated per square inch of coil surface area per degree C temperature difference between the average coil temperature and the surrounding air. When plotted against the watts per square inch of surface area, $PA$, a family of curves results. Each curve is dependent on the relative thermal contact between the core (or other heat
sink) and the windings. From the values obtained, \( P \) and \( K \) can be found from the following relationships.

\[
\begin{align*}
K &= SM \times LK \\
}\tag{32}
\end{align*}
\]

\[
\begin{align*}
P &= PA \times SM = CI \times V \\
}\tag{33}
\end{align*}
\]

In the above equations, \( SM \) is the surface area of the coil in square inches.

Bobbins for small electromagnets are usually of a plastic material, which may be considered a thermal insulator. Therefore, poor thermal contact has been assumed for the heat dissipation coefficient in this project. This will be better as a worst case during the design phase of a coil even if better thermal contact is present, as it will predict a higher final temperature and thereby call attention to a marginal condition. The curve fitting of \( LK \) versus \( PA \) for a coil in poor thermal contact with its core for use in the computer programs of this project is discussed in Chapter IV.

The remaining thermal constant, \( C \), is calculated using equation (34).

\[
\begin{align*}
C &= 180 \times WT \\
}\tag{34}
\end{align*}
\]

This equation assumes that the windings account for all of the energy which is stored by the coil. If a heat sink is present, the heat capacity of the heat sink will have to be accounted for by modifying equation (34). Also assumed are copper wire windings. Since the thermal capacity of copper is 180 joules/lb/deg-C, it is only necessary to multiply this
constant by the weight of the copper in pounds, WT, to arrive at the thermal capacity, C, measured in joules per degree C. For comparison, the constant of 180 would change to 433 for aluminum, 225 for steel and 200 for brass.

The weight of the wire, WT, is found by multiplying the volume of the wire by the pounds per cubic centimeter of copper. It should be pointed out that the insulation is assumed to be negligible for the enamel coated wire. Combining a copper density of 0.019589 pounds per cubic centimeter and the wire packing density of 0.7854 * RW with the winding volume factors, gives equation (35) for calculating the wire weight in pounds.

\[
WT = 0.015385 \times AP \times WW \times RW \times LW \times PI / 4 \quad (35)
\]

The surface area of the windings can be derived simply from the geometry of the coil. It will be equal to the length of the windings, LW, times their outside perimeter. Since the average turn length, AP, is already known, the outside perimeter can be calculated easily. Equation (36) gives this perimeter and is based on a recognition of the fact that the difference between it and the average turn length is the circumference of a circle whose radius is half the winding width.

\[
WP = AP + PI \times WW \quad (36)
\]

The surface area in square centimeters is now given by equation (37).

\[
SA = M \times LW \times WP \quad (37)
\]
Variable M is a multiplier for the number of coils. For the example problem, M = 1. Because the various constants are given in terms of square inches, the conversion must be made to these units. Equation (37a) converts SA sq-cm to SM sq-in.

\[
SM = \frac{SA}{2.54} = \frac{SA}{2.54} 
\]

(37a)

When the values of the variables which have been previously calculated are used in the above equations, the following results are obtained for the example being considered.

\[
WP = 1.9823 \text{cm} \quad SA = 1.6354 \text{sq-cm} \quad SM = 0.2535 \text{sq-in} 
\]

\[
P = 0.093 \text{watts} \quad PA = 0.3669 \text{watts/sq-in} 
\]

\[
WT = 0.00111 \text{lbs} \quad C = 0.1957 
\]

Using the chart in Ref 4, for the value of PA calculated, LK is 0.0064 watts/sq-in/degC. With this information, the remaining items can be calculated.

\[
K = 0.00162 \text{watts/degC} \quad ST = 57.3 \text{degC rise} 
\]

\[
TC = 120.8 \text{sec} 
\]

Enamel insulation can operate at temperatures of up to 90 degrees C before it begins to degrade (Ref 4 and 5). Since all of the constants and equations developed in this section assume an air temperature of 20 deg C, a steady state temperature rise of 70 deg C should be avoided. If the geometry of the available space will not permit a lower temperature coil to be designed, then the time to reach a 70 degrees Celsius temperature rise cannot be exceeded.
Equation (29) can be rearranged to find the time to reach 70 deg C.

\[ t = -\frac{C}{K} \times (\log(P / K - 70) - \log(P / K)) \] (38)

Since the steady state temperature rise for the example shown is less than 70 deg C, this equation will not be used.

When a coil heats, the resistance of the copper increases. As a result of this change in resistance, the current drawn will decrease for a constant supply voltage. Depending on the amount of heating experienced, this effect can be significant. The nominal resistance values given in the standard wire tables assume a temperature of 20 degrees Celsius, which agrees with the assumed operating temperature of the coils in this paper. Resistance values at other temperatures are determined by equation (39).

\[ RE = CR \times \frac{T + 234}{254} \] (39)

In this equation, \( RE \) is the resistance at the (elevated) temperature and \( T \) is the coil temperature in degrees Celsius. Once the new resistance is known, the coil characteristics can be recalculated to determine the effects of the elevated temperature on them.

For the example being considered in this chapter, the steady state temperature rise is given as 57.3 degrees. Since the ambient temperature is 20 degrees, the final coil temperature is 77.3 degrees Celsius. Plugging this value for \( T \) into equation (39) results in a coil resistance of 118.6 ohms at the elevated temperature. This results in a
reduction of the coil current from 0.031 amps to 0.025 amps, and the total number of amp-turns is, therefore, reduced to 24.8 from the 30.8 calculated previously. The net result is a twenty percent loss of holding force.

All of the thermal data has now been presented. One modifier, worthy of note, is that if one or more surfaces of the coil are insulated from the surrounding air, the surface area should be reduced accordingly.

2.12 Other Items of Interest

Only a few items remain which might need to be looked at when analyzing a coil. If the inductance of the coil is needed, such as, when calculating a decay time constant in the electrical circuit, the equation for that inductance in henries, LH, is as follows.

\[ LH = NC \times \text{(FLUX IN WEBERS)} / CI \]  \hspace{1cm} (40) 

By equation (17), the flux in maxwells is given as \( BA \times AG \). To convert to webers, the maxwells must be divided by \( 1E8 \). Therefore, for the units being considered in this project, the inductance, LH, can be found by equation (41).

\[ LH = NC \times BA \times AG / 100000 / CI \]  \hspace{1cm} (41) 

For the constants calculated, \( LH = 0.336 \) henries

Another item is residual magnetism. This can be a significant factor in some design situations. It is not considered by this project, however. To calculate the residual force, the hysteresis loop for the full B-H curve
from the operating point on that curve must be known. The remnant flux density found at NI = 0 is then inserted into the force equation to find the residual magnetism. Since this factor is so dependent on the previous history of the coil, and the full B-H curves not readily available for every operating point; and since this does not affect the maximum holding force coil which will fit in a given volume, the topic is not covered in detail. It is somewhat covered by allowing a maximum flux density to be specified during the design process, which will be covered later.

2.13 Conclusions

This concludes the discussion of a conventional design and analysis of a bipolar D.C. electromagnet. To arrive at a better design, the product designer would now have to assume new dimensions for the various parts and recalculate the expected holding force and other items of interest. These design trials would continue until an assumed optimum had been reached or the individual stops looking. The remainder of this paper will be devoted to developing two optimization methods which relieve the designer of these iterations. The second method requires no knowledge of magnetics to use.

The example presented in Chapter II is based on a production coil. Assuming that the original designer performed some type of optimization, the methods to be presented will be used to show how that designer could have
benefitted from their use. Holding force improvements of up to fifty percent will be calculated for constraints which match the limit constraints on volume, voltage and current of the production design.

It would be possible to verify the temperature rise in the coil by either measuring the value directly with a thermocouple or using a wheatstone bridge to determine the resistance change. While this has not been done, experience with the assembly used for demonstration in this chapter indicates that the predicted steady state temperature is too high. The most likely reason for this can be found in the assumptions which lead to the surface area of the coil.

As suggested by Reference (4), the outside surface of the coil has been treated as smooth, with an area equal to the length of the windings times their outside perimeter. In actuality, the surface area is at least 57% larger than this due to the radius of each wire. This conclusion is based on half the circumference of a wire divided by its diameter.

Since the temperature rise is approximately proportional to 1.1 times the surface area, the final temperature rise might be better approximated with a value which is 2/3 of that predicted in this chapter. Without the required experimental data to support this, no changes will be made to the heat equations in this paper, even though experience would dictate otherwise. This will be left for future study.
CHAPTER III
INITIAL INVESTIGATIONS AND FIRST OPTIMIZATION METHOD

3.1 Introduction

Before submitting the design project proposal, a feasibility study was conducted to determine the relative merits of the chosen topic. Its purpose was to answer three basic questions. 1) Is there an optimal design for a given set of design constraints? 2) Is this solution unique or is it a family of equivalent designs? 3) How sensitive is the design to changes in the independent variables? This chapter will show that there is a unique optimum solution for the set of constraints given and that it is sensitive to changes in the independent variables.

A preliminary look at the equation system presented in chapter II, reveals a set of equations which are so complex that a normal differentiation of them, with respect to each of the independent variables, does not end in meaningful results. The variables are so inter-related that it is difficult to separate the effects of one from another. In addition, because of the iterative loop to determine how many of the amp-turns are in the iron and how many are in the air, the equation system is not a straight forward one. Rather, it is two sets of related equations with an unknown function joining them.
Because of these difficulties, a graphical approach was chosen as a preliminary method for use in the feasibility study, and will be presented here. A very simple computer program, similar to that in Appendix A, was written and used for this study. During this feasibility stage, the curve fitting equations which are included in the Appendix A program, had not been developed yet. As a result, wire constants were contained in an extensive look up table. The simpler form has been presented for compactness. Chapter IV will discuss these curve fits in detail.

A close examination of the equations presented in the previous chapter reveals that if those items, which are determined by the manufacturing processes, are held fixed, there remain only six independent variables which uniquely describe the coil. The process dependent variables are: BF, Cl, C2, W, V, RW, and G. This leaves FW, CD, CW, R, LW and WG (wire gage) as the independent variables. FW will be set equal to WW for the remainder of this paper. It is up to the user to add the necessary difference to Cl and subtract it from the overall width and depth allowed to guarantee a manufacturable design.

When setting up the optimal design methods, an attempt was made to anticipate what requirements would exist for an individual trying to fit a maximum holding force electro-magnet in a given volume. At the onset of the design process, the dimensions for the core are unknown.
Therefore, specifying a range on flange width or winding length would not necessarily yield a design which would fit within the bounds. For this reason, overall length, width and depth limits need to be specified rather than FW and LW. Ranges on the remaining independent variables would need to be defined, as well as the values for the process dependent variables. With these concepts in mind, the first optimal design method was developed and the presentation of it follows.

3.2 Assumptions for the First Optimization Method

Because of the two dimensional nature of the graphical solution, all six of the independent variables cannot be varied at one time. Thus, several must be held constant while the others are allowed to vary. The graphs which will be presented hold coil current, voltage, core area and overall depth constant. The core width and overall width then become directly dependent on the core depth, while the overall length and total amp-turns are a function of both the core depth and wire gage.

Several engineering assumptions and simplifications have been made for this first method. One of these assumptions is that as the total amp-turns increases, the amp-turns in the core will also increase. Since the magnetization curves for any material have values for B which monotonically increase with increasing H, this is a
valid assumption. This is further supported by the molecular model of magnetization (Ref 6), which states that, as the field is initially applied, some of the atoms within any given grain readily align themselves with that field. Interactions between neighboring atoms and grains, however, keep some of the atoms in an alternate orientation. It takes a higher incremental applied field to produce a given change in the B field as H is increased, until a saturation level is reached. This can be considered the point when all of the atoms are arranged parallel to the applied field, and no additional flux can be carried by the material.

This atomic model also explains the hysteresis loop of a full B-H curve which will not be considered in this paper. It will be considered the responsibility of the designer to analyze the effects of this hysteresis loop on the final design. The assumption is made that the material being used is fully demagnetized before use, and therefore, only the initial magnetization curve needs to be considered. Neither residual magnetism nor coercive forces are analyzed.

With the first assumption that as the total amp-turns increase so do the amp-turns in the iron, the breakdown of where the amp-turns are divided can be ignored as a first engineering approximation. Two other simplifications are that the corner radii on the core are equal to zero, and the area of the gap, AG, is equal to the core area, CA. For the small air gaps involved, setting these areas equal is
reasonable since the additional area created by the half gap perimeter around the core pole is negligible. In chapter XI, it will be shown that the optimal design will aim for corner radii of zero, and therefore, the other simplification is also reasonable.

3.3 First Optimization Method

Using these assumptions and simplifications, the calculating process can begin. Since the core area is being held constant, then for any given core depth, the core width will be defined by:

\[ CW = \frac{CA}{CD} \] (42)

The flange width, FW, can be determined by rearranging equation (6) and setting DO equal to the maximum allowable depth.

\[ FW = \frac{(DO - CD - 2 * W)}{2} \] (43)

All of the unknowns in equation (7) have now been determined, so WO can be calculated. Similarly, CP, NT and AP can be calculated by equations (3), (12) and (4).

The only remaining unknown is LW. For the design method being considered, coil current, CI, is being held constant. By a combination of equations (1),(10) and (11), LW can be determined.

\[ LW = \frac{V}{CI} \div \frac{FW}{RW} \div \frac{W2}{AP} \div \frac{OC}{2} \] (44)

Now that the winding length has been determined, the total path length for the metal, PL can be calculated using
equation (9).

All of the characteristics of the coil for any given core depth have now been determined, or could be calculated, if desired. The heart of the first design method lies in bringing together the assumptions made earlier with only those values which have been calculated thus far.

One of the assumptions made is that the flux density increases monotonically with the applied magnetizing force. Since this magnetizing force is directly proportional to the amp-turns in the iron, and since another assumption is that as the total amp-turns, NT, increase, so do the number of amp-turns in the iron, it follows that increasing the total amp-turns increases the flux density. By equation (22), the magnetizing force, H, is also inversely proportional to the metal path length, PL. Therefore, it should follow that the flux density will increase as the quotient, total amp-turns divided by PL, increases.

3.4 An Example of the First Method

The situation now exists that for any given wire gage and core depth, a unique value of NT/PL will be determined. Figures 3 through 5 show example plots of these values for three different core areas and a range of wire gages. These values have been calculated by the program in Appendix A.

Maximum overall length, width and depth, as well as the operating voltage and current, are set equal to the values
TOTAL AMP TURNS / IRON PATH LENGTH

FIRST DESIGN METHOD \( \frac{W_{\text{Core Area}}}{0.09 \text{ cm}^2} \)
OVERALL DEPTH = 0.635
CORE AREA = 0.1225
C1 = 0.285  C2 = 0.07
BF = 0.15  RW = 1  R = 0
V = 3 volts  CI = 0.035Amp

FIRST DESIGN METHOD  \%
CORE AREA = 0.1225 cm²

TOTAL AMP TURNS / IRON PATH LENGTH

FIGURE 4
FIRST DESIGN METHOD \( w/ \text{CORE AREA} = 0.16 \text{ cm}^2 \)

OVERALL DEPTH = 0.635
CORE AREA = 0.160
C1 = 0.285  C2 = 0.07
BF = 0.15  RW = 1  R = 0
V = 3 volts  C1 = 0.035 AMP

OVERALL WIDTH = 1.01

WIRE GAGE NO.

TOTAL AMP TURNS / IRON PATH LENGTH

FIGURE 5
obtained from the production design presented in chapter II. Those points which produce overall lengths which are less than or equal to the specified maximum overall length of 2.01 are emphasized. The locus of those end points is then joined with the dotted curve. All designs which satisfy the maximum length requirement must fall inside of the parabolic shaped, dashed curve shown. In addition, the maximum overall width of 1.01 is plotted. All designs which satisfy this requirement must fall above that line.

Ignoring the metal (also called iron) magnetization curve for a little while longer, it should follow that the maximum holding force coil for any given core area will occur at the maximum value of NT/PL which meets all of the design constraints. Because discrete values of core area have been used and the best possible answer for a design will probably occur between them, intermediate wire size values must be considered for each core area plot. The results of the calculations which follow for the best answer from each core area graph can then be plotted and the optimum core area deduced.

Figure 3, with core area equal to 0.09 sq-cm will be used to demonstrate a method of finding the intermediate wire size number for the maximum NT/PL design. It can be seen that this occurs at the point where the dashed line representing a length of 2.01 and the line for maximum width cross. Dropping down to the horizontal axis indicates an
absissa of 8.9 NT/PL. Since this design falls on the curve for the overall length equal to 2.01, LW can be determined from equation (8) by setting LO = 2.01. Using equation (9), PL can be found to equal 4.495. Multiplying NT/PL by PL results in a total amp-turns of 40.1. The current draw for the coil was previously set to 0.035 amp as one of the constants for the plot. Dividing the total amp-turns by this number of amps gives 1143 as the number of turns on the coil, NC. With this information, the wires per square centimeter, W2 can be found using equation (1). From a previous discussion it is known that:

\[ W2 = \frac{1}{ID / ID} \]  \hspace{1cm} (45)

where ID is the diameter over the insulation of the wire.

With this identity, the insulated diameter, ID, is determined to be equal to 0.0086 cm. Interpolation on the wire tables or the use of an equation which will be developed in chapter IV, reveals that this ID nominally corresponds to a wire gage of 40.43.

All required inputs for determining the holding force of the maximum NT/PL design are now known. Because the saturation effects of the B-H curve for the iron are being ignored, NT/PL would be directly proportional to B. Since the total developed force, as defined by equation (25), is proportional to CA and to the square of B, squaring NT/PL and multiplying by CA should give an indication of final holding force. The value calculated for each graph of core area
can then be compared and the best design found.

Unfortunately, the B-H curve cannot be ignored. Figure 6 shows both this assumed equation and the actual ideal holding force, as a function of core area, for each of the maximum NT/PL designs from Figures 3, 4 and 5, as well as an additional sample at a core area of 0.0625 sq-cm.

As can be seen, the curves agree closely when the core area is reduced from the largest being considered, until the maximum holding force is reached. The assumed equation then continues to rise while the holding force drops back off rapidly. Later examples with the final optimization method will show that the best design occurs at the knee in the force curve, where B no longer increases rapidly with increased H, yet CA is as large as possible while still permitting the high value of B to be achieved.

3.5 Conclusions

In conclusion, a core area of slightly less than 0.1225 sq-cm seems to be the maximum force design which is allowed by the design constraints. The wire size will be slightly less than 41.5, and the core approximately square. This last conclusion comes from an examination of the values for CD and CW next to each plotted point. Everything to the left of the peak is square, while to the right there is a gradual deviation from square. Since a square has the smallest perimeter for a given area, examination of equations (3), (4)
Comparison of Highest Force Designs

Common Requirements:

- DX = 0.635
- WX = 1.01
- LX = 2.01
- C1 = 0.285
- C2 = 0.07
- BF = 0.15
- RW = 1
- R = 0
- V = 3 volts
- CI = 0.035 amp

![Graph showing theoretical holding force vs. core area](image)

Figure 6
and (13), indicates that a square should maximize NT for any core area selected. The constraint on overall width is causing a deviation from this at larger core areas as seen in Figure 5.

Taken collectively, figures 3 through 6 imply that the solution found is unique. The parabolic curves of figures 3 through 5 look very much like conic sections. If these graphs were replotted in force and stacked to create a three dimensional figure, they would form a steep hill for each wire size. Figure 6, which represents the locus of peaks of those hills shows, that there is one which is definitely higher than the rest. Thus, the solution can be considered unique for a given set of constraints. The only time two equivalent solutions would occur is if two different wire lines in figures 3 through 5 crossed precisely at the maximum solution point.

To determine the exact solution, several more charts like Figures 3 through 5, would have to be generated until the best design is found. If a whole number is required for the wire size, designs would have to be limited to falling on a wire line. One of the advantages of this method is that it permits the designer to see graphically which direction to move in to meet additional design restrictions. It can also be seen which constraints should be opened up to allow for more possible choices. For example, referring to Figure 4, it can be seen that increasing the maximum overall width or
length, or some combination of both, would give a higher force design, which would fall on an integral number wire gage line. A case of incompatible specs could also be found. It is conceivable that a set of constraints could exist where no feasible designs could be found. The graphical approach shown would indicate that and the direction of changes for solving the incompatibility could be seen.

The method also has some disadvantages. One is that the overall depth has been set to the maximum. Using overall width as an example on Figure 4, had it been set to 2.0, the best design would have occurred at an overall width of 1.134 and not the maximum 2.0 allowed. In addition, number 41 wire would be used instead of 41.5. Thus, the final design is not always at the maximum space allowed. Similarly, the best design may not always be at the maximum overall depth, but rather at some other value. To determine if this is the case, another set of (3) graphs at some lower maximum overall depth would have to be constructed and compared to the first. At least three sets would have to be constructed to find the best operating point.

Likewise, a change in any of the other givens, such as voltage, would require a new set of charts unless the current is scaled proportionally. The biggest drawback is that the method does not meet the basic goal of this project, which is to have the method independent of the users' knowledge of it or magnetics. The method described is excellent for use by a
non-novice who wants to determine what options are available for changing a final design.

One feature, which was not possible to show with the scale of the graphs in this paper, is the placement of the overall length dimensions next to each wire curve at each core depth. Originally, this work was done at a larger scale to permit this, and a better feel for the rate of change of the length could be obtained. With the graphs shown, the 2.01 limit line is treated as an absolute. It is necessary to refer to the computer printout for the intermediate values, and information is lost in the transaction.

While it might be possible to computerize the graphing function, and thereby reduce the time required for the method, it was felt that other methods would be better suited for use on a digital computer. As a result of this fact, plus the combination of disadvantages already discussed, another approach has been pursued for a user friendly, computerized design method. The presentation of it will be made in the next several chapters.
CHAPTER IV
CURVE FITS

4.1 Introduction

Before any automation can be attempted, there are several pieces of information which are either in tabular or graphical form that must be curve fit. The alternate choice would be to have a series of look up tables. These would require a search and interpolation each time they are referenced. Clearly, a good curve fit has the faster execution time and does not suffer from the inherent round off present in any tabulated data.

4.2 Bare Wire Diameters

The first item of concern is the diameter of the bare wire, since most of the wire constants are related to this. The aim is to find an equation which accurately relates wire gage number to the corresponding wire diameter. Such an equation can be generated when it is recognized that the wire diameters follow a geometric progression (Ref 7). Thus, the diameter ratio of two successive gage number wires is a constant. In the discussions which follow, initial calculations will be in the english system of units to simplify comparisons with the standard wire tables. Conversions will then be made to the
cgs system for compatibility with the other equations.

Because the data presented in standard wire tables has been rounded to the nearest 0.0001 inch, the ratio of neighboring wire number diameters will appear to vary slightly. One method of finding the true value would be to determine every ratio over the range of wire sizes of interest and then compute their average. A simpler method is to choose two wire gages which are n numbers apart, find the ratio of their diameters and then take the nth root of that ratio.

This second method is the one used. Number 0000 wire has a 0.460 inch diameter while #36 wire has a 0.005 inch diameter. The ratio of the diameters is 1/92, and they are separated by 39 wire gages. Taking the 39th root of 1/92 yields a constant of 0.890525717. To relate the wire gages to the corresponding diameters, it is necessary to solve the following equation, which is based on the geometric progression relationship described earlier.

\[
\frac{\text{dia of #n}}{\text{dia of #m}} = (0.890525717)^{n-m}
\]

Setting \( n = 36 \), where the diameter is known to be 0.005, and \( m = 0 \), and solving for the diameter of #0 wire gives the desired final equation.

\[
\text{dia of #n} = 0.324860745 \times (0.890525717)^{n} \quad (46)
\]

This equation has been checked against all of the wire sizes from 14 through 44 and has been found to have an average error of -0.005% with a maximum error range of -1.12% to
+1.44%. This "error" is actually roundoff in the table values. Appendix G contains a table which compares the diameters found by equation (46) and standard wire table values. Also in that Appendix is a copy of a standard wire table page for single build, enamel coated wire. Multiplying the values obtained in inches by 2.54 gives the diameter in centimeters.

4.3 Ohms per Unit Length

The bare wire diameter can now be used to find the resistance of any wire diameter by the following equation.

\[
R = k \frac{L}{A}
\]  

(47)

In equation (47), \(R\) is the resistance in ohms, \(k\) is the resistance of 1 mil-foot of wire in ohms, \(L\) is the length of the wire in feet and \(A\) is the area in circular mils. A circular mil is simply the square of the diameter of the wire which is measured in mils. The constant \(k\) has a numerical value of 10.372. For the coil equations developed, it is desirable to find the ohms per inch rather than the total resistance and have the diameter measured in inches rather than mils. Equation (47) can be rearranged to be in the more useful form of equation (48) by converting \(L\) to inches and \(A\) to square inches.

\[
OI = \frac{(8.64333333E-7)}{WD} \div WD
\]  

(48)

Here \(OI\) is the ohms per inch and \(WD\) is the wire diameter in inches. Equation (48) can be used to convert from ohms per
inch to ohms per centimeter, OC. 

\[ OC = 0I / 2.54 \]  

(49)

As a check, resistances found by equation (48) have been compared to the standard wire table values. Appendix G contains a summary of this analysis. The average error is +0.03% with a range of -2.79% to +2.28%. There is no trend to this error since the sign is random throughout the wire range checked. Therefore, the equation and constants can be considered an excellent match.

4.4 Insulated Wire Diameters

No information could be found for calculating the overall diameter of the enamel insulated wire. However, equation (46) can be rearranged to produce equation (50).

\[ IN = \text{LOG}(ID/0.324860745) / \text{LOG}(0.890525717) \]  

(50)

In this equation, IN is an effective wire number for the insulated wire and ID is the diameter over the insulation. The insulated diameters, ID, can then be plugged into this equation to arrive at a resultant effective wire number. If the insulated wire gage values are then plotted against their corresponding bare wire diameter gages, WG, a straight line results. The line has a slope of 0.967 and an intercept of 0.221. Thus, an effective wire number for the insulated wire can be determined from the bare wire gage number.

\[ IN = 0.967 \times WG + 0.221 \]  

(51)

The overall diameter can then be found from equation (52).
A comparison between insulated diameters found by equation (52) and those in the standard wire tables is shown in Appendix G, and indicates a slight error. To get a perfect match with the wire tables, the constants would need to be adjusted slightly. The average error is +0.826%, which means that the calculated diameter is larger than the table value by that amount. This has a range of -0.67% to +3.68% with the larger errors occurring at the larger wire gages. The insulated wire diameter is used only in equation (45) to find the turns per unit area. An overestimate of the wire diameter by 2% will only reduce the calculated number of turns per area by 4%. The fact that this is in the direction of helping the coil winder and that some books recommend a reduced random wind factor at higher gage numbers (Ref 9), lead to the decision not to adjust the constants. More significantly, the calculated values fall well within the dimensional tolerances allowed in the tables.

4.5 Thermal Coefficients

The last fit to be discussed in this section is for the heat dissipation coefficient, K, versus the watts per square inch of effective coil radiating surface. Using data taken from a graph (Ref 4), which was plotted between 0.2 and 0.8 watts per sq-in, an exponential equation was assumed and then adjusted with a slope equation. The resulting equation
agrees extremely well with the data taken, but may not apply outside the range checked.

\[ LK = \frac{\exp(PA)}{107.23 \times (PA+0.194) \times (PA+0.194)+191.5} \] (53)

LK is the dissipation coefficient and PA is the power per square inch of surface area.

4.6 B-H Curve Digitization

The discussion of the choice for entering the magnetization curve will be left for Chapter VIII when that program module is presented in detail.
5.1 Introduction

The complete program is a user friendly set of five program modules, stored on a single 5-1/4 inch floppy disk, which are in repeated interaction with one another. They are written for use on an Apple II+ computer equipped with a single disc drive and monitor. A dot matrix printer with a graphics dump driver, such as the Grappler, is also recommended but not required.

The purpose of the complete package is to provide a method of designing the highest holding force horseshoe type D.C. electromagnet which will fit within given space constraints and is subject to other user defined limits. It will also analyze an existing coil design and display the results on a monitor or printer. One of the primary goals in developing this program is to make it as user friendly as possible. The user should not be required to have more than a minimal knowledge of magnetics, the program, or its inner workings. As a result, the graphics capabilities of the Apple computer are heavily utilized. In addition, single keystroke entries are used wherever possible, and user responses are checked against possible correct responses. In the event of entry errors, the program will ask for the
necessary information again. The program works extremely well and meets all the initial goals.

5.2 Program Structure and File Management

The reader is referred to Figure 7, for a better understanding of the module inter-relationships. This figure is a block diagram showing how the modules are connected and the direction of information flow. Each block will be discussed separately in its own chapter, while the purpose of this chapter is to look at the overall structure.

One item, which stands out in the flow chart, is the frequent use of sequential files. These are used to pass information from one module to another. The file RUN TYPE contains only four pieces of information. Its purpose is to help each module determine which task should be performed from its list of several possible tasks. These four items are: 1) The bobbin style being considered, AA. This information is used to choose the correct picture to draw or make minor equation changes as dictated by the bobbin and core configurations. 2) Type of study, TS, helps to choose the order of module execution. In addition, it works in conjunction with AA to draw the correct pictures. There are two basic types of study, design and analysis. Depending on which module is being exited, however, this variable can take on any of four values. 3) Entry type, ET, can take on any of three values. A "one" indicates that data will be entered
PROGRAM FLOW

FIGURE 7

NOTE:
PROGRAM MODULES
IN RECTANGLES,
SEQUENTIAL FILES
HAVE RADII
from the keyboard, "two" is temporarily used in some modules to view the catalog, and "three" is for entry from a disk stored file. 4) Name of file, NF$, is the title of the design being studied. It will eventually be the name of the @FINAL DESIGN file on the flow chart, as well as, appear on the input and output drawings for the coil.

The second frequently used sequential file is named @TEST COIL. This is a working file for all the coil information, and is added to or modified by each program module. A file does not take on its final name until the user is finished with it and decides to keep it on the disk for permanent storage. This avoids cluttering up the program disk with undesirable intermediate designs.

]MATERIAL FILE is a generic name for the material specification file. It contains the information describing the initial magnetization portion of the B-H curve for the material named by the title of the file.

One item of note is that all design files are preceded by an @, while all material files are preceded by a square right hand bracket in the disk catalog. The average user will be unaware of this feature, and when entering material or design names, has the option of placing the prefix on the name. However, the program will automatically add the proper prefix if it is not present before storing it on disk, but subtracts it before putting the information on a final drawing. The reason for the prefixes is that the sequential
files for this program are very short. As a result there could be up to 105 files on any design disk (limited by the number of file names allowed on a disk, not by disk capacity). To make it easier to find materials or designs in a catalog listing, the prefix has been added so that the user can quickly scan for the proper file type, and not have to read each name in its entirety. Appendix I shows a sample catalog listing.

5.3 Memory Management

An obvious question might be, why use these sequential files at all? Why not have one large program instead of five smaller modules? The answer can be found in the diagram of Figure 8, which shows three memory maps of the Apple II+, to a scale of 0.1 inch per 1K of memory. One of the ground rules when developing this program was that it had to be capable of running on a standard Apple II computer equipped with a single disk drive, but not necessarily additional memory or other special equipment. The left column of the memory map shows the standard configuration. HGR1 and HGR2 are the two high resolution graphics pages and cannot be moved. If a program is not using either, that memory is available.

If, however, graphics are to be used, then the block of memory for the page being used cannot be utilized or crossed by the resident program. In addition, under normal
MEMORY MAP

48K (49152) -
38K (38912) -
24K (24576) -
16K (16384) -
8K (8192) -
2K (2048) -
0 -

DOS

VARIABLE STORAGE

HGR2
HGR1

PROGRAM

HGR1

UNAVAILABLE

NORMAL
APPLE

COIL
DESIGN

ALL
OTHERS

(2544)

SHAPE
FILE

FIGURE 8
circumstances, a Basic program is entered starting at the first available memory location which is 2048 ($0803). Therefore, if programs are written in Basic, and HGR1 is used, the length of that program is limited to 6K. HGR2 can be written on instead of HGR1 to increase that amount to 14K, but this has several drawbacks whose details are not important to this discussion.

Returning to Figure 7, it can be seen that all of the programs except the Introduction exceed the 6K limit. Since HGR1 is a basic premise on which the concept for this user friendly program is based, and the language being used is Basic, an alternate approach or computer is required. Fortunately, an alternate approach is available.

The default starting address for an Applesoft program can be altered by Poking the new values into memory locations 103 and 104. Final results are the two memory maps shown to the right of the normal Apple column in Figure 8. The starting address for all of the program modules, except the Coil Design program, is placed above HGR1.

Unfortunately, there is an upper limit to programs placed above HGR1, which is determined by the disk operating system (DOS). Although the previous situation has been improved by an expansion of available program space to 22K, all of the program modules cannot reside in memory at the same time because of their combined sizes. In addition, the Coil Design program is still too big to fit above HGR1 and
have enough room for its required variable storage. Thus, the reason for the final memory management. If each module could operate as a stand alone program, and if the coil design module did not require graphics, then there would be sufficient memory capacity in a standard Apple computer to accommodate the project. The sequential files behave like a COMMON statement in Fortran, and also can be used in a manner similar to the EQUIVALENCE statement in Fortran. This last feature was necessary because of the use of an existing program for the design module. Conflicts of variable names would have resulted unless equivalence could be used. The alternative would be to change variable names, and thereby avoid conflicts. Not very desirable for many reasons!

5.4 Shapefile

The final item of discussion, before describing each module in detail, is the block called SHAPEFILE (Ref 10). This contains the character generators for writing on the high resolution graphics pages. Normally it is not possible to write text on the graphics screens. To overcome this deficiency, the programmer must generate the character set, and store it in a shape table for later use. This is the function of SHAPEFILE. It has been stored at the bottom of memory to safeguard it against the possibility of being overwritten by stored variables and programs. The starting address for COIL DESIGN is placed immediately above this.
5.5 Final Note

At this point, the memory capacity and its organization has been established. Now upper limits can be placed on the program sizes and the programming for the problem can begin.

Each program module chapter contains a section describing any computer dependent commands used in that module. In the companion Appendix, a variable cross reference and program length message are listed along with the complete module code. These pieces of information are intended for the individual interested in modifying a program or transferring it to another computer system.

Because many of the commands are related to the graphics required for user friendliness, the simplest method of transfer to another system would be to eliminate these entirely. While this will remove one of the main features of the program, it will leave an engineering tool which will perform its intended task well. The drawback will be that the user will have to rely on word prompts rather than pictures.
6.1 Module Purpose

This module serves as an introduction to the design or analysis process, and determines the path which will be taken through the block diagram of Figure 7. Since the program is intended to be for use by individuals who may not be familiar with the terminology used, a purely word based prompting technique is undesirable. It is said that a picture is worth a thousand words, and is, therefore, the medium of choice when maximum user friendliness is desired.

6.2 Program Flow

Figure 9b, shows the drawing generated by PAGE 1, on the monitor after clearing the title screen, 9a, it had created previously. Once the picture has been displayed, the user is asked to enter the coil type to be studied. When any key is pressed, the program checks to make sure it is either a 1, 2, 3 or 4. If not, the question is repeated. If so, the user is asked to confirm the entry with a Y/N response.

Rather than describe the user friendliness features in each module, the blanket statement will be made here that for every entry, maximum user friendliness has been considered. Single keystrokes are used whenever possible,
SMALL
D.C. BIPOLAR
ELECTROMAGNET
DESIGN

OPTIMIZATION & ANALYSIS
BY
JOHN J. BREEN
1984

(PROGRAM RUNNING: PLEASE WAIT)

FIGURE 9a PAGE 1 TITLE SCREEN

FIGURE 9b PAGE 1 PROMPTING SCREEN
and prompts are clearly worded. If possible, the program checks for the validity of a response and reprompts if warranted. Default values are suggested in many questions, and a single strike of the RETURN key will accept the default. While there are certainly some potential loopholes in this logic, great pains have been taken to account for likely user errors and questions.

Continuing with PAGE 1, the next prompt asks if the user wishes to analyze or design a coil. This generates a value for the variable TS.

The final set of questions relate to the study name, NF$. When the design name is entered, PAGE 1, will add the @ sign if it is missing, and then checks the disk to find if it already exists. If it does, the user can choose between overwriting the file from the keyboard, entering a new name after reviewing the catalog, or entering the information already stored in that file from the disk. If the file does not exist, there is a choice of entering the new data from the keyboard, or reviewing the catalog to find a file which does exist. From these final prompts, NF$ and ET are generated and the values stored in the file RUN TYPE.

The screen now clears and a message appears that the input/output module is being loaded, so have patience. This completes the function of the short PAGE 1 program.
6.3 Special Program Notes

A program listing followed by a variable cross reference listing can be found in Appendix B. This cross reference lists each variable used in the module and the line numbers in which it occurs. The file length is also listed if a rearrangement of memory is considered.

Since this program is basically a picture generator, its conversion to other systems is not likely. Most of the related commands are unique to an Apple computer. Therefore, if it is desirable to transfer the program in this project to a different system, it would be best to eliminate this module and only ask the limited number of questions needed with word prompts. These should be placed at the front end of the PAGE 2-A module or its equivalent.
CHAPTER VII

PAGE 2-A PROGRAM MODULE

7.1 Introduction

This module is the central controller and input/output manager for the entire program concept. It generates the coil pictures on which the various dimensions are displayed, and organizes any information which must be passed to the printer, monitor, disk or another program module. The size of the program is dictated by the graphing and user friendly features it contains rather than its basic functions.

During the keyboard entry phase of the program, the graphics become interactive. When the coil drawing is first generated on the screen, no dimensions are present. Only the dimension lines, arrows and variable identifiers are in place. As each entry is made, it is placed on the drawing at its proper location. In a similar manner, when a change is made, the screen immediately erases the old dimension and inserts the new one. This dynamic screen, in conjunction with good word prompts, make the program extremely easy to use, and eliminate the need for operating instructions.

7.2 Program Size Considerations

The demands on this module, for the memory space available, are significant. Because graphics are used
extensively by it, the module has to reside either above or below the high resolution graphics page one. This immediately places an upper limit on its size.

The biggest factor on size is the graphics requirement. If the eight individual pictures required were stored on disk as separate files, they would require 34 sectors apiece for a total of 272 sectors. This amounts to half a disk just for 8 pictures. Since a single drive is a requirement of the program design, this storage is unacceptable. A second alternative is to have a separate picture generating module for each drawing. This is again not very compact or clean.

By a careful design of the eight pictures and the locations of their dimension lines and related dimensions, a more compact form results. The program is set up to reuse as many lines of code as possible. To this end, whenever a picture is required, all lines common to every drawing are drawn first, followed by a branch to the lines for round or square cores. A series of subsequent branches for drawing all those features common to everything which follows it are executed, until the correct picture is completed.

A similar problem occurred with the entry of data from the keyboard or disk. Sixty potential pieces of information must be managed, though only about a third of them are required for any given display. Subroutines for each entry are used. For simplicity, a different calling block is used for each type of picture.
Finally, the change routines which are required take a large amount of code. This has been handled by a careful choice of the order in which the change questions have been arranged in the program. A branching technique, similar to the drawing one mentioned, is then used. Whenever a dimensional change request is made by the user, the program searches through a list of variable names. When the desired variable is found, the corresponding dimension on the drawing is erased, using the same program lines which originally put it there. The user is then told what the current value is and is asked to enter a new value. Wherever possible, default values are suggested, and will be chosen with the single stroke of the return key.

The result is a very efficient program, which handles all eight drawings, sixty pieces of information, keyboard entry, disk entry, module execution management, and changes, as well as, output requirements in less disk space than would be occupied by two graphics pages. The drawings, which will be discussed and shown in detail in Chapter XI, are very readable and serve their purpose well.

7.3 Other Functions

Before permitting an exit to the ANALYSIS module, PAGE 2-A, checks to be certain that the material file specified exists. If it does not, the user is given the option of either changing the material or branching to the B-H module.
for material entry. Otherwise, the analysis is started.

In addition to the material check, many others are made before an exit to the COIL DESIGN module can be executed. All maximum and minimum values are checked to be certain that they are not inverted. In addition, some basic calculations are made to be certain that the maximum wire space allowed, in combination with the maximum gage number and voltage, will permit the maximum coil current specification to be met. More fundamentally, a check is made to be certain that the combination of requirements allows for any flange width or winding length at all. Should any of these incompatibilities exist, an error message results, with suggested corrections. Otherwise, the specifications are considered acceptable, and the coil design can almost begin. Reference to Figure 8, reveals that the COIL DESIGN module must reside at a different location in memory than PAGE 2-A. Therefore, the last function performed by this module is to relocate the starting address for the next Applesoft program.

7.4 Special Programming Notes

This module is almost exclusively machine dependent. All of the graphing functions are unique to the Apple computer, as are the sequential file management instructions and memory location commands. Therefore, transfer of this input/output module to another system is not recommended. Instead, the programmer is encouraged to write a different
module.

Appendix C, contains a complete program listing in addition to the length message and variable cross-reference.
CHAPTER VIII

B-H ENTRY PROGRAM MODULE

8.1 Program Function and Flow

The purpose of this module is to provide a simple means of entering a D.C. magnetization curve, like the examples shown in Figure 2, and Appendix F. It does not assume that the operator even understands what a B-H curve is. It is only necessary that he has the appropriate information for the material of interest, plotted on semi-logarithmic axes, available for digitization. Units of entry can be any that the user chooses. Values are converted to kilogausses and oersteds, however, before they are saved to the disk.

Data is checked as it is entered to verify that it follows the rules of a monotonically increasing function. Violations of these rules result in a flashing error message and a reprompt for the value requested. Up to 40 points may be entered, and are continuously displayed in chart form on the monitor screen. Figure 10, shows a sample of the entry screen for the 50/50 NI-FE (SOLID) file. On the monitor, the headers would show in inverse. An entry of E, for any value, signals the end of the entry process and the start of the editing phase.

Full editing features are supported, including add, delete, insert and change. When one of these functions is requested, the table of values is adjusted appropriately and
<table>
<thead>
<tr>
<th>H</th>
<th>B</th>
<th>H</th>
<th>B</th>
</tr>
</thead>
<tbody>
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<td>1)</td>
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<td>.5</td>
<td>21)</td>
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</tr>
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<td>12</td>
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<td>3.5</td>
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</tr>
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<td>15</td>
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<tr>
<td>11)</td>
<td>4500</td>
<td>15.41</td>
<td>31)</td>
</tr>
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</tr>
<tr>
<td>20)</td>
<td></td>
<td></td>
<td>40)</td>
</tr>
</tbody>
</table>

VALUES IN OERSTEDS: KILOGAUSSES

FIGURE 10: B-H ENTRY PAGE SHOWING 50/50 NI-FE (SOLID)
prompts for the necessary information are displayed.

When the data entry process is completed, the information is stored on a disk under the name of the material.

This name is preceded by the right square bracket prefix mentioned in Chapter V. If the file already exists, the program will verify that it should be overwritten before doing so. Renaming of the file is allowed at this point, if the existing file is to be kept.

After the saving process, control is returned to PAGE 2-A, unless more materials are to be entered. Should more entries be required, or an existing file need editing, the module will restart itself and begin the entry process again.

8.2 Basic Concept

It was felt that the entry process had to satisfy three fundamental requirements, the first of which is user friendliness. Some curve fitting techniques require careful selection of the data points to obtain a good match. This demands a full understanding on the part of the user of the technique being used, which is a violation of the user friendly concept.

The second two requirements are related to the computer. First, the method must result in an accurate representation of the actual B-H curve. Finally, whatever method is chosen must allow for easy interpolation between inputted points.
One of the difficulties with many curve fitting techniques is that they agree at the given points, but deviate considerably between them. It is also possible that one technique would not apply for all possible curves desired. This might require decisions on the part of the user for deciding which method would best apply. This is again anti-user friendly.

Close examination of the large variety of curves shown in Appendix F, reveals that they can be approximated quite well with a minimal number of straight line segments. Assuming that these are a good representation of possible curves, then if straight lines work for them it would satisfy all of the requirements and be the simplest to execute and understand.

Several curves were approximated, and most required less than 10 line segments for the process. The Apple monitor can conveniently display 40 data points in a static chart, and thereby define 39 line segments. Since this exceeded the typical expected number by a wide margin, 40 was chosen as the maximum number of data points, and the foundation for the program format settled.

8.3 Observations on the Method

Once again referring to Figure 10, it can be seen that the curve for 50/50 NI-FE (SOLID) has been represented by only 10 line segments. If plotted against the original curve
in Figure 2, the points along the line segments are almost indistinguishable from the original. Similarly, cold drawn carbon steel was approximated by 8 segments and oriented 3% silicon strip by 12. The original curves for these materials can be found in Appendix F.

The method is very quick and easy, and requires little instruction. The accuracy is well within that which would be obtained by reading the curves for a manual analysis. The method, therefore, meets all the stated requirements and works well with the other program modules which use the information.

8.4 Special Programming Notes

Generally, the program is straightforward and warrants little mention. Its complexity is determined more by the user friendly requirement than the function it serves. One Apple related trick is needed to make the concept work, however. This is the POKE 34,X statement found in subroutine 1500. The function of this statement is to produce a static display from the top of the screen down to line number X. All lines below X scroll normally. The static display can then be written to, using horizontal and vertical tabs.
CHAPTER IX
ANALYSIS PROGRAM MODULE

9.1 Program Function and Flow

The primary function of the ANALYSIS program module is to analyze the characteristics of a D.C. bipolar electromagnet whose physical dimensions are known. The equations used are essentially identical to those presented in Chapter II. The resulting calculations are displayed on the monitor, printed out, or not shown at all, based on a user selected option.

A second (optional) function is to repeat only those calculations which apply to holding force over a user selected range of voltage and air gaps. This shows the sensitivity of the force to those parameters. Based on the range of force and voltage, a graph of this data is scaled and plotted to fill the monitor screen. If the print option has been chosen, a copy of the graph is sent to a dot matrix printer. In addition, the data used to generate the graph is listed.

Before exiting to PAGE 2-A, where a picture is generated of the analyzed coil, all of the data, with the exception of the sensitivity information, is stored in the @TEST COIL file on disk. As shown on Figure 7, the analysis module may be called directly by PAGE 2-A, when TS is set to unity in the
PAGE 1 program. It may also serve as an intermediary between the COIL DESIGN and PAGE 2-A modules.

9.2 Assumptions and Constants

Several assumptions are made when making the temperature related calculations. One is that the core is in poor thermal contact with the windings and, therefore, has no heat capacity. Another is that the surrounding air temperature is at a constant 20 degrees celsius. A final assumption is that the air is free to circulate about the entire coil winding surface area. This last assumption may not be valid for a double bobbin design when the coils are in close proximity with one another. It may also not apply if the coil is mounted in such a way that one or more faces are effectively insulated against thermal convection.

These combined assumptions are the basis for the choice of the equation which determines $L_K$, the heat dissipation coefficient. If some of the surface area is insulated, a modification of the surface area equation would correct for this. However, if any of the other factors do not agree with the assumptions stated previously, Ref. 4 should be consulted for a more detailed explanation of required changes.

The program will also point out those constraints which have been violated by the design, if constraints have been specified. To allow for accumulated round-off effects, an arbitrary error threshold of one percent must be exceeded to
set off a violation flag.

During the initial calculations, a check is also made of the number of turns specified, versus the potential number of windings for the bobbin. Any difference greater than five percent will result in a message being displayed. This will tell the user if the bobbin is over- or under-filled, and asks which of three options should be executed. These are to either accept the over/under-fill condition by setting the winding width to the calculated value, adjust the winding factor to fill the winding space, or review the calculations. Based on the choice made, the ensuing calculations are modified accordingly.

9.3 Amp Turn Distribution Calculations

With the exception of the amp-turn distribution calculations, the equations and methods used in this program module are identical to those presented in Chapter II. The reader will recall that this distribution of the mmf between the iron and air is determined by a series of trials which consist of a guess, followed by an involved calculation sequence. While it is true that the computer can carry out this iterative process without difficulty, it can be time consuming. For the ANALYSIS module this is not a big concern since the iterations are only carried out once. In the COIL DESIGN module, however, which will be described in Chapter X, these iterations must be carried out twice per independent
variable per basepoint in the search process. Depending on the number of base points required, the time consumed can become an important factor. For consistency, the ANALYSIS and COIL DESIGN modules should use the same search technique.

As a result of the design module concerns, a technique for finding the amp-turn distribution has been developed. The result is one equation with one unknown, requiring few iterations to solve. The equation manipulations required and simplifications made are as follows. Figure 11, shows the terms and graphical representation of the concepts described in this section. Most texts use the Greek letter phi to represent flux. To be consistent with the programs presented, however, F will be used, with variants of FL and FU.

In the example problem presented in Chapter II, one of the calculations which had to be made during the iterative loop was dictated by equation (23). This was necessary because a relationship between the flux density, B, and magnetizing force, H, was known for both the iron and air paths. For the air, equation (14) indicated that B and H were equal in the cgs system. For the iron, some function defined by the initial magnetization curve described the relationship. Equation (23) was used to tie these two known relationships together.

The beauty of the B-H relationship is that it is independent of part geometry. This allows the publication of
FIGURE 11  FLUX vs mmf FOR INTERPOLATION
one curve for each material. However, to simplify the discussion which follows, it would be better to have a relationship between flux and H. In section 2.5, it was stated that flux must be conserved. At the pole/air interface, the flux is not being divided, but is only changing medium. The flux in the air, therefore, must equal the flux in the iron. By equation (17), the flux is equal to the flux density, $B$, times the area through which it is passing. Since the core area and gap area are being treated as constants, it is possible to scale the $B$ axis for both the air and iron by their appropriate areas, so that both $HA$ and $HI$ will be plotted against a common vertical axis of flux.

For the air, a combination of equations (14) and (17) indicates that there is still a straight line relationship between flux and $H$.

$$FLUX = AG \times HA$$ (54)

Plugging in equation (15) for $H$, gives the desired end relationship relating flux to the amp turns in the air, $NA$.

$$FLUX = (AG \times 0.4 \times \pi / G) \times NA$$ (55)

This line is shown in Figure 11, and its slope is defined by the quantity in parentheses in equation (55).

For the iron, the relationship between $B$ and $H$ has been reduced to a series of straight line segments, when $H$ is plotted on a logarithmic axis. Taking the logarithm of both sides of equation (15) gives equation (56).

$$\log (HI) = \log (NI) + \log (0.4 \times \pi / PL)$$ (56)
With equation (56), an identity now exists which will allow the flux to be plotted against the logarithm of the amp turns in the iron. This plot will still be a straight line for any segment in the material file, and is also drawn in Figure 11. It must be remembered that the horizontal axis for the amp turns in the iron is logarithmic, while that for the air is a cartesian grid.

The end points of the line segments for the B-H curve of the iron are stored in the material file, and are, therefore, known. From the relationships presented in Chapter II, the flux and number of amp turns in the iron and air can be calculated from these values. These are indicated by the dotted lines in Figure 11. Once the iron and air amp turns are defined at an end point, the total number of amp turns at that point is simply their sum. The computer can be used to scan through the material file to find a pair of end points which bracket the total number of amp turns available. That point will correspond to some as yet unknown flux, air amp turns and iron amp turns. This is also shown in Figure 11.

Through the use of similar triangles, the relationships defined by equation (57) can be found.

\[
\frac{\log(N_{ia}) - \log(N_{il})}{\log(N_{iu}) - \log(N_{il})} = \frac{F_a - F_l}{F_u - F_l} = \frac{N_{A_a} - N_{A_l}}{N_{A_u} - N_{A_l}} \tag{57}
\]

Equation (58), is determined by applying equation (20), for the aim point being sought.
\[ \text{NIa} = \text{NT} - \text{NAa} \quad (58) \]

Setting the first and last identities of equation (57) equal, and applying the identity in (58), gives equation (59).

\[ \log (\text{NIa}) + \text{AA} \times \text{NIa} = \text{KK} \quad (59) \]

where \( \text{AA} = \left( \log (\text{NIu}) - \log (\text{NIL}) \right) / (\text{NAu} - \text{NA1}) \quad (59a) \)

and \( \text{KK} = \text{AA} \times (\text{NT} - \text{NA1}) + \log (\text{NIL}) \quad (59b) \)

All of the variables in equation (59) are known, with the exception of \( \text{NIa} \). In the computer programs presented, a modified interval halving technique is used to find the aim number of amp turns in the iron. In addition, the equations in the program are slightly messier than the ones presented here. The simpler form was found too late to be incorporated in the programs. Using the identities available in this paper, however, it is easy to show that the two solutions are identical. The details will not be presented here.

As an experiment, the Newton-Raphson method was tried in place of the bisection technique with no improvement in the error. Since the bisection technique gives acceptable answers and the final listings were complete, the listings shown contain the bisection method. Newton-Raphson would be guaranteed to converge, based on the physical requirements of the variables in equation (59). Errors, resulting from round off and any techniques used, are shown by a difference in the two values of total amp turns printed out in the sample runs presented in Chapter XI.
9.4 Special Programming Notes

Appendix E, contains a listing, program length message and variable line cross reference of the ANALYSIS module. Aside from the file management techniques, common to all of the programs in this project and the graphics functions, there are no equipment dependent commands. For this reason, the module can be easily converted to other systems.
CHAPTER X
COIL DESIGN MODULE

10.1 Introduction

The purpose of this module is to design the maximum holding force coil, which will meet all of the user specified constraints. If no such design can be found, a design, which satisfies as many of the requirements as possible, will be suggested and violations will be indicated.

The program is an application of the P519RE MODSER SEARCH ALGORITHM PROGRAM, developed by Prof. Ray C. Johnson (Ref 1). As such, all of the program code, with the exception of subroutines 8500, 9000 and lines 500 through 610, are from that program. Many of the features of the original are not used and, therefore, could have been eliminated. However, it is conceivable that they might be needed by someone making a modification of the overall project program presented in this paper. For this reason, all of the original code has been left in place, with modifications for the Apple computer made as required.

The details of the program will not be covered in depth. Rather, a discussion of the applications and related problems will be presented. The only places these details will be interjected is when a point being presented will be clarified by such a discussion.
10.2 Optimization Problem Embedment

The format of the program requires that the programmer embed his particular optimization problem as program code in subroutine 9000. The item Q, to be optimized must be in the form of a minimization problem, with Q expressed as a function of the independent variables. Since the actual quantity to be optimized for this project is force, which must be maximized, the inverse of it is taken as Q for the search process. This turns the problem into the required minimization format, since the inverse of a large quantity is small. The cases of zero or negative force cannot exist, since the calling module, PAGE 2-A, checks for gross incompatibilities before starting the optimum design search process. Therefore, some positive force will always exist at the search start point, even though it may be of small magnitude.

Inequality constraints of the optimization problem are handled with the R() equations, expressed as functions of the independent variables. These are arranged in such a way that the value calculated for each R(), must be greater than, or equal to zero, for an acceptable design. If this condition does not exist during the search process for any of the R() values, then those particular constraints are violated and a corresponding penalty P, is imposed on Q. The sum of the squares of the values of R(), which are less than zero, is multiplied by a penalty coefficient to form the
parabolic type penalty function used. The P value so calculated is then used to augment the optimization quantity Q, to help bring the design back into the feasible design space for the search process.

In the presentation of the equation system for subroutine 9000 which follows, the variable names used throughout this paper will be presented for continuity. In the actual program, the variables are elements of a common array. This avoids conflicts with existing program variable names, and makes the entry and exit statements more compact by allowing FOR-NEXT loops to be used. REM statements in the program listing make translation easy for those interested.
Basic Equations:

Opt Qty Q = 1/FT
Force FT = 2.8696831 * BA * BA * AG
Gap Area AG = (CD-2*R)*(CW-2*R)+2*(CD-2*R)*(R+G/2)+2*(CW-2*R)*(R+G/2)+(R+G/2)*PI*(R+G/2)*(R+G/2)
FIDensAir BA = HA
HAir HA = 0.4*PI*NA/G/2
AmpT-Air NA = NT-NI
AmpT-Tot NT = V/OC/AP
AmpT-Iron NI = **** note: iterative loop required
HIron HI = 0.4*PI*Nl/PL
PathLen-I PL = 2*(LW+2*(BF+M*FW+M*W+C1+C2+2*CW))
FIDensIrn BI = BA*AG/CA
AvPthWire AP = CP+2*PI*(W+FW/2)
CorPerim CP = 2*(CD+CW+(PI-4)*R)
Ohm/Cm OC = 2.54*(8.6433E-7)/WD/WD
WirDiaBar WD = 2.54*(.324860745)*(.890525717) WG
InsDia ID = 2.54*(.324860745)*(.890525717) (.967*WG+.221)
NoTrnsCal NC = M*FW*RW/ID/ID
Wir/in2 W2 = 1/ID/ID
RatioArea RA = AG/CA
CoilResis CR = M*OC*LW*FW*W2*AP*RW
Coil CI = V/CR
Inductanc LH = NC*CR*BA*AG/V
DepthOver DO = 2*(W+FW)+CD
WidthOver WO = 2*(CW+M*W+M*FW)+C2
LenOver LO = 2*(CW+BF)+LW+C1

Independent Variables: WG,LW,FW,R,CW,CD

Unitized Indep Variables:
V(1) = WG/GX note:GX is max wire gage
V(2) = LW/XL note:XL is max flange length
V(3) = FW/SX note:SX is max flange width
V(4) = R/RX note:RX is max radius
V(5) = CW/XW note:XW is max core width
V(6) = CD/XD note:XD is max core depth
Note: V(5) and V(6) for rectangular core cross section only. All others apply for any case.

(continued on next page)
Limits on Independent Variables:

<table>
<thead>
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<th>Unitized Max</th>
<th>Min Limit</th>
<th>Unitized Min</th>
</tr>
</thead>
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<td>1) GX</td>
<td>CX(1)=1</td>
<td>GN</td>
<td>CN(1)=GN/GX</td>
</tr>
<tr>
<td>2) XL</td>
<td>CX(2)=1</td>
<td>ML</td>
<td>CN(2)=ML/XL</td>
</tr>
<tr>
<td>3) SX</td>
<td>CX(3)=1</td>
<td>SN</td>
<td>CN(3)=SN/SX</td>
</tr>
<tr>
<td>4) RX</td>
<td>CX(4)=1</td>
<td>RN</td>
<td>CN(4)=RN/RX</td>
</tr>
<tr>
<td>5) XW</td>
<td>CX(5)=1</td>
<td>NW</td>
<td>CN(5)=NW/XW</td>
</tr>
<tr>
<td>6) XD</td>
<td>CX(6)=1</td>
<td>ND</td>
<td>CN(6)=ND/XD</td>
</tr>
</tbody>
</table>

Note: 5) and 6) for rectangular core section only.

Inequality Constraints:

Basic inequality | Unitized R() equation
---|---
WX=>WO | R(1) = 1-WO/WX
WO=>WN | R(2) = WO/WX-WN/WX
DX=>DO | R(3) = 1-DO/DX
DO=>DN | R(4) = DO/DX-DN/DX
LX=>LO | R(5) = 1-LO/LX
LO=>LN | R(6) = LO/LX-LN/LX
BX=>BI | R(7) = 1-BI/BX
IX=>CI | R(8) = 1-CI/IX
HX=>LH | R(9) = 1-LH/HX
LH=>HN | R(10) = LH/HX-HN/HX
GX=>WG | R(11) = 1-WG/GX
WG=>GN | R(12) = WG/GX-GN/GX
RX=>R | R(13) = 1-R/RX
R =>RN | R(14) = R/RX-RN/RX
SX=>FW | R(15) = 1-SX/SW
FW=>SN | R(16) = FW/SX-SN/SX
XL=>LW | R(17) = 1-XL/XW
LW=>ML | R(18) = LW/XL-ML/XL
BI=>0 | R(19) = BI/BX
CI=>0 | R(20) = CI/CX
XD=>CD | R(21) = 1-CD/XD
CD=>ND | R(22) = CD/ND-ND/CD
XW=>CW | R(23) = 1-CW/XW
CW=>NW | R(24) = CW/XW-NW/XW
CW=>2*R | R(25) = 1-CW/XW
CD=>2*R | R(26) = 1-CD/CD

Note: Inequalities (21) through (26) are for rectangular core cross sections only. All other inequalities apply for all types.

It is neither the intent nor the scope of this paper to attempt to describe the equation system presented above. A few comments will be made, however, in an attempt to clarify the basic concepts.

The section under the heading of Basic Equations is...
simply a restatement of equations presented in Chapter II, and also used in the ANALYSIS program module. The only additional equation is that for the optimization quantity, Q, which has already been discussed.

The next two sections of the preceding equation system apply to the independent variables. The independent variables, V(), are the items which the program will vary during the search process in an attempt to find the lowest value of Q. The final section in the preceding equation system summarizes the inequality constraints and the corresponding functions for the R()'s previously discussed.

All independent variables and inequality constraints must be unitized. The basic reason for this is to cause all of the independent variables and the inequality constraints to carry equal weight. The greater the order of magnitude difference between the various independent variables, the greater the importance of scaling becomes. To scale the independent variables, they are divided by the maximum value allowed. Then the unitized independent variables, V(), have an upper limit of one, and a lower limit of no less than zero. In the event that only a lower limit is present, unitization is handled differently. Since that does not occur in this equation system, it will not be discussed.

Finally, the regional constraints are scaled by making the varying component of the R() equations, in each case between zero and unity, when the inequality constraint is on
the verge of violation during the search process.

10.3 Notable Problems

Several unique problems present themselves in the preceding equation system. When the P519RE program is normally used, it is set up for one set of conditions. For the problem being considered in this project, that is not true. There are four different bobbin configurations, each of which results in a variant of the equation system. A method had to be developed, therefore, which would allow one version of the COIL DESIGN module to be used for all possible conditions. The alternative would be to have a different design module for every possible bobbin type. Aside from the fact that the program occupies 81 disk sectors, which would fill a disk with less than 7 variations, there are a large number of possible combinations. For starters, there are the four basic bobbin types. Within those, any one or combination of variables could be set to a fixed value. A variant for each of those possibilities would be required. It can be seen that this would quickly get out of hand.

The solution is to arrange the variables in such a way that the first several are common to all bobbin types. There is then a branch to any remaining variables. The inequality constraints and variable limits can be arranged in a similar manner. Using the bobbin type, the program can determine how
many variables, constraints and inequalities to look for, and where to branch when required.

For variables set to a fixed value, upper and lower limits can usually be set an arbitrarily small distance apart and, thereby, essentially hold the variable fixed. The first problem with this is that the arbitrary value must be chosen. More important, for each basepoint during the search process, the program must return to subroutine 9000 twice for each variable. This is done to determine the effects on the optimization quantity of changes in each of the variables. Because of the length of time to execute this program, extra excursions to subroutine 9000 must be avoided. An invariant "variable" would cause two such excursions per basepoint.

To circumvent this problem, and simultaneously avoid multiple versions of COIL DESIGN, a solution has been found. Referring to the program listing in Appendix F, line number 4015 has been added. CD(I), is a measure of the difference between the upper and lower unitized limits for each variable, V(I). For any of these that are equal to zero, the program will set the gradient contribution for that variable equal to zero, and then go to the next variable. Normally, lines 4020 through 4070, would add and subtract finite difference increments, CD(I) to and from V(I), and go to subroutine 9000, for each case. With this approach, only the active elements of the gradient vector, GB(I), are calculated for each actual independent variable.
The next problem requires some more explanation. An appropriate penalty function tuning parameter, CP, must be estimated for the search process of automated optimal design. The value for CP, must create a proper balance between penalty function P, and optimization quantity Q, to assure proper movement in the search process. In addition, penalty function P, is periodically strengthened as the search process approaches the solution point, by successively increasing a factor FP, in the calculation of P.

As previously explained, penalty function P, is added to the optimization quantity Q, to form a penalized optimization quantity, X. It is X, which is minimized by the automated optimal design search process of the program. The search process continues from basepoint to basepoint, decreasing X, in each case, until the minimum value of X is found. At this point, some or all of the constraints may be violated. The constraint walls of penalty function P, are then steepened, by increasing FP by a factor of 8. The process is repeated, until a new minimum is found for X, and then FP is multiplied by 8 again, and so on. Eventually, the value of FP becomes so large that if incompatible specifications do not exist, the optimum design solution point is approximately located, which meets the design limits. One of the many advantages of this method is that by allowing excursions beyond the feasible design space, answers are obtained even when incompatible specifications exist, which gives the designer
an idea of which limits are active.

One of the drawbacks is that when an equation system has an unconstrained minimum, which is far removed from the feasible design space, the initial excursion with FP equal to unity can be great. It can then take many basepoints and FP increases to bring the search back within the design bounds. This is especially true if the optimizing function in $Q$ is steep enough to overpower the penalty function, FP. The degree of this problem is also affected by the quality of the starting point. The closer the start point is to the final solution, the less severe the problem is likely to be.

This difficulty was encountered with the first runs of the program. Several hours and over two hundred base points were required to make the excursion to the first minimum and then return to the neighborhood of feasible designs. The answers so derived are correct, but the time factor is unacceptable.

Because the program is supposed to be user friendly, it would not be within the rules to ask the user to define a starting point, and therefore, a built in shotgun routine is used for this purpose. This routine sprays the $n$-dimensional design space of the independent variables with randomly selected points, to find the lowest value for $Q$ to start the search from. Theoretically, with enough such trials, the best design can be found. The time required would be large, however, to guarantee that the solution found was even close
to the best. Therefore, an upper limit must be placed on the number of shotgun trials allowed before the conjugate gradient search process is begun.

In the interest of time, a risky solution has been tried. The answers obtained agree with the several full time runs made with the same constraints, and are consistent with other runs made with slightly different constraints and bobbin types. During the shotgun routine in subroutine 2000, some lines of code have been added. Initially, FP is set to 262144 in line 57. The normal shotgun search proceeds until the minimum number of trials, MN, is reached. For the example, MN is equal to 50. If the penalty function P, is zero for the design of lowest X, then that basepoint is accepted as a starting point and FP, is retained. If not, the search continues until a P of zero is found or the maximum number of points, MX, is reached. For this example, MX is equal to 100.

If no starting point has been found, which falls within the feasible design space, then FP, is reduced by a factor of eight, and the process repeated. In the worst case, a situation will arise where FP gets back to unity, as in the unmodified program, without finding a start point meeting all constraints, as defined by a P of zero. There are two dangers to this solution.

The first is that the tuning parameter, CP, is determined by the steps from the start point. If CP is
poorly set, it is very possible that a situation will arise where either no motion will occur about a basepoint causing the program to apparently hang or the program will prematurely decide that the best solution has been found. This could happen when the start point is actually very far removed from the actual solution point. It is less likely to occur as the initial start point gets closer to the solution point. The highest number of shotgun trials is desired, therefore, while still keeping the time to a reasonable level.

The second potential problem requires a trip into n-dimensional space. Since that is difficult to imagine, the example will be limited to three dimensions. Think of a curved trough winding its way around a mountain in a gradually descending direction. Eventually, this trough leads to the best solution. It is entirely possible that the curve of the trough could extend beyond an imaginary vertical limit wall during its curved descent before coming back through the wall into the acceptable space domain. If the limit function is too steep, the descent will stop where the wall and trough meet, even though there is a better solution on the other side of the mountain which could be reached if the limit were shallower.

Without a lot of trials using many different configurations and limits, it is almost impossible to determine if this last problem exists. Again, the best
solution is to spend more time during the initial shotgun search trying to find a spot in the trough on the correct side of the mountain.

One way to check a solution is to repeat the design process. If the same solution is found, the chances are good that the global optimization solution point has been reached. If another solution with the same value of Q, is found, but different values for the independent variables, a region containing a range of equivalent designs has probably been found, and any solution between these two solutions will likely give the same answer for force. Again, the best solution has been found. If, however, a different value of Q has been found at the end of the searches, then a problem has been encountered in the automated optimal design search process. The solution is to set FP to unity in line 57, as in the original form, and wait for the design process to end. Occasional checks of solutions, using FP equal to one, are advised until a better base can be established to prove or disprove the validity of the change described.

For the designs tested, no problems occurred and, therefore, the code has been left in the shotgun subroutine. In the event that a set of design constraints exist, which do not yield a start point with an initial value of zero for the penalty function P, then the approach presented will reduce the initial value of FP, to unity. Since this is equivalent to the unmodified program, and since the option exists for
setting FP, to unity in line 57, the extra code can do no harm. The benefit of the extra code is that it successfully found the same solution as the originally intended method in approximately one fifth the number of basepoints, and thus one fifth the amount of time.

10.4 Programming Notes

This program was converted from an original version available in the TRS-80 Basic language. Two modifications have been made. The first, was to remove the double precision calculations, since they are not available on the Apple II+ microcomputer. The second, was to add an occasional A=FRE(0) command at strategic locations as a housecleaning measure, which is compatible with an Apple microcomputer. If transferred to another system, the original version should be restored. Other than this, no special system dependent commands exist.
CHAPTER XI

SAMPLE COMPUTER TRIALS AND OBSERVATIONS

11.1 Introduction

The aim of this chapter will be to demonstrate the effectiveness of the design process developed for this project. To do this, a commercially produced electromagnet of the general size being considered has been found and measured. Its outside dimensions, operating voltage and current are shown in Figure 12, and appear as maximum limits. These will then become the design constraints for the trials which follow.

In addition to an analysis of the production design, which is identical to that presented in Chapter II, there are five input configurations given for the trials. They have been chosen for two basic reasons. The first is to determine which of the four core shape and bobbin combinations shown in Figure 9, gives the maximum holding force permitted by the design constraints. The second is to provide a thorough check of the equation variations in each of the program modules dictated by these coil varieties.

To satisfy this second purpose, a fifth trial is needed. When executing the designs for the rectangular bobbins, a maximum core corner radius of zero is specified to insure rectangular core cross sections. The fifth run is a
variation on this cross section which sets the maximum corner radius equal to half of the maximum core width or depth. This checks the inequality constraint equations of the COIL DESIGN module, which require that the corner radii be less than half of the smallest core dimension. If this condition is violated, some of the equations in the equation system become invalid.

11.2 Sample Runs

Figures 12 through 35, on the next 24 pages, show the summary pages for the five runs being considered. The intermediate results for the design phases are not included to reduce the output to a reasonable level. The highlights of those results will be discussed in section 11.3.

For each of the five trial examples, there are four figures. The first one is the drawing of the design requirements, which were used as the inputs to the COIL DESIGN module. For each of the five examples, the maximum and minimum outside dimensions, overall core limits, wire size limits, and electrical requirements are identical. In addition, those factors, which are set by the manufacturing limitations, C1, C2, BF, W, RW and V, are the same. Core material and an assumed air gap are likewise equal. The only difference between the two single bobbin, rectangular core runs, is that the last one allows the corner radii to take on a value different from zero.
The second figure in each group is a drawing of the optimum design found by the COIL DESIGN module. Included on these drawings are all of those dimensions and inputs necessary for manufacturing a sample of the design. Special features, such as mounting tabs, are left to the designer, since they do not affect the magnetic or electrical characteristics of the coil. In addition, the assumption is made that adequate clearance has been allowed for, in dimension C2, and the overall width and depth, to increase the bobbin flange widths. This is to allow for the deficiencies in equation (1), discussed in section 2.2.

The third figure is the graph and a partial listing from the sensitivity study. It shows the no-loss holding force as a function of operating voltage for three different air gaps. In each case, the voltage range is from zero to 6.5 volts, and the arbitrary air gaps chosen are 0.0015, 0.003 and 0.0045 centimeters. The point indicated by 3 volts on the 0.0015cm air gap curve is the design point for each of the coils. Had the design requirements been different, the final design and thus these curves would also be different. The objective of the sensitivity study is to show the designer how the coil will behave under conditions varying slightly from the single design point.

Normally, the full output of the sensitivity study would show the voltage and force used to generate the graph for each of the airgaps considered. For brevity, only the
information for the designed air gap is shown. 

The final "figure" is the full listing from the ANALYSIS program module. It shows not only the analysis of the expected performance of the device, but also the input requirements to, and the specified dimensions from, the COIL DESIGN module. The first example, labeled "Production Design" shows design constraints, even though the design was not subjected to the optimization program. These dimensions have been placed in the listing for reference. With the exception of the maximum core width and depth dimensions, these design constraints should match the actual dimensions. 

The reader should take more than a brief look at these figures before continuing to section 11.3, where they will be discussed in detail. This will make the discussions in that section more meaningful.
FIGURE 12: DESIGN REQUIREMENTS FOR PRODUCTION DESIGN

FIGURE 13: ACTUAL DIMENSIONS FOR PRODUCTION DESIGN
VOLTAGE AND AIRGAP SENSITIVITY FOR PRODUCTION DESIGN

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<th>VOLTAGE</th>
<th>IDEAL FORCE (OZ)</th>
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<tr>
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<td>6.5</td>
<td>47.6825422</td>
</tr>
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</table>

FIGURE 14: GAP AND VOLTAGE SENSITIVITY FOR PRODUCTION DESIGN WITH LISTING FOR FIRST GAP ONLY
SAMPLE RUN FOR A SINGLE BOBBIN, RECTANGULAR CORE
SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

COIL NAME: PRODUCTION DESIGN
COIL TYPE: SINGLE BOBBIN, RECTANGULAR CORE
OPERATING VOLTAGE: 3
COIL RESISTANCE: 97.3121734
CORE MATERIAL: 50/50 NI-FE (SOLID)
THEORETICAL, NO LOSS HOLDING FORCE (OZ): 35.6110349
EXPECTED HOLDING FORCE (OZ): 22.7910623
****PHYSICAL DIMENSIONS & CONSTANTS****
OVERALL LENGTH: 2.01
OVERALL DEPTH: .635
OVERALL WIDTH: 1.01
WINDING LENGTH: .825
BOBBIN WALL THICKNESS: .064
BOBBIN FLANGE THICKNESS: .15
ARMATURE/BOBBIN CLEARANCE: .285
WINDING CLEARANCE: .07
AIR GAP: 1.5E-03
STEEL PATH LENGTH: 4.5
CORE WIDTH: .3
CORE DEPTH: .295
CORNER RADIUS: 0
CORE PERIMETER: 1.19
CORE AREA: .0885
AIRC HAP AREA (FRINGING): .0893942672
WINDING SURFACE AREA: 1.64145992
************** WINDING DATA **************
WIRE GAGE NUMBER: #42
TURNS SPECIFIED: 993
TURNS POSSIBLE: 1663.68481
RANDOM WIND: 1
WINDING WIDTH: .0632679935
BARE WIRE DIA: 6.33406496E-03
OHMS/CM OF WIRE: .0547204868
EFFECTIVE INSUL. WG: 40.835
INSULATED WIRE DIA: 7.25010641E-03
THEORETICAL TURNS/SQ CM = 19024.4118
CURRENT AT 3 VOLTS: .0308286199
AVERAGE TURN LENGTH: 1.79088612
INDUCTANCE, HENRIES: .339254274
S.S. TEMP RISE, DEG C: 56.819184

FIGURE 15: ANALYSIS LISTING FOR PRODUCTION DESIGN
(CONTINUED ON NEXT PAGE)
THERMAL TIME CONST: 124.908268
RESISTANCE @S.S.TEMP: 111.418295
CURRENT @THAT TEMP: 0.269255602
IDEAL FORCE @THAT TEMP @ 3 VOLTS = 28.7479808

********** MAGNETIC DATA **********
TOTAL AMP-URNS (ACTUAL): 30.6128195
TOTAL AMP-URNS (AIR+IRON): 30.5397908
AMP-URNS IN IRON: 2.41224221
AMP-URNS IN AIR: 28.1275486
OERSTEDS IN IRON: .673625103
OERSTEDS IN AIR: 11782.04
KILOGAUSSES IN IRON: 11.9010941
KILOGAUSSES IN AIR: 11.78204
IRON SAT KILOGAUSS: 15.41

********** DESIGN CONSTRAINTS **********
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: .635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: .5
MIN CORE WIDTH: 0
MAX CORE DEPTH: .5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: .035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

*** Special Note ***
This analysis is for an existing production design.
It was not designed with the optimization program.
Design Constraints are the actual dimensions calculated from this assembly, and are used in all remaining design trials as design constraints to make direct comparisons easier.

DESIGN HINTS: IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

*DESIGN CONSTRAINTS*

MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: 0.635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: 0.5
MIN CORE WIDTH: 0
MAX CORE DEPTH: 0.5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: 0.035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

DESIGN HINTS: IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

**SAMPLE LISTING CONTINUED**

THERMAL TIME CONST: 124.908268
RESISTANCE @S.S.TEMP: 111.418295
CURRENT @THAT TEMP: 0.269255602
IDEAL FORCE @THAT TEMP @ 3 VOLTS = 28.7479808

********** MAGNETIC DATA **********
TOTAL AMP-TURNS (ACTUAL): 30.6128195
TOTAL AMP-TURNS (AIR+IRON): 30.5397908
AMP-TURNS IN IRON: 2.41224221
AMP-TURNS IN AIR: 28.1275486
OERSTEDS IN IRON: .673625103
OERSTEDS IN AIR: 11782.04
KILOGAUSSES IN IRON: 11.9010941
KILOGAUSSES IN AIR: 11.78204
IRON SAT KILOGAUSS: 15.41

********** DESIGN CONSTRAINTS **********
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: 0.635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: 0.5
MIN CORE WIDTH: 0
MAX CORE DEPTH: 0.5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: 0.035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

DESIGN HINTS: IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

**SAMPLE LISTING CONTINUED**

THERMAL TIME CONST: 124.908268
RESISTANCE @S.S.TEMP: 111.418295
CURRENT @THAT TEMP: 0.269255602
IDEAL FORCE @THAT TEMP @ 3 VOLTS = 28.7479808

********** MAGNETIC DATA **********
TOTAL AMP-TURNS (ACTUAL): 30.6128195
TOTAL AMP-TURNS (AIR+IRON): 30.5397908
AMP-TURNS IN IRON: 2.41224221
AMP-TURNS IN AIR: 28.1275486
OERSTEDS IN IRON: .673625103
OERSTEDS IN AIR: 11782.04
KILOGAUSSES IN IRON: 11.9010941
KILOGAUSSES IN AIR: 11.78204
IRON SAT KILOGAUSS: 15.41

********** DESIGN CONSTRAINTS **********
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: 0.635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: 0.5
MIN CORE WIDTH: 0
MAX CORE DEPTH: 0.5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: 0.035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

DESIGN HINTS: IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)
FIGURE 16: DESIGN REQUIREMENTS FOR TEST-SQ-S-D3

FIGURE 17: OPTIMAL DESIGN FOR TEST-SQ-S-D3
FIGURE 18: GAP AND VOLTAGE SENSITIVITY FOR TEST-SQ-S-D3 
WITH LISTING FOR FIRST GAP ONLY
SAMPLE RUN FOR A SINGLE BOBBIN, RECTANGULAR CORE SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

COIL NAME: TEST-SQ-S-D3
COIL TYPE: SINGLE BOBBIN, RECTANGULAR CORE
OPERATING VOLTAGE: 3
COIL RESISTANCE: 85.7314358
CORE MATERIAL: 50/50 NI-Fe (SOLID)
THEORETICAL, NO LOSS HOLDING FORCE (OZ): 49.5609966
EXPECTED HOLDING FORCE (OZ): 31.7190378

****PHYSICAL DIMENSIONS & CONSTANTS****
OVERALL LENGTH: 2.01084969
OVERALL DEPTH: .635156443
OVERALL WIDTH: .998625621
FLANG WIDTH: .0676721706
WINDING LENGTH: .76056841
BOBBIN WALL THICKNESS: .064
BOBBIN FLANGE THICKNESS: .15
ARMATURE/BOBBIN CLEARANCE: .285
WINDING CLEARANCE: .07
AIRGAP: 1.5E-03
STEEL PATH LENGTH: 4.42504373
CORE WIDTH: .33264064
CORE DEPTH: .371812102
CORNER RADIUS: 0
CORE PERIMETER: 1.40890548
CORE AREA: .123679816
AIRGAP AREA (FRINGING): .124738262
WINDING SURFACE AREA: 1.70080295

***************WINDING DATA***************
WIRE GAGE NUMBER: #41.4850841
Turns Specified: 872.399078
Turns Possible: 872.399069
Random Wind: 1
WINDING WIDTH: .0676721706
BARE WIRE DIA: .6.7237313E-03
OHMS/CM OF WIRE: .0485617446
EFFECTIVE INSUL. WG: 40.3370763
INSULATED WIRE DIA: 7.68097937E-03
THEORETICAL TURNS/SQ CM = 16949.8868
CURRENT AT 3 VOLTS: .0349929985
AVERAGE TURN LENGTH: 2.02362774
INDUCTANCE, HENRIES: .365920659
S.S. TEMP RISE, DEG C: 61.2650785

FIGURE 19: ANALYSIS LISTING FOR TEST-SQ-S-D3 (CONTINUED ON NEXT PAGE)
THERMAL TIME CONST: 132.207211
RESISTANCE @ S.S. TEMP: 99.6594453
CURRENT @ THAT TEMP: 0.0301025155
IDEAL FORCE @ THAT TEMP @ 3 VOLTS = 39.3710353

************* MAGNETIC DATA *************
TOTAL AMP-TURNS (ACTUAL): 30.5278593
TOTAL AMP-TURNS (AIR+IRON): 30.4312144
AMP-TURNS IN IRON: 2.34038302
AMP-TURNS IN AIR: 28.0908313
OERSTEDS IN IRON: 664628922
OERSTEDS IN AIR: 11766.6599
KILOGAUSSES IN IRON: 11.8673585
KILOGAUSSES IN AIR: 11.7666599
IRON SAT KILOGAUSS: 15.41

************* DESIGN CONSTRAINTS *************
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: 0.635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: 0.5
MIN CORE WIDTH: 0
MAX CORE DEPTH: 0.5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: 0.035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

DESIGN HINTS:
IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN-changing those limits may change the final solution.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

FIGURE 19: ANALYSIS LISTING FOR TEST-SQ-S-D3 (cont)
FIGURE 20: DESIGN REQUIREMENTS FOR TEST-RND-S-D4

FIGURE 21: OPTIMAL DESIGN FOR TEST-RND-S-D4
VOLTAGE AND AIRGAP SENSITIVITY FOR TEST-RND-S-D4

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<th>GAP</th>
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<th>IDEAL FORCE (OZ)</th>
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<tr>
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<tr>
<td>1.5E-03</td>
<td>6.5</td>
<td>50.972612</td>
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</table>

FIGURE 22: GAP AND VOLTAGE SENSITIVITY FOR TEST-RND-S-D4
WITH LISTING FOR FIRST GAP ONLY
SAMPLE RUN FOR A SINGLE BOBBIN, ROUND CORE
SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

COIL NAME: TEST-RND-S-D4
COIL TYPE: SINGLE BOBBIN, ROUND CORE
OPERATING VOLTAGE: 3
COIL RESISTANCE: 85.7171389
CORE MATERIAL: 50/50 NI-FE (SOLID)
THEORETICAL, NO LOSS HOLDING FORCE (OZ): 38.3173211
EXPECTED HOLDING FORCE (OZ): 24.5230855

**********PHYSICAL DIMENSIONS & CONSTANTS****
OVERALL LENGTH: 2.00960823
OVERALL DEPTH: .593406122
OVERALL WIDTH: 1.00993862
FLANGE WIDTH: .0594368115
WINDING LENGTH: .73154323
BOBBIN WALL THICKNESS: .064
BOBBIN FLANGE THICKNESS: .15
ARMATURE/BOBBIN CLEARANCE: .285
WINDING CLEARANCE: .07
AIRGAP: 1.5E-03
STEEL PATH LENGTH: 4.40609008
CORE RADIUS: .17326625
CORE PERIMETER: 1.08866395
CORE AREA: .0943143601
AIRGAP AREA (FRINGING): .0951326253
WINDING SURFACE AREA: 1.36377238

***************WINDING DATA*****************
WIRE GAGE NUMBER: #42.265761
TURNS SPECIFIED: 877.985896
TURNS POSSIBLE: 877.985885
RANDOM WIND: 1
WINDING WIDTH: .0594368115
BARE WIRE DIA: 6.14186842E-03
OHMS/CM OF WIRE: .058198791
EFFECTIVE INSUL. WG: 41.0919909
INSULATED WIRE DIA: 7.03726625E-03
THEORETICAL TURNS/SQ CM = 20192.5904
CURRENT AT 3 VOLTS: .034998835
AVERAGE TURN LENGTH: 1.67751406
INDUCTANCE, HENRIES: .282734816
S.S. TEMP RISE, DEG C: 73.3459029

****WARNING: COIL EXCEEDS 70 DEG C RISE
OVERHEATING WILL DEGRADE INSULATION
TIME TO REACH 70 DEG C = 342.159165 SEC
DO NOT EXCEED THIS TIME.
ALLOW AT LEAST THIS MUCH TIME BETWEEN
ACTUATIONS WHICH ARE OF THIS LENGTH

FIGURE 23: ANALYSIS LISTING FOR TEST-RND-S-D4
(CONTINUED ON NEXT PAGE)
THERMAL TIME CONST: 110.822574
RESISTANCE @70 DEG C: 102.590591
CURRENT @THAT TEMP: .0292424477
IDEAL FORCE @THAT TEMP @3VOLTS=28.9404781

*************MAGNETIC DATA*************
TOTAL AMP-TURNS(Actual): 30.7284831
TOTAL AMP-TURNS(Air+Iron): 30.6907342
AMP-TURNS IN IRON: 2.40761853
AMP-TURNS IN AIR: 28.2831156
OERSTEDS IN IRON: .686663825
OERSTEDS IN AIR: 11847.2038
KILOGAUSSES IN IRON: 11.9499893
KILOGAUSSES IN AIR: 11.8472038
IRON SAT KILOGAUSS: 15.41

**********DESIGN CONSTRAINTS**********
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: .635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: .5
MIN CORE WIDTH: 0
MAX CORE DEPTH: .5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: .25
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: .035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

DESIGN HINTS:
IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

FIGURE 23: ANALYSIS LISTING FOR TEST-RND-S-D4 (cont)
FIGURE 24: DESIGN REQUIREMENTS FOR TEST-SQ-D-D

FIGURE 25: OPTIMAL DESIGN FOR TEST-SQ-D-D
FIGURE 26: GAP AND VOLTAGE SENSITIVITY FOR TEST-SQ-D-D
WITH LISTING FOR FIRST GAP ONLY
SAMPLE RUN FOR A DOUBLE BOBBIN, RECTANGULAR CORE SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>COIL NAME:</td>
<td>TEST-SQ-D-D</td>
</tr>
<tr>
<td>COIL TYPE:</td>
<td>DOUBLE BOBBIN,RECTANGULAR CORE</td>
</tr>
<tr>
<td>OPERATING VOLTAGE:</td>
<td>3</td>
</tr>
<tr>
<td>COIL RESISTANCE:</td>
<td>85.7189312</td>
</tr>
<tr>
<td>CORE MATERIAL:</td>
<td>50/50 NI-Fe (SOLID)</td>
</tr>
<tr>
<td>THEORETICAL,NO LOSS HOLDING FORCE (OZ):</td>
<td>51.1549686</td>
</tr>
<tr>
<td>EXPECTED HOLDING FORCE (OZ):</td>
<td>32.7391799</td>
</tr>
<tr>
<td><strong>PHYSICAL DIMENSIONS &amp; CONSTANTS</strong></td>
<td></td>
</tr>
<tr>
<td>OVERALL LENGTH:</td>
<td>2.0107306</td>
</tr>
<tr>
<td>OVERALL DEPTH:</td>
<td>63521718</td>
</tr>
<tr>
<td>OVERALL WIDTH:</td>
<td>1.00976745</td>
</tr>
<tr>
<td>FLANGE WIDTH:</td>
<td>0.0292383872</td>
</tr>
<tr>
<td>WINDING LENGTH:</td>
<td>0.858916697</td>
</tr>
<tr>
<td>BOBBIN WALL THICKNESS:</td>
<td>0.064</td>
</tr>
<tr>
<td>BOBBIN FLANGE THICKNESS:</td>
<td>0.15</td>
</tr>
<tr>
<td>ARMATURE/BOBBIN CLEARANCE:</td>
<td>0.285</td>
</tr>
<tr>
<td>WINDING CLEARANCE:</td>
<td>0.07</td>
</tr>
<tr>
<td>AIRGAP:</td>
<td>1.5E-03</td>
</tr>
<tr>
<td>STEEL PATH LENGTH:</td>
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<tr>
<td>CORE WIDTH:</td>
<td>0.283406952</td>
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<tr>
<td>CORE DEPTH:</td>
<td>0.448740406</td>
</tr>
<tr>
<td>CORNER RADIUS:</td>
<td>0.0</td>
</tr>
<tr>
<td>CORE PERIMETER:</td>
<td>1.46429472</td>
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<tr>
<td>CORE AREA:</td>
<td>0.127176151</td>
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<tr>
<td>AIRGAP AREA (FRINGING):</td>
<td>0.128276139</td>
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<tr>
<td>WINDING SURFACE AREA:</td>
<td>3.52177968</td>
</tr>
<tr>
<td><strong>WINDING DATA</strong></td>
<td></td>
</tr>
<tr>
<td>WIRE GAGE NUMBER:</td>
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<tr>
<td>TURNS SPECIFIED:</td>
<td>875.582503</td>
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<tr>
<td>TURNS POSSIBLE:</td>
<td>875.582495</td>
</tr>
<tr>
<td>RANDOM WIND:</td>
<td>1</td>
</tr>
<tr>
<td>WINDING WIDTH:</td>
<td>0.0292383872</td>
</tr>
<tr>
<td>BARE WIRE DIA:</td>
<td>6.62680734E-03</td>
</tr>
<tr>
<td>OHMS/CM OF WIRE:</td>
<td>0.0499926652</td>
</tr>
<tr>
<td>EFFECTIVE INSUL.WG:</td>
<td>40.4581782</td>
</tr>
<tr>
<td>INSULATED WIRE DIA:</td>
<td>7.57388474E-03</td>
</tr>
<tr>
<td>THEORETICAL TURNS/SQ CM=</td>
<td>17432.6181</td>
</tr>
<tr>
<td>CURRENT AT 3 VOLTS:</td>
<td>0.0349981032</td>
</tr>
<tr>
<td>AVERAGE TURN LENGTH:</td>
<td>1.95827368</td>
</tr>
<tr>
<td>INDUCTANCE,HENRIES:</td>
<td>37831403</td>
</tr>
<tr>
<td>S.S.TEMP RISE,DEG C:</td>
<td>32.9281411</td>
</tr>
</tbody>
</table>

**FIGURE 27: ANALYSIS LISTING FOR TEST-SQ-D-D**
(CONTINUED ON NEXT PAGE)
THERMAL TIME CONST: 33.546317
RESISTANCE @S.S.TEMP: 90.0818698
CURRENT @THAT TEMP: .0333030387
IDEAL FORCE @THAT TEMP @3VOLTS= 46.7425541

************ MAGNETIC DATA ************
TOTAL AMP-TURNS (ACTUAL): 30.6437265
TOTAL AMP-TURNS (AIR+IRON): 30.5630167
AMP-TURNS IN IRON: 2.42034058
AMP-TURNS IN AIR: 28.1426761
OERSTEDS IN IRON: .670756832
OERSTEDS IN AIR: 11.788.3766
KILOGAUSSES IN IRON: 11.8903381
KILOGAUSSES IN AIR: 11.7883766
IRON SAT KILOGAUSS: 15.41

************ DESIGN CONSTRAINTS ************
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: .635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE DIA: 0
**PX VIOLATED
MIN CORE DIA: 0
MAX CORE WIDTH: .5
MIN CORE WIDTH: 0
MAX CORE DEPTH: .5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: .035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

DESIGN HINTS:
IF ANY FINAL DIMENSIONS ARE AT OR NEAR
THEIR LIMITS, THEN CHANGING THOSE LIMITS
MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY
INCREASING THE SURFACE AREA (OR LX)

FIGURE 27: ANALYSIS LISTING FOR TEST-SQ-D-D (cont)
FIGURE 28: DESIGN REQUIREMENTS FOR TEST-RND-D-D

FIGURE 29: OPTIMAL DESIGN FOR TEST-RND-D-D
VOLTAGE AND AIRGAP SENSITIVITY FOR TEST-RND-D-D

<table>
<thead>
<tr>
<th>GAP</th>
<th>VOLTAGE</th>
<th>IDEAL FORCE (OZ)</th>
</tr>
</thead>
<tbody>
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<td>1.5E-03</td>
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</tr>
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<td>1</td>
<td>2.90926667</td>
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<td>13.4507776</td>
</tr>
<tr>
<td>1.5E-03</td>
<td>2.5</td>
<td>20.2992553</td>
</tr>
<tr>
<td>1.5E-03</td>
<td>3</td>
<td>27.2367363</td>
</tr>
<tr>
<td>1.5E-03</td>
<td>3.5</td>
<td>30.4359474</td>
</tr>
<tr>
<td>1.5E-03</td>
<td>4</td>
<td>33.3406152</td>
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<td>4.5</td>
<td>36.8662101</td>
</tr>
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<td>5</td>
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<tr>
<td>1.5E-03</td>
<td>5.5</td>
<td>36.7347376</td>
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<td>1.5E-03</td>
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<tr>
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<td>6.5</td>
<td>37.4293757</td>
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FIGURE 30: GAP AND VOLTAGE SENSITIVITY FOR TEST-RND-D-D WITH LISTING FOR FIRST GAP ONLY
SAMPLE RUN FOR A DOUBLE BOBBIN, ROUND CORE
SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

COIL NAME: TEST-RND-D-D
COIL TYPE: DOUBLE BOBBIN, ROUND CORE
OPERATING VOLTAGE: 3
COIL RESISTANCE: 85.7154207
CORE MATERIAL: 50/50 NI-Fe (SOLID)
THEORETICAL, NO LOSS HOLDING FORCE (OZ): 27.2367363
EXPECTED HOLDING FORCE (OZ): 17.4315112

*** PHYSICAL DIMENSIONS & CONSTANTS***

OVERALL LENGTH: 1.97440005
OVERALL DEPTH: .470043968
OVERALL WIDTH: 1.01008794
FLANGE WIDTH: .0222470196
WINDING LENGTH: .794300195
BOBBIN WALL THICKNESS: .064
BOBBIN FLANGE THICKNESS: .15
ARMATURE/BOBBIN CLEARANCE: .285
WINDING CLEARANCE: .07
AIRGAP: 1.5E-03
STEEL PATH LENGTH: 4.43378819
CORE RADIUS: .148774964
CORE PERIMETER: .934780671
CORE AREA: .0695359805
AIRGAP AREA (FRINGING): .0702388332
WINDING SURFACE AREA: 2.34586503

*************** WINDING DATA ****************

WIRE GAGE NUMBER: #43.1059588
TURNS SPECIFIED: 861.588985
TURNS POSSIBLE: 861.588985
RANDOM WIND: 1
WINDING WIDTH: .0222470196
BARE WIRE DIA: 5.57177512E-03
OHMS/CM OF WIRE: .07071765
EFFECTIVE INSUL. WG: 41.9044622
INSULATED WIRE DIA: 6.40461727E-03
THEORETICAL TURNS/SQ CM = 24378.8736
CURRENT AT 3 VOLTS: .0349995366
AVERAGE TURN LENGTH: 1.4067956
INDUCTANCE, HENRIES: 200995832
S.S. TEMP RISE, DEG C: 46.8358855

FIGURE 31: ANALYSIS LISTING FOR TEST-RND-D-D
(CONTINUED ON NEXT PAGE)
THERMAL TIME CONST: 24.1183862
RESISTANCE @ S.S.TEMP: 94.7715199
CURRENT @ THAT TEMP: .0316550795
IDEAL FORCE @ THAT TEMP @ 3 VOLTS = 23.1842807

************* MAGNETIC DATA *************
TOTAL AMP-TURNS (ACTUAL): 30.1552152
TOTAL AMP-TURNS (AIR+IRON): 29.9782969
AMP-TURNS IN IRON: 2.22699839
AMP-TURNS IN AIR: 27.7512985
OERSTEDS IN IRON: .631182321
OERSTEDS IN AIR: 11624.4367
KILOGAUSSES IN IRON: 11.7419337
KILOGAUSSES IN AIR: 11.6244367
IRON SAT KILOGAUSS: 15.41

********** DESIGN CONSTRAINTS **********
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: .635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE DIA: .5
MIN CORE DIA: 0
MAX CORE WIDTH: .5
MIN CORE WIDTH: 0
MAX CORE DEPTH: .5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: .25
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: .035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

DESIGN HINTS:
IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

FIGURE 31: ANALYSIS LISTING FOR TEST-RND-D-D (cont)
FIGURE 32: DESIGN REQUIREMENTS FOR CORE SHAPE TEST

FIGURE 33: OPTIMAL DESIGN FOR CORE SHAPE TEST
VOLTAGE AND AIRGAP SENSITIVITY FOR CORE SHAPE TEST

<table>
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<tr>
<th>GAP</th>
<th>VOLTAGE</th>
<th>IDEAL FORCE(02)</th>
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<td>1.5E-03</td>
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<td>14.490173</td>
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<td>25.3141497</td>
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<td>59.7093711</td>
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<td>63.247283</td>
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<td>63.8669531</td>
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<td>1.5E-03</td>
<td>6</td>
<td>64.4971118</td>
</tr>
<tr>
<td>1.5E-03</td>
<td>6.5</td>
<td>65.1357018</td>
</tr>
</tbody>
</table>

FIGURE 34: GAP AND VOLTAGE SENSITIVITY FOR CORE SHAPE TEST WITH LISTING FOR FIRST GAP ONLY
SAMPLE RUN FOR A SINGLE BOBBIN, UNCONSTRAINED CORE SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

COIL NAME: CORE SHAPE TEST
COIL TYPE: SINGLE BOBBIN, RECTANGULAR CORE
OPERATING VOLTAGE: 3
COIL RESISTANCE: 85.7247655
CORE MATERIAL: 50/50 NI-FE (SOLID)
THEORETICAL, NO LOSS HOLDING FORCE (OZ): 49.6827594
EXPECTED HOLDING FORCE (OZ): 31.796966

****PHYSICAL DIMENSIONS & CONSTANTS****
OVERALL LENGTH: 2.00841072
OVERALL DEPTH: .635277121
OVERALL WIDTH: .995048396
FLANGE WIDTH: .0703393029
WINDING LENGTH: .767040924
BOBBIN WALL THICKNESS: .064
BOBBIN FLANGE THICKNESS: .15
ARMATURE/BOBBIN CLEARANCE: .285
WINDING CLEARANCE: .07
AIR GAP: 1.5E-03
STEEL PATH LENGTH: 4.42550004
CORE WIDTH: .328184895
CORE DEPTH: .366598515
CORNER RADIUS: .0141314864
CORE PERIMETER: 1.36530568
CORE AREA: .120140672
AIR GAP AREA (FRINGING): .121166419
WINDING SURFACE AREA: 1.69468826

*************** WINDING DATA ***************
WIRE GAGE NUMBER: #41.4200803
TURNS SPECIFIED: 901.266209
TURNS POSSIBLE: 901.266208
RANDOM WIND: 1
WINDING WIDTH: .0703393029
BARE WIRE DIA: 6.77459784E-03
OHMS/CM OF WIRE: .0478352381
EFFECTIVE INSUL. WG: 40.2742177
INSULATED WIRE DIA: 7.73716314E-03
THEORETICAL TURNS/SQ CM = 16704.6158
CURRENT AT 3 VOLTS: .0349957213
AVERAGE TURN LENGTH: 1.98840697
INDUCTANCE, HENRIES: .373005434
S.S. TEMP RISE, DEG C: 61.4507456

FIGURE 35: ANALYSIS LISTING FOR CORE SHAPE TEST
(CONTINUED ON NEXT PAGE)
THERMAL TIME CONST: 136.577254
RESISTANCE @ S.S. TEMP: 99.7143539
CURRENT @ THAT TEMP: .0300859393
IDEAL FORCE @ THAT TEMPERATURE @ 3 VOLTS = 39.7441485

************ MAGNETIC DATA ************
TOTAL AMP- Turns (ACTUAL): 31.540461
TOTAL AMP- Turns (AIR+IRON): 31.3672126
AMP- TURNS IN IRON: 2.8303554
AMP- TURNS IN AIR: 28.536857
OERSTEDS IN IRON: .803689898
OERSTEDS IN AIR: 11953.4907
KILOGAUSSSES IN IRON: 12.0555482
KILOGAUSSSES IN AIR: 11.9534907
IRON SAT KILOGAUSS: 15.41

************ DESIGN CONSTRAINTS ************
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: .635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: .5
MIN CORE WIDTH: 0
MAX CORE DEPTH: .5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: .25
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: .035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41
DESIGN HINTS:
IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

FIGURE 35: ANALYSIS LISTING FOR CORE SHAPE TEST (cont)
11.3 Observations and Conclusions

The computer program has found a definite maximum for each of the bobbin configurations. To check if they are unique, the test for equivalent designs described at the end of section 10.3 has been tried on the single round, and single rectangular bobbin configurations. After making three design runs with each type, no difference was found between runs. While this is not a rigorous test, it is strong evidence that the designs are unique, for the constraints imposed, since the different start points generated for each run should have ended in slightly different solutions, in the event of equivalent configurations.

Most of the points about the physical dimensions for the Production Design have already been discussed in Chapter II, and will not be repeated here. One point which will be made is that the bobbin is underfilled more than the amount which would be expected for winding allowance. From figure 15, it can be seen that the winding width is 0.042cm less than the flange width. It is this condition which accounts for the biggest difference between this design and the optimized design using the same bobbin configuration.

When first viewing the sensitivity graphs, a common observation is that they do not look right. Because the three gaps are equally spaced, it is felt that the apparent space between adjacent curves should be the same. The difference in their appearance turns out to be an optical
illusion since, in fact, they are the same distance apart.

The calculations which follow will help to tie together the
discussion in Chapter II, the sensitivity graphs, and the
experiments which are covered in Chapter XII. In the
discussion which follows, it will be assumed that the airgap
difference between any two curves in a sensitivity plot is
unknown. This will result in a full excercising of the
thought process being developed. Figure 14, will be used as
an example.

Equation (25), can be rearranged so that for any known
force, the corresponding effective flux density can be
calculated.

\[ BA = \sqrt{\frac{FT}{Kl}} / AG \]  \hspace{1cm} (60)

For the small airgaps involved, it can be seen from
equation (19), that the area of the gap, AG, is essentially
constant for the small gaps discussed in this paper. This
simplification is most valid if AG, for the center curve, is
used.

With the simplification that AG is constant, equation
(60), is not directly dependent on the length of the airgap.
Thus, for any specific force level, the flux density in the
air will have a unique value, regardless of which airgap
curve is chosen. Since the core area is constant and the
area of the airgap is essentially constant, then equation
(23), states that this force level will also correspond to a
specific flux density in the iron, BI.
From the initial magnetization curve, it is known that the relationship between B and H, for any one material, is a single valued one. Because the flux density in the iron, BI, is a unique value for any given force, it follows that HI, is also unique. Finally, from equation (15), it can be seen that the amp turns in the iron, NI, is similarly known since the iron path length, PL, is a constant.

\[ NI = HI \times PL / PI / 0.4 \]  

Equation (20), dictates that the total amp turns in the system is equal to the sum of the amp turns in the iron and those in the air. It has been shown that for any given force level, the amp turns in the iron is a constant. Therefore, at that force level, for any number of total amp turns in, the amp turns in the air can be calculated. Stated slightly differently, since NI, is a constant then for any change in NT, along a constant force line there will be an equal change in NA.

\[ d(NT) = d(NA) \]  

For a given coil, the number of turns is a constant. Similarly, the total coil resistance is also a constant. By equation (10), it follows that for any voltage, the current is known. Multiplying the current by the number of turns gives the total amp turns for the coil.

\[ NT = NC \times V / CR \]  

A combination of equations (62) and (63), results in equation (64).
\[ d(NA) = d(V) \times (NC / CR) \quad (64) \]

A combination of equations (14) and (15), results in equation (65), which relates BA, NA and G. The constant of 2 is needed to account for the two airgaps. To keep the units of BA consistently in kilogausses for this section, rather than mixing with the gauss specified by equation (14), BA is multiplied by a factor of 1000.

\[ 1000 \times BA = HA = 0.4 \times \pi \times NA / G / 2 \quad (65) \]

By rearranging (65), the airgap, G, can be calculated for any known NA and BA.

\[ G = 0.4 \times \pi \times NA / BA / 2000 \quad (66) \]

From the sensitivity graph, NA is not directly known if the situation existed where the gap was not known. However, if two different gaps exist at the same value of BA, and thus of force, then the difference between them is expressed by equation (67).

\[ d(G) = d(NA) \times 0.4 \times \pi / BA / 2000 \quad (67) \]

This relationship gives a very important piece of information toward explaining the different slopes of the three gap curves in any one sensitivity plot. For a fixed airgap difference, the extra NA required to move from one airgap curve to the next along a constant force line, increases for increasing force directly proportional to the corresponding increase in BA.

The logic in this argument has moved at a quick pace. Hopefully the reader has followed it, as the arguments
presented will be used repeatedly in later sections. Many different avenues of equation manipulations were tried before the one just described was arrived at for explaining the shapes of the different airgap curves. Except for two implicit assumptions, the equations should result in a precise prediction of differences in airgap for any one force level. The first of these is the simplification that the area of the airgap is essentially unaffected by changes in the airgap. While this is very dependent on how large the airgap is relative to the area of the core, for the dimensions existing in any of the examples being considered here, it is a reasonable simplification. Using the Production Design, as an example, by equation (19), the gap areas corresponding to airgaps of 0.0015, 0.003 and 0.0045 centimeters are 0.0894, 0.0903 and 0.0912 sq-cm respectively. This is only a 1% change in area for gap steps which are large relative to the airgaps.

The second assumption is that as the airgaps increase, the flux leakages do not also increase significantly. Section 2.10, alluded to a complex set of leakage paths at the poles. One of the many factors determining these paths is the airgap (Ref 11). Since no calculations have been made for these leakages, the validity of this second assumption will go unchecked in this paper.

The reasons for this complicated derivation will become clearer in Chapter XII. It has been presented, at this time,
so that the equations can be used to manipulate the known data from the computer runs as a validity check before applying them to unknown experimental data.

To check the logic presented, an example using the Production Design sensitivity graph of figure 14, will be carried out. It has been stated that the logic should apply at any force level. Therefore, a level of 12 ounces will be chosen. As seen on that graph, a horizontal line has been drawn for the 12 ounce force. If the distance between any two adjacent air gap curves is carefully measured and scaled, it is found that it corresponds to 1.65 volts. As predicted by equation (67), the voltage difference between the 0.0015 and 0.003 curves is the same as that between the 0.003 and 0.0045 curves, within the ability to measure it.

From the output listing of figure 15, the coil resistance is calculated to be 97.312 ohms and the number of turns is given as 993. Entering these values and the 1.65 volt difference into equation (64), says that the additional amp turns required to overcome the increase in air gap between two adjacent curves at the same force level is equal to 16.837 amp turns. For a force of 12 ounces and a gap area of 0.0903sq-cm, equation (60), indicates a flux density in the air of 6.8053 kilogausses. Applying equation (67), gives the result that the predicted airgap difference should be 0.00155, which agrees quite well with the actual value of 0.0015. Errors in reading the 1.65V difference could account
for this minor discrepancy.

As a second check, BA at a force of 20 ounces would equal 8.6605 kilogausses by equation (60). Inserting this value into a combination of equations (67) and (64), predicts a voltage difference of 2.1 volts. A measurement at that force level concurs with this result.

One final note on the sensitivity curve is, if the distance from the vertical axis to the 0.0015 curve is measured at the two force levels just discussed, the value is essentially equal to the distance between the 0.0015 and 0.003 curves. Examination of the output listing for the coil explains this. The amp turns in the iron is less than 10% of the total amp turns in the system for the material being considered. Therefore, as a first approximation, all of the amp turns in the system could be considered as being in the air at small airgaps below the knee of the B-H curve. If this assumption is made, then the distance from the vertical axis to the first curve should match that between the first and second since the gap difference is the same.

Another observation which can be made about the sensitivity curves is that for every one of the designs, the knee of the force curve coincides with the design point of three volts and an airgap of 0.0015cm. This makes sense, since the only reason the force does not increase as a square of the voltage is that the B-H curve for the iron is limiting the increase. A check of the kilogauss levels in the iron,
for all designs, shows that they are all within 0.16 of 11.9 kilogauss. Referring to figure 2, it can be seen that this corresponds to a point where the knee of the B-H curve has just been passed. The designs have, therefore, optimized the trade-off between increases in core area and flux density. Increases in core area will increase the mean path length of the wire. According to equation (12), this will result in a decrease in total amp turns and, thus, a decrease in the flux density. Since the force increases as the square of the flux density and proportional to the area, this design exists where the balance of the competing variables lie.

One of the objectives of the runs selected is to find the best configuration of bobbin for the specified constraints. This turns out to be the square core with a double bobbin, which has a no-loss holding force of 51.2oz. This is closely followed by the single bobbin square design with 49.6oz. These are both approximately 50% higher than the production design with only 35.6oz. The single round design was only slightly better than the production one with 38.32oz, while the double round design finished a dead last with only 27.2oz of no-loss holding force.

The core shape test is identical in every respect to the single square bobbin design for all practical purposes. This makes sense, since a rectangular bobbin utilizes the available space more fully than a round one. The slight differences between the core shape test and a purely
rectangular design would be lost in any manufacturing process. No further mention will be made of this run except to point out that during the search process, the R(25) and R(26) inequality equations seem to have worked, since the design did not wander off into imaginary space. When an inequality does not work properly, this often happens. The objective of this run is, therefore, met.

The major reason for the poorer performance of the round designs can be found by comparing the overall depth. For every one of the designs, the maximum length and width were filled. For all the rectangular designs, the maximum depth was also matched. In the case of the round designs, however, the maximum width limited the size of the overall coil and prevented the depth from reaching the allowed maximum. The double round bobbin overall depth is only 3/4 of the amount permitted by the design limits.

Steady state temperature rise is the only other factor which showed a significant difference from among the four basic types considered. Due to the decrease in surface area, for the same power input, the single round bobbin exceeded the 70 degree temperature difference allowed, while the other three stayed below the limit. The double square design is the best by a significant margin, being approximately half of the value reached by the single square type. Even if the two facing surfaces of the double design are considered to be insulated, the double bobbin configuration has enough
additional surface area to stay cooler than the single one.

One final point of interest can be made by comparing the predicted design from the first optimization method with the same configuration bobbin in the second. In figure 6, the locus of best designs was assumed to be somewhat symmetrical. The result is a prediction that the core area should be slightly less than 0.1225sq-cm, with a wire number near 41.5, and a holding force of 50oz. The force of the final design is 49.6oz, the wire gage 41.49 and the area 0.124sq-cm. This is as close to a perfect match as can be expected. The minor difference in area indicates that the locus of maximum designs should have been skewed slightly to the right, thereby aligning itself even closer with the (CA)*(NT)*(NT)/PL line. The design methods can, therefore, be treated as equally good for the constraints considered, and it can be considered the designer's choice for which method to use. Each has advantages and disadvantages which must be weighed when choosing a method to use.

For the design constraints of the example problems, a designer must choose the bobbin style that best suits his needs. If the only factors to be considered are holding force and temperature rise, then the double rectangular bobbin is a clear winner. This must be weighed against the complication to the manufacturing process caused by the interconnection between the two bobbins. A further manufacturing concern is that the wire is more prone to
breakage during the winding process with a rectangular core than a round one. This is a result of the dynamic loads imposed on the wire as the winding radius fluctuates on the rectangular design. The radii on the bobbin walls have been assumed to help alleviate this problem.

There are three items from the COIL DESIGN module output which are not shown in any of the outputs in this paper. They do not have any bearing on the solution, and the average user would not be aware of their existence. The first item is the number of basepoints required for the search process. With the changes to the initial value of FP, between 55 and 63 basepoints, were required for the four basic types, while the core shape test run required 96. Without the change to FP, 272 points were needed for the rectangular core, single bobbin design.

A second item of interest is the number of function evaluations required. The four basic types took about 360 each, the core shape test, 548, and the unaltered single square run, 1529.

The last item of interest for those familiar with the P519RE program is the number of resets required. This is an indication of how many times the program ended up in a corner. If the number of resets is too high, the answer obtained becomes questionable. For the unaltered program, this number was 14, which is more than is usually desired. The other runs had a range of from two to six, which is not
unreasonable for a problem that has not gone through the decomposition process.

In summary, the program met or exceeded all of its goals, and produced useful results. All program modules worked properly and the resulting package is easy to use and highly user friendly. The point, which cannot be stressed enough, is that the design calculated is the highest force coil possible, subject to the given constraints. When an actual sample is built, the somewhat arbitrary loss factor may not be exactly correct, and as a result, the force measured may vary slightly from the predicted number. With the exception of manufacturing improvements affecting the airgap, however, nothing will improve the potential holding force within the constraints supplied. If more force is required, then the requirements must be changed. Changing the number of turns, wire size, or core area will only decrease the performance of the coil for unchanged requirements.
12.1 Purpose of the Experiments

There are four reasons for running these experiments, which can be summarized as follows:

1) Compare the computer run results with actual assemblies

2) Determine the effective airgap to use in the computer runs, based on force measurements

3) Determine if the 64% force loss constant used in the ANALYSIS program module is reasonable. It must be remembered that this factor affects only the absolute level of force calculated, but does not affect the optimum design. If the loss factor is off, only the scale of the force plot needs to be changed

4) Find the effect of core density on the holding force and B-H curve characteristics.

The fourth point needs some explanation. For the production of high volume, low cost holding coils, the use of solid stock is discouraged. The reason for this is that in addition to the forming or punching operation required to produce the initial core blank, a grinding operation must be performed to achieve good pole faces. This secondary operation can increase the costs appreciably. The alter-
native is to use a powdered metal core, which is formed in a press and then sintered. The result is an inexpensive part, with consistent pole surfaces from part to part.

The material chosen for the powder is 50/50 Nickel Iron. As seen in the B-H curve for that material, it is a high permeability material, that is, for low amounts of mmf, the resulting flux density is high. For small coils, the available total amp turns is small, as dictated by available space. Therefore, a high permeability material is required to get useful work out of the system. The material also has a very small hysteresis loop, resulting in low residual magnetism when the power is shut off. In addition to the favorable magnetic properties of nickel-iron, the corrosion resistance is high, resulting in a material which can be safely used in adverse environmental conditions.

The disadvantage of the sintered material is that its density can vary, depending on the pressure used to compact the part, and the amount of material in the mold at the time of compaction. The saturation level for the flux is known to be lowered by a decrease in the density, but the amount is not published. The reason for this is that the B-H curves are so dependent on the end users manufacturing process that the powdered metal vendors do not make this information available. In addition to density variations, the other major contributors to material property variations are the heat treating steps required to remove residual magnetic
effects, when producing any magnetic material.

Since this B-H curve data for the various densities of sintered powdered nickel iron is difficult to obtain, one of the minor subgoals of this project was to determine the B-H curves for various densities of the 50/50 nickel-iron material.

12.2 Description of Apparatus and Experiments

Figure 36, shows a sketch of the equipment used for the holding force experiments. An electromagnet bobbin, wound to the specifications of the Production Design coil of figure 13, is mounted vertically in an aluminum nest. Aluminum is chosen to avoid any magnetic losses into the surrounding equipment. The leads for the coil are then attached to a variable D.C. power supply and a digital volt meter.

A core sample is slipped into the bobbin for each test run. One bobbin is used for all of the tests to eliminate bobbin variations from one core test to the next. In this manner, only core density and airgap variation will exist between sample runs. Similarly, one armature, of the highest density available, is used for all the powdered metal core tests. Since the magnetic path length of the armature is relatively small, the core effects will predominate. Had the alternative of separate armatures been used, the variations in surface characteristics could have overshadowed the core
VARIABLE D.C. POWER SUPPLY WITH DIGITAL VOLTMETER

PRODUCTION DESIGN BOBBIN WITH TEST CORE INSERTED

LINKS FOR TORQUE ISOLATION

CUP FOR WEIGHTS (BBS)

SKETCH OF APPARATUS
note: bobbin held vertical in an aluminum nest

ENLARGEMENT OF ARMATURE CROSS-SECTION AND HOLDER SHOWING CENTERING FEATURE

FIGURE 36: HOLDING FORCE EXPERIMENTS EQUIPMENT
and pole face contributions being studied.

Also shown in figure 36, is the armature holder and armature cross section. A small indentation is made in the top surface of the armature, and a matching point built into the armature holder. By doing this, two things are guaranteed. The first, is that the load being applied to the magnet is at its centerline, which is assumed in the force equation. The second, is to avoid any torque on the armature during a force measurement. Common experience says that when lifting a magnet off a flat surface, it should be tipped to reduce the force required to separate it from the surface. To avoid this effect, care must be taken to avoid any torque on the armature when trying to measure the maximum straight steady pull force developed.

In keeping with this requirement, two loops of wire are placed between the armature holder and test weight to isolate the two. The test weight consists of a large softdrink cup containing a counted number of BB's. The weight of the armature and other equipment hanging from it is 18 grams.

For each data point collected, the power supply is set to the voltage of interest. Some number of BB's are placed in the cup, and the armature held against the pole faces of the magnet with the fingers of the experimenter. Power is then applied to the windings, and a check made to see if the weight can be supported. If so, the power is shut off, more
weight added to the cup, and the process repeated until the magnet can no longer hold the trial weight. The last load which can be reliably held, is recorded as the holding force for the device. One important point is that the power is applied to the coil for only a short period of time in an attempt to circumvent heating problems.

When the airgap experiment is run, shims are placed along the full face of the armature, and the holding force trials are run as described above. Five different shim stock thicknesses have been tried. The thinnest three consist of one, two and three thicknesses of clear wrapper from a cigarette package, measuring approximately 0.0019cm each. The two thickest spacers are pieces of brass of the thickness specified.

12.3 Experimental Results and Calculations

The first experiment uses the shims described above to determine the relative size of the airgap between the unaltered poles and armature. Figure 37 shows the results in graphical form. For the graph shown, one core and armature of the highest density of sintered 50/50 Ni-Fe available is used. This corresponds to the 16-ton sample, which will be described later. Due to the uncertainty zone about the actual holding force, the midpoint between the weight, which could be held consistently, and one which could not be held at all, has been recorded to the nearest 10 BB's. One BB has
Figure 37  Holding Force vs. Voltage for Several Airgaps

with 16 Ton Sintered 50/50 Ni-Fe Core
an average weight of 0.345 grams, and the range of uncertainty is on the order 10 BB's.

It can be seen that the trend of force versus airgap is the same as that previously shown in the sensitivity graphs from the computer runs. If, however, equation (67), is applied to the difference between neighboring airgap curves the calculated voltage difference is approximately half of that actually measured. The initial concern was that the equations, which have been developed, ignored the fact that there are two airgaps in the system. A careful check has not detected such an error, though one might exist. Unfortunately, the equations used in the computer programs, and those used to perform the sensitivity analysis in section 11.3, are the same. Therefore, it makes sense that they be self-consistent. At this point in time, one possible explanation for the discrepancy appears to be that the losses are larger than expected. A factor of two seems too large, however.

A second, more plausible explanation, lies in the size of the gaps being considered. Since the shims are of the same relative size as an airgap between two "flat" surfaces, and since the airgaps in the test are created by multiple layers of material, it is very probable that each of the shims, plus the surfaces between them, are effectively making a double contribution.

Recognizing that a discrepancy exists, the concepts
which lead to equation (67) should apply even if the equation does not produce the exact answer. With this, if it is assumed that all the amp-turns available are in the air for the no shim curve, then the ratio of the distance between the vertical axis and the no shim curve, and the distance between the no shim curve and 0.0019cm shim curve, should be equal to the ratio of the airgaps. The actual airgap will be slightly smaller than this, although any errors will be small for a high permeability material. When measured at the 2,3,4 and 7 ounce force lines, there is an average ratio of 4.07. The range of values is from 3.94 to 4.28 with no order to them. Using this ratio, the effective airgap should be approximated by a value equal to one fourth the 0.0019cm gap difference between the first two curves. Thus, a gap of 0.00047cm might be assumed for each airgap for a 16-ton part. This is one third of the value used in the computer runs. If, however, the discrepancy between the predicted and apparent airgaps is taken into account, the gap could be double this value, or 0.00094cm.

In actual practice, it is better to design for the larger airgap expected. Then, holding forces will only improve with improved manufacturing processes. The computer runs are still valid, and the airgap chosen is less than 0.001cm larger than the value inferred by the experimental results. Any surface imperfection will more than mask this difference. In addition, the sample used for the test happens to be the
best of four tried, so that any other one would have given a different result. The direction of that change is to larger airgaps. A final point is that the solid core force experiment will demonstrate an apparent airgap of 0.0011cm. Therefore, all values indicate that the first guess for an airgap between two flat surfaces is a good one, and should continue to be used.

12.4 Core Density Experimental Results

A graph of the data for the second experiment of force versus voltage for different core densities is shown in figure 38. When the parts of different density were manufactured for these samples, the same amount of 100 mesh powder was inserted in the die before pressing. The result was a series of parts of all the same weight, but of different thickness. To allow the use of one bobbin, and to eliminate cross sectional area variation, the parts were ground to the same thickness as the thinnest part. They were then hydrogen annealed to remove the internal stresses induced by the machining operation. These stresses can significantly affect the magnetic characteristics of a magnetic material.

A plot of measured part density as a function of press tonnage is shown in figure 39. Only one cubic shaped sample of each material measuring 0.25cm on a side was used in making these density measurements. For this reason, small
FIGURE 38
HOLDING FORCE vs VOLTAGE FOR SEVERAL SINTERED 50/50NI FE CORE DENSITIES
Figure 39  Sintered 50/50 Nickel Iron Density and Airgap vs Pressure
errors in weight or size, plus material defects, could greatly affect the absolute values calculated. What is important in figure 39, is the relative change in density with pressure. It can be seen that definite improvements in density result from increases in the pressure up to 8 tons per square inch. Above this point, the returns are small, and the likelihood of tool breakage large.

The force versus part density graph of figure 38, shows this same trend. Large relative improvements in holding force are experienced for increases in density up to the density corresponding to 8-tons pressure. A doubling of the 8-ton pressure, however, yields only a 10% increase in holding force.

In addition to the higher holding forces, a second piece of information can be obtained from figure 38. Down at the lower end of the curves, it can be seen that there is a displacement horizontally, which tends to move to the right as the density decreases. This can be the result of one of two phenomena. The first would be that as the part density decreases, more surface irregularities occur and, therefore, the effective airgap increases. By measuring the voltage difference between curves for one force level, it should be possible to calculate those airgaps by the techniques developed in this paper. These have been carried out, assuming the 0.0019cm airgap difference between the first two curves, and are shown in figure 39. If this is a cause and
effect, the trend is very definite for the points chosen. The absolute airgaps might be in error by the factor of two discussed previously, but the trend should be correct.

The second possible explanation for the displacement could be found with the B-H curves for the material. When making the airgap calculations, it is assumed that the flux density and amp turns in the iron are the same for any give force. If, however, there is a difference in the amount of mmf required to reach a specific flux density for each of the materials, then the airgap calculations are invalid. This difference could be the result of either a shift of the B-H curve to the right with density decreases, or a vertical scaling of the B-H curve with density. Without the B-H curves, it is difficult to predict which theory best explains the effect. This is the intent of the experiment presented in Chapter XIII.

12.5 Solid Core Experimental Results

Using a solid nickel iron core and armature, the holding force measurements were repeated for this experiment. A different armature was required, because the sintered material armature could become the limiting factor on the amount of flux which the iron path passes. This concern is based on the results of the previous experiment. Since the density of the 16-ton part is less than that of solid nickel iron, and since it has been shown that density affects the
holding force and, thus, the flux density, the concern is justified. A second solid core was, therefore, cut and used as an armature.

Two additional remarks need to be made concerning the core used for the test. The first is that the amount of protrusion above the bobbin, Cl, is only 0.038 cm. A check with the computer reveals that this has only a very small affect on the expected holding force. A difference of only 0.25 ounces out of 50 is likely. The second note is that during the manufacturing process, the core necked down slightly at the bend during the bending operation. Section 2.10 indicated that this section of the core saturates first. Therefore, this area is likely to be the limiting section of metal path. As a result, expected flux densities might not be reached, or at the very least, deviations of the holding force near the knee of the B-H curve knee can be expected.

Figure 40, shows the plotted experimental results. The force level reached at the maximum of 6 volts is more than fifty percent higher than that attained by the best sintered core. The earlier assumption, therefore, which determined the need for a solid armature, is correct.

One of the goals of these experiments is to determine how closely the computer trials predict the actual performance of an assembly. To do this, an airgap must be assumed, and the force loss multiplier checked. When the solid core experimental results are compared to the results
Figure 40: Solid 50/50 Nickel Iron Core and Armature Predicted and Measured Holding Force
from the core density experiment, the solid core plot is not parallel to the other curves. It is slightly steeper, and falls between the 5- and 8-ton lines. Taking the average airgap for the samples, and assuming the theory that the effective airgap is larger than the shim thickness due to the extra surfaces of the shims, an airgap of 0.0011cm per pole is assumed for the solid sample.

A computer run is then made using this gap and the shorter core protrusion value. The predicted no loss holding force is compared with the measured force at six volts, and the ratio taken. Using this ratio as a force loss multiplication factor, the computer prediction and experimental data can be compared.

The result is shown in figure 40. The derived multiplication factor is 0.645, which is nearly identical with the 64% factor assumed during the initial computer runs. Therefore, for the configuration presented, the assumed loss factor can be used with confidence. Future trials with different configurations will be required to determine if the complex loss factors should be added to the program to account for alternate designs.

From the graph, it can be seen that the experimental and predicted values are identical until the knee of the force curve is reached. This can be due to any combination of three factors. 1) The core necking, which has been presented earlier, 2) loss factors which require more mmf to produce the
expected flux density than predicted or 3) experimental error. Regardless of which combination of factors is chosen, the conclusion is that the computer predictions agree even more closely than might normally be expected. In addition, gap lengths and loss factors are reasonable. More important, the method, for determining the airgap from gap curves developed for this project, does work. Gaps created at the interface between shims is, therefore, the likely explanation for the discrepancy described earlier. At this point, the B-H curves for the sintered samples are not available and, therefore, a similar set of calculations cannot be made for that experimental data to further strengthen the validity of the methods developed and presented herein.

12.6 Observations and Conclusions

Even if the airgap calculation method discrepancy is not correctly explained by the extra gaps at the shim interfaces, a number of checks can be made on the equations and assumptions presented with the experimental data. One of these is shown by the graph in figure 41. Here, equation (60), has been used to calculate the flux density corresponding to loads of 2, 3, 4 and 7 ounces. The gap area has been assumed to be 0.089sq-cm. The data from the force versus airgap experiment, (figure 37), is then plotted as the voltage needed to overcome an increase in airgap versus the calculated flux density. A family of lines results. Each
Figure 41: Voltage Increase vs Flux Density for Fixed Airgaps.
one corresponds to a different gap increase over the no shim case.

The key to understanding this graph, is that it is the increase in voltage to overcome the additional airgap that is plotted on the vertical axis. Any material B-H relationships have been accounted for in the no shim curve. If equation (65), is applied at two different flux densities for the same airgap and subtracted, equation (68). results.

\[ d(BA) = d(NA) \times \left( 0.4 \times \pi / G / 2000 \right) \]  

(68)

This should not be confused with equation (67), which applies at a constant value of BA.

Since the only variables in equation (68), are BA and NA, then the two should change in a linear manner. The fact they do not in figure 41, supports the leakage equation (27). It takes a larger number of amp turns in the air to produce an equal change in the flux density, because the leakages are increasing with flux density. Therefore, the constant loss assumed by the adjustment to the total holding force in the ANALYSIS program is not exactly correct, as described in the discussion on leakage in chapter II. However, the solid core experiment demonstrated that 64% is a good number for the case being considered.

The data from figure 41 has been rearranged in figure 42 to show the increase in voltage over the no shim curve versus the increase gap over the no shim curve as a function of the force levels checked. Combining equations (67) and (64), for
FIGURE 42
INCREASE IN VOLTAGE vs INCREASE IN AIRGAP for CONSTANT FORCE
constant force lines results in equation (69).

\[ d(G) = d(V) \times (NC \times 0.4 \times \pi / BA / CR / 2000) \] (69)

The change in the airgap driving voltage should be proportional to the change in airgap for a constant BA. The slope of the line should be given by the quantity in parentheses in (69). Figure (42), bears this out, except for the magnitude of the slope. It is off by the factor of 2, mentioned earlier, which again implies that the measured and effective gaps are different.

In conclusion, the general effect of changes in values presented earlier in this paper are born out by the experimental data. Without necessary B-H curves, further checks cannot be made to strengthen the validity of the project or suggest areas which need further investigation.

The next chapter will present the results of experiments aimed at finding those B-H curves.
CHAPTER XIII
B-H CURVE DETERMINATION EXPERIMENT

13.1 Purpose of the Experiment

The goal of this experiment is to determine the B-H characteristics of the various samples of sintered 50/50 nickel-iron used in the experiments presented in Chapter XII. Due to problems encountered during the work and time constraints, the full goal has not been realized. Partial results will be presented for those wishing to complete the task. The data, which would have been provided by this test, is only needed to further substantiate the information presented, and in no way is of primary importance to the project.

13.2 Description of the Apparatus and Procedure

One core from each of the density samples was drawn for the testing. One leg from each core was removed, and a sample measuring 0.274 cm square by 1.651 cm of each was ground. These were then passed through the normal hydrogen annealing process to remove any residual magnetism and internal stresses.

The samples were then placed in an AC Magnetometer for measurement of the B-H curves. The theory of operation of this piece of equipment is to have two coils around the
sample. An excitation coil is used to set up an alternating magnetic field. A secondary coil is also located around the sample along the same cylindrical axis as the primary coil. The purpose of this secondary coil is to detect and measure the strength of the magnetic field.

To make a measurement, a reading is first made with no sample in the chamber. The knobs are then adjusted until no signal is outputted from the secondary coil. This step is to remove the B-H characteristics of air from the readings so that only the material characteristics are measured. Samples are then individually inserted into the chamber, and the equipment varies the induced field between positive and negative limits specified by the user. An integral computer stores the data and displays the resulting B-H curve on a monitor or paper print.

13.3 Presentation of Data

During the first trials, the B-H curves were measured and plots produced. When they were compared to the curves for solid nickel iron, the flux density levels at saturation seemed reasonable. The location of the curve on the H axis did not seem to agree, therefore, a second set of samples was generated to make DC Magnetization measurements (Ref 12). These samples had to be lighter than the first ones to be compatible with that piece of equipment.

The set of samples were generated in a manner similar to
the first, with dimensions of 0.25cm cubed. When the data was taken again with this second set of samples by the alternate method, the same saturation levels were measured, but the knee of the curve shifted by a factor of 10 on the H axis. A return to the first method of measurement with the second set of samples agreed with the readings from the second method, which showed that a material sample dependency existed.

The problem turned out to be an effect known as surface demagnetization (Ref 13). This is a characteristic of the surface of a material which counteracts the magnetic field. It should be dependent on the geometry of the part only, and not a function of the material being tested. If the magnitude of the effect is known, then a demagnetization correction factor can be applied to the B-H curve to eliminate the condition, thereby, resulting in a curve which is independent of the part geometry.

The sum of the correction factors for the three axes is equal to unity. For a cube, the correction factor should be 1/3 for any direction perpendicular to one of its faces. When this factor was tried on the samples, it did not work. On some, the correction seemed to work, while on others, an overcorrection was noted. It appeared that the material did not behave homogeneously, so after considerable effort, the investigation had to be dropped.

The curves shown in figure 43 are the uncorrected curves
FIGURE 43

UNCORRECTED B-H CURVES FOR SEVERAL SAMPLES OF SINTERED AND SOLID 50/50 NICKEL IRON MAGNETIZED ALONG PART LENGTH

NOTE: NUMBERS ARE PRESS TONNAGES FOR SINTERED SAMPLES.
SAMPLE DIMENSIONS:
0.274cm × 0.274cm × 1.651cm
for the first long samples, superimposed on one graph. The curves represent the full B-H curve for the materials. For those familiar with these curves, it can be seen that there is no hysteresis loop to them.

Also shown are the measured flux density levels at the extreme of the curves. The important thing to remember about these uncorrected curves is that the vertical axis is right. When the proper correction is applied, the shape of the curve will change by a shifting of individual points toward the vertical axis. The saturation level will not change.

13.4 Observations and Conclusions

It would be possible at this point to take the information obtained by the above investigation, combine it with the experimental results found earlier, stir in some assumptions and arrive at a set of B-H curves for the various densities of material. This way a relationship could be sought which related the results with the density. The relationship might result in a factor which could be multiplied times the B-H curve for solid nickel-iron for use in the computer program. Then a question could ask for the material density and arrive at the information necessary for designing or analyzing a coil.

After several hours of data manipulation, the exercise was dropped. The effort was not compatible with the relative importance of the information to the overall project.
CHAPTER XIV

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

All the primary objectives of this project have been met or exceeded. A maximum holding force configuration has been demonstrated for each of the design constraint combinations tested. In addition, the solutions all appear to be unique, for each set of constraints, as described in sections 3.5 and 10.3. Several additional computer trials appear in Appendix J, which show that no general conclusions can be drawn about the best ratio of core volume to winding volume.

The first two trials analyze the TEST-SQ-S-D3 coil, (Figures 16 through 19), with two different core materials. The materials chosen are cold rolled steel and oriented 3% silicon strip. This second material is usually available in sheet stock, however, the trial was made to demonstrate a material with a higher permeability than 50/50 Ni-Fe. As expected, the holding forces are different with each core.

The final two trials demonstrate that the configuration changes with core material. To make these runs, the design constraints of the TEST-SQ-S-D3 coil have been retained, but the material changed to cold rolled steel and 3% Si-strip. The result is a different configuration for each, with higher holding forces than when those materials were inserted in the TEST-SQ-S-D3 bobbin, indicating that optimization works.
Two complimentary methods of finding the optimum design for a set of user defined constraints have been developed, which arrive at the same solution. The second method developed is extremely user friendly and requires no knowledge of the program or magnetics to use. The intended user is the mechanical designer who has an idea of the approximate space available for an electromagnet, but has no idea of the force potential for the volume present. This program suits that user's need very well, and is a vehicle for passing valuable experience. Future designers will not have to go through the learning experience that has been required to carry out this project.

The program is also a valuable analysis tool for an existing design. It gives the designer many of the pieces of information needed to determine the level of performance that can be expected from a given design, and in the event of minor changes, a feel for how the performance will be affected by those changes.

A good data base has been started, with the experimental results presented, for correlating the computer output to actual electromagnet samples. The correlation for the single configuration presented is very good. At this point in time, it is felt that the program, equations and concepts developed in the paper can be used confidently.

Several topics have gone uncovered or only lightly presented, and deserve additional study. The first of these
is the completion of the B-H curve generation for the various density samples of nickel iron. Some questions which would have to be answered by this study include 1) Why did one correction factor not seem to work for all samples? 2) Why does the factor for a cube not agree with published data? 3) Is there a relationship that can be fit to an equation which relates the B-H curve for the solid nickel-iron material to its less dense sintered counterparts? At first thought, it would seem that the values of flux should be directly proportional to the density. The reason for this hypothesis is as follows: If it is assumed that the lowering of density is the result of randomly spaced, microscopic pockets of air, then the cross-sectional area of metal at any point should be reduced by the presence of that air. On the average, the metal should occupy a percentage of the cross section proportional to the ratio of the part density to the density of the solid metal. Examination of the flux densities shown in figure 43, do not agree with this.

Conversely, the air might be considered to present a set of small airgaps within the material. A model of the magnetic properties of each grain would then have to be devised, complete with surface demagnetization effects and interactions with neighboring grains. This study could become very involved and of a highly technical nature.

Another study suggested by this project is to include the detailed loss coefficients in the ANALYSIS and/or DESIGN
modules to determine their effects on the final design. It is not unthinkable that a different design could result if these factors are taken into account. For example, the core poles may tend to move apart, or the area of the core might increase slightly, to reduce the flux density. This would reduce the losses and increase the area. The resulting design, would probably predict a lower force than that shown by the methods developed for this project, but might come closer to the actual force for all coil configurations. This is not to say the methods developed here are not good, because they provide a better tool than existed before. Any method can be improved, and this one is no exception.

The idea suggested in section 2.10 could be pursued more thoroughly. This involves increasing the cross-sectional area of the yoke, and tapering it toward the poles in an effort to combat the interpolar flux leakage. Ignoring the manufacturing concerns, this study would determine if the idea has any merit, or if some other factor counteracts the flux loss gains to result in no design improvements.

Several improvements could be made on the program package developed. For example, some simple code changes could be made to allow the use of a second disk drive for data storage, instead of using the program disk for that purpose. This would permit write protection of the program disk to reduce the possibility of erasure. Other improvements relate to speeding up the package, such as
compiling the Basic program into machine code to reduce computation time. Also, when using the ANALYSIS module, it is necessary to return to the PAGE 2-A module and redraw the coil picture before changes can be made. It would be possible to either simply make changes in the ANALYSIS module itself, rather than exiting, or to re-display the existing picture with the correct POKE statements, since the values on it have not changed. The first choice would eliminate the time required to load each module while the second would eliminate the long drawing time.

A more significant change would be to combine the two optimization methods developed in this paper by using the first method to find the start point for the search process of the second method. The shotgun search works, but is literally a hit-or-miss proposition. The first optimization method would provide a more intelligent search for a good starting point.

When working with a high production design, changes during the life of the product are inevitable. Often, one of the constraints imposed is that the fewest number of parts in an assembly be affected. Currently the program is not well suited for experimentation with existing parts. For example, if it is desired to increase the holding force for a given assembly, without changing any of the tooled parts, the only variables left are the wire size and number of turns. It was stated previously that a design determined by the
optimization processes developed in this paper will be the maximum force permitted by the given constraints. One of the givens must be modified, therefore, to have a difference in the windings produce any force change.

Examination of the equation system reveals that either the supply voltage or the permissible current draw must be increased. In particular, equation 13, indicates that for a fixed supply voltage, the total amp turns can only be increased by a reduction in the average path or ohms per centimeter of the wire. For a given bobbin, the average path cannot be changed appreciably, therefore, the ohms per centimeter is the only real variable. This implies that once the bobbin and core geometries have been established, the total number of amp turns is determined solely by the wire gage used to wind it. The number of turns will only change the total resistance. This discussion required a working knowledge of the equation system. It would be an improvement if the program could convey this information to the user.

In a similar manner, for a revision of the current requirement, it might be desirable to determine which winding width would be required for each available wire size to match the required resistance. Referring to the equation system, it is possible to combine equations 11, 1, 3 and 4 to arrive at a quadratic equation for solving the winding width, WW.

\[ A * WW^2 + B * WW - CR / RW = 0 \]  

Where \[ A = PI * LW * W2 * OC \]
\[ B = (CP + 2 \times PI \times W) \times LW \times W^2 \times OC \]  

These manipulations are not difficult when the equation system is known, but the average user is not well-versed in it. It would be desirable to have these types of calculations readily available and identified in the program.

A final topic of study would be to use the tools developed to analyze the designs which would result from different design constraints. Trends could be found, which would aid a designer by setting up guidelines for what types of bobbin shape is best. For example: Is a long slender coil better or worse than a short fat one of the same volume? Under what circumstances are double bobbins better than single ones and vice versa? Is the round configuration ever better than a rectangular one? The list could go on and on.

Based on the results of this study, samples could be built to test the theory against reality.

In any study of this magnitude, as many questions have been raised as have been answered. A good foundation has been established, however, and merits building upon.
APPENDIX A
FIRST OPTIMIZATION METHOD

On the following page is the sample listing of a program similar to the one used to generate the data for the plots in chapter 3. Modifications have been made to include the wire data curve fit equations developed in chapter 4.
FIRST OPTIMIZATION METHOD LISTING USING MODIFIED XLISTER

1    REM  FIRST OPTIMIZATION METHOD, DEVELOPED BETWEEN  
      FEBRUARY 1983 AND FEBRUARY 1984
5    CC = 8.6433E - 7
6    S$ = "----------"
7    AA = .324860745
8    BB = .890525717
10   PI = 3.14159

: K3 = 1 / 2.54
: K4 = 2.54
20   READ C1,C2,BF,I,V,CA,W,DX,RW
25   PRINT C1,C2,BF,I,V,CA,W,DX,RW
27   PRINT "H","CD","CW","LO","WO",S$,"NC","PL","FW","L"
30   FOR WN = 35 TO 45
35       PRINT WN
60       WD = K4 * AA * BB * WN
70       ID = K4 * AA * BB * (.967 * WN + .221)
80       W2 = 1 / ID / ID
90       OC = K4 * CC / WD / WD
100  FOR CD = .1 TO .45 STEP .025
110      CW = CA / CD
120      FW = (DX - CD - 2 * W) / 2
130      O3 = OC / ID / ID
140      U3 = V / I / O3
150      CP = 2 * (CD + CW)
160      AP = CP + 2 * PI * (W + FW / 2)
170      U2 = U3 / AP
180      L = U2 / FW / RW
190      PL = 2 * (L + 2 * BF + FW + W + C1 + C2 + 2 * CW)
200      NC = L * FW * RW / ID / ID
210      NI = NC * I
220      H = NI / PL
230      LO = 2 * (CW + BF) + L + C1
240      DO = 2 * (W + FW) + CD
250      WO = 2 * (CW + W + FW) + C2
260      PRINT H,CD,CW,LO,WO,S$,NC,PL,FW,L
270   NEXT
280   NEXT
300  DATA  .285,.07,.15,.035,3,.1225,.064,.635,1
APPENDIX B
PAGE 1 PROGRAM MODULE

B.1 Program Listing . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 178
B.2 Program Length and Cross Reference. . . . . . . . . . . . . . . 183
178

PAGE 1 LISTING USING A MODIFIED BEAGLE BROTHERS XLISTER

5 REM PAGE 1 VERSION 1-29-84;21:11
10 D$ = CHR$ (4)
15 HOME
20 HGR
25 TEXT
30 : REM GENERATE TITLE PAGE
35 : VTAB 1
40 : HTAB 18
45 : PRINT "SMALL"
50 : VTAB 3
55 : HTAB 15
60 : INVERSE
65 : PRINT "D.C.BIPOLAR"
70 : VTAB 5
75 : HTAB 14
80 : PRINT "ELECTROMAGNET"
85 : VTAB 7
90 : HTAB 17
95 : PRINT "DESIGN"
100 : NORMAL
105 : VTAB 9
110 : HTAB 18
115 : PRINT "----"
120 : VTAB 12
125 : HTAB 9
130 : PRINT "OPTIMIZATION & ANALYSIS"
135 : VTAB 14
140 : HTAB 19
145 : PRINT "BY"
150 : VTAB 16
155 : HTAB 14
160 : PRINT "JOHN J. BREEN"
165 : VTAB 18
170 : HTAB 18
175 : PRINT "1984"
180 : VTAB 23
185 : HTAB 5
190 : PRINT "(PROGRAM RUNNING: PLEASE WAIT)"
195 REM START DRAWING PAGE 1 UNDER TITLE PAGE
200 HCOLOR= 3
205 HPLLOT 0,0 TO 279,0 TO 279,159 TO 0,159 TO 0,0
210 HPLLOT 209,0 TO 209,159
215 HPLLOT 139,0 TO 139,159
220 HPLLOT 69,0 TO 69,159
225 HPLLOT 15,20 TO 45,20 TO 45,50 TO 15,50 TO 15,20
230 HPLLOT 25,30 TO 35,30 TO 35,40 TO 25,40 TO 25,30
235 HPLLOT 45,30 TO 55,30 TO 55,40 TO 45,40
240 HPLLOT 15,70 TO 45,70 TO 45,115 TO 15,115 TO 15,70 TO 15,75 TO 45,75 TO 45,65 TO 55,65 TO 55,125 TO 25,
125 TO 25,115
90  HPlot 15,110 TO 45,110
95  HPlot 25,70 TO 25,65 TO 35,65 TO 35,70
100 HPlot 104,20 TO 134,20 TO 134,50 TO 104,50
     TO 74,20 TO 74,50 TO 104,50
105 HPlot 84,30 TO 94,30 TO 94,40 TO 84,40 TO 84,30
110 HPlot 114,30 TO 124,30 TO 124,40 TO 114,40 TO 114,30
115 HPlot 104,70 TO 134,70 TO 134,115 TO 74,115 TO 74,70
     TO 104,70 TO 104,115
120 HPlot 74,75 TO 134,75
125 HPlot 74,110 TO 134,110
130 HPlot 84,115 TO 84,125 TO 124,125 TO 124,115
135 HPlot 84,70 TO 84,65 TO 94,65 TO 94,70
140 HPlot 114,70 TO 114,65 TO 124,65 TO 124,70
145 HPlot 154,70 TO 184,70 TO 184,115 TO 154,115 TO 154,70
     TO 154,75 TO 184,75 TO 184,65 TO 194,65 TO 194,125
     TO 164,125 TO 164,115
150 HPlot 154,110 TO 184,110
155 HPlot 164,70 TO 164,65 TO 174,65 TO 174,70
160 S = 1
   : ST = 154
   : H = 169
   : K = 35
   : R = 15
   : E = 184
   : GOSUB 545
165 ST = 184
   : H = 189
   : R = 5
   : E = 194
   : GOSUB 545
170 ST = 164
   : H = 169
   : E = 174
   : GOSUB 545
175 FOR I = 1 TO 5
   : READ X
   : HPlot X,30 TO X,39
   : NEXT I
   : FOR I = 1 TO 7
   : READ X
   : HPlot X,32 TO X,37
   : NEXT
180 DATA 154,184,214,244,274,164,174,194,224,234,254,264
185 HPlot 244,70 TO 274,70 TO 274,115 TO 214,115 TO 214,70
     TO 244,70 TO 244,115
190 HPlot 214,75 TO 274,75
195 HPlot 214,110 TO 274,110
200 HPlot 224,115 TO 224,125 TO 264,125 TO 264,115
205 HPlot 224,70 TO 224,65 TO 234,65 TO 234,70
210 HPlot 254,70 TO 254,65 TO 264,65 TO 264,70
215  ST = 214
    :  H = 229
    :  R = 15
    :  E = 244
    :  GOSUB 545
220  ST = 244
    :  H = 259
    :  E = 274
    :  GOSUB 545
225  ST = 254
    :  E = 264
    :  R = 5
    :  GOSUB 545
230  ST = 224
    :  H = 229
    :  E = 234
    :  GOSUB 545
235  REM  LOAD SHAPEFILE AT THE BOTTOM OF MEMORY. THIS FILE
       CONTAINS ASCII CHARACTERS FOR THE HI-RES SCREEN
240  PRINT D$;"LOAD SHAPEFILE,A$800"
    :  POKE 232,0
    :  POKE 233,8
245  HCOLOR= 3
    :  SCALE= 2
    :  ROT= 0
250  SH = 12
    :  X = 35
    :  Y = 140
    :  GOSUB 540
255  SH = 13
    :  X = 104
    :  Y = 140
    :  GOSUB 540
260  SH = 14
    :  X = 169
    :  Y = 140
    :  GOSUB 540
265  SH = 15
    :  X = 244
    :  Y = 140
    :  GOSUB 540
270  SCALE= 1
    :  SH = 10
    :  XDRAW SH AT 35,145
    :  XDRAW SH AT 106,145
    :  XDRAW SH AT 167,145
    :  XDRAW SH AT 248,139
    :  DRAW SH AT 246,141
275  POKE -16304,0
    :  POKE -16300,0
    :  POKE -16301,0
REM BEGIN PROMPTING PROCESS TO FILL RUN TYPE
HOME
: VTAB 24
: PRINT "ENTER Coil TYPE (1-4):"
: GET A$
: VTAB 23
: HTAB 23
: PRINT A$
PRINT "IS THIS CORRECT? (Y/N):"
: GET B$
IF B$ = "Y" THEN AA = VAL (A$)
* IF AA > 0 AND AA < 5 THEN GOTO 305
GOTO 285
PRINT "ENTER CHOICE (1 OR 2):"
PRINT " 1. ANALYZE EXISTING DESIGN"
PRINT " 2. NEW DESIGN"
GET TS$
: TS = VAL (TS$)
: IF TS < 1 OR TS > 2 THEN GOTO 305
INPUT "ENTER NAME FOR DESIGN:"
; NF$
: IF LEFTS$ (NF$, 1) = "@" THEN NF$ = RIGHTS$ (NF$, LEN (NF$) - 1)
DF$ = "@" + NF$
PRINT
: PRINT D$; "OPEN "; DF$
ONERR GOTO 395
PRINT D$; "READ "; DF$
INPUT N
PRINT D$; "CLOSE"
HOME
: TEXT
: PRINT "FILE ALREADY EXISTS; CHOOSE (1-3):"
PRINT " 1. OVERWRITE FILE FROM KEYBOARD"
PRINT " 2. LOOK AT CATALOG AND RENAME"
PRINT " 3. ENTER FILE FROM DISK"
GET ET$
: ET = VAL (ET$)
: PRINT D$; "DELETE "; DF$
: GOTO 480
GOTO 350
PRINT
: PRINT D$; "DELETE "; DF$
PRINT "FILE DOESN'T EXIST; CHOOSE (1, 2):"
PRINT " 1. CREATE NEW FILE FROM KEYBOARD"
PRINT " 2. LOOK AT CATALOG AND RENAME"
GET ET$
: ET = VAL (ET$)
IF ET = 2 THEN TEXT
* : HOME
* : PRINT
* : PRINT D$;"CATALOG"
* : GOTO 315
430 IF ET = 1 THEN GOTO 480
435 GOTO 395
440 IF N = (AA) THEN 480
445 PRINT "COIL TYPES DON'T AGREE; CHOOSE (1, 2)"
450 PRINT "1. CHANGE TO COIL TYPE IN FILE"
455 PRINT "2. REDO ENTRY PROCESS"
460 GET A$
465 IF A$ = "1" THEN AA = N
* : GOTO 480
470 IF A$ = "2" THEN GOTO 275
475 GOTO 445
480 PRINT
: PRINT D$; "OPEN RUN TYPE"
485 PRINT D$; "DELETE RUN TYPE"
490 PRINT D$; "OPEN RUN TYPE"
495 PRINT D$; "WRITE RUN TYPE"
500 PRINT AA
: PRINT TS
: PRINT ET
: PRINT NF$
505 PRINT D$; "CLOSE"
510 TEXT
: HOME
515 INVERSE
: HTAB 7
: VTAB 12
: PRINT "LOADING INPUT/OUTPUT MODULE"
520 NORMAL
: VTAB 23
: HTAB 14
: PRINT "HAVE PATIENCE"
525 POKE 216, 0
: REM CLEAR ONERR FLAG. OTHERWISE DOS COMMANDS MAY HANG
530 PRINT
: PRINT D$; "RUN PAGE 2-A"
535 GOTO 530
: REM WHO KNOWS WHY?
540 DRAW SH AT X,Y
: RETURN
545 FOR X = ST TO E
: Y = S * ( SQR (R * R - (X - H) * 2) + .49) + K
: HPLOT X,Y
: Y = 2 * K - Y
: HPLOT X,Y
: NEXT
: RETURN
PROGRAM LENGTH IS 3597 ($E0D) BYTES

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>A$</td>
<td>285, 295, 460, 465, 470</td>
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<td>AA</td>
<td>295, 440, 465, 500</td>
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<tr>
<td>B$</td>
<td>290, 295</td>
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<tr>
<td>D$</td>
<td>10, 240, 325, 335, 345, 385, 395, 425, 480, 485, 490, 495, 505, 530</td>
</tr>
<tr>
<td>DP$</td>
<td>320, 325, 335, 385, 395</td>
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<tr>
<td>ET$</td>
<td>370, 415, 420</td>
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<td>160, 165, 170, 215, 220, 230, 545</td>
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<td>I</td>
<td>175</td>
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<tr>
<td>K</td>
<td>160, 545</td>
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<td>340, 440, 465</td>
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<tr>
<td>TS</td>
<td>310, 500</td>
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<tr>
<td>X</td>
<td>175, 250, 255, 260, 265, 540, 545</td>
</tr>
<tr>
<td>Y</td>
<td>250, 255, 260, 265, 540, 545</td>
</tr>
</tbody>
</table>
APPENDIX C
PAGE 2-A PROGRAM MODULE

C.1 Program Listing ....................... 185
C.2 Program Length and XRef ............... 217
PAGE 2-A LISTING USING A MODIFIED BEAGLE BROTHERS XLISTER

5 REM PAGE 2-A VERSION 2-12-84; 14:03
10 D$ = CHR$ (4)
15 REM Rounding Functions for Printout
20 DEF FN R4(X) = ( INT ( (X + .000049) * 10000) ) / 10000
25 DEF FN R3(X) = ( INT ( (X + .00049) * 1000) ) / 1000
30 DEF FN R2(X) = ( INT ( (X + .0049) * 100) ) / 100
35 DEF FN R1(X) = ( INT ( (X + .049) * 10) ) / 10
40 HGR
 : POKE - 16302, 0
45 D = 1
 : F = 2
50 HCOLOR = 3
55 REM Determine Type of Study and Bobbin
60 PRINT D$; "OPEN RUN TYPE"
65 PRINT D$; "READ RUN TYPE"
70 INPUT AA
 : INPUT TS
 : INPUT ET
 : INPUT GF$
75 PRINT D$; "CLOSE RUN TYPE"
80 DF$ = "@" + GF$
85 REM Set Equation and Picture Modifiers
90 IF AA = 1 OR AA = 3 THEN M = 1
 * : GOTO 100
95 M = 2
100 IF AA < 3 THEN MM = 1
 * : GOTO 115
105 MM = 2
110 REM Read Input Data
115 IF TS = 4 THEN DF$ = "@TEST COIL"
 * : GOSUB 135
 * : TS = 1
 * : ET = 3
 * : GOTO 200
120 IF TS = 3 THEN DF$ = "@TEST COIL"
 * : GOSUB 135
 * : ET = 3
 * : GOTO 200
125 IF ET = 3 THEN TT = TS
 * : GOSUB 135
 * : TS = TT
 * : GOTO 200
130 NF$ = GF$
 : GOTO 200
135 PRINT
 : PRINT D$; "OPEN " ; DF$
140 PRINT D$; "READ " ; DF$
145 GOSUB 3100
150 PRINT
PRINT D$;"CLOSE"
NF$ = GF$
RETURN
REM BEGIN CREATING PICTURES
REM COMMON TO ALL
HPLOT 117,105 TO 117,50 TO 132,50 TO 132,105
: IF M = 1 THEN HPLOT TO 117,105
HPLOT 140,50 TO 135,50 TO 135,65 TO 140,65
HPLOT 140,30 TO 195,30 TO 195,85 TO 140,85 TO 140,30
HPLOT 150,30 TO 150,85
HPLOT 185,30 TO 185,85
HPLOT 195,50 TO 210,50 TO 210,105
: IF M = 1 THEN HPLOT TO 135,105 TO 135,90 TO 190,90 TO 195,85
HPLOT 20,0 TO 20,28
HPLOT 35,16 TO 35,47
HPLOT 41,16 TO 41,47
HPLOT 135,0 TO 135,48
HPLOT 140,0 TO 140,28
HPLOT 185,23 TO 185,28
HPLOT 195,23 TO 195,28
HPLOT 132,107 TO 132,120
IF M = 2 THEN 290
HPLOT 135,107 TO 135,120
HPLOT 67,105 TO 105,105
HPLOT 67,90 TO 105,90
SCALE= 1
: ROT= 0
: SH = 49
IF M = 1 THEN DRAW SH AT 102,90
DRAW SH AT 167,90
ROT= 32
DRAW SH AT 167,85
IF M = 2 THEN 330
DRAW SH AT 102,105
HPLOT 102,85 TO 102,105
ROT= 16
DRAW SH AT 135,5
DRAW SH AT 185,25
DRAW SH AT 132,115
DRAW SH AT 35,20
ROT= 48
DRAW SH AT 140,5
DRAW SH AT 195,25
DRAW SH AT 135,115
DRAW SH AT 41,20
HPLOT 135,5 TO 130,5
HPLOT 140,5 TO 145,5
HPLOT 185,25 TO 180,25
HPLOT 195,25 TO 200,25
HPLOT 132,115 TO 127,115
405  HPlot 135,115 TO 140,115
410  HPlot 35,20 TO 30,20
415  HPlot 167,90 TO 167,95
420  HPlot 167,85 TO 167,80
425  HPlot 41,20 TO 46,20
430  X = 50
    : Y = 18
    : W$ = "W=
    : GOSUB 11000
435  X = 150
    : Y = 3
    : W$ = "Cl=
    : GOSUB 11000
440  X = 205
    : Y = 23
    : W$ = "BF=
    : GOSUB 11000
445  X = 145
    : Y = 113
    : W$ = "G=
    : GOSUB 11000
450  X = 165
    : Y = 75
    : W$ = "C2=
    : D = 4
    : GOSUB 11000
    : D = 1
455  X = 220
    : Y = 48
    : W$ = "RW=
    : GOSUB 11000
460  X = 220
    : Y = 68
    : W$ = "V=
    : GOSUB 11000
465  X = 220
    : Y = 108
    : W$ = "NOTE..."
    : GOSUB 11000
470  X = 220
    : Y = 118
    : W$ = "DIM. IN"
    : GOSUB 11000
475  X = 215
    : Y = 128
    : W$ = "CENTIMETERS"
    : GOSUB 11000
480  X = 10
    : Y = 138
    : W$ = "CORE MATERIAL= 
    : GOSUB 11000
188

X = (139 - ( LEN (NF$)) * 3)  
: Y = 168  
: W$ = NF$  
: GOSUB 11000

X = 57  
: Y = 153  
: W$ = "D.C. HORSESHOE ELECTROMAGNET"  
: GOSUB 11000

IF M = 1 THEN 550

H PLOT 140,105 TO 140,90 TO 195,90 TO 195,85 TO 195,105
H PLOT 150,105 TO 150,90
H PLOT 185,105 TO 185,90
H PLOT 135,120 TO 135,67
H PLOT 67,50 TO 92,50
H PLOT 67,65 TO 92,65
H PLOT 89,50 TO 102,90 TO 102,85
SH = 49
ROT= 32
: DRAW SH AT 89,65

ROT= 0
: DRAW SH AT 89,50

ON MM GOTO 560,665
REM COMMON TO DES&ANAL SQ

H PLOT 20,30 TO 85,30 TO 85,85 TO 20,85 TO 20,30
H PLOT 41,50 TO 64,50 TO 64,65 TO 41,65 TO 41,50
H PLOT 41,44 TO 64,44 TO 70,50 TO 70,65 TO 64,71 TO 41,71 TO 35,65 TO 35,50 TO 41,44
H PLOT 41,107 TO 41,125
H PLOT 64,107 TO 64,125
SH = 49
ROT= 48
: DRAW SH AT 41,115

ROT= 16
: DRAW SH AT 64,115

H PLOT 64,115 TO 36,115
IF M = 2 THEN 630
H PLOT 41,90 TO 64,90 TO 64,105 TO 41,105 TO 41,90
ROT= 56
: DRAW SH AT 64,105

H PLOT 64,105 TO 75,116 TO 80,116
GOTO 655

ROT= 56
: DRAW SH AT 64,65

H PLOT 64,65 TO 75,76 TO 75,116 TO 80,116
H PLOT 20,105 TO 20,90 TO 85,90 TO 85,105
H PLOT 41,107 TO 41,67
H PLOT 64,107 TO 64,67
ON TS GOSUB 1130,820,1130
POKE -16301,0
ON TS GOTO 1300,1345,1400
REM COMMON TO DES&ANAL RND
670  \$ = 1
   \$T = 20
   \$H = 48
   \$K = 57
   \$R = 28
   \$E = 76
   \$GOSUB 805
675  \$T = 35
   \$R = 13
   \$E = 61
   \$GOSUB 805
680  \$T = 41
   \$R = 7
   \$E = 55
   \$GOSUB 805
685  IF M = 1 THEN K = 98
   \$GOSUB 805
690  IF M = 2 THEN S = 2
   \$ST = 23
   \$E = 73
   \$K = 119
   \$R = 28
   \$GOSUB 805
695  \$HPLOT 41,54 TO 41,59
700  \$HPLOT 35,53 TO 35,60
705  \$HPLOT 20,52 TO 20,61
710  \$HPLOT 55,54 TO 55,59
715  \$HPLOT 61,53 TO 61,60
720  \$HPLOT 76,52 TO 76,61
725  \$HPLOT 20,25 TO 20,48
730  \$HPLOT 35,40 TO 35,48
735  \$HPLOT 41,40 TO 41,49
740  IF M = 2 THEN 770
745  \$HPLOT 41,95 TO 41,100
750  \$HPLOT 55,95 TO 55,100
755  \$HPLOT 67,90 TO 55,90
760  \$HPLOT 67,105 TO 55,105
765  \$GOTO 780
770  \$HPLOT 67,50 TO 55,50
775  \$HPLOT 67,65 TO 55,65
780  ON TS \$GOSUB 1130,820,1130
782  \$POKE -16301,0
785  IF TS = 2 THEN \$GOTO 1470
790  REM RND ANAL
795  X = 100
   \$Y = 80
   \$WS = "PD="
   \$D = 4
   \$GOSUB 11000
   \$D = 1
800  ON TS \$GOTO 1425,1470,1525
FOR X = ST TO E
    Y = ( SQR (R * R + .0001) - (X - H)^2 ) + .49) + K
    IF S = 1 THEN HPLTO X, Y
    Y = 2 * K - Y
    NEXT HPLTO X, Y
RETURN

REM COMMON SING DES REQ
HPLTO 18,30 TO 0,30
HPLTO 10,30 TO 10,45
HPLTO 20,10 TO 25,10
HPLTO 117,107 TO 117,111
HPLTO 117,120 TO 117,135
HPLTO 210,107 TO 210,135
HPLTO 117,127 TO 140,127
HPLTO 187,127 TO 210,127
HPLTO 93,82 TO 93,85 TO 111,85 TO 111,82
HPLTO 18,48 TO 18,45 TO 0,45 TO 0,48
HPLTO 184,136 TO 187,136 TO 187,118 TO 184,118
HPLTO 143,136 TO 140,136 TO 140,118 TO 143,118
HPLTO 28,18 TO 25,18 TO 25,0 TO 28,0
HPLTO 18,87 TO 18,90 TO 0,90 TO 0,87
IF M = 2 THEN 910
HPLTO 0,105 TO 39,105
HPLTO 10,105 TO 10,90
SH = 49
    ROT= 32
    DRAW SH AT 10,105
SH = 49
    ROT= 48
    DRAW SH AT 20,10
DRAW SH AT 117,127
ROT= 16
    DRAW SH AT 210,127
ROT= 0
    DRAW SH AT 10,30
X = 30
    Y = 4
    W$ = "DX="
    GOSUB 11000
X = 30
    Y = 11
    W$ = "DN="
    GOSUB 11000
X = 220
    Y = 32
    W$ = "GX=#"
    GOSUB 11000
X = 220
    Y = 38
    W$ = "GN=#"
GOSUB 11000
X = 220
Y = 58
W$ = "IX="
GOSUB 11000
X = 220
Y = 78
W$ = "BX="
GOSUB 11000
X = 220
Y = 88
W$ = "HX="
GOSUB 11000
X = 145
Y = 121
W$ = "LX="
GOSUB 11000
X = 145
Y = 128
W$ = "LN="
GOSUB 11000
X = 4
Y = 85
W$ = "WX="
D = 4
GOSUB 11000
X = 11
Y = 85
W$ = "WN="
GOSUB 11000
D = 1
IF MM = 2 THEN GOTO 1070
REM SQ DES REQ
HPLOT 80, 10 TO 85, 10
HPLOT 85, 0 TO 85, 16
HPLOT 85, 24 TO 85, 28
HPLOT 80, 16 TO 80, 1 TO 77, 1
HPLOT 3, 106 TO 0, 106 TO 0, 132 TO 3, 132
ROT = 16
DRAW 49 AT 85, 10
ROT = 0
X = 5
Y = 108
W$ = "XD/ND="
GOSUB 11000
X = 96
Y = 80
W$ = "XW=
D = 4
GOSUB 11000
D = 1
X = 85
Y = 110
W$ = "RX=
GOSUB 11000
X = 85
Y = 117
W$ = "RN=
GOSUB 11000
D = 1
 RETURN
REM RND DES REQ
HPLLOT 18,30 TO 33,30
IF M = 1 THEN HPLLOT 39,105 TO 42,105
HPLLOT 71,10 TO 76,10
HPLLOT 76,0 TO 76,16
HPLLOT 76,24 TO 76,45
HPLLOT 71,16 TO 71,1 TO 68,1
HPLLOT 117,111 TO 117,120
ROT = 16
DRAW 49 AT 76,10
ROT = 0
X = 96
Y = 80
W$ = "PX=
D = 4
GOSUB 11000
X = 103
Y = 80
W$ = "PN=
GOSUB 11000
D = 1
 RETURN
REM COMMON ANAL
HPLLOT 150,12 TO 150,28
HPLLOT 35,0 TO 35,16
HPLLOT 185,12 TO 185,23
SH = 49
ROT = 16
DRAW SH AT 20,5
DRAW SH AT 185,15
ROT = 48
DRAW SH AT 35,5
DRAW SH AT 150,15
HPLOT 20.5 TO 15,5
HPLOT 35.5 TO 40.5
HPLOT 190.15 TO 150,15
X = 45
Y = 3
W$ = "FW="
GOSUB 11000
X = 195
Y = 13
W$ = "LW="
GOSUB 11000
X = 220
Y = 38
W$ = "WG=#"
GOSUB 11000
X = 220
Y = 58
W$ = "N="
GOSUB 11000
IF MM = 2 THEN RETURN
REM SQ ANAL
X = 5
Y = 108
W$ = "CD="
GOSUB 11000
X = 100
Y = 80
W$ = "CW="
D = 4
GOSUB 11000
D = 1
X = 85
Y = 114
W$ = "R="
GOSUB 11000
RETURN
REM PRINTING ROUTINE CALLS FOLLOW
REM PRINT FOR SQ ANAL INPUT
HOME
VTAB 24
IF ET = 3 THEN GOTO 1325
GOSUB 1800
GOSUB 1810
GOSUB 1820
GOSUB 1830
GOSUB 1840
GOSUB 1850
GOSUB 1860
GOSUB 1885
1315 GOSUB 1895
1320 GOTO 2105
1325 GOSUB 1805
1330 GOSUB 1915
1335 GOTO 2105
1340 REM PRINT FOR SQ DES INPUT
1345 HOME
1350 IF ET = 3 THEN GOTO 1375
1355 GOSUB 1670
1360 GOSUB 1810
1365 GOSUB 1820
1370 GOSUB 1830
1375
: GOSUB 1640
1365 GOSUB 1600
: GOSUB 1620
1370 GOTO 2105
1375 GOSUB 1675
: GOSUB 1690
: GOSUB 1700
: GOSUB 1715
: GOSUB 1725
: GOSUB 1740
: GOSUB 1750
: GOSUB 1765
: GOSUB 1775
: GOSUB 1785
: GOSUB 1795
1380 GOSUB 1815
: GOSUB 1825
: GOSUB 1845
: GOSUB 1865
: GOSUB 1900
: GOSUB 1915
: GOSUB 1935
: GOSUB 1950
: GOSUB 1985
: GOSUB 2000
: GOSUB 2010
: GOSUB 2030
: GOSUB 1660
1385 GOSUB 1615
: GOSUB 1635
1390 GOTO 2105
1395 REM PRINT FOR SQ DES OUTPUT
1400 HOME
: VTAB 24
1405 GOSUB 1805
: GOSUB 1815
: GOSUB 1825
: GOSUB 1835
: GOSUB 1845
: GOSUB 1855
: GOSUB 1880
: GOSUB 1890
1410 GOSUB 1900
: GOSUB 1915
: GOSUB 1925
: GOSUB 1965
: GOSUB 1975
: GOSUB 2010
: GOSUB 2030
1415 GOTO 2105
1420 REM PRINT FOR RND ANAL INPUT
1425 HOME
  : VTAB 24
1430 IF ET = 3 THEN GOTO 1450
1435 GOSUB 1800
  : GOSUB 1810
  : GOSUB 1820
  : GOSUB 1830
  : GOSUB 1840
  : GOSUB 1850
  : GOSUB 1860
  : GOSUB 1885
  : GOSUB 1895
1440 GOSUB 1905
  : GOSUB 2005
  : GOSUB 2025
  : GOSUB 2035
1445 GOTO 2105
1450 GOSUB 1805
  : GOSUB 1815
  : GOSUB 1825
  : GOSUB 1835
  : GOSUB 1845
  : GOSUB 1855
  : GOSUB 1860
  : GOSUB 1890
  : GOSUB 1900
1455 GOSUB 1915
  : GOSUB 2010
  : GOSUB 2030
  : GOSUB 2040
1460 GOTO 2105
1465 REM PRINT FOR RND DES INPUT
1470 HOME
  : VTAB 24
1475 IF ET = 3 THEN GOTO 1500
1480 GOSUB 1695
  : GOSUB 1705
  : GOSUB 1720
  : GOSUB 1730
  : GOSUB 1745
  : GOSUB 1755
  : GOSUB 1770
  : GOSUB 1780
  : GOSUB 1790
1485 GOSUB 1810
  : GOSUB 1820
  : GOSUB 1840
  : GOSUB 1860
  : GOSUB 1895
  : GOSUB 1905
  : GOSUB 2005
REM PRINT FOR RND DES OUTPUT
1525 HOME
1530 GOSUB 1805
1535 GOSUB 1900
1540 GOTO 2105
1599 REM INPUT STATEMENTS FOLLOW
1600 INPUT "ENTER MAX INDUCTANCE(HENRIES), HX=(RETURN=5):";A$
1605 IF A$ = "" THEN HX = 5
   * : GOTO 1615
1610  HX = VAL (A$)
1615  X = 238
  : Y = 88
  : A = FN R2(HX)
  : W$ = STR$ (A)
  : GOSUB 11000
  : RETURN
1620  INPUT "ENTER MIN INDUCTANCE (HENRIES),HN=(RETURN=0):";A$
1625  IF A$ = "" THEN HN = 0
  *: GOTO 1635
1630  HN = VAL (A$)
1635  X = 238
  : Y = 98
  : A = FN R2(HN)
  : W$ = STR$ (A)
  : GOSUB 11000
  : RETURN
1640  INPUT "ENTER MAX FLUX DENSITY (KILOGAUSSES),BX=(DEFAULT =B.SAT):";BX$
1645  BX = VAL (BX$)
1650  IF BX$ = "" THEN BX = 0
  *: X = 238
  *: Y = 78
  *: W$ = "BSAT"
  *: GOSUB 11000
  *: RETURN
1655  IF BX > 20 THEN PRINT "BX MUST BE <= 20"
  *: GOTO 1640
1660  X = 238
  : Y = 78
  : A = FN R2(BX)
  : W$ = STR$ (A)
  : IF BX = 0 THEN W$ = "BSAT"
1665  GOSUB 11000
  : RETURN
1670  INPUT "ENTER MAX CORNER RAD,RX=";RX
1675  X = 103
  : Y = 110
  : A = FN R2(RX)
  : W$ = STR$ (A)
  : GOSUB 11000
  : RETURN
1680  INPUT "ENTER MIN CORNER RAD,RN=(RETURN=0)";A$
  : IF A$ = "" THEN RN = 0
  *: GOTO 1690
1685  RN = VAL (A$)
1690  X = 103
  : Y = 117
  : A = FN R2(RN)
  : W$ = STR$ (A)
  : GOSUB 11000
RETURN

1695  INPUT "ENTER MAX OVERALL DEPTH, DX="; DX
1700  X = 48
   : Y = 4
   : A = FN R2(DX)
   : W$ = STR$(A)
   : GOSUB 11000
   : RETURN

1705  INPUT "ENTER MIN OVERALL DEPTH, DN=(RETURN=0)"; A$
   : IF A$ = "" THEN DN = 0
   : GOTO 1715
1710  DN = VAL (A$)
1715  X = 48
   : Y = 11
   : A = FN R2(DN)
   : W$ = STR$(A)
   : GOSUB 11000
   : RETURN

1720  INPUT "ENTER MAX OVERALL WIDTH, WX="; WX
1725  X = 4
   : Y = 67
   : A = FN R2(WX)
   : W$ = STR$(A)
   : D = 4
   : GOSUB 11000
   : D = 1
   : RETURN

1730  INPUT "ENTER MIN OVERALL WIDTH, WN=(RETURN=0)"; A$
   : IF A$ = "" THEN WN = 0
   : GOTO 1740
1735  WN = VAL (A$)
1740  X = 11
   : Y = 67
   : A = FN R2(WN)
   : W$ = STR$(A)
   : D = 4
   : GOSUB 11000
   : D = 1
   : RETURN

1745  INPUT "ENTER MAX OVERALL LENGTH, LX="; LX
1750  X = 163
   : Y = 121
   : A = FN R2(LX)
   : W$ = STR$(A)
   : GOSUB 11000
   : RETURN

1755  INPUT "ENTER MIN OVERALL LENGTH, LN=(RETURN=0)"; A$
   : IF A$ = "" THEN LN = 0
   : GOTO 1765
1760  LN = VAL (A$)
1765  X = 163
Y = 128
A = FN R2(LN)
WS = STR$(A)
GOSUB 11000
RETURN
1770 INPUT "ENTER MAX CURRENT (AMPS), IX="; IX
1775 X = 238
Y = 58
A = FN R2(IX)
WS = STR$(A)
GOSUB 11000
RETURN
1780 INPUT "ENTER MAX WIRE GAGE NO., GX="; GX
1785 X = 244
Y = 32
A = FN R1(GX)
WS = STR$(A)
GOSUB 11000
RETURN
1790 INPUT "ENTER MIN WIRE GAGE NO., GN="; GN
IF GN = 0 THEN PRINT "GN MUST BE > 0"
* GOTO 1790
1795 X = 244
Y = 38
A = FN R1(GN)
WS = STR$(A)
GOSUB 11000
RETURN
1800 VTAB 24
INPUT "ENTER FLANGE WIDTH, FW="; FW
1805 X = 63
Y = 3
A = FN R3(FW)
WS = STR$(A)
GOSUB 11000
RETURN
1810 INPUT "ENTER WALL THICKNESS, W="; W
1815 X = 62
Y = 18
A = FN R3(W)
WS = STR$(A)
GOSUB 11000
RETURN
1820 INPUT "ENTER ARMATURE CLEARANCE, Cl="; Cl
1825 X = 168
Y = 3
A = FN R3(Cl)
WS = STR$(A)
GOSUB 11000
RETURN
1830 INPUT "ENTER WINDING LENGTH, LW="; LW
INPUT "ENTER BOBBIN FLANGE THICKNESS, BF="; BF
X = 223
: Y = 23
: A = FN R3(BF)
: WS = STR$(A)
: GOSUB 11000
: RETURN

INPUT "WIRE GAGE NUMBER, WG="; WG
X = 244
: Y = 38
: A = FN R1(WG)
: WS = STR$(A)
: GOSUB 11000
: RETURN

INPUT "RANDOM WIND FACTOR (RETURN=1), RW="; RW$
RW = VAL (RW$)
IF RW$ = "" THEN RW = 1
: GOTO 1880
IF RW > 1 THEN PRINT "RW MUST BE <=1"
: GOTO 1860

INPUT "NUMBER OF TURNS, N="; N
X = 232
: Y = 58
: A = FN R1(N)
: WS = STR$(A)
: GOSUB 11000
: RETURN

INPUT "OPERATING VOLTAGE, V="; V
X = 232
: Y = 68
: A = FN R3(V)
: WS = STR$(A)
: GOSUB 11000
: RETURN

INPUT "AIR GAP (PER POLE), G=(RET=.002)"; A$
: IF A$ = "" THEN G = .002
: GOTO 1915
G = VAL (A$)
X = 157
Y = 113
A = FN R4(G)
W$ = STR$ (A)
GOSUB 11000
RETURN
1920 INPUT "CORE DEPTH, CD=": CD
1925 X = 5
Y = 118
A = FN R3(CD)
W$ = STR$ (A)
GOSUB 11000
RETURN
1930 INPUT "ENTER MAX CORE DEPTH, XD=": XD
1935 X = 5
Y = 114
A = FN R3(XD)
W$ = STR$ (A)
GOSUB 11000
RETURN
1940 INPUT "ENTER MIN CORE DEPTH, ND=(RETURN=0)"; A$
   IF A$ = "" THEN ND = 0
   GOTO 1950
1945 ND = VAL (A$)
1950 X = 5
Y = 120
A = FN R3(ND)
W$ = STR$ (A)
GOSUB 11000
RETURN
1955 INPUT "CORE RADIUS, R=(RETURN=0)"; A$
   IF A$ = "" THEN R = 0
   GOTO 1965
1960 R = VAL (A$)
1965 X = 97
Y = 114
A = FN R3(R)
W$ = STR$ (A)
GOSUB 11000
RETURN
1970 INPUT "CORE WIDTH, CW=": CW
1975 X = 100
Y = 62
A = FN R3(CW)
W$ = STR$ (A)
D = 4
GOSUB 11000
D = 1
RETURN
1980 INPUT "ENTER MAX CORE WIDTH, XW=": XW
1985 X = 96
Y = 62
: A = FN R3(XW)
: WS = STR$ (A)
: D = 4
: GOSUB 11000
: D = 1
: RETURN

1990 INPUT "ENTER MIN CORE WIDTH,NW=(RETURN=0)"; A$
: IF A$ = "" THEN NW = 0
*: GOTO 2000

1995 NW = VAL (A$)

2000 X = 103
: Y = 62
: A = FN R3(NW)
: WS = STR$ (A)
: D = 4
: GOSUB 11000
: D = 1
: RETURN

2005 INPUT "CORE MATERIAL="; CM$

2010 X = 94
: Y = 138
: WS = CM$
: GOSUB 11000
: IF LETFS (CM$, 1) = CHR$ (93) THEN CM$ = RIGHT$ (CM$, (LEN (CM$) - 1))

2015 DM$ = CHR$ (93) + CM$

2020 RETURN

2025 INPUT "CORE CLEARANCE,C2="; C2

2030 X = 165
: Y = 57
: D = 4
: A = FN R3(C2)
: WS = STR$ (A)
: GOSUB 11000
: D = 1
: RETURN

2035 INPUT "POLE DIA.,PD="; PD

2040 X = 100
: Y = 62
: A = FN R3(PD)
: WS = STR$ (A)
: D = 4
: GOSUB 11000
: D = 1
: RETURN

2045 INPUT "ENTER MAX POLE DIA.,PX="; PX
: RX = PX / 2

2050 X = 96
: Y = 62
: A = FN R3(PX)
: WS = STR$ (A)
D = 4
: GOSUB 11000
: D = 1
: RETURN

2055 INPUT "ENTER MIN POLE DIA.,PN=(RETURN=0)";A$
: IF A$ = "" THEN PN = 0
: * : RN = 0
: * : GOTO 2065

2060 PN = VAL (A$)
: RN = PN / 2

2065 X = 103
: Y = 62
: A = FN R3(PN)
: W$ = STR$ (A)
: D = 4
: GOSUB 11000
: D = 1
: RETURN

2100 REM BEGIN CHANGES SEQUENCE

2105 PRINT "DO YOU WISH TO CHANGE ANY VALUES?(Y/N):";
: GET A$

2110 IF A$ = "Y" THEN FL = 1
: * : GOTO 2125

2115 IF A$ < > "N" THEN 2105

2120 GOTO 2500

2125 IF TS = 3 THEN TS = 1

2130 INPUT "ENTER ONE VARIABLE ID:";A$

2135 REM COMMON TO ALL

2140 D = 1

2145 IF A$ = "W" THEN HOME
: * : GOSUB 1815
: * : VTAB 24
: * : PRINT "CURRENT W=":W
: * : GOSUB 1810
: * : GOTO 2105

2150 IF A$ = "CI" THEN HOME
: * : GOSUB 1825
: * : VTAB 24
: * : PRINT "CURRENT CI=":Cl
: * : GOSUB 1820
: * : GOTO 2105

2155 IF A$ = "BF" THEN HOME
: * : GOSUB 1845
: * : VTAB 24
: * : PRINT "CURRENT BF=":BF
: * : GOSUB 1840
: * : GOTO 2105

2160 IF A$ = "RW" THEN HOME
: * : GOSUB 1880
: * : VTAB 24
: * : PRINT "CURRENT RW=":RW
* : GOSUB 1860
* : GOTO 2105
2165 IF A$ = "V" THEN HOME
* : GOSUB 1900
* : VTAB 24
* : PRINT "CURRENT V=":V
* : GOSUB 1895
* : GOTO 2105
2170 IF A$ = "G" THEN HOME
* : GOSUB 1915
* : VTAB 24
* : PRINT "CURRENT G=":G
* : GOSUB 1905
* : GOTO 2105
2175 IF LEFT$(A$,2) = "CM" OR A$ = "CORE MATERIAL" THEN HOME
* : GOSUB 2010
* : VTAB 24
* : PRINT "CURRENT CM$=";CM$
* : GOSUB 2005
* : GOTO 2105
2180 IF A$ = "C2" THEN HOME
* : D = 4
* : GOSUB 2030
* : VTAB 24
* : PRINT "CURRENT C2=":C2
* : GOSUB 2025
* : D = 1
* : GOTO 2105
2185 ON AA GOTO 2190,2190,2195,2195
2190 IF A$ = "R" THEN HOME
* : GOSUB 1965
* : VTAB 24
* : PRINT "CURRENT R=":R
* : GOSUB 1955
* : GOTO 2105
2195 ON TS GOTO 2275,2205,2275
2200 REM COMMON TO ALL DESIGN
2205 IF A$ = "DX" THEN HOME
* : GOSUB 1700
* : VTAB 24
* : PRINT "CURRENT DX=":DX
* : GOSUB 1695
* : GOTO 2105
2210 IF A$ = "DN" THEN HOME
* : GOSUB 1715
* : VTAB 24
* : PRINT "CURRENT DN=":DN
* : GOSUB 1705
* : GOTO 2105
2215 IF A$ = "WX" THEN HOME
* : GOSUB 1725
* : VTab 24
* : PRINT "CURRENT WX=";WX
* : GOSUB 1720
* : GOTO 2105

2220 IF A$ = "WN" THEN HOME
* : GOSUB 1740
* : VTab 24
* : PRINT "CURRENT WN=";WN
* : GOSUB 1730
* : GOTO 2105

2225 IF A$ = "LX" THEN HOME
* : GOSUB 1750
* : VTab 24
* : PRINT "CURRENT LX=";LX
* : GOSUB 1745
* : GOTO 2105

2230 IF A$ = "LN" THEN HOME
* : GOSUB 1765
* : VTab 24
* : PRINT "CURRENT LN=";LN
* : GOSUB 1755
* : GOTO 2105

2235 IF A$ = "BX" THEN HOME
* : GOSUB 1785
* : VTab 24
* : PRINT "CURRENT BX=";BX
* : GOSUB 1780
* : GOTO 2105

2240 IF A$ = "IX" THEN HOME
* : GOSUB 1775
* : VTab 24
* : PRINT "CURRENT IX=";IX
* : GOSUB 1770
* : GOTO 2105

2245 IF A$ = "GX" THEN HOME
* : GOSUB 1785
* : VTab 24
* : PRINT "CURRENT GX=";GX
* : GOSUB 1780
* : GOTO 2105

2250 IF A$ = "GN" THEN HOME
* : GOSUB 1795
* : VTab 24
* : PRINT "CURRENT GN=";GN
* : GOSUB 1790
* : GOTO 2105

2255 IF A$ = "HX" THEN HOME
* : GOSUB 1615
* : VTab 24
* : PRINT "CURRENT HX=";HX
* : GOSUB 1600
* : GOTO 2105
2260 IF A$ = "HN" THEN HOME
  * : GOSUB 1635
  * : VTAB 24
  * : PRINT "CURRENT HN=";HN
  * : GOSUB 1620
  * : GOTO 2105
2265 ON AA GOTO 2305,2305,2345,2345
2270 REM COMMON TO ALL ANAL
2275 IF A$ = "FW" THEN HOME
  * : GOSUB 1805
  * : VTAB 24
  * : PRINT "CURRENT FW=";FW
  * : GOSUB 1800
  * : GOTO 2105
2280 IF A$ = "LW" THEN HOME
  * : GOSUB 1835
  * : VTAB 24
  * : PRINT "CURRENT LW=";LW
  * : GOSUB 1830
  * : GOTO 2105
2285 IF A$ = "WG" THEN HOME
  * : GOSUB 1855
  * : VTAB 24
  * : PRINT "CURRENT WG=";WG
  * : GOSUB 1850
  * : GOTO 2105
2290 IF A$ = "N" THEN HOME
  * : GOSUB 1890
  * : VTAB 24
  * : PRINT "CURRENT N=";N
  * : GOSUB 1885
  * : GOTO 2105
2295 ON AA GOTO 2365,2365,2385,2385
2300 REM SQ DES
2305 IF A$ = "XD" THEN HOME
  * : GOSUB 1935
  * : VTAB 24
  * : PRINT "CURRENT XD=";XD
  * : GOSUB 1930
  * : GOTO 2105
2310 IF A$ = "ND" THEN HOME
  * : GOSUB 1950
  * : VTAB 24
  * : PRINT "CURRENT ND=";ND
  * : GOSUB 1940
  * : GOTO 2105
2315 IF A$ = "XW" THEN HOME
  * : GOSUB 1985
  * : VTAB 24
* : PRINT "CURRENT XW=";XW
* : GOSUB 1980
* : GOTO 2105
2320 IF A$ = "NW" THEN HOME
* : GOSUB 2000
* : VTAB 24
* : PRINT "CURRENT NW=";NW
* : GOSUB 1990
* : GOTO 2105
2325 IF A$ = "RX" THEN HOME
* : GOSUB 1675
* : VTAB 24
* : PRINT "CURRENT RX=";RX
* : GOSUB 1670
* : GOTO 2105
2330 IF A$ = "RN" THEN HOME
* : GOSUB 1690
* : VTAB 24
* : PRINT "CURRENT RN=";RN
* : GOSUB 1680
* : GOTO 2105
2335 GOTO 2105
2340 REM RND DES
2345 IF A$ = "PX" THEN HOME
* : GOSUB 2050
* : VTAB 24
* : PRINT "CURRENT PX=";PX
* : GOSUB 2045
* : GOTO 2105
2350 IF A$ = "PN" THEN HOME
* : GOSUB 2065
* : VTAB 24
* : PRINT "CURRENT PN=";PN
* : GOSUB 2055
* : GOTO 2105
2355 GOTO 2105
2360 REM SING SQ ANAL
2365 IF A$ = "CD" THEN HOME
* : GOSUB 1925
* : VTAB 24
* : PRINT "CURRENT CD=";CD
* : GOSUB 1920
* : GOTO 2105
2370 IF A$ = "CW" THEN HOME
* : GOSUB 1975
* : VTAB 24
* : PRINT "CURRENT CW=";CW
* : GOSUB 1970
* : GOTO 2105
2375 GOTO 2105
2380 REM RND ANAL
2385  IF A$ = "PD" THEN HOME
  * : GOSUB 2040
  * : VTAB 24
  * : PRINT "CURRENT PD=";PD
  * : GOSUB 2035
  * : GOTO 2105
2390  GOTO 2105
2499  REM OUTPUT OPTIONS
2500  HOME
 : TEXT
2505  PRINT "CHOOSE ONE (1-5):"
2510  HTAB 5
 : PRINT "1.PRINT OUT COIL INFORMATION"
2515  HTAB 5
 : PRINT "2.SAVE COIL INFORMATION TO DISK"
2520  HTAB 5
 : PRINT "3.MAKE MORE CHANGES"
2525  ON TS GOTO 2530,2540,2530
2530  HTAB 5
 : PRINT "4.PERFORM ANALYSIS"
2535  GOTO 2545
2540  HTAB 5
 : PRINT "5.BEGIN NEW DESIGN"
2545  HTAB 5
 : PRINT "5.QUIT"
2550  GET A$
 : A = VAL (A$)
2555  ON A GOTO 2565,2580,2730,2750,3245
2560  ON A GOTO 2500,2500,2105,3035,3245
2565  PRINT
 : PRINT
 : INVERSE
 : PRINT "BE SURE PRINTER IS TURNED ON"
 : NORMAL
 : PRINT
 : PRINT "HIT RETURN WHEN READY"
 : GET A$
2570  PRINT
 : PRINT D$;"PR#1"
 : PRINT CHR$ (9);"G"
 : PRINT D$;"PR#0"
2575  GOTO 2560
2580  ONERR GOTO 2640
2585  PRINT
2590  ET = 3
 : DF$ = "@" + NF$
2595  PRINT D$;"OPEN ";DP$
2600  PRINT D$;"READ ";DP$
2605  INPUT AN
 : INPUT BN
 : INPUT CN
2610 PRINT D$;"CLOSE"
2615 PRINT "FILE ALREADY EXISTS. CHOOSE(1-2):"
  : PRINT " 1.OVERWRITE EXISTING FILE"
  : PRINT " 2.RENAME NEW FILE"
2620 GET A$
2625 IF A$ = "1" THEN 2645
2630 IF A$ = "2" THEN 2690
2635 GOTO 2615
2640 PRINT
  : PRINT D$;"CLOSE"
2645 POKE 216,0
2650 PRINT
  : PRINT D$;"OPEN ";DF$
2655 PRINT D$;"DELETE ";DF$
2660 PRINT D$;"OPEN ";DF$
2665 PRINT D$;"WRITE ";DF$
2670 GOSUB 3200
2675 REM
2680 PRINT D$;"CLOSE"
2685 GOTO 2560
2690 PRINT "DO YOU WANT TO REVIEW THE CATALOG(Y/N)"
2695 GET A$
2700 IF A$ = "Y" THEN PRINT
  * : PRINT D$;"CATALOG"
  * : GOTO 2710
2705 IF A$ <> "N" THEN GOTO 2690
2710 INPUT "ENTER FILENAME:";NF$
2715 IF LEFT$(NF$,1) = "@" THEN NF$ = RIGHT$(NF$, (LEN(NF$) - 1))
2720 DF$ = "@" + NF$
2725 GOTO 2580
2730 DF$ = "@TEST COIL"
2735 POKE - 16304,0
  : POKE - 16297,0
  : POKE - 16300,0
  : POKE - 16301,0
2740 HOME
  : VTAB 24
2745 GOTO 2560
2750 DM$ = CHR$(93) + CM$
2755 ONERR GOTO 2975
2760 PRINT D$;"OPEN ";DM$
2765 PRINT D$;"READ ";DM$
2770 INPUT BB
2775 PRINT D$;"CLOSE"
2780 POKE 216,0
2785 IF TS <> 2 THEN GOTO 2950
2790 IF DX < DN THEN PRINT "DX MUST BE > DN"
  * : GOTO 2505
2795 IF LX < LN THEN PRINT "LX MUST BE > LN"
  * : GOTO 2505
2800 IF WX < WN THEN PRINT "WX MUST BE > WN"
   * : GOTO 2505
2805 IF GX < GN THEN PRINT "GX MUST BE > GN"
   * : GOTO 2505
2810 ON MM GOTO 2815,2895
2815 IF XD < ND THEN PRINT "XD MUST BE > ND"
   * : GOTO 2505
2820 IF RX < RN THEN PRINT "RX MUST BE > RN"
   * : GOTO 2505
2825 IF XW < NW THEN PRINT "XW MUST BE > NW"
   * : GOTO 2505
2830 XL = (LX - 2 * NW - 2 * BF - C1)
   : ML = (LN - 2 * XW - 2 * BF - C1)
   : ML = (ML > 0) * ML + 0
   : IF XL < 0 THEN PRINT "MAX LENGTH,LX,IS TOO SHORT"
   * : GOTO 2505
2835 F1 = (WX - 2 * (NW + M * W) - C2) / 2 / M
2840 IF F1 < 0 THEN PRINT "MAX WIDTH,WX,IS TOO NARROW"
   * : GOTO 2505
2845 F2 = (DX - ND - 2 * W) / 2
2850 IF F2 < 0 THEN PRINT "MAX DEPTH,DX,IS TOO SHALLOW"
   * : GOTO 2505
2855 SX = (F1 < F2) * F1 + (F2 < F1) * F2
2860 F1 = (WN - 2 * (XW + M * W) - C2) / 2 / M
   : IF F1 < 0 THEN F1 = 0
2865 F2 = (DN - XD - 2 * W) / 2
   : IF F2 < 0 THEN F2 = 0
2870 SN = (F2 > F1) * F2 + (F1 > F2) * F1
2875 PRINT XL,ML,SX,SN
2880 REM RELOCATE APPELSOFT PROGRAM START LOCATION FOR COIL
   : DESIGN MODULE
2885 GOSUB 3035
2887 HOME
   : VTAB 12
   : HTAB 9
   : INVERSE
   : PRINT "LOADING DESIGN MODULE"
   : NORMAL
2890 LOC = 2544
   : POKE LOC - 1,0
   : POKE 103,LOC - INT (LOC / 256) * 256
   : POKE 104, INT (LOC / 256)
   : PRINT
   : PRINT D$;"RUN COIL DESIGN"
2895 IF PX < PN THEN PRINT "PX MUST BE > PN"
   * : GOTO 2505
2900 RX = PX / 2
   : RN = PN / 2
2905 ML = (LN - 2 * PX - 2 * BF - C1)
   : ML = (ML > 0) * ML + 0
   : XL = (LX - 2 * PN - 2 * BF - C1)
* IF XL < 0 THEN PRINT "MAX LENGTH,LX,IS TOO SHORT"
* GOTO 2505
2910 F1 = (WX - 2 * (PN + M * W) - C2) / 2 / M
* IF F1 < 0 THEN PRINT "MAX WIDTH,WX,IS TOO NARROW"
* GOTO 2505
2915 F2 = (DX - PN - 2 * W) / 2
* IF F2 < 0 THEN PRINT "MAX DEPTH,DX,IS TOO SMALL"
* GOTO 2505
2920 SX = (F1 < = F2) * F1 + (F2 < F1) * F2
2925 F1 = (WN - 2 * (XW + M * W) - C2) / 2 / M
* IF F1 < 0 THEN F1 = 0
2930 F2 = (DN - PX - 2 * W) / 2
* IF F2 < 0 THEN F2 = 0
2935 SN = (F2 = > F1) * F2 + (F1 > F2) * F1
2940 GOTO 2885
2945 REM BRANCH TO ANALYSIS PROGRAM STARTS HERE
2950 IF AA > 2 THEN 2960
2955 IF R > CD / 2 AND R > CW / 2 THEN PRINT "R IS TOO LARGE"
* POP
* GOTO 2505
2960 ET = 3
: GOSUB 3035
2962 HOME
: VTAB 12
: HTAB 8
: INVERSE
: PRINT "LOADING ANALYSIS MODULE"
: NORMAL
2965 PRINT D$;"RUN ANALYSIS"
2970 REM OPTION TO BRANCH TO B-H PROGRAM MODULE FOLLOWS
2975 PRINT "CORE MATERIAL FILE DOES NOT EXIST"
2980 POKE 216,0
2985 PRINT "CHOOSE ONE (1-3):"
2990 PRINT " 1.RETURN AND CHANGE MATERIAL"
2995 PRINT " 2.READ CATALOG"
3000 PRINT " 3.CREATE A NEW MATERIAL FILE"
3005 GET A$
: A = VAL (A$)
3010 ON A GOTO 2730,3015,3025
3015 PRINT
: PRINT D$;"CATALOG"
3020 GOTO 2975
3025 ET = 3
: GOSUB 3035
3027 HOME
: VTAB 12
: HTAB 8
: INVERSE
: PRINT "LOADING B-H ENTRY MODULE"
: NORMAL
3030 PRINT
   : PRINT D$; "RUN B-H"
3035 PRINT
   : PRINT D$; "OPEN @TEST COIL"
3040 PRINT D$; "DELETE @TEST COIL"
3045 PRINT D$; "OPEN @TEST COIL"
3050 PRINT D$; "WRITE @TEST COIL"
3055 GOSUB 3200
3060 PRINT D$; "CLOSE"
3065 RETURN
3100 REM INPUT FROM DISK SUBROUTINE
3105 INPUT AA
   : INPUT TS
   : INPUT ET
   : INPUT NF$
   : INPUT SX
   : INPUT FW
   : INPUT W
   : INPUT LW
   : INPUT BF
   : INPUT C1
   : INPUT C2
3110 INPUT RW
   : INPUT V
   : INPUT G
   : INPUT CM$
   : INPUT DG
   : INPUT CW
   : INPUT R
   : INPUT WG
   : INPUT N
   : INPUT PL
3115 INPUT AP
   : INPUT FT
   : INPUT CI
   : INPUT BA
   : INPUT NI
   : INPUT NA
   : INPUT NT
   : INPUT CR
   : INPUT WO
   : INPUT DO
3120 INPUT LO
   : INPUT WX
   : INPUT WN
   : INPUT DX
   : INPUT DN
   : INPUT LX
   : INPUT LN
   : INPUT IX
   : INPUT BX
INPUT GX
3125 INPUT GN
 : INPUT X1
 : INPUT N1
 : INPUT RX
 : INPUT RN
 : INPUT XW
 : INPUT NW
 : INPUT LH
 : INPUT ST
 : INPUT TC
3130 INPUT HI
 : INPUT BI
 : INPUT HA
 : INPUT SN
 : INPUT SA
 : INPUT CA
 : INPUT AG
 : INPUT NC
 : INPUT BS
 : INPUT XL
 : INPUT ML
 : INPUT HX
 : INPUT HN
3135 IF AA < 3 THEN CD = DG
 * : XD = X1
 * : ND = N1
 * : GOTO 3145
3140 PD = DG
 : PX = X1
 : PN = N1
 : CW = 0
 : R = 0
 : XW = 0
 : NW = 0
3145 RETURN
3199 REM OUTPUT TO DISK SUBROUTINE
3200 IF AA < 3 THEN DG = CD
 * : X1 = XD
 * : N1 = ND
 * : GOTO 3210
3205 DG = PD
 : X1 = PX
 : N1 = PN
 : XW = PX
 : NW = PN
3210 PRINT AA
 : PRINT TS
 : PRINT ET
 : PRINT NF$
 : PRINT SX
: PRINT FW
: PRINT W
: PRINT LW
: PRINT BF
: PRINT Cl
: PRINT C2
3215 PRINT RW
: PRINT V
: PRINT G
: PRINT CM$
: PRINT DG
: PRINT CW
: PRINT R
: PRINT WG
: PRINT N
: PRINT PL
3220 PRINT AP
: PRINT FT
: PRINT CI
: PRINT BA
: PRINT NI
: PRINT NA
: PRINT NT
: PRINT CR
: PRINT WO
: PRINT DO
3225 PRINT LO
: PRINT WX
: PRINT WN
: PRINT DX
: PRINT DN
: PRINT LX
: PRINT LN
: PRINT IX
: PRINT BX
: PRINT GX
3230 PRINT GN
: PRINT X1
: PRINT N1
: PRINT RX
: PRINT RN
: PRINT XW
: PRINT NW
: PRINT LH
: PRINT ST
: PRINT TC
3235 PRINT HI
: PRINT BI
: PRINT HA
: PRINT SN
: PRINT SA
REM SUBROUTINE FOR WRITING ON HI-RES SCREEN FOLLOWS.
TAKEN DIRECTLY FROM "SOFTGRAPH" BY DAVID DURKEE.
PUBLISHED IN SOFTALK MAGAZINE, JAN 1983 THROUGH APR 1983.

REM REQUIRES "SHAPEFILE" BE LOADED AT $0800. POKE 232-233 WITH DIFFERENT VALUES FOR OTHER LOCATIONS.

C = 6
: IF D > 2 THEN C = - 6
: FOR CT = 1 TO LEN (W$)
L = ASC (MID$ (W$,CT,1))
: IF 64 < L AND L < 91 THEN SH = L - 42
: IF L > 48 AND L < 58 THEN SH = L - 37
: IF L = 32 THEN 11160
: IF L > 39 AND L < 48 THEN SH = L - 36
: IF L = 48 THEN SH = 37
: IF L > 34 AND L < 38 THEN SH = L - 34
: IF L = 61 THEN SH = 21
: IF L = 63 THEN SH = 22
: IF L = 94 THEN SH = 49
: PRINT "ERR-NO SHAPE FOR CHARACTER: " CHR$ (L); CHR$(7)
GOTO 11150
XDRAW SH AT X,Y
: IF D / 2 < > INT (D / 2) THEN X = X + C
: GOTO 11180
: IF D / 2 = INT (D / 2) THEN Y = Y + C
NEXT CT
RETURN
PROGRAM LENGTH IS 17939 ($4613) BYTES

AA  70, 90, 100, 2185, 2265, 2295, 2950, 3105, 3135, 3200, 3210
AG  3130, 3235
AN  2605
AP  3115, 3220
BA  3115, 3220
BB  2770
BF  1840, 1845, 2155, 2830, 2905, 3105, 3210
BI  3130, 3235
BN  2605
BS  3130, 3235
BX  1645, 1650, 1655, 1660, 2235, 3120, 3225
BX$  1640, 1645, 1650
C   11000, 11160, 11170
CL  1820, 1825, 2150, 2830, 2905, 3105, 3210
C2  2025, 2030, 2180, 2835, 2860, 2910, 2925, 3105, 3210
CA  3130, 3235
CD  1920, 1925, 2365, 2955, 3135, 3200
CI  3115, 3220
CM$  2005, 2010, 2015, 2175, 2750, 3110, 3215
CN  2605
CR  3115, 3220
CT  11020, 11030, 11180
CW  1970, 1975, 2370, 2955, 3110, 3140, 3215
DS  10, 60, 65, 75, 135, 140, 150, 2570, 2595, 2600, 2610, 2640, 2650, 2655, 2660, 2665, 2680, 2700, 2760, 2765, 2775, 2890, 2965, 3015, 3030, 3035, 3040, 3045, 3050, 3060
DF$  80, 115, 120, 135, 140, 2590, 2595, 2600, 2650, 2655, 2660, 2665, 2720, 2730
DG  3110, 3135, 3140, 3200, 3205, 3215
DMS 2015, 2750, 2760, 2765
DN  1705, 1710, 1715, 2210, 2790, 2865, 2930, 3120, 3225
DO  3115, 3220
APPENDIX D
B-H PROGRAM MODULE

D.1 Program Listing .................. 222
D.2 Program Length and XRef .......... 232
B-H LISTING USING A MODIFIED BEAGLE BROTHERS XLISTER

5       REM       B-H VERSION 2-24-84;23:56
10      DEF FN RZ(X) = VAL ( LEFT$( STR$( X),7))
15      DIM BH(42,2)
:   FOR I = 0 TO 41
:     BH(I,1) = 0
:     BH(I,2) = 0
:   NEXT
20      D$ = CHR$(4)
25      REM DISPLAY INSTRUCTIONS
30      HOME
:   INVERSE
:   HTAB 13
:   PRINT "B-H CURVE ENTRY"
:   NORMAL
35      VTAB 3
:   PRINT "YOU ARE ALLOWED 40 POINTS MAXIMUM TO APPRXIMATE WITH STRAIGHT LINE SEGMENTS THE B-H CURVE WHEN PLOTTED ON SEMI-LOG SCALES WITH MAGNETIZING FORCE H ON THE LOGARITHMIC AXIS."
40      HTAB 17
:   PRINT "VALUES OF H ARE ENTERED FIRST, FOLLOWED BY THEIR CORRESPONDING BV VALUE. ENTRIES MUST BE IN ORDER FROM LOWEST TO HIGHEST VALUES. ANY DECREASING VALUE WILL RESULT IN AN ERROR. AN ENTRY OF "E" FOR H WILL TERMINATE THE ENTRY"
45      PRINT "PROCESS AFTER WHICH CHANGES MAY BE MADE. THE HIGHEST VALUE OF B WILL BE CONSIDERED THE SATURATION LEVEL, WHICH WILL DETERMINE A LIMIT OF ANY DESIGN SEARCH."
50      VTAB 23
:   HTAB 8
:   PRINT "(HIT ANY KEY TO CONTINUE)
55      KE = PEEK (49152)
:   IF KE < 128 THEN 55
60      POKE 49168,0
65      HOME
:   PRINT "PREFERRED UNITS ARE OERSTEDS FOR MAGNETIC FORCE (H) AND KILOGAUSSES FOR INTRINSIC INDUCTION (B). ALL OTHERS WILL BE CONVERTED IF THEY APPEAR BELOW:"
70      VTAB 6
:   PRINT "ENTER UNITS COMBINATION (1-4):"
75      PRINT " 1. OERSTEDS:KILOGAUSSES (CGS)"
80      PRINT " 2. AMP-TURNS/M:WEBERS/SQ.M (MKS)"
85      PRINT " 3. AMP-TURNS/IN:WEBERS/SQ.IN (JIS)"
90      PRINT " 4. AMP-TURNS/IN:KILOLINES/SQ.IN(ENGLISH)"
95      PRINT " 5. OTHER"
100     GET AS
:   A = VAL (A$)
223

: IF A < 1 OR A > 5 THEN 65
105  REM BRANCH FOR CONVERSION FACTOR
110  ON A GOSUB 1200,1215,1230,1245,1260
115  REM GET MATERIAL FOR ENTRY
120  ONERR GOTO 165
125  PRINT D$;"OPEN @TEST COIL"
130  PRINT D$;"READ @TEST COIL"
135  FOR I = 1 TO 14
140    INPUT ZZ$
145  NEXT
150  INPUT CM$
155  PRINT D$;"CLOSE"
160  GOTO 175
165  INPUT "ENTER MATERIAL NAME:";CM$
170  POKE 216,0
175  PRINT "CORE MATERIAL IS:";CM$
180  PRINT "DO YOU WISH TO CHANGE THE NAME?(Y/N):"
185  GET A$
190  IF A$ = "Y" THEN 165
195  IF A$ < > "N" THEN 175
200  REM SQUARE RIGHT BRACKET PRECEX CHECK AND ADD
205  IF LEFT$ (CM$,1) = CHR$ (93) THEN CM$ = RIGHT$ (CM$, (LEN (CM$) - 1))
210  DM$ = CHR$ (93) + CM$
215  ONERR GOTO 300
220  REM CHECK TO SEE IF FILE EXISTS
225  PRINT D$;"OPEN ";DM$
230  PRINT D$;"READ ";DM$
235  INPUT BB
240  PRINT D$;"CLOSE"
245  PRINT "MATERIAL ALREADY ON DISK.CHOOSE(1-2):"
250  PRINT " 1.LOOK AT CATALOG & CHANGE NAME"
255  PRINT " 2.INPUT FILE FROM DISK"
260  GET A$
265  IF A$ = "1" THEN PRINT
266    PRINT D$;"CATALOG"
267    GOTO 165
270  IF A$ < > "2" THEN 245
275  GOSUB 1610
280  GOSUB 1300
285  EN = NH
290  GOSUB 1500
295  GOTO 370
300  GOSUB 1300
305  POKE 216,0
310  BH(0,2) = 0
311    BH(0,1) = 0
312    NH = 0
313    XX = 13
314    Y = 1
: II = 1
: JJ = 20
320 FOR I = II TO JJ
325 GOSUB 1400
330 NE = I
335 NEXT
340 X = 25
: XX = 33
: Y = -19
: II = 21
: JJ = 40
345 FOR I = II TO JJ
350 GOSUB 1400
355 NE = I
360 NEXT
365 IF NE > NH THEN NH = NE
370 NE = NH
375 REM START CHANGE ROUTINES IF DESIRED
380 HTAB 1
: VTAB 24
: PRINT "DO YOU WISH TO MAKE ANY CHANGES(Y/N)?"
385 A = FRE(0)
390 GET A$
395 IF A$ = "N" THEN GOSUB 1300
*: GOTO 840
400 IF A$ < > "Y" THEN GOTO 380
405 PRINT "CHOOSE: I(NSERT), D(DELETE), C(HANGE), A(DD)"
: PRINT "ENTER CHOICE(I, D, C, A):";
: GET A$
410 IF A$ < > "I" THEN 645
415 HTAB 1
: VTAB 24
: PRINT "INSERT AFTER WHICH ENTRY?(0-39):"; EN
420 IF EN < > INT(EN) OR EN < 0 OR EN > 39 THEN 415
425 IF EN = NH THEN GOTO 820
430 NH = NH + 1
: IF NH > 40 THEN NH = 40
435 NE = NH
440 EN = EN + 1
445 FOR I = 40 TO EN + 1 STEP -1
450 BH(I,1) = BH(I - 1,1)
455 BH(I,2) = BH(I - 1,2)
460 NEXT
465 GOSUB 1300
470 IF EN < 20 THEN 530
475 FOR I = 1 TO 20
480 GOSUB 615
485 NEXT
490 IF EN = 20 THEN 510
495 FOR I = 21 TO EN
500 GOSUB 630
505  NEXT
510  FOR I = EN + 1 TO NH  
515    GOSUB 630
520  NEXT
525  GOTO 720  
530  IF EN = 0 THEN 550
535  FOR I = 1 TO EN  
540    GOSUB 615
545  NEXT
550  IF NH < = 20 THEN 590
555  FOR I = EN + 1 TO 20
560    GOSUB 615
565  NEXT
570  FOR I = 21 TO NH  
575    GOSUB 630
580  NEXT
585  GOTO 720
590  FOR I = EN + 1 TO NH  
595    GOSUB 615
600  NEXT
605  EN = EN + 1  
610  GOTO 720
615  VTAB I + 1
       : HTAB 5
       : PRINT ( FN RZ(BH(I,1)))
620  VTAB I + 1
       : HTAB 13
       : PRINT ( FN RZ(BH(I,2)))
625  RETURN
630  VTAB I - 19
       : HTAB 25
       : PRINT ( FN RZ(BH(I,1)))
635  VTAB I - 19
       : HTAB 33
       : PRINT ( FN RZ(BH(I,2)))
640  RETURN
645  IF A$ < > "D" THEN 705
650  HTAB 1
       : VTAB 24
       : INPUT "DELETE WHICH ENTRY?(1-40):";EN
655  IF EN < > INT (EN) OR EN < 1 OR EN > 40 THEN 650
660  NH = NH - 1
       : NE = NH
665  FOR I = EN TO 40
670    BH(I,1) = BH(I + 1,1)
675    BH(I,2) = BH(I + 1,2)
680  NEXT
685  GOSUB 1300
690  EN = NH
695  GOSUB 1500
700  GOTO 380
IF A$ < > "C" THEN 765
HTAB 1
: VTAB 24
: INPUT "CHANGE WHICH ENTRY?(1-40):"; EN
IF EN < > INT (EN) OR EN < 1 OR EN > 40 THEN 710
X = (EN > 20) * 20 + 5
: XX = (EN > 20) * 20 + 13
: Y = EN + (EN < 21) * 20 - 19
HTAB X
: VTAB Y
: PRINT ""
: REM 16 SPACES
HTAB 1
: VTAB 24
: INPUT "ENTER VALUE OF H:"; BH(EN,1)
IF BH(EN,1) < = BH(EN - 1,1) OR BH(EN,1) > = BH(EN + 1, 1) THEN VTAB (Y)
* : HTAB X
* : FLASH
* : PRINT "ERROR"
* : NORMAL
* : GOTO 730
VTAB Y
: HTAB X
: PRINT ""
: VTAB Y
: HTAB X
: PRINT ( FN RZ(BH(EN,1)))
HTAB 1
: VTAB 24
: INPUT "ENTER VALUE OF B:"; BH(EN,2)
IF BH(EN,2) < = BH(EN - 1,2) OR BH(EN,2) > = BH(EN + 1, 2) THEN VTAB Y
* : HTAB XX
* : FLASH
* : PRINT "ERROR"
* : NORMAL
* : GOTO 745
VTAB Y
: HTAB XX
: PRINT ""
: VTAB Y
: HTAB XX
: PRINT ( FN RZ(BH(EN,2)))
GOTO 380
IF A$ < > "A" THEN 380
HTAB 1
: VTAB 24
: INPUT "ADD AFTER WHICH ENTRY?"; EN
IF EN = 0 THEN GOTO 195
IF EN < > INT (EN) OR EN < 1 OR EN > 40 THEN 770
785  NH = EN
    : NE = EN
790  FOR I = EN + 1 TO 40
795      BH(I,1) = 0
800      BH(I,2) = 0
805  NEXT
810  GOSUB 1300
815  GOSUB 1500
820  IF EN > 19 THEN X = 25
     *  : XX = 33
     *  : Y = - 19
     *  : II = EN + 1
     *  : JJ = 40
     *  : GOTO 345
825  X = 5
     : XX = 13
     : Y = 1
     : II = EN + 1
     : JJ = 20
     : GOTO 320
830  REM BEGIN CONVERSION TO KILOGAUSSES AND OERSTEDS
835  GOSUB 1300
840  INVERSE
     : VTab 22
     : HTAB 5
     : PRINT "VALUES IN OERSTEDS:KILOGAUSSES"
     : NORMAL
     : VTab 3
     : HTAB 5
     : POKE 34,22
845  II = 1
     : JJ = 20 + (NH < 20) * (NH - 20)
850  FOR I = II TO JJ
855      BH(I,1) = BH(I,1) * FH
860      VTab I + 1
     : HTAB 5
     : PRINT ( FN RZ(BH(I,1)) )
865      BH(I,2) = BH(I,2) * FB
870      VTab I + 1
     : HTAB 13
     : PRINT ( FN RZ(BH(I,2)) )
875  NEXT
880  IF NH < 21 THEN 940
885  X = 25
     : XX = 33
     : Y = - 19
     : II = 21
     : JJ = NH
890  FOR I = II TO JJ
895      BH(I,1) = BH(I,1) * FH
900      VTab (I - 19)
HTAB 25: PRINT ( FN RZ(BH(I,1)))

905 BH(I,2) = BH(I,2) * FB
910 VTAB (I + Y)

HTAB XX: PRINT ( FN RZ(BH(I,2)))

915 NEXT
920 REM CLEAR SCREEN AND SAVE MATERIAL TO DISK
925 POKE 34,0
930 DM$ = CHR$ (93) + CM$
935 ONERR GOTO 1095
940 PRINT

PRINT D$; "OPEN "; DM$
945 PRINT D$; "DELETE "; DM$
950 PRINT D$; "OPEN "; DM$
955 PRINT D$; "WRITE "; DM$
960 PRINT BH(NH,2)
965 PRINT NH
970 FOR I = 1 TO NH
975 PRINT BH(I,1)

: PRINT BH(I,2)
980 NEXT
985 PRINT D$; "CLOSE"
990 REM REPEAT ENTRY PROCESS OR EXIT
995 POKE 34,0

HOME
1000 PRINT "CHOOSE (1-3):
1005 PRINT " 1.RETURN TO INPUT/OUTPUT"
1010 PRINT " 2.ENTER ANOTHER MATERIAL"
1015 PRINT " 3.QUIT"
1020 GET A$

A = VAL (A$)
1025 IF A = 3 THEN END
1030 IF A = 2 THEN GOTO 165
1035 IF A < > 1 THEN GOTO 1000
1040 PRINT

PRINT D$; "OPEN RUN TYPE"
1045 PRINT D$; "READ RUN TYPE"
1050 INPUT AA

: INPUT TS
: INPUT ET
: INPUT NF$
1055 PRINT D$; "CLOSE"
1060 ET = 3
1065 PRINT D$; "DELETE RUN TYPE"
1070 PRINT D$; "OPEN RUN TYPE"
1075 PRINT D$; "WRITE RUN TYPE"
1080 PRINT AA

: PRINT TS
: PRINT ET
: PRINT NF$
1085 PRINT D$;"CLOSE"
1087 HOME
  : VTAB 12
  : HTAB 6
  : INVERSE
  : PRINT "LOADING INPUT/OUTPUT MODULE"
  : NORMAL
1090 PRINT
  : PRINT D$;"RUN PAGE 2-A"
1095 INPUT "ENTER FILENAME";CM$
  : DM$ = CHR$ (93) + CM$
1100 GOTO 940
1199 REM CONVERSION FACTOR SUBROUTINES
1200 FH = 1
1205 FB = 1
1210 RETURN
1215 FH = .01257
  : REM MARKS HANDBOOK, EQUALS 4*PI/1000
1220 FB = 10
1225 RETURN
1230 FH = .49474
  : REM .4*(PI)/2.54
1235 FB = .006452
  : REM 10*.0254\t2
1240 RETURN
1245 FH = .49474
  : REM .4(PI)/2.54
1250 FB =
1255 RETURN
1260 INPUT "INPUT RATIO OF 1 OERSTED TO YOUR H UNITS:";FH
1265 INPUT "INPUT RATIO OF 1 KILOGAUSS TO YOUR B UNITS:";FB
1299 REM HEADER GENERATOR SUBROUTINE
1300 POKE 34,0
1305 HOME
1310 POKE 34,22
1315 INVERSE
  : VTAB 1
  : HTAB 5
  : PRINT " H "
  : VTAB 1
  : HTAB 13
  : PRINT " B "
  : VTAB 1
  : HTAB 25
  : PRINT " H "
  : VTAB 1
  : HTAB 33
  : PRINT " B "
  : NORMAL
1320 FOR I = 1 TO 9
  : VTAB (I + 1)
HTAB 2
PRINT I;"
NEXT
FOR I = 10 TO 20
VTAB (I + 1)
HTAB 1
PRINT I;"
NEXT
FOR I = 21 TO 40
VTAB (I - 19)
HTAB 21
PRINT I;"
NEXT
INVERSE
VTAB 22
HTAB 5
PRINT "VALUES ARE IN UNITS OF ENTRY"
NORMAL
VTAB 3
HTAB 4
POKE 34, 22
RETURN
REM READ IN FROM KEYBOARD SUBROUTINE
HTAB 1
VTAB 24
INPUT "ENTER VALUE OF H:"; H$
IF H$ = "E" THEN GOTO 365
BH(I, 1) = VAL (H$)
IF BH(I, 1) <= BH(I - 1, 1) THEN VTAB (I + Y)
  HTAB X
  FLASH
  PRINT "ERROR"
  NORMAL
  GOTO 1400
VTAB (I + Y)
  HTAB X
  PRINT ""
  VTAB (I + Y)
  HTAB X
  PRINT ( FN RZ(BH(I, 1)))
VTAB 24
INPUT "ENTER VALUE OF B:"; B$
IF B$ = "E" THEN GOTO 365
BH(I, 2) = VAL (B$)
IF BH(I, 2) <= BH(I - 1, 2) THEN VTAB (I + Y)
  HTAB XX
  FLASH
  PRINT "ERROR"
  NORMAL
  GOTO 1425
VTAB (I + Y)
: HTAB XX
: PRINT " "
: VTAB (I + Y)
: HTAB XX
: PRINT ( FN RZ(BH(I,2)))
1450 REM RETURN
1500 REM PRINT OUT SUBROUTINE FOR EXISTING VALUES
1505 IF EN < 21 THEN GOTO 1535
1510 X = 25
  : XX = 33
  : Y = - 19
1515 FOR I = 21 TO EN
1520  VTAB I + Y
  : HTAB X
  : PRINT ( FN RZ(BH(I,1)))
1525  VTAB I + Y
  : HTAB XX
  : PRINT ( FN RZ(BH(I,2)))
1530 NEXT
1535 X = 5
  : XX = 13
  : Y = 1
1540 SC = 20
  : IF EN < 20 THEN SC = EN
1545 FOR I = 1 TO SC
1550  VTAB I + Y
  : HTAB X
  : PRINT ( FN RZ(BH(I,1)))
1555  VTAB I + Y
  : HTAB XX
  : PRINT ( FN RZ(BH(I,2)))
1560 NEXT
1565 RETURN
1600 REM READ IN FROM DISK SUBROUTINE
1605 INPUT "ENTER FILENAME: "; CM$
1610 DM$ = CHR$(93) + CM$
1615 ON ERR GOTO 1600
1620 PRINT
  : PRINT D$; "OPEN "; DM$
1625 PRINT D$; "READ "; DM$
1630 INPUT BS
  : INPUT NH
1635 FOR I = 1 TO NH
1640  INPUT BH(I,1)
1645  INPUT BH(I,2)
1650 NEXT
1655 PRINT D$; "CLOSE"
1660 POKE 216, 0
1665 RETURN
PROGRAM LENGTH IS 6938 ($1B1A) BYTES

A  100, 110, 385, 1020, 1025, 1030, 1035
A$ 100, 185, 190, 195, 260, 265, 270, 390, 395, 400, 405, 410, 645, 705, 765, 1020
AA 1050, 1080
B$ 1425, 1430, 1435
BB 235
BH( 15, 310, 450, 615, 620, 630, 635, 670, 675, 730, 735, 740, 745, 750, 755, 795, 800, 855, 860, 865, 870, 895, 900, 905, 910, 960, 975, 1410, 1415, 1420, 1435, 1440, 1445, 1520, 1525, 1550, 1555, 1640, 1645
BS 1630
CM$ 150, 165, 175, 205, 210, 930, 1095, 1605, 1610
D$ 20, 125, 130, 155, 225, 230, 240, 265, 940, 945, 950, 955, 985, 1030, 1080, 1090, 1095, 1100
1105, 1110, 1150, 1160
DM$ 210, 225, 230, 930, 940, 945, 950, 955, 985, 1030, 1610, 1620, 1625
E 40
ET 1050, 1060, 1080
FB 865, 905, 1205, 1220, 1235, 1250, 1265
PH 855, 895, 1200, 1215, 1230, 1245, 1260
H$ 1400, 1405, 1410
1545, 1550, 1555, 1640, 1645
II 315, 320, 340, 345, 820, 825, 845, 850, 885, 890
JJ 315, 320, 340, 345, 820, 825, 845, 850, 885, 890
KE 55
NE 330, 355, 365, 370, 435, 660, 785
NF$ 1050, 1080
NH 285, 310, 365, 370, 425, 430, 435, 510, 550, 570, 590, 660, 690, 785, 845, 880, 885, 960, 965, 970, 1630, 1635
RZ( 10, 615, 620, 630, 635, 740, 750, 755, 860, 870, 900, 910, 1420, 1445, 1520, 1525, 1550, 1555, 1640, 1645
SC 1540, 1545
TS 1050, 1080
X 10, 315, 340, 720, 725, 735, 740, 820, 825, 885, 1415, 1420, 1510, 1520, 1535, 1550
XX 315, 340, 720, 750, 755, 820, 825, 885, 910, 1440, 1445, 1510, 1515, 1535, 1555
Y 315, 340, 720, 725, 735, 740, 750, 755, 820, 825, 885, 910, 1415, 1420, 1440, 1445, 1510, 1520, 1525, 1535, 1550, 1555
ZZ$ 140
APPENDIX E

ANALYSIS PROGRAM MODULE

E.1 Program Listing ........................................... 234
E.2 Program Length and XRef ............................... 249
ANALYSIS LISTING USING A MODIFIED BEAGLE BROTHERS XLISTER

5       REM ANALYSIS PORTION OF PROGRAM:VERSION 2-08-84;23:15
10     DIM BH(41,2)
15   PI = 3.141592654
20   EP = .00001
25   SF = 0
30   PP = 0
35   K1 = 2.8696831
40   D$ = CHR$(4)
45 REM READ INPUT DATA
50   PRINT D$;"OPEN @TEST COIL"
55   PRINT D$;"READ @TEST COIL"
60      INPUT AA
65      INPUT TS
70      INPUT ET
75      INPUT NF$
80      INPUT SX
85      INPUT FW
90      INPUT W
95      INPUT LW
100     INPUT BF
105     INPUT C1
110     INPUT C2
115     INPUT RW
120     INPUT V
125     INPUT G
130     INPUT CM$
135     INPUT DG
140     INPUT CW
145     INPUT R
150     INPUT WG
155     INPUT N
160     INPUT PL
165     INPUT AP
170     INPUT FT
175     INPUT CI
180     INPUT BA
185     INPUT NI
190     INPUT NA
195     INPUT NT
200     INPUT CR
205     INPUT WO
210     INPUT DO
215     INPUT LO
220     INPUT WX
225     INPUT WN
230     INPUT DX
235     INPUT DN
240     INPUT LX
INPUT LN
INPUT IX
INPUT BX
INPUT GX
80 INPUT GN
INPUT XI
INPUT N1
INPUT RX
INPUT RN
INPUT XW
INPUT NW
INPUT LH
INPUT ST
INPUT TC
85 INPUT HI
INPUT BI
INPUT HA
INPUT SN
INPUT SA
INPUT CA
INPUT AG
INPUT NC
INPUT BS
INPUT XL
INPUT ML
INPUTHX
INPUT HN
90 PRINT D$;"CLOSE"
95 REM SET UP EQUATION & CONSTANT MODIFIERS FOR DIFFERENT
CONFIGURATIONS
100 IF AA = 1 OR AA = 3 THEN M = 1
* : GOTO 110
105 M = 2
110 TS = 3
115 IF AA < 3 THEN CD = DG
* : GOTO 130
120 CD = DG
: CW = CD
: R = CD / 2
125 REM READ CORE MATERIAL FILE
130 DM$ = CHR$ (93) + CMS
135 PRINT D$;"OPEN ";DM$
140 PRINT D$;"READ ";DM$
145 INPUT BS
: INPUT NH
150 FOR I = 1 TO NH
155 INPUT BH(I,1)
160 INPUT BH(I,2)
165 NEXT
170 PRINT D$;"CLOSE"
175 REM BEGIN ANALYSIS
    PI * (R + G / 2) * R
: REM AREA OF THE AIRGAP, CORRECTED FOR FRINGING
PL = 2 * (LW + 2 * BF + M * FW + M * W + C1 + C2 + 2 * CW)
: REM STEEL PATH LENGTH
AD = .324860745
: BD = .890525717
: REM WIRE CONSTANTS
WD = AD * BD * WG
: REM BARE WIRE DIAMETER
OI = (8.64333333E - 7) / WD / WD
: REM OHMS PER INCH
OC = OI / 2.54
: REM OHMS PER CM
CP = 2 * (CD + CW + (PI - 4) * R)
: REM CORE PERIMETER
WD = WD * 2.54
: REM BARE WIRE DIA IN CM
GG = G * 2000
: REM SCALED AIRGAP FOR MU OF 1 WHEN WORKING IN
   KILOGAUSS/OERSTED INSTEAD OF GAUSS/OERSTED,
   MULTIPLIED BY 2 AIRGAPS
: REM STEEL CORE AREA
REM MUST COMPARE N TO CALCULATED VALUE. IF DIFFERENT,
   ASK IF RW DIFF OR IS BOBBIN OVER/UNDERWOUND.
   THEN ALTER CALCULATIONS ACCORDING TO ANSWER.
IN = .967 * WG + .221
: REM EFFECTIVE WIRE NUMBER OF INSULATED WIRE
ID = (AD * BD * IN) * 2.54
: REM DIA OF INSULATED WIRE
W2 = 1 / ID / ID
: REM THEORETICAL WIRES/SQ CM
NC = RW * M * LW * FW * W2
: REM CALCULATED THEORETICAL NUMBER OF TURNS
IF NC > (N * 1.05) THEN PRINT "BOBBIN IS UNDERFILLED."
    CHOOSE ONE:
*: PRINT " 1.EXTRA FLANGE WIDTH FOR TOLERANCE"
*: PRINT " 2.USE A NEW RANDOM WIND FACTOR"
*: PRINT " 3.REVIEW CALCULATIONS"
*: GOTO 285
IF NC < (N * .95) THEN PRINT "BOBBIN IS OVERFILLED."
    CHOOSE ONE:
*: PRINT " 1.CONTINUE WITH OVERFILL"
*: PRINT " 2.USE NEW RANDOM WIND FACTOR"
*: PRINT " 3.REVIEW CALCULATIONS"
*: GOTO 270
WW = FW
237

: GOTO 360
270 GET A$
    : A = VAL (A$)
    : IF A < 1 OR A > 3 THEN 260
275 WW = FW
280 ON A GOTO 300, 305, 315
285 GET A$
    : A = VAL (A$)
    : IF A < 1 OR A > 3 THEN GOTO 255
290 WW = FW
295 ON A GOTO 300, 305, 315
300 WW = N / W2 / M / LW / RW
    : GOTO 360
305 RW = RW * N / NC
    : IF RW > 1 THEN PRINT "RW MUST BE <=1 OR WIRES WON'T FIT"
*: GOTO 260
310 GOTO 360
315 PRINT "THEORETICAL NUMBER OF TURNS=", NC
320 PRINT "SPECIFIED NUMBER OF TURNS=", N
325 PRINT "THEORETICAL FLANGE FOR SPEC. TURNS=", N * ID *
    ID / LW / M
330 PRINT "THEORETICAL RANDOM WIND FACTOR=1"
335 PRINT "SPECIFIED RANDOM WIND FACTOR=", RW
340 PRINT "THEORETICAL SPACE UTILIZATION FACTOR=0.7854"
345 PRINT "CALCULATED SPACE UTILIZATION FACTOR=", N * .7854
*: RW / NC
350 PRINT "SPECIFIED SPACE UTILIZATION FACTOR=", .7854 * RW
355 GOTO 255
360 AP = CP + 2 * PI * (W + WW / 2)
    : REM AVERAGE PATH LENGTH
365 NT = V / OC / AP
    : REM TOTAL AMP TURNS
370 CR = OC * M * LW * WW * RW * AP * W2
    : REM COIL RESISTANCE
375 RA = AG / CA
    : REM AREA RATIO
380 REM FIND SEGMENT OF B-H CURVE WHICH STRADDLES THE
    OPERATING POINT
385 FOR I = 1 TO NH
390 NI = PL * BH(I,1) / K2
395 NA = BH(I,2) * GG / RA / K2
400 IF I = 1 AND (NI + NA) > NT THEN PRINT "TOO LOW ON
    B-H CURVE TO ANALYZE"
*: PRINT "WILL CONTINUE WITH NI, NA, BI, BA=0"
*: HI = 0
*: BI = 0
*: NI = 0
*: HA = 0
*: BA = 0
*: NA = 0
* : GOTO 550
* : REM VALID FOR SENSITIVITY ANALYSIS ONLY-SHOULD END
405 IF (NI + NA) > NT THEN GOTO 435
410 NL = NI
415 FL = BH(I,2) * CA
420 NEXT
425 PRINT "TOO HIGH ON B-H CURVE TO ANALYZE"
: END
430 T = -(C / K) * LOG (70 * K / P)
435 NU = NI
440 HU = BH(I,1)
445 HL = BH(I - 1,1)
450 FU = BH(I,2) * CA
455 FL = BH(I - 1,2) * CA
460 M1 = (FU - FL) / (LOG (HU) - LOG (HL))
465 A1 = K2 * AG / GG / M1
470 K5 = A1 * NT + LOG (NL) - FL / M1
475 VV = -A1 * NL + K5 - LOG (NL)
480 UU = A1 * NU - K5 + LOG (NU)
485 NI = (NL * UU + NU * VV) / (VV + UU)
490 ER = -A1 * NI + K5 - LOG (NI)
495 IF ABS (ER) < EP * FL THEN GOTO 525
500 ON (SGN (ER) + 2) GOTO 505,5,515
505 NU = NI
510 GOTO 475
515 NL = NI
520 GOTO 475
525 HI = NI * K2 / PL
: REM OERSTEDS IN IRON
530 BI = ((FU - FL) * (HI - HL) / (HU - HL) + FL) / CA
: REM KILOGAUSSES IN IRON
535 BA = BI / RA
: REM KILOGAUSSES IN AIR
540 HA = BA
: REM KILO-OERSTEDS IN AIR
545 NA = HA * GG / K2
: REM AMP-TURNS IN AIR
550 NM = NA + NI
: REM TOTAL AMP TURNS
555 FT = K1 * BA * BA * AG
: REM TOTAL FORCE IN OZ
560 IF SF = 1 THEN RETURN
565 LH = N * CR * BA * AG / V / 100000
: REM INDUCTANCE IN HENRIES
570 SA = M * LW * (AP + PI * WW)
: REM SURFACE AREA
575 WO = 2 * (CW + M * W + M * FW) + C2
: REM OVERALL WIDTH
580 DO = 2 * (W + FW) + CD
: REM OVERALL DEPTH
585 LO = 2 * (CW + BF) + LW + C1
590 REM OVERALL LENGTH
590 CI = V / CR
600 REM CURRENT DRAW AT VOLTAGE SPECIFIED
600 NC = M * LW * FW * W2
600 SM = SA / 2.54 / 2.54
605 REM SURF AREA SQ IN
605 PA = CI * CI * CR / SM
605 REM WATTS/SQ IN SURF
610 LK = EXP (PA) / (107.23 * (PA + .194) * (PA + .194) + 191.5)
615 REM HEAT DISSIPATION COEFF, POOR THERMAL CONTACT,
615 WATTS/SQ IN/DEG TEMP DIFF; ROTERS PP185
620 K = SM * LK
620 REM HEAT DISSIPATION CAPACITY, WATTS/DEG C
620 WT = AP * WW * (1.9589E - 02) * LW * 0.7854 * RW * PI/4
625 C = 180 * WT
625 REM HEAT CAPACITY OF COPPER IN JOULES/DEG C
630 P = CI * V
630 REM COIL POWER
635 ST = PA / LK
635 REM STEADY STATE TEMPERATURE RISE IN DEG C
640 RE = (((ST < 70) * ST + (ST = > 70) * 70) + 20 + 234) * CR / 254
645 REM RESISTANCE @ELEVATED TEMP
645 IE = V / RE
645 REM CURRENT @ELEVATED TEMP
650 T1 = NM
650 T2 = NI
650 T3 = NA
650 T4 = HI
650 T5 = HA
650 T6 = BI
650 T7 = BA
650 T8 = FT
650 T9 = NT
650 SF = 1
655 NT = NT * CR / RE
655 REM GOSUB 385
660 T0 = FT
665 NM = T1
665 NI = T2
665 NA = T3
665 HI = T4
665 HA = T5
665 BI = T6
665 BA = T7
665 FT = T8
665 NT = T9
665 SF = 0
670 TC = C / K
   : REM THERMAL TIME CONSTANT IN SEC. ONE TIME CONSTANT
      GETS TEMPERATURE RISE TO 63% OF STEADY STATE.
      TWO GIVES 86%. 3 GIVES 95%. 4 GIVES 98%
675 REM OUTPUT ANALYSIS AND COIL PARAMETERS TO DISK
680 IF AA < 3 THEN DG = CD
   * : GOTO 690
685 DG = CD
690 PRINT
   : PRINT D$; "DELETE @TEST COIL"
695 PRINT D$; "OPEN @TEST COIL"
700 PRINT D$; "WRITE @TEST COIL"
705 PRINT AA
   : PRINT TS
   : PRINT ET
   : PRINT NF$
   : PRINT SX
   : PRINT FW
   : PRINT W
   : PRINT LW
   : PRINT BF
   : PRINT C1
   : PRINT C2
710 PRINT RW
   : PRINT V
   : PRINT G
   : PRINT CM$
   : PRINT DG
   : PRINT CW
   : PRINT R
   : PRINT WG
   : PRINT N
   : PRINT PL
715 PRINT AP
   : PRINT FT
   : PRINT CI
   : PRINT BA
   : PRINT NI
   : PRINT NA
   : PRINT NT
   : PRINT CR
   : PRINT WO
   : PRINT DO
720 PRINT LO
   : PRINT WX
   : PRINT WN
   : PRINT DX
   : PRINT DN
   : PRINT LX
   : PRINT LN
   : PRINT IX
PRINT BX
PRINT GX
PRINT GN
PRINT Xl
PRINT NI
PRINT RX
PRINT RN
PRINT XW
PRINT NW
PRINT LH
PRINT ST
PRINT TC
PRINT HI
PRINT BI
PRINT HA
PRINT SN
PRINT SA
PRINT CA
PRINT AG
PRINT NC
PRINT BS
PRINT XL
PRINT ML
PRINT HX
PRINT HN
PRINT D$;'CLOSE'
REM DISPLAY ANALYSIS
PRINT "HOW DO YOU WANT ANALYSIS OUTPUT?:"  
PRINT " 1.SENT TO PRINTER"
PRINT " 2.DISPLAYED ON SCREEN ONLY"
PRINT " 3.NOT DISPLAYED"
PRINT "CHOOSE ONE (1-3):"
GET A$
A = VAL (A$)
IF A = 2 THEN 800
IF A = 3 THEN 1355
IF A = 1 THEN PRINT
* : PRINT
* : INVERSE
* : PRINT "BE SURE PRINTER IS TURNED ON"
* : NORMAL
* : PRINT
* : PRINT "HIT RETURN WHEN READY"
* : GET A$
PRINT D$;'PR#1'
PRINT CHR$ (9);"80N"
GOTO 800
GOTO 745
PRINT "COIL NAME:";NF$
ON AA GOTO 810,820,815,825
A$ = "SINGLE BOBBIN, RECTANGULAR CORE"
: GOTO 830
A$ = "SINGLE BOBBIN, ROUND CORE"
: GOTO 830
A$ = "DOUBLE BOBBIN, RECTANGULAR CORE"
: GOTO 830
A$ = "DOUBLE BOBBIN, ROUND CORE"
PRINT "COIL TYPE:";A$
PRINT "OPERATING VOLTAGE:";V
PRINT "COIL RESISTANCE:";CR
PRINT "CORE MATERIAL:";CM$
PRINT "THEORETICAL, NO LOSS HOLDING FORCE(OZ):";FT
PRINT "EXPECTED HOLDING FORCE (OZ):";(FT * .64)
PRINT "****PHYSICAL DIMENSIONS & CONSTANTS****"
PRINT "OVERALL LENGTH:";LO
PRINT "OVERALL DEPTH:";DO
PRINT "OVERALL WIDTH:";WO
PRINT "FLANGE WIDTH:";FW
PRINT "WINDING LENGTH:";LW
PRINT "BOBBIN WALL THICKNESS:";W
PRINT "BOBBIN FLANGE THICKNESS:";BF
PRINT "ARMATURE/BOBBIN CLEARANCE:";Cl
PRINT "WINDING CLEARANCE:";C2
PRINT "AIRGAP:";G
PRINT "STEEL PATH LENGTH:";PL
IF AA < 3 THEN 935
PRINT "CORE RADIUS:";R
GOTO 950
PRINT "CORE WIDTH:";CW
IF A = 2 THEN PRINT "HIT ANY KEY TO CONTINUE"

*: GET A$
PRINT "CORE DEPTH:";DG
PRINT "CORNER RADIUS:";R
PRINT "CORE PERIMETER:";CP
PRINT "CORE AREA:";CA
PRINT "AIRGAP AREA (FRINGING):";AG
PRINT "WINDING SURFACE AREA:";SA
PRINT "******************WINDING DATA******************"
PRINT "WIRE GAGE NUMBER:";WG
PRINT "TURNS SPECIFIED:";N
PRINT "TURNS POSSIBLE:";NC
PRINT "RANDOM WIND:";RW
PRINT "WINDING WIDTH:";WW
PRINT "BARE WIRE DIA:";WD
PRINT "OHMS/CM OF WIRE:";OC
PRINT "EFFECTIVE INSUL.WG:";IN
PRINT "INSULATED WIRE DIA:";ID
PRINT "THEORETICAL TURNS/SQ CM=";W2
PRINT "CURRENT AT ";V; " VOLTS:";CI
PRINT "AVERAGE TURN LENGTH:";AP
PRINT "INDUCTANCE, HENRIES:";LH
1037 IF A = 2 THEN PRINT "HIT ANY KEY TO CONTINUE"
    * : GET A$
1040 PRINT "S.S. TEMP RISE, DEG C:"; ST
1045 IF ST <= 70 THEN 1065
1050 PRINT "****WARNING: COIL EXCEEDS 70 DEG C RISE"
    : PRINT "OVERHEATING WILL DEGRADE INSULATION"
1055 T = -(C / K) * (LOG (P / K - 70) - LOG (P / K))
1060 PRINT "TIME TO REACH 70 DEG C:"; T; "SEC"
    : PRINT "DO NOT EXCEED THIS TIME."
    : PRINT "ALLOW AT LEAST THIS MUCH TIME BETWEEN"
    : PRINT "ACTUATIONS WHICH ARE OF THIS LENGTH"
1065 PRINT "THERMAL TIME CONST:"; TC
1070 IF ST <= 70 THEN PRINT "RESISTANCE @ S.S. TEMP:"; RE
    * : GOTO 1080
1075 PRINT "RESISTANCE @ 70 DEG C:"; RE
1080 PRINT "CURRENT @ THAT TEMP:"; IE
1085 PRINT "IDEAL FORCE @ THAT TEMP @": V; "VOLTS="; T0
1090 PRINT "*************** MAGNETIC DATA ***************"
1095 PRINT "TOTAL AMP-URNS(ACTUAL):"; NT
1100 PRINT "TOTAL AMP-URNS(AIR+IRON):"; NM
1105 PRINT "AMP-URNS IN IRON:"; NI
1110 PRINT "AMP-URNS IN AIR:"; NA
1115 PRINT "OERSTEDS IN IRON:"; HI
1120 PRINT "OERSTEDS IN AIR:"; (HA * 1000)
1125 PRINT "KILOGAUSSES IN IRON:"; BI
1130 PRINT "KILOGAUSSES IN AIR:"; BA
1135 PRINT "IRON SAT KILOGAUSS:"; BS
1137 IF A = 2 THEN PRINT "HIT ANY KEY TO CONTINUE"
    * : GET A$
1140 PRINT "************** DESIGN CONSTRAINTS **************"
1145 IF LX = 0 THEN PRINT "NONE"
    * : GOTO 1350
1150 PRINT "MAX OVERALL LENGTH:"; LX
1155 IF LO > LX * 1.01 THEN PRINT "***LX VIOLATED"
1160 PRINT "MIN OVERALL LENGTH:"; LN
1165 IF LO < LN * .99 THEN PRINT "***LN VIOLATED"
1170 PRINT "MAX OVERALL DEPTH:"; DX
1175 IF DO > DX * 1.01 THEN PRINT "***DX VIOLATED"
1180 PRINT "MIN OVERALL DEPTH:"; DN
1185 IF DO < DN * .99 THEN PRINT "***DN VIOLATED"
1190 PRINT "MAX OVERALL WIDTH:"; WX
1195 IF WO > WX * 1.01 THEN PRINT "***WX VIOLATED"
1200 PRINT "MIN OVERALL WIDTH:"; WN
1205 IF WO < WN * .99 THEN PRINT "***WN VIOLATED"
1210 IF AA = 2 OR AA = 4 THEN PRINT "MAX CORE DIA:"; PX
    * : IF DG > PX * 1.01 THEN GOSUB 1325
    * : PRINT "MIN CORE DIA:"; PN
    * : IF DG < PN * .99 THEN GOSUB 1330
    * : GOTO 1275
1215 PRINT "MAX CORE WIDTH:"; XW
1220 IF CW > XW * 1.01 THEN PRINT "***XW VIOLATED"
PRINT "MIN CORE WIDTH:";NW
IF CW < NW * .99 THEN PRINT "***NW VIOLATED"
PRINT "MAX CORE DEPTH:";X1
IF DG > X1 * 1.01 THEN PRINT "***X1 VIOLATED"
PRINT "MIN CORE DEPTH:";N1
IF DG < N1 * .99 THEN PRINT "***N1 VIOLATED"
PRINT "MAX CORE CORNER RAD:";RX
IF R > RX * 1.01 THEN PRINT "***RX VIOLATED"
PRINT "MIN CORE CORNER RAD:";RN
IF R < RN * .99 THEN PRINT "***RN VIOLATED"
PRINT "MAX CURRENT @ ";V;" VOLTS:";IX
IF CI > IX * 1.01 THEN PRINT "***IX VIOLATED"
PRINT "MAX WIRE GAGE NUMBER:";GX
IF WG > GX * 1.01 THEN PRINT "***GX VIOLATED"
PRINT "MIN WIRE GAGE NUMBER:";GN
IF WG < GN * .99 THEN PRINT "***GN VIOLATED"
IF BX = 0 THEN BX = BH(NH,2)
PRINT "MAX KILOGAUSS IN CORE:";BX
IF BI > BX * 1.01 THEN PRINT "***BX VIOLATED"
GOTO 1335
PRINT "***PX VIOLATED"
RETURN
PRINT "***PN VIOLATED"
RETURN
IF A = 2 THEN PRINT "HIT ANY KEY TO CONTINUE"
* : GET A$
PRINT "DESIGN HINTS:"
PRINT "IF ANY FINAL DIMENSIONS ARE AT OR NEAR"
PRINT "THEIR LIMITS, THEN CHANGING THOSE LIMITS"
PRINT "MAY CHANGE THE FINAL SOLUTION."
PRINT "TEMPERATURE RISE CAN BE REDUCED BY"
PRINT "INCREASING THE SURFACE AREA (OR LX)"
REM RETURN TO PAGE 2-A
PRINT
PRINT D$;"PR#0"
PRINT D$;"OPEN RUN TYPE"
PRINT D$;"READ RUN TYPE"
INPUT AA
: INPUT TS
: INPUT ET
: INPUT NF$
PRINT D$;"CLOSE"
TS = 4
PRINT D$;"DELETE RUN TYPE"
PRINT D$;"OPEN RUN TYPE"
PRINT D$;"WRITE RUN TYPE"
PRINT AA
: PRINT TS
: PRINT ET
: PRINT NF$
1400 PRINT D$; "CLOSE"
1405 PRINT D$; "PR#0"
1410 GOSUB 1500
1415 PRINT
    PRINT D$; "PR#0"
1420 HOME
    INVERSE
    HTAB 6
    VTAB 12
    PRINT "LOADING INPUT/OUTPUT MODULE"
    NORMAL
    VTAB 21
    HTAB 5
    PRINT "THIS MAY SEEM TO TAKE AWHILE:"
    VTAB 23
    HTAB 2
    PRINT "BUT IT SURE BEATS DOING IT BY HAND!"
1425 PRINT
    PRINT D$; "RUN PAGE 2-A"
1499 REM PERFORM VOLTAGE/GAP SENSITIVITY
1500 PRINT "DO YOU WISH TO PERFORM VOLTAGE AND AIR"
    PRINT "GAP SENSITIVITY?(Y/N)"
    GET A$
1505 IF A$ = "N" THEN RETURN
1510 IF A$ < > "Y" THEN 1500
1515 SF = 1
1520 PRINT "OUTPUT SHOULD BE SENT TO:"
1525 PRINT " 1. SCREEN ONLY"
1530 PRINT " 2. PRINTER"
1535 GET A$
1540 IF A$ = "1" THEN 1555
1545 IF A$ < > "2" THEN 1520
1550 PF = 1
1555 INPUT "ENTER MAX VOLTAGE:"; VX
1560 INPUT "MIN AIRGAP:"; NG
1565 INPUT "MAX AIRGAP:"; XG
1570 INPUT "ENTER NUMBER OF TEST GAPS:"; GS
1575 IF GS = 1 THEN SG = 0
    * : GOTO 1585
1580 SG = (XG - NG) / (GS - 1)
1585 VS = INT (VX / .5) + 1
1590 DIM SS(VS, GS)
1595 HOME
    INVERSE
    VTAB 12
    HTAB 14
    PRINT "I'M THINKING"
    NORMAL
1600 G = NG
1605 REM LOOP FOR GAP TRIALS
1610 FOR II = 1 TO GS
GG = G * 2000
V = 0
REM LOOP FOR VOLTAGE STEPS
FOR JJ = 1 TO VS
  REM SET V STEP CONSTANT TO A SMALLER VALUE FOR
  A SMOOTHER PLOT
  V = V + .5
  GOSUB 360
  SS(JJ,II) = FT
NEXT JJ
G = G + SG
NEXT
REM BEGIN SCALE AND PLOT ROUTINE
XI = INT (116 / (VX + 1))
YI = 166 / (INT (SS(VS,1) + 5))
HGR
  : HCOLOR= 3
  : SCALE= 1
  : ROT= 0
  : D = 1
  : F = 2
POKE -16302,0
HPL 40,0 TO 40,166 TO 272,166
FOR I = 2 TO VS STEP 2
  X = XI * I + 40
  HPL X,163 TO X,169
  XL = X - XI
  HPL XL,165 TO XL,167
  W$ = STR$ (I / 2)
  Y = 174
  GOSUB 11000
NEXT
FOR I = 4 TO INT (SS(VS,1) + 4) STEP 4
  Y = 166 - I * YI
  HPL 37,Y TO 43,Y
  W$ = STR$ (I)
  X = 37 - LEN (W$) * 6
  Y = Y - 2
  GOSUB 11000
NEXT
FOR I = 1 TO GS
  X = 40 + XI
  Y = 166 - (YI * SS(I,I))
  HPL X,Y
FOR J = 2 TO VS
  X = 40 + XI * J
  Y = 166 - (YI * SS(J,I))
  HPL TO X,Y
NEXT
NEXT
W$ = "VOLTAGE"
REM PRINTOUT VALUES FOR SENSITIVITY GRAPH
1860 TEXT
    : HOME
    : INVERSE
    : PRINT "BE SURE PRINTER IS TURNED ON"
    : NORMAL
    : PRINT
    : PRINT "HIT RETURN WHEN READY"
    : GET A$
1865 PRINT
    : PRINT D$;"PR#1"
    : PRINT CHR$ (9);"G"
1870 PRINT D$;"PR#1"
    : PRINT CHR$ (9);"80N"
1875 PRINT
    : PRINT
    : PRINT "VOLTAGE AND AIRGAP SENSITIVITY FOR ";NF$
1880 PRINT
    : PRINT
1885 PRINT "GAP", "VOLTAGE", "IDEAL FORCE(oz)"
1890 FOR I = 1 TO GS
1895 FOR J = 1 TO VS
1900 PRINT (NG + (I - 1) * SG),(J * .5),SS(J,I)
1905 NEXT
1910 NEXT
1915 PF = 0  
: SF = 0  
: RETURN
10998 REM SUBROUTINE FOR WRITING ON HI-RES SCREEN. TAKEN
DIRECTLY FROM "SOFTGRAPH" BY DAVID DURKEE.
PUBLISHED IN SOFTALK MAGAZINE, JAN 1983 THROUGH APR
1983
10999 REM REQUIRE "SHAPEFILE" BE LOADED AT $0800. CHANGE
LOCATIONS 232-233 WITH POKES FOR OTHER SHAPETABLE
START LOCATIONS
11000 C = 6  
: IF D > 2 THEN C = - 6
11010 ROT= 16 * (D + F + 1)
11020 FOR CT = 1 TO LEN (W$)
11030 L = ASC ( MID$ (W$,CT,1))
11040 IF 64 < L AND L < 91 THEN SH = L - 42  
*: GOTO 11150
11050 IF L > 48 AND L < 58 THEN SH = L - 37  
*: GOTO 11150
11060 IF L = 32 THEN 11160
11070 IF L > 39 AND L < 48 THEN SH = L - 36  
*: GOTO 11150
11080 IF L = 48 THEN SH = 37  
*: GOTO 11150
11090 IF L > 34 AND L < 38 THEN SH = L - 34  
*: GOTO 11150
11100 IF L = 61 THEN SH = 21  
*: GOTO 11150
11110 IF L = 63 THEN SH = 22  
*: GOTO 11150
11120 IF L = 94 THEN SH = 49  
*: GOTO 11150
11130 PRINT "ERR-NO SHAPE FOR CHARACTER: " CHR$ (L);
CHR$ (7)
11140 GOTO 11160
11150 XDRAW SH AT X,Y  
11160 IF D / 2 < > INT (D / 2) THEN X = X + C  
*: GOTO 11180
11170 IF D / 2 = INT (D / 2) THEN Y = Y + C
11180 NEXT CT
11190 RETURN
PROGRAM LENGTH IS 12606 ($313E) BYTES

A    270, 280, 285, 295, 770, 775, 780, 785
A$   270, 285, 770, 785, 810, 815, 820, 825, 830, 1500, 1505, 1510, 1535, 1540, 1545, 1850, 1860
A1   465, 470, 475, 480, 490
AA   60, 100, 115, 680, 705, 805, 920, 1210, 1365, 1395
AD   190, 195, 240
AG   85, 180, 375, 465, 555, 565, 730, 960
AP   70, 360, 365, 370, 570, 620, 715, 1030
BA   70, 535, 540, 555, 650, 665, 715, 1130
BD   190, 195, 240
BF   60, 185, 585, 705, 795
BH(  10, 155, 160, 390, 395, 415, 440, 445, 450, 455, 1305
BI   85, 530, 535, 650, 665, 730, 1125, 1315
BS   85, 145, 730
BX   75, 720, 1305, 1310, 1315
C    430, 625, 670, 1055, 11000, 11160, 11170
C1   60, 185, 585, 705, 900
C2   60, 185, 575, 705, 905
CA   85, 225, 375, 415, 450, 455, 530, 730, 955
CD   115, 120, 180, 210, 225, 580, 680, 685
CI   70, 590, 605, 630, 715, 1025, 1280
CM$  65, 130, 710, 845
CP   210, 360, 950
CR   70, 370, 565, 590, 605, 640, 655, 715, 840
CT   11020, 11030, 11180
CW   65, 120, 180, 185, 210, 225, 575, 585, 710, 935, 1220, 1230
D    1685, 1835, 11000, 11010, 11160, 11170
DS   40, 50, 55, 90, 135, 140, 170, 690, 695, 700, 735, 790, 1350, 1355, 1360, 1370, 1380, 1385, 1390, 1400, 1405, 1415, 1425, 1865, 1870
DG   65, 115, 120, 680, 685, 710, 940, 1210, 1240, 1250
DMS  130, 135, 140
DN   75, 720, 1180, 1185
DO   70, 580, 715, 870, 1175, 1185
DX   75, 720, 1170, 1175
E    200, 620
EP   20, 495
ER   490, 495, 500
ET   60, 705, 1365, 1395
F    1685, 11010
FL   415, 455, 460, 470, 495, 530
FT   70, 555, 650, 660, 665, 715, 850, 855, 1650
FU   450, 460, 530
FW   60, 185, 250, 265, 275, 290, 575, 580, 595, 705, 880
G    65, 180, 220, 710, 910, 1600, 1615, 1660
GG   220, 395, 465, 545, 1615
GN   80, 725, 1295, 1300
GS   1570, 1575, 1580, 1590, 1610, 1780, 1890
GX 75, 720, 1285, 1290
HA 85, 540, 545, 650, 665, 730, 1120
HI 85, 525, 530, 650, 665, 730, 1115
HL 445, 460, 530
HN 85, 730
HU 440, 460, 530
HX 85, 730
I 150, 155, 160, 385, 390, 395, 400, 415, 440, 445, 450, 455, 1700, 1705, 1725, 1745, 1750, 1760, 1780, 1790, 1810, 1890, 1900
ID 240, 245, 325, 1015
IE 645, 1080
II 1610, 1650
IN 235, 240, 1010
IX 75, 720, 1275, 1280
J 1800, 1805, 1810, 1895, 1900
JJ 1630, 1650, 1655
K 430, 615, 670, 1055
K1 10, 555
K2 35, 390, 395, 465, 525, 545
K5 470, 475, 480, 490
L 11030, 11040, 11050, 11060, 11070, 11080, 11090, 11100, 11110, 11120, 11130
LH 80, 565, 725, 1035
LK 610, 615, 635
LN 75, 720, 1160, 1165
LO 75, 585, 720, 865, 1155, 1165
LW 60, 185, 250, 300, 325, 370, 570, 585, 595, 705, 885
LX 75, 720, 1145, 1150, 1155
M 100, 105, 185, 250, 300, 325, 370, 570, 575, 595
ML 460, 465, 470
ML 85, 730
N 65, 255, 260, 300, 305, 320, 325, 345, 710, 980
N1 80, 725, 1245, 1250
NA 70, 395, 400, 405, 545, 550, 650, 665, 715, 1110
NC 85, 250, 255, 260, 305, 315, 345, 565, 595, 730, 985
NF$ 60, 705, 800, 1365, 1395, 1875
NG 1560, 1580, 1600, 1840, 1900
NH 145, 150, 385, 1305
NI 70, 390, 400, 405, 410, 435, 485, 490, 505, 515, 525, 550, 650, 665, 715, 1105
NL 410, 470, 475, 485, 515
NM 550, 650, 665, 1100
NT 70, 365, 400, 405, 470, 650, 665, 715, 1095
NU 435, 480, 485, 505
NW 80, 725, 1225, 1230
OC 205, 365, 370, 1005
OI 200, 205
P 430, 630, 1055
PA 605, 610, 635
PF 25, 1550, 1850, 1915
XI  80, 725, 1235, 1240
XG  1565, 1580, 1845
XI  1675, 1705, 1715, 1785, 1805
XL  85, 730, 1715, 1720
XW  80, 725, 1215, 1220
Y   1730, 1750, 1755, 1765, 1790, 1795, 1810, 1815, 1830, 1835, 1840, 1845, 1850, 11150, 11170
YI  1680, 1750, 1790, 1810
APPENDIX F

COIL DESIGN PROGRAM MODULE

F.1 Program Listing .................................................. 254
F.2 Program Length and XRef ........................................ 282
COIL DESIGN LISTING USING A MODIFIED BEAGLE BROTHERS XLISTER

1    REM  COIL DESIGN 2-12-84;14:15
2    REM  THIS IS THE MODSER ALGORITHM PROGRAM, P519RE,  
        9-12-83 VERSION, MODIFIED FOR USE ON AN APPLE II+  
        COMPUTER WITH AN EPSON 70 PRINTER. LINES 500 TO  
        1000, SUBROUTINES 8500 AND 9000 CONTAIN THE SPECIAL  
        PROGRAMMING FOR THE COIL DESIGN.
3    REM  THE MODSER ALGORITHM AND PROGRAM P519RE WERE  
        DEVELOPED BY RAY C. JOHNSON, PHD., P.E.
4    REM  MAIN PROGRAM follows
5    D$ = CHR$ (4)
6    REM  FOR DOUBLE PRECISION, VARIABLES B,D,E,G,H,O-Y  
        SHOULD BE DBL PREC.
7    REM  MAIN PROGRAM follows
8    Z$ = "INITIAL CALCULATIONS:"  
        PRINT Z$
9    PRINT
10   FOR I = 1 TO NV  
11      CD(I) = (CX(I) - CN(I)) / AL  
12      NEXT
13   A = 0.  
14   FOR I = 1 TO NV  
15      A = A + (CX(I) - CN(I)) ↑ 2  
16      NEXT  
17     AD = SQR (A) / AB  
18     FD = AB * AD / AS  
19     FS = FD / 5  
20     FX = FS / ZT  
21     FH = AD / 2
22
23   IF NE = 0 AND NR = 0 THEN FM = 0  
24     GOTO 55  
25
26   IF MX > 0 THEN GOSUB 2000
27
28   IF MX > 0 THEN GOSUB 2000
29
30   IF MX > 0 THEN GOSUB 2000
31
32   IF MX > 0 THEN GOSUB 2000
: DC = 0.00
: KA = 0
: NX = 0
: DL = AD
: IT = 0
: CP = 0.

80 FOR I = 1 TO NV
: VB(I) = CS(I)
: V(I) = VB(I)
: NEXT
: IF MS = 0 THEN GOSUB 9000

* : GOTO 90

81 REM FOR DBL PREC, IN LINE 80, VB(I) SHOULD = CDBL(CS(I))

82 FOR IS = 1 TO MS
: OK(IS) = OS(IS)
: OI(IS) = OK(IS)
: NEXT
: GOSUB 9000

90 IF NU > 0 THEN FOR IU = 1 TO NU
* : UB(IU) = U(IU)
* : NEXT

95 IF MS = 0 THEN 100

96 FOR IS = 1 TO MS
: SK(IS) = S(IS)
: NEXT

100 IF KG > 0 THEN FOR JG = 1 TO KG
* : NB(JG) = N(JG)
* : NEXT

110 IF NE > 0 THEN FOR IE = 1 TO NE
* : EB(IE) = E(IE)
* : NEXT

120 IF NR > 0 THEN FOR IR = 1 TO NR
* : RB(IR) = R(IR)
* : NEXT

130 QB = Q
: BB = B
: HB = H
: WB = W
: PB = P
: XB = X
: GOSUB 1000
: Z$ = "START OF MODSER SEARCH PROCESS:"
: PRINT Z$
: GOSUB 1010
: Z$ = "BASE POINT PRINTOUTS FOLLOW:"
: PRINT Z$

131 A = FRE (0)
140 GOSUB 1020
: GOSUB 1010
: IF KT = 1 THEN GOSUB 8080
* : GOTO 160
150 ON NP GOSUB 8070,8080,8200
160 GOSUB 3000
170 GOSUB 5000
: FE = FR
180 Z$ = "JT,FB,FE=
 : PRINT Z$;JT,FB,FE
190 XI = 0.000
 : FOR I = 1 TO NV
 : GX = VA(I) - VB(I)
 : XI = XI + GX * GX
 : NEXT
 : GOSUB 40600
 : DB = X3
 : PRINT "DB=";DB
 : REM DB SHOULD BE SINGLE PREC.
195 IF KA = 1 THEN DL = DB
 * : KA = 0
200 IF DB > FS THEN 210
201 IF ME = 3 THEN 222
202 IF ME = 2 THEN ME = 3
 * : GOTO 222
204 IF ME = 0 THEN ME = 1
 * : FX = FX / 10
 * : FS = FS / 10
 * : GOTO 222
206 IF ME = 1 THEN ME = 2
 * : FX = FX / 10
 * : FS = FS / 10
 * : GOTO 222
210 IF KT >= KX THEN 1060
220 GOSUB 1950
 : K = K + 1
 : KT = KT + 1
 : GOTO 140
222 PRINT "ME=";ME
 : IF CP = 0. THEN 230
224 IF FP < FM THEN 250
230 IF K = 1 AND ME = 3 THEN 260
240 K = 0
 : IF CP = 0. THEN 210
250 FP = AM * FP
 : Z$ = "PENALTY INCREASED AT 250,WITH FP="
 : PRINT Z$;FP
 : GOSUB 1020
252 FOR I = 1 TO NV
 : V(I) = VA(I)
 : NEXT
 : IF MS > 0 THEN FOR IS = 1 TO MS
 * : OI(IS) = OA(IS)
 * : NEXT
GOSUB 9000
: BA = B
: HA = H
: WA = W
: PA = P
: XA = X

IF NE > 0 THEN FOR IE = 1 TO NE
  : EA(IE) = E(IE)
  : NEXT

IF NR > 0 THEN FOR IR = 1 TO NR
  : RA(IR) = R(IR)
  : NEXT

KA = 1
: GOTO 210

KE = KE + 1
: Z$ = "TERMINATION TEST COUNT KE="
: PRINT Z$;KE
: GOSUB 1020

GX = DB + DC
: IF GX > 0.000 THEN GY = DC + DD
: AC = GY / GX
: GOTO 270

AC = 1.E20

IF AC <= 1 THEN Z$ = "DIVERGENCE ANTICIPATED, WITH AC="
  : PRINT Z$;AC
  : Z$ = "WENT TO 240 FOR NEXT LOOP"
  : PRINT Z$
  : GOSUB 1020
  : GOTO 240

Z$ = "CONVERGENCE ANTICIPATED, WITH AC="
  : PRINT Z$;AC
  : FT = (AC - 1) * 6 * FS
  : Z$ = "READY FOR TERMINATION TEST AT 290, AND FT="
  : PRINT Z$;FT

IF DB > FT THEN Z$ = "TERMINATION TEST FAILED AT 290.
  WENT TO 240 FOR NEXT LOOP."
  : PRINT Z$
  : GOSUB 1020
  : GOTO 240

Z$ = "TERMINATION TEST PASSED AT 290"
: PRINT Z$

GOSUB 1000
: GOSUB 1000
: Z$ = "SOLUTION FOUND IS AT (K+1), NOW TRANSFERRED TO
      (K) STORAGE FOR PRINTOUT"
  : PRINT Z$
  : PRINT

KK = 0
: GOSUB 1950
: GOSUB 4000
: XI = 0.000
: FOR I = 1 TO NV
:   XI = XI + GB(I) * GB(I)
: NEXT
: GOSUB 40600
: GM = X3
: GOSUB 8080
320  PRINT "GM=";GM
: GOSUB 1010
322  REM Z$ = "DOUBLE PRECISION VB(I) FOR I=1,...,NV ARE=
      " PRINT Z$: FOR I = 1 TO NV: PRINT VB(I),: NEXT : PRINT : IF NU = 0 THEN 326
324  REM Z$ = "DOUBLE PRECISION UB(IU) FOR IU=1,...,NU AR
      E =": PRINT Z$: FOR IU = 1 TO NU: PRINT UB(IU),: NEXT : PRINT
326  GOSUB 1010
: FOR I = 1 TO NV
:   V(I) = VB(I)
: NEXT
: IF MS > 0 THEN FOR IS = 1 TO MS
* : OI(IS) = OK(IS)
*: NEXT
327  GOSUB 9000
: GOSUB 10000
: PRINT
: GOSUB 1000
330  Z$ = "MF,MG,MR,NX="
: PRINT Z$;MF,MG,MR,NX
340  GOSUB 1010
: PRINT "CG(I):"
345  PRINT "AA,TS,ET,SX,FW,W,LW,BF,C1,C2,RW,V,G,DG,CW,R,WG,
      N,PL,AP,PT,CI,BA,N1,NA,NT,CR,WO,DO,LO,WX,WN,DX,
      DN,LX,LN,IX,BX,GX,GN,X1,N1,RX,RN,XW,NW,LH,ST,TC,
      HI,BI,HA,SN,SA,CA,AG,NC,BS,XL,ML,HX,HN,HD,BD,ED,
      EP,K1,K2,NH:"
350  FOR I = 1 TO 62
:     PRINT CG(I),
:   NEXT
360  PRINT
: PRINT "Z(I):"
365  PRINT "--,--,RA,WD,ID,OC,W2,CP,NL,FL,NU,HU,HL,FU,A1,
      K5,VV,UU,ER:"
370  FOR I = 1 TO 20
:     PRINT Z(I),
:   NEXT
380  PRINT
: PRINT "M(I):"
390  FOR I = 1 TO 3
:     PRINT M(I),
:   NEXT
400  PRINT
: PRINT "R(I):"
PRINT "R CONSTRAINTS ARE (BUT UNITIZED):"
: PRINT "WX-WO,WO-WN,DX-DO,DO-DN,LX-LO,LO-LN,BX-BI,IX-CI,
  HX-LH,LH-HN,GX-WG,WG-GN,RX-R,R-RN,SX-FW,FW-SN,
  XL-LW,LW-ML,BI,CI,XL-CD,CD-NL,XW-CW,CW-NW;"
FOR I = 1 TO NR
  PRINT R(I),
NEXT
CG(2) = 3
CG(3) = 3
PRINT
  POKE 216,0
  PRINT D$;"DELETE @TEST COIL"
D$ = CHR$ (4)
POKE 216,0
PRINT
  PRINT D$;"OPEN @TEST COIL"
PRINT D$;"WRITE @TEST COIL"
FOR I = 1 TO 3
  PRINT CG(I)
NEXT
PRINT NF$
FOR I = 4 TO 13
  PRINT CG(I)
NEXT
PRINT CM$
FOR I = 14 TO 62
  PRINT CG(I)
NEXT
PRINT D$;"CLOSE"
PRINT
  PRINT D$;"OPEN RUN TYPE"
PRINT D$;"READ RUN TYPE"
INPUT AA
  INPUT TS
  INPUT ET
  INPUT NF$
PRINT D$;"CLOSE"
TS = 3
ET = 3
PRINT D$;"DELETE RUN TYPE"
PRINT D$;"OPEN RUN TYPE"
PRINT D$;"WRITE RUN TYPE"
PRINT AA
  PRINT TS
  PRINT ET
  PRINT NF$
PRINT D$;"CLOSE"
PRINT D$;"PR#0"
HOME
  INVERSE
  HTAB 8
VTAB 12
PRINT "LOADING ANALYSIS PROGRAM"
NORMAL
LOC = 16384
POKE LOC - 1,0
POKE 103,LOC - INT (LOC / 256) * 256
POKE 104, INT (LOC / 256)
PRINT
PRINT D$; "RUN ANALYSIS"
GOTO 600
END
REM ***MINOR SUBROUTINES***
FOR I = 1 TO 79
PRINT "*";
NEXT
PRINT
RETURN
FOR I = 1 TO 74
PRINT "-";
NEXT
PRINT
RETURN
FOR I = 1 TO 25
PRINT "-";
NEXT
PRINT
RETURN
DIM C(KC),CD(NV),CG(NG),CN(NV),CS(NV),CX(NV),DN(NV),
DP(NV),DV(NV),E(NE),EA(NE),EB(NE),ES(NE),F(NP),
GB(NV),GC(NV),GS(NV),N(KG),NA(KG),NB(KG),NC(KG),
NS(KG),OA(MS),OD(MS),OE(MS),OF(MS),OG(MS),OI(MS),
OK(MS),OS(MS)
DIM RG(NR)
DIM R(NR),RA(NR),RB(NR),RS(NR),S(MS),SA(MS),SD(MS),
SE(MS),SF(MS),SK(MS),SB(NV),SC(NV),TB(NV),U(NU),
UA(NU),UB(NU),US(NU),V(NV),VA(NV),VB(NV),VD(NV),
VE(NV),VF(NV),VG(NV),VS(NV),VT(NV),VD(NV),YE(NV),
YP(NV),YS(NV)
RETURN
Z$ = "KT=KK STOP REVIEW; BASE POINT PRINTOUT;"
GOSUB 1010
GOSUB 1010
PRINT Z$
GOSUB 8080
FOR M = 1 TO 3
PRINT
NEXT
REM ? "ENTER 'GOTO 220' FOR NEXT LOOP IF DESIRED"
REM STOP
PRINT "MAX BASEPOINTS, KK=";KK
PRINT "IF YOU WISH TO CONTINUE, THEN"
: INPUT "ENTER NEW KX: "; KX
1070 IF KX > KT THEN GOTO 220
1075 KX = KT
: GOTO 1065
1898 REM **NEW BASE POINT ANALYSIS SUBROUTINE 1900:**
1900 FOR I = 1 TO NV
: V(I) = VB(I)
: NEXT
: IF MS > 0 THEN FOR IS = 1 TO MS
*: OI(IS) = OK(IS)
*: NEXT
1902 GOSUB 9000
: QB = Q
: BB = B
: HB = H
: WB = W
: PB = P
: XB = X
: IF NU > 0 THEN FOR IU = 1 TO NU
*: UB(IU) = U(IU)
*: NEXT
1905 IF MS > 0 THEN FOR IS = 1 TO MS
*: SK(IS) = S(IS)
*: NEXT
1910 IF NE > 0 THEN FOR IE = 1 TO NE
*: EB(IE) = E(IE)
*: NEXT
1920 IF NR > 0 THEN FOR IR = 1 TO NR
*: RB(IR) = R(IR)
*: NEXT
1930 IF KG > 0 THEN FOR JG = 1 TO KG
*: NB(JG) = N(JG)
*: NEXT
1940 RETURN
1948 REM **MAIN PROGRAM (K) STORAGE INDEX SUBROUTINE 1950:**
1950 DD = DC
: DC = DB
: FOR I = 1 TO NV
: GC(I) = GB(I)
: SC(I) = SB(I)
: NEXT
1960 QB = QA
: BB = BA
: HB = HA
: WB = WA
: PB = PA
: XB = XA
: FOR I = 1 TO NV
: VB(I) = VA(I)
: NEXT
1965 IF MS > 0 THEN FOR IS = 1 TO MS
REM ***SUBROUTINE 2000: SG SEARCH***
2000 KS = 1
2001 GOSUB 8755
2002 V(1) = CX(1)
2003 IF NV > 4 THEN V(5) = .9 * CN(5) + .1 * CX(5)
2004 GOSUB 9000
2005 PRINT "KS,P,Q,V(I)="
2006 XG = X
2007 QG = Q
2008 PG = P
2009 FOR I = 1 TO NV
2010 FOR I = 1 TO NV
2011 V(I) = CN(I) + RND(1) * (CX(I) - CN(I))
PRINT KS,V(1),P,Q
PRINT
2020 IF X < XG THEN XG = X
* : QG = Q
* : PG = P
* : FOR I = 1 TO NV
  * : VG(I) = V(I)
* : NEXT
* : S1 = 0
2030 IF KS < MN THEN 2040
2032 IF PG = 0 AND S1 = 0 THEN 2050
2040 IF KS < MX THEN KS = KS + 1
* : GOTO 2010
2045 IF FP < = 1 THEN PRINT "SHOTGUN DID NOT FIND A POINT WHICH MEETS ALL CONSTRAINTS"
  * : PRINT "SETTING FP=1. BE PREPARED FOR 6 TO 8 HOUR RUN TIME"
  * : FP = 1
  * : FOR I = 1 TO NR
  * : PRINT RG(I),
  * : NEXT
  * : GOTO 2050
2046 FP = FP / 8
  : PRINT "FP REDUCED TO:";FP
  : FOR I = 1 TO NR
    : PRINT RG(I),
    : NEXT
  : GOTO 2010
2050 Z$ = "SG SEARCH GAVE FOLLOWING POINT:
  : PRINT
  : PRINT
  : PRINT Z$
  : PRINT
  : Z$ = "QG,PG,XG="
  : PRINT Z$,QG,PG,XG
  : PRINT
2060 Z$ = "VG(I) FOR I=1,...,NV ARE="
  : PRINT Z$
  : FOR I = 1 TO NV
    : PRINT VG(I),
    : NEXT
  : PRINT
2069 A = FRE (0)
2070 FOR I = 1 TO NV
  : CS(I) = VG(I)
  : NEXT
  : RETURN
2998 REM ***SUBROUTINE 3000:SEARCH DIRECTION SB(I),TB(I), AT VB(I);FOR I=1 TO NV***
3000 GOSUB 4000
3010 IF ND = 1 OR DC = 0. THEN 3100
3015 IF KA > 0 THEN 3100
3020 IF ND = 2 OR KG = 0 THEN 3150
3030 JG = 1
3040 IF NB(JG) < > NC(JG) THEN 3090
3050 IF JG = KG THEN 3150
3060 JG = JG + 1
: GOTO 3040
3090 NX = NX + 1
: Z$ = "NX,JG="
: PRINT Z$,NX,JG
3100 FOR I = 1 TO NV
: SB(I) = - GB(I)
: NEXT
: ID = 1
: GOTO 3200
3150 GX = 0.000
: GY = GX
3160 FOR I = 1 TO NV
: GX = GX + (GB(I) - GC(I)) * GB(I)
: GY = GY + (GB(I) - GC(I)) * SC(I)
: NEXT
: IF GY = 0. THEN Z$ = "GY=0. AT 3160; GOTO 3100"
: PRINT Z$
: GOTO 3100
3170 WK = GX / GY
: FOR I = 1 TO NV
: SB(I) = - GB(I) + WK * SC(I)
: NEXT
: ID = 2
3200 PRINT "ID=";ID
3210 DT = 0.000
: FOR I = 1 TO NV
: DT = DT + GB(I) * SB(I)
: NEXT
: IF DT < 0. THEN 3240
3215 IF DT = 0. AND ID = 1 THEN Z$ = "STATIONARY POINT FOUND AT 3215,WITH ID,DT="
: PRINT Z$;ID,DT
: RETURN
3220 IF ID = 2 THEN MR = MR + 1
: GOTO 3100
3230 Z$ = "FAILED DESCENT DIRECTION TEST AT 3220,WITH GX="
: PRINT Z$;GX
: STOP
3240 XI = 0.000
: FOR I = 1 TO NV
: XI = XI + SB(I) * SB(I)
: NEXT
: GOSUB 40600
3250 FOR I = 1 TO NV
: IF X3 > 0.000 THEN TB(I) = SB(I) / X3
* : GOTO 3260
3251 TB(I) = 0.000
3260 NEXT
  : RETURN
3998 REM ***SUBROUTINE 4000: GRADIENT GB(I) AT BASE POINT
   VB(I);FOR I=1 TO NV***
4000 MG = MG + 1
   : FOR I = 1 TO NV
   : V(I) = VB(I)
   : NEXT
   : IF MS = 0 THEN 4010
4001 FOR IS = 1 TO MS
   : OI(IS) = SK(IS)
   : NEXT
4010 FOR I = 1 TO NV
4015 IF CD(I) = 0 THEN GB(I) = 0
   * : NEXT
4020 VT(I) = V(I)
4030 V(I) = VB(I) + CD(I)
   : GOSUB 9000
   : DP(I) = X
4040 V(I) = VB(I) - CD(I)
   : GOSUB 9000
   : DN(I) = X
4050 GB(I) = (DP(I) - DN(I)) / 2 / CD(I)
4060 V(I) = VT(I)
4070 NEXT
4080 RETURN
4998 REM ***SUBROUTINE 5000: LINE SEARCH FOR (K+1) BASE POINT
   - VA(I),I=1 TO NV;AND CP TUNING CALCULATIONS***
5000 REM
5005 IF DT = 0. AND ID = 1 AND KT > 1 AND CP < > 0. THEN
   FR = 0.
   * : FB = 0.
   * : J = 0
   * : GOTO 5230
5010 IF KT = 1 THEN FR = AD
   * : GOTO 5040
5015 IF KA > 0 THEN FR = CL * DL
   * : GOTO 5040
5020 IF DC = 0. THEN FR = FS / 2
   * : GOTO 5040
5030 IF DC < AD THEN FR = CA * DC
   * : GOTO 5040
5031 FR = AD
5040 FB = FR
5050 FOR I = 1 TO NV
   : DV(I) = FR * TB(I)
   : NEXT
5100 JT = 0
   : J = 0
: QD = QB
: WD = WB
: XD = XB
: FOR I = 1 TO NV
:   YD(I) = 0.000
:   VD(I) = VB(I)
: NEXT
: IF MS = 0 THEN 5150
5110 FOR IS = 1 TO MS
:   OG(IS) = SK(IS)
:   OD(IS) = OK(IS)
:   SD(IS) = SK(IS)
: NEXT
5150 QF = QE
:   WF = WE
:   XF =XE
: FOR I = 1 TO NV
:   YF(I) = YE(I)
:   VF(I) = VE(I)
: NEXT
: IF MS = 0 THEN 5160
5155 FOR IS = 1 TO MS
:   OF(IS) = OE(IS)
:   SF(IS) = SE(IS)
: NEXT
5160 QE = QD
:   WE = WD
:   XE = XD
: FOR I = 1 TO NV
:   YE(I) = YD(I)
:   VE(I) = VD(I)
: NEXT
: IF MS = 0 THEN 5170
5165 FOR IS = 1 TO MS
:   OE(IS) = OD(IS)
:   SE(IS) = SD(IS)
: NEXT
5170 JT = JT + 1
:   J = J + 1
5180 FOR I = 1 TO NV
:   YD(I) = YE(I) + DV(I)
:   VD(I) = VB(I) + YD(I)
:   V(I) = VD(I)
: NEXT
: IF MS = 0 THEN 5190
5185 FOR IS = 1 TO MS
:   OD(IS) = OG(IS)
:   OI(IS) = OD(IS)
: NEXT
5190 GOSUB 9000
: IF MS = 0 THEN 5192
FOR IS = 1 TO MS
    SD(IS) = S(IS)
    OG(IS) = SD(IS)
    NEXT
MF = MF + 1
QD = Q
WD = W
XD = X
IF CP = 0. AND WD > = WE AND WD > 0. THEN 5500
NN = 0
IF J > = 2 THEN 5260
IF XD < = XE THEN MC = 1
    GOTO 5150
GZ = FX * CR
    IF FR < = GZ THEN FOR I = 1 TO NV
        VA(I) = VD(I)
        V(I) = VA(I)
    NEXT
    GOTO 5235
IF MS = 0 THEN 5287
FOR IS = 1 TO MS
    OA(IS) = OD(IS)
    OI(IS) = OA(IS)
    NEXT
    GOTO 5287
J = 0
FR = CR * FR
FOR I = 1 TO NV
    DV(I) = CR * DV(I)
    NEXT
    GOTO 5170
IF XD < XE THEN 5350
GX = XD + XF - 2 * XE
    IF GX = 0 THEN DS = FR
    GOTO 5272
DS = FR * (XD - XE) / GX
XI = 0.000
    FOR I = 1 TO NV
        XI = XI + YD(I) * YD(I)
    NEXT
    GOSUB 40600
    YJ = X3
    YM = YJ - FR / 2 - DS
IF YM < 0.000 THEN Z$ = "FAILED TEST AT 5280"
    PRINT Z$
    GOTO 5318
FOR I = 1 TO NV
    YS(I) = YM * TB(I)
    VA(I) = VB(I) + YS(I)
    V(I) = VA(I)
IF MS = 0 THEN 5287
FOR IS = 1 TO MS
OU = OD(IS)
OV = OE(IS)
OW = OF(IS)
GOSUB 5288
OI(IS) = GZ
NEXT
GOSUB 9000
GOTO 5290
GW = OV - OU
GX = OW - OU
GY = (4 * GW - GX) / GV
GX = (GW - GY * FR) / GU
GW = GT * (GX * GT + GY)
GZ = GW + OU
RETURN
MF = MF + 1
QA = Q
BA = B
HA = H
WA = W
PA = P
XA = X
IF NU > 0 THEN FOR IU = 1 TO NU
UA(IU) = U(IU)
NEXT
IF MS = 0 THEN 5295
FOR IS = 1 TO MS
OA(IS) = OI(IS)
SA(IS) = S(IS)
NEXT
IF NE > 0 THEN FOR IE = 1 TO NE
EA(IE) = E(IE)
NEXT
IF NR > 0 THEN FOR IR = 1 TO NR
RA(IR) = R(IR)
NEXT
IF KG > 0 THEN FOR JG = 1 TO KG
NA(JG) = N(JG)
NEXT
IF XA > XB THEN 5305
RETURN
Z$ = "FAILED FUNCTION DECREASE TEST AT 5300"
PRINT Z$
GZ = FX * CR
IF FR > GZ THEN PRINT "WENT TO 5320 AND 5250"
* : GOTO 5320
5312  RETURN
5314  GZ = FX * CR
  : IF FR > GZ THEN PRINT "WENT TO 5320 FROM 5314"
* : GOTO 5320
5316  IF ABS(YM) > GZ THEN PRINT "WENT TO 5320 FROM 5316"
* : GOTO 5320
5318  FOR I = 1 TO NV
  : VA(I) = VB(I)
  : V(I) = VA(I)
  : NEXT
  : IF MS = 0 THEN 5287
5319  FOR IS = 1 TO MS
  : OA(IS) = OK(IS)
  : OI(IS) = OA(IS)
  : NEXT
  : GOTO 5287
5320  QE = QF
  : WE = WF
  : XE = XF
  : FOR I = 1 TO NV
  : YE(I) = YF(I)
  : VE(I) = VF(I)
  : NEXT
  : IF MS > 0 THEN FOR IS = 1 TO MS
* : OE(IS) = OF(IS)
* : SE(IS) = SF(IS)
* : NEXT
5322  GOTO 5250
5350  IF J > JX THEN Z$ = "J>JX AT 5350;STOP REVIEW"
* : GOSUB 1000
* : PRINT Z$
* : GOSUB 8080
* : STOP
5370  IF FR > FH THEN 5150
5375  IF MC < 1 THEN MC = 1
* : GOTO 5150
5380  FR = 2 * FR
  : QE = QF
  : WE = WF
  : XE = XF
  : FOR I = 1 TO NV
  : DV(I) = 2 * DV(I)
  : YE(I) = YF(I)
  : VE(I) = VF(I)
  : NEXT
  : IF MS = 0 THEN MC = 0
* : GOTO 5382
5381  FOR IS = 1 TO MS
  : OE(IS) = OF(IS)
  : SE(IS) = SF(IS)
: NEXT
: MC = 0

5382 GOTO 5150
5500 IF KP > 0 THEN 5502
5501 IF QD > QE THEN NN = 0
* : Z$ = "IN PENALTY ZONE AT 5500 WITH WD>WE,BUT NO TUNE
      SINCE QD>QE"
* : PRINT Z$
* : GOTO 5210

5503 IF NN = 0 THEN 5600
* : REM ***AT FIRST PROBE EDGE OF PENALTY ZONE***
5510 IF KP = 0 THEN KP = 1
* : GOTO 5150
5511 KP = 2
: GOTO 5700
: REM ***CP CALCULATION***
5598 REM **SEGMENT 5600:FOR CP SELF-TUNING PROCESS**
5600 Z$ = "START SEGMENT 5600 - AT EDGE OF PENALTY ZONE WITH
      WD>WE AND QD<QE"
: PRINT Z$
5610 FOR I = 1 TO NV
: VB(I) = VE(I)
: NEXT
: IF MS = 0 THEN 5620
5615 FOR IS = 1 TO MS
: OK(IS) = OE(IS)
: NEXT
5620 GOSUB 1900
: NT = ND
: ND = 1
: GOSUB 3000
: FB = FR
: NN = 1
: KP = 0
: ND = NT
: GOTO 5050
5700 Z$ = "READY FOR CP CALCULATION AT 5700"
: PRINT Z$
5710 IF WD < > WF THEN CP = .75 * (QF - QD) / (WD - WF)
5720 Z$ = "AT (J-2), AND KP=0:QF,WF="
: PRINT Z$;QF,WF
5730 Z$ = "AT (J-1), AND KP=1:QE,WE="
: PRINT Z$;QE,WE
5740 Z$ = "AT (J), AND KP=2:QD,WD"
: PRINT Z$;QD,WD
5750 Z$ = "REVIEW CALCULATED CP="
: PRINT Z$;CP
5760 FOR M = 1 TO 3
: PRINT
: NEXT
: PRINT "ENTER GOTO 5790 TO CHANGE CP OR GOTO 5800 TO
RETAIN CP
: GOTO 5800
: REM STOP IS USUALLY HERE
5790 INPUT "ENTER NEW CP=";CP
5800 Z$ = "FOR USE IN SEARCH TO FOLLOW, CP=
: PRINT Z$;CP
5805 A = FRE (0)
5810 FOR I = 1 TO NV
: VB(I) = VE(I)
: NEXT
: IF MS = 0 THEN GOSUB 1900
* : GOTO 5820
5815 FOR IS = 1 TO MS
: OK(IS) = OE(IS)
: NEXT
: GOSUB 1900
5820 Z$ = "RETURNING TO LINE SEARCH WITH TUNED CP AND NEW
BASE POINT:"
: PRINT Z$
: GOSUB 1010
: GOSUB 8080
5830 NT = ND
: ND = 1
: GOSUB 3000
: FR = AD
: NN = 2
: ND = NT
: FB = FR
: GOTO 5050
5840 REM *END OF CP SELF-TUNING PROCESS*
7997 REM *INPUT DATA PRINTOUT*
7999 REM * INPUT DATA PRINTOUT *
8000 Z$ = "AB,AE,AG,AL,AM,AS,ZT,CA,CL,CR, JX,KX="
: PRINT Z$
: PRINT AB,AE,AG,AL,AM,AS,ZT,CA,CL,CR, JX,KX
: PRINT
8010 Z$ = "KC,KG,MD,MN,MS,MX,NX,NE,NF,NG,NP, NR,NU,NV="
: PRINT Z$
: PRINT KC,KG,MD,MN,MS,MX,NX,NE,NF,NG,NP, NR,NU,NV
: PRINT
8020 Z$ = "CN(I) FOR I=1,...,NV ARE="
: PRINT Z$
: FOR I = 1 TO NV
: PRINT CN(I),
: NEXT
: PRINT
8030 Z$ = "CX(I) FOR I=1,...,NV ARE="
: PRINT Z$
: FOR I = 1 TO NV
: PRINT CX(I),
: NEXT
PRINT
8040 IF NG = 0 THEN 8050
8045 Z$ = "CG(IG) FOR IG=1,...,NG ARE="
    PRINT Z$
    FOR IG = 1 TO NG
        PRINT CG(IG),
    NEXT
    PRINT
8050 IF MX > 0 THEN 8060
8052 Z$ = "SPECIFIED CS(I) FOR I=1,...,NV ARE="
    PRINT Z$
    FOR I = 1 TO NV
        PRINT CS(I),
    NEXT
    PRINT
8055 IF MS = 0 THEN 8060
8057 Z$ = "SPECIFIED OS(IS) FOR IS=1,...,MS ARE="
    PRINT Z$
    FOR IS = 1 TO MS
        PRINT OS(IS),
    NEXT
    PRINT
8060 IF KC = 0 THEN 8072
8061 Z$ = "CALCULATED CONSTANTS C(IC) FOR IC=1,...,KC ARE ="
    PRINT Z$
    FOR IC = 1 TO KC
        PRINT C(IC),
    NEXT
    PRINT
    GOTO 8072
8068 REM *NP=1,MINIMAL BASE POINT PRINTOUT OPTION*
8070 Z$ = "KT,VB(1),XB,QB="
    PRINT
    PRINT Z$
    PRINT KT,VB(1),XB,QB
    PRINT
8072 GOSUB 1010
    GOSUB 1020
    GOTO 8072
8078 REM *NP=2,FULL BASE POINT PRINTOUT OPTION*
8080 Z$ = "KT,K,XB,QB="
    PRINT
    PRINT Z$
    PRINT KT,K,XB,QB
    PRINT
8090 Z$ = "VB(I) FOR I=1,...,NV ARE="
    PRINT Z$
    FOR I = 1 TO NV
        PRINT VB(I),
    NEXT
    PRINT
8095 IF MS = 0 THEN 8100
8096 ZS = "OK(IS) FOR IS=1,...,MS ARE=
   : PRINT ZS
   : FOR IS = 1 TO MS
   : PRINT OK(IS),
   : NEXT
   : PRINT
8097 ZS = "SK(IS) FOR IS=1,...,MS ARE=
   : PRINT ZS
   : FOR IS = 1 TO MS
   : PRINT SK(IS),
   : NEXT
   : PRINT
8100 IF NU > 0 THEN ZS = "UB(IU) FOR IU=1,...,NU ARE="
   * : PRINT ZS
   * : FOR IU = 1 TO NU
   * : PRINT UB(IU),
   * : NEXT
   * : PRINT
8110 IF NE > 0 THEN ZS = "EB(IE) FOR IE=1,...,NE ARE="
   * : PRINT ZS
   * : FOR IE = 1 TO NE
   * : PRINT EB(IE),
   * : NEXT
   * : PRINT
8120 IF NR > 0 THEN ZS = "RB(IR) FOR IR=1,...,NR ARE="
   * : PRINT ZS
   * : FOR IR = 1 TO NR
   * : PRINT RB(IR),
   * : NEXT
   * : PRINT
8130 IF KG > 0 THEN ZS = "NB(JG) FOR JG=1,...,KG ARE="
   * : PRINT ZS
   * : FOR JG = 1 TO KG
   * : PRINT NB(JG),
   * : NEXT
   * : PRINT
8135 A = FRE (0)
8140 GOSUB 1010
   : GOSUB 1020
   : RETURN
8200 RETURN
   : REM ****NO BASEPOINT PRINTOUT; NP=3
8496 REM ***SUBROUTINE 8500:INPUT DATA AND CALCULATED CONSTANTS***
8498 REM **INACTIVATE ANY 'DATA' NOT IN USE, BY DATA**
8500 PRINT "DO YOU WANT:"
   : PRINT " 1.MIN. BASEPOINT PRINTOUT (SHORTER)"
   : PRINT " 2.FULL BASEPOINT PRINTOUT (LONG TIME)"
   : PRINT " 3.NO BASEPOINT PRINTOUT (NO INFO)"
   : GET A$
NP = VAL (A$)
IF NP < 1 OR NP > 3 THEN 8500
8501 PRINT "FP AFFECTS THE STOPPING CRITERIA FOR"
PRINT "THE SEARCH PROCESS."
PRINT "AN INITIAL VALUE OF 1 TAKES LONGER TO"
PRINT "EXECUTE, BUT HAS A HIGHER CONFIDENCE"
PRINT "FACTOR."
PRINT "A HIGHER VALUE OF FP MAY STOP THE"
PRINT "SEARCH PREMATURELY."
8502 PRINT "FP SHOULD BE A POWER OF 8."
8503 INPUT "ENTER FP (RETURN=262144)";A$
IF A$ = "" THEN FP = 262144
* : GOTO 8505
8504 FP = VAL (A$)
8505 PRINT "DO YOU WISH OUTPUT SENT TO THE PRINTER? (Y/N)"
GET A$
IF A$ = "N" THEN 8520
8510 IF A$ < > "Y" THEN 8500
8515 HOME
PRINT
PRINT D$;"PR#1"
PRINT CHR$ (9);"80N"
8520 Z$ = "MODSER - APPLICATION OF P519RE FOLLOWS (9-12-83 VERSION)"
PRINT Z$
GOSUB 1000
8525 Z$ = "INPUT DATA:"
PRINT Z$
PRINT
8530 AP = 3.141593
AR = 57.29578
CP = 0.
KP = 0
8535 READ AB,AE,AG,AL,AM,AS,CT,CA,CL,CR,JX,KX
8540 DATA 10.,.5,1.E03,1.E05,8.,2.E04,2.,.85,.25,.25,100,500
8545 PRINT D$;"OPEN @TEST COIL"
8550 PRINT D$;"READ @TEST COIL"
8555 INPUT AA
8560 PRINT D$;"CLOSE"
8565 DIM M(3)
IF AA = 1 OR AA = 3 THEN M(2) = 1
* : GOTO 8575
8570 M(2) = 2
8575 IF AA < 3 THEN M(3) = 1
* : NV = 6
* : NR = 26
* : GOTO 8585
8580 M(3) = 2
NV = 4
NR = 20
8585 READ KC,KG,MD,MN,MS,MX,ND,NE,NF,NG,NU
DATA 5, 0, 0, 50, 0, 100, 2, 0, 0, 69, 0
DIM Z(20), BH(40, 2)
GOSUB 1030
PRINT D$; "OPEN @TEST COIL"
PRINT D$; "READ @TEST COIL"
FOR I = 1 TO 3
  INPUT CG(I)
NEXT
INPUT NF$
FOR I = 4 TO 13
  INPUT CG(I)
NEXT
INPUT CM$
FOR I = 14 TO 62
  INPUT CG(I)
NEXT
PRINT D$; "CLOSE"
CG(63) = 0.825146292
CG(64) = 0.890525717
CG(65) = 2.1954066E-06
CG(66) = 0.00001
CG(67) = 2.8696831
CG(68) = AP * .4
C(5) = CG(13) * 2000
FOR I = 1 TO NV
  CX(I) = 1
NEXT
CN(1) = CG(40) / CG(39)
CN(2) = CG(60) / CG(59)
CN(3) = CG(53) / CG(4)
IF M(3) = 2 THEN CN(4) = CG(44) / CG(43)
GOTO 8665
CN(5) = CG(46) / CG(45)
CN(6) = CG(42) / CG(41)
CN(4) = 1
IF CG(43) < > 0 THEN CN(4) = CG(44) / CG(43)
C(1) = CG(32) / CG(31)
C(2) = CG(34) / CG(33)
C(3) = CG(36) / CG(35)
IF CG(61) = 0 THEN CG(61) = 5
C(4) = CG(62) / CG(61)
PRINT D$; "OPEN ]"; CM$
PRINT D$; "READ ]"; CM$
INPUT CG(58)
  INPUT CG(69)
FOR I = 1 TO CG(69)
  INPUT BH(I, 1)
  INPUT BH(I, 2)
NEXT
PRINT D$; "CLOSE"
IF CG(38) = 0 THEN CG(38) = CG(58)
IF NG = 0 THEN 8725
REM FOR IG = 1 TO NG: READ CG(IG): NEXT: REM CHANGED FOR FILE READING
IF MX > 0 THEN 8735
FOR I = 1 TO NV
: READ CS(I)
: NEXT
: REM **SPECIFIED START POINT DATA (CASE OF NO SG)**
IF MS = 0 THEN 8745
FOR IS = 1 TO MS
: READ OS(IS)
: NEXT
IF KC = 0 THEN 8985
GOSUB 8000
GOTO 8765
Z(9) = 2 * AP * CG(44)
CG(20) = Z(9) + 2 * AP * (CG(6) + CG(4))
Z(5) = CG(63) * CG(64) * (CG(39))
Z(6) = CG(63) * CG(64) * (.967 * CG(39) + .221)
Z(7) = CG(65) / Z(5) / Z(5)
IF (CG(12) / CG(37)) < (CG(4) * CG(59) * CG(11) * CG(20) * Z(7) / Z(6) / Z(6)) THEN 8985
PRINT "CANNOT FIND A SOLUTION."
PRINT "MAX WIRE VOLUME INSUFFICIENT FOR "
PRINT "MAX CURRENT SPEC TO BE MET."
PRINT "SHOULD SEARCH CONTINUE FOR CLOSEST FIT?"
PRINT ".(Y/N)"
GET A$
IF A$ = "N" THEN PRINT
* PRINT D$; "RUN PAGE 2-A"
IF A$ < > "Y" THEN 8790
RETURN
GOSUB 8000
RETURN
***SUBROUTINE 9000: ANALYSIS AT GIVEN V POINT***
**HERE USER PROGRAMS EQUATIONS FOR: (1) U(IU), FOR IU=1 TO NU; (2) N(JG), FOR JG=1 TO KG; (3) Q; (4) E(IE), FOR IE=1 TO NE; (5) R(IR), FOR IR=1 TO NR**
REM ** USE MODSER REFORMULATION STRATEGY FOR THESE EQUATIONS AND DECISION-MAKING LOGIC PROGRAMMED HERE **
** USE L COUNTER IF NECESSARY, INSTEAD OF I **
** LINES 9000 - 9945 ARE AVAILABLE **
CG(17) = V(1) * CG(39)
REM WG
CG(7) = V(2) * CG(59)
REM LW
277

9010 CG(5) = V(3) * CG(4)
    : REM FW
9015 CG(16) = V(4) * CG(43)
    : REM R
9020 IF M(3) = 2 THEN 9040
9025 CG(15) = V(5) * CG(45)
    : REM CW
9030 CG(14) = V(6) * CG(41)
    : REM CD
9035 GOTO 9050
9040 CG(15) = CG(16) * 2
    : REM CW
9045 CG(14) = CG(16) * 2
    : REM CD
9050 Z(1) = CG(14) - 2 * CG(16)
9055 Z(2) = CG(15) - 2 * CG(16)
9060 Z(3) = CG(16) + CG(13) / 2
9065 CG(56) = Z(1) * Z(2) + 2 * Z(1) * Z(3) + 2 * Z(2) * Z(3) + AP * Z(3) * Z(3)
    : REM AG
9070 CG(55) = Z(1) * Z(2) + 2 * Z(1) * CG(16) + 2 * Z(2) * CG(16) + AP * CG(16) * CG(16)
    : REM CA
9075 Z(4) = CG(56) / CG(55)
    : REM RA
9080 CG(19) = 2 * (CG(7) + 2 * CG(8) + M(2) * CG(5) + M(2) * CG(6) + CG(9) + CG(10) + 2 * CG(15))
    : REM PL
9085 Z(5) = CG(63) * CG(64) * CG(17)
    : REM WD IN CM
9090 Z(6) = CG(63) * CG(64) / (.967 * CG(17) + .221)
    : REM ID IN CM
9095 Z(7) = CG(65) / Z(5) / Z(5)
    : REM OC
9100 Z(8) = 1 / Z(6) / Z(6)
    : REM W2
9105 IF AA > 2 THEN Z(9) = 2 * AP * CG(16)
    * : GOTO 9115
    * : REM AP RND
9110 Z(9) = 2 * (CG(14) + CG(15) + (AP - 4) * CG(16))
    : REM CP RECT
9115 CG(20) = Z(9) + 2 * AP * (CG(6) + CG(5) / 2)
    : REM AP
9120 CG(18) = CG(11) * M(2) * CG(7) * CG(5) * Z(8)
    : REM N
9125 CG(26) = CG(12) / Z(7) / CG(20)
    : REM NT
9130 CG(27) = Z(7) * M(2) * CG(7) * CG(5) * CG(11) * CG(20) * Z(8)
    : REM CR
9135 REM FIND B-H SEGMENT WHICH STRADDLES THE OPERATING
POINT

FOR L = 1 TO CG(69)

CG(24) = CG(19) * BH(L,1) / CG(68)
  REM NI AT SEGMENT END

CG(25) = BH(L,2) * C(5) / Z(4) / CG(68)
  REM NA AT SEGMENT END

IF L = 1 AND (CG(24) + CG(25)) > CG(26) THEN PRINT
  "TOO LOW ON B-H CURVE TO ANALYZE"

  PRINT "WILL CONTINUE WITH NI,NA,BI,BA=0"

  CG(50) = 0
  CG(51) = 0
  CG(24) = 0
  CG(52) = 0
  CG(23) = 0
  CG(25) = 0
  CG(21) = 1E - 5

  GOTO 9300

  REM SHOULD HAVE STOPPED, NEED BETTER

IF (CG(24) + CG(25)) > CG(26) THEN 9185

Z(10) = CG(24)
  REM NL

Z(11) = BH(L,2) * CG(55)
  REM FL

NEXT

PRINT "TOO HIGH ON B-H CURVE TO ANALYZE"

END

Z(12) = CG(24)
  REM NU

Z(13) = BH(L,1)
  REM HU

Z(14) = BH(L - 1,1)
  REM HL

Z(15) = BH(L,2) * CG(55)
  REM PU

M(1) = (Z(15) - Z(11)) / (LOG(Z(13)) - LOG(Z(14)))
  REM M1

Z(16) = CG(68) * CG(56) / C(5) / M(1)
  REM A1

Z(17) = Z(16) * CG(26) + LOG(Z(10)) - Z(11) / M(1)
  REM K5

Z(18) = Z(17) - Z(16) * Z(10) - LOG(Z(10))
  REM VV

Z(19) = Z(16) * Z(12) - Z(17) + LOG(Z(12))
  REM UU

CG(24) = (Z(10) * Z(19) + Z(12) * Z(18)) / (Z(18) + Z(19))
  REM NI

Z(20) = Z(17) - Z(16) * CG(24) - LOG(CG(24))
  REM ER

IF ABS(Z(20)) < CG(66) * CG(24) THEN GOTO 9270

ON (SGN(Z(20) + 2)) GOTO 9250,10,9260
279

9250 Z(12) = CG(24)
    : REM NU
9255 GOTO 9220
9260 Z(10) = CG(24)
    : REM NL
9265 GOTO 9220
9270 CG(50) = CG(24) * CG(68) / CG(19)
    : REM HI
9275 CG(51) = (((Z(15) - Z(11)) * (CG(50) - Z(14))) / (Z(13)
    - Z(14)) + Z(11)) / CG(55)
    : REM BI
9280 CG(23) = CG(51) / Z(4)
    : REM BA
9285 CG(52) = CG(23)
    : REM HA IN KILO-OERSTEDS
9290 CG(25) = CG(52) * C(5) / CG(68)
    : REM NA
9295 CG(21) = CG(23) * CG(23) * CG(56) * CG(67)
    : REM FT
9300 Q = 1 / CG(21)
9305 CG(47) = CG(18) * CG(27) * CG(23) * CG(56) / CG(12)
    / 100000
    : REM LH
9310 CG(54) = M(2) * CG(7) * (CG(20) + AP * CG(5))
    : REM SA
9315 CG(28) = 2 * (CG(15) + M(2) * CG(6) + M(2) * CG(5))
    + CG(10)
    : REM WO
9320 CG(29) = 2 * (CG(6) + CG(5)) + CG(14)
    : REM DO
9325 CG(30) = 2 * (CG(15) + CG(8)) + CG(7) + CG(9)
    : REM LO
9330 CG(22) = CG(12) / CG(27)
    : REM CI
9335 CG(48) = 0
    : REM ST
9340 CG(49) = 0
    : REM TC
9345 R(1) = 1 - CG(28) / CG(31)
9350 R(2) = CG(28) / CG(31) - C(1)
9355 R(3) = 1 - CG(29) / CG(33)
9360 R(4) = CG(29) / CG(33) - C(2)
9365 R(5) = 1 - CG(30) / CG(35)
9370 R(6) = CG(30) / CG(35) - C(3)
9375 R(7) = 1 - CG(51) / CG(38)
9380 R(8) = 1 - CG(22) / CG(37)
9385 R(9) = 1 - CG(47) / CG(61)
9390 R(10) = CG(47) / CG(61) - C(4)
9395 R(11) = 1 - V(1)
9400 R(12) = V(1) - CN(1)
9405 R(13) = 1 - V(4)
R(14) = V(4) - CN(4)
R(15) = 1 - V(3)
R(16) = V(3) - CN(3)
R(17) = 1 - V(2)
R(18) = V(2) - CN(2)
R(19) = CG(51) / CG(38)
R(20) = CG(22) / CG(37)
IF M(3) = 2 THEN 9949
R(21) = 1 - V(6)
R(22) = V(6) - CN(6)
R(23) = 1 - V(5)
R(24) = V(5) - CN(5)
R(25) = 1 - 2 * CG(16) / CG(15)
R(26) = 1 - 2 * CG(16) / CG(14)
REM
REM
REM
REM
B = H =
IF NE = 0 THEN 9970
FOR IE = 1 TO NE
    B = B + E(IE) * E(IE)
NEXT
IF NR = 0 THEN 9990
FOR IR = 1 TO NR
    IF R(IR) < 0. THEN H = H + R(IR) * R(IR)
NEXT
W = B + H
P = CP * FP * W
X = Q + P
RETURN
REM ***SUBROUTINE 10000:FINAL ITEMS***
REM ** HERE USER PROGRAMS FINAL ITEMS OF INTEREST, BY
F(JF) EQUATIONS, FOR JF=1 TO NF **
REM * LINES 10010 - 10980 ARE AVAILABLE *
IF NF = 0 THEN RETURN
GOSUB 1010
ZFS = "FINAL ITEMS F(JF) FOR JF=1,...,NF ARE=
PRINT ZFS
REM ***
REM **
REM *
REM *
REM ***
FOR JF = 1 TO NF
    PRINT F(JF),
NEXT
RETURN
REM *****P518 - TRS-80 DOUBLE PRECISION SUBROUTINES
FOLLOW FOR REST OF PROGRAM P519

RESERVED VARIABLE NAMES ARE XI, X1, X2, X3, X4, X9, II, I0, II, I1 AND I3

**SQUARE ROOT**

40594 REM ***SQUARE ROOT***

40600 X3 = SQR (XI)
        : IF X3 = 0.000 THEN RETURN

40601 X3 = (X3 + XI / X3) / 2
        : RETURN
PROGRAM LENGTH IS 19642 ($4CBA) BYTES

<p>| A   | 50, 131, 2069, 5805, 8135 |
| A$  | 8500, 8505, 8510, 8790, 8795, 8800 |
| AA  | 560, 590, 8565, 8575, 8755, 9105 |
| AB  | 50, 53, 8000, 8535 |
| AC  | 262, 263, 270, 280 |
| AD  | 50, 55, 70, 5010, 5030, 5031, 5805 |
| AE  | 53, 8000, 8535 |
| AG  | 2000, 8000, 8535 |
| AL  | 40, 8000, 8535 |
| AM  | 250, 8000, 8535 |
| AP  | 8530, 8640, 8755, 8760, 8765, 9065, 9070, 9105, 9110, 9115, 9310 |
| AR  | 8530 |
| AS  | 50, 53, 8000, 8535 |
| B   | 130, 253, 1902, 5290, 9950, 9960, 9990 |
| BA  | 253, 1960, 5290 |
| BB  | 130, 1902, 1960 |
| BH  | 8695, 9145, 9150, 9170, 9190, 9195, 9200 |
| CA  | 5030, 8000, 8535 |
| CD  | 40, 1030, 4015, 4030, 4040, 4050 |
| CG  | 350, 500, 520, 530, 540, 1030, 2002, 8045, 8610, 8620, 8630, 8640, 8650, 8655, 8690, 8695, 8697, 8710, 8755, 8760, 8765, 8770, 8775, 8780, 8785, 9000, 9005, 9010, 9015, 9025, 9030, 9040, 9045, 9050, 9055, 9060, 9065, 9070, 9075, 9080, 9085, 9090, 9095, 9105, 9110, 9115, 9120, 9125, 9130, 9140, 9145, 9150, 9155, 9160, 9165, 9170, 9185, 9200, 9210, 9215, 9230, 9235, 9240, 9250, 9260, 9270, 9275, 9280, 9285, 9290, 9295, 9300, 9305, 9310, 9315, 9320, 9325, 9330, 9335, 9340, 9345, 9350, 9355, 9360, 9365, 9370, 9375, 9380, 9385, 9390, 9435, 9440, 9470, 9475 |
| CL  | 5015, 8000, 8535 |
| CM$ | 535, 8625, 8675, 8680 |
| CP  | 70, 222, 240, 2000, 5005, 5200, 5710, 5750, 5790, 5800, 8530, 9990 |
| CR  | 5230, 5250, 5310, 5314, 8000, 8535 |
| CS  | 80, 1030, 2070, 8052, 8730 |
| C   | 1030, 8061, 8640, 8665, 8670, 9150, 9210, 9290, 9350, 9360, 9370, 9390 |
| D$  | 18, 505, 510, 515, 545, 550, 555, 565, 575, 580, 585, 595, 597, 602, 8515, 8600, 8605, 8635, 8675, 8680, 8705, 8795 |
| DB  | 190, 195, 200, 262, 290, 1950 |
| DC  | 70, 262, 1950, 3010, 5020, 5030 |
| DD  | 262, 1950 |
| DL  | 70, 195, 5015 |
| DN  | 1030, 4040, 4050 |
| DP  | 1030, 4030, 4050 |</p>
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APPENDIX G
WIRE DATA INFORMATION

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APPENDIX H
INITIAL MAGNETIZATION CURVES FOR MATERIALS

The graph shown in this appendix is frequently used in textbooks on magnetism. The particular source for this sample is "Permanent Magnet Manual" from the Magnetic Materials Section of the General Electric Company, Edmore Michigan.
D-C Magnetization Curves For Various Magnetic Materials
APPENDIX I
SAMPLE OF DISK CATALOG

The sample catalog from the project disk is included in this appendix to show the use of a prefix before the material and design files. The purpose of this prefix is to make a visual scan of the listing quicker when searching for a particular file type. Normally, the files would not be arranged in the convenient order shown in this sample.
APPENDIX I

CATALOG OF PROJECT DISK
***DO NOT LOCK RUN TYPE OR @ FILES***
***DO NOT WRITE PROTECT DISK***

DISK VOLUME 254

*A 002 HELLO
*A 005 FIRST OPT
*A 015 WIRE DATA
*B 003 SHAPEFILE
*A 016 PAGE 1
*A 072 PAGE 2-A
*A 029 B-H
*A 051 ANALYSIS
*A 081 COIL DESIGN
 T 002 RUN TYPE
*T 003 TEST PATTERN
*T 002 J50/50 NI-FE (SOLID)
*T 002 JCOLD ROLLED STEEL
*T 002 JORIENTED 3% SI STRIP
 T 003 @TEST COIL
 T 003 @TEST-SQ-S-D3
 T 003 @TEST-RND-S-D4
 T 003 @TEST-SQ-D-D
 T 003 @TEST-RND-D-D
 T 003 @PRODUCTION DESIGN

306 SECTORS USED, 238 SECTORS FREE
APPENDIX J
ADDITIONAL COMPUTER TRIALS

J.1 TEST-SQ-S-D3 w/COLD ROLLED STEEL CORE ....... 298
J.2 TEST-SQ-S-D3 w/ORIENTED 3% Si-Strip .......... 302
J.3 TEST-SQ-S-D5 Optimized with ORIENTED 3% Si-Strip ... 306
J.4 TEST-SQ-S-D7 Optimized with COLD ROLLED STEEL ... 310
Pages 298 to 301 show the performance of the TEST-SQ-S-D3 coil assembly with a cold rolled steel core. Several observations can be made when comparing it to the TEST-SQ-S-D3 assembly (pages 109 to 112), which is optimized for a solid 50/50 Ni-Fe core, and to the TEST-SQ-S-D7 coil (pages 310 to 313), which is optimized for the steel.

1) The holding force at the design point of 3V and a 0.0015cm airgap is highest for any material in the coil assembly designed for that material and operating point.

2) The dimensions for an optimized assembly are different for each set of constraints and material chosen.

3) Cold Rolled Steel has been chosen for this example since it is a lower permeability material than either the Solid 50/50 Ni-Fe or the Si-Strip. Because of the limited volume available, the optimized coil design example for the Cold Rolled Steel is not close to saturation like the other two materials. A comparison with the trials using the other materials shows this by the fact that the steel sensitivity curve does not flatten out at the optimization point.

4) Note that the overall width on the optimized design is not filled, as Chapter III predicted might happen for some sets of constraints. The overall length restricted it.

5) Because the steel is a low permeability material, the distance from the vertical axis to the first airgap curve is not equal to the distance between adjacent curves with the same difference in gap. Compare this to the 50/50 Ni-Fe discussion on page 135.
VOLTAGE AND AIR GAP SENSITIVITY FOR TEST-SQ-S-D3CRS

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GAP AND VOLTAGE SENSITIVITY FOR TEST-SQ-S-D3CRS
WITH LISTING FOR FIRST GAP ONLY
SAMPLE RUN FOR A SINGLE BOBBIN, RECTANGULAR CORE
SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

COIL NAME: TEST-SQ-S-D3CRS
COIL TYPE: SINGLE BOBBIN, RECTANGULAR CORE
OPERATING VOLTAGE: 3
COIL RESISTANCE: 85.7314358
CORE MATERIAL: COLD ROLLED STEEL
THEORETICAL, NO LOSS HOLDING FORCE (OZ): 20.312058
EXPECTED HOLDING FORCE (OZ): 12.9997171

**** PHYSICAL DIMENSIONS & CONSTANTS ****
OVERALL LENGTH: 2.01084969
OVERALL DEPTH: .635156443
OVERALL WIDTH: .998625621
FLANGE WIDTH: .0676721706
WINDING LENGTH: .76056841
BOBBIN WALL THICKNESS: .064
BOBBIN FLANGE THICKNESS: .15
ARMATURE/BOBBIN CLEARANCE: .285
WINDING CLEARANCE: .07
AIRGAP: 1.5E-03
STEEL PATH LENGTH: 4.42504373
CORE WIDTH: .33264064
CORE DEPTH: .371812102
CORNER RADIUS: 0
CORE PERIMETER: 1.40890548
CORE AREA: .123679816
AIRGAP AREA (FRINGING): .124738262
WINDING SURFACE AREA: 1.70080295

************** WINDING DATA **************
WIRE GAGE NUMBER: #41.4850841
TURNS SPECIFIED: 872.399078
TURNS POSSIBLE: 872.399069
RANDOM WIND: 1
WINDING WIDTH: .0676721706
BARE WIRE DIA: 6.7237313E-03
OHMS/CM OF WIRE: .0485617446
EFFECTIVE INSUL. WG: 40.3370763
INSULATED WIRE DIA: 7.68097937E-03
THEORETICAL TURNS/SQ CM = 16949.8868
CURRENT AT 3 VOLTS: .0349929985
AVERAGE TURN LENGTH: 2.02362774
INDUCTANCE, HENRIES: .234257701
S.S. TEMP RISE, DEG C: 61.2650785

ANALYSIS LISTING FOR A COLD ROLLED STEEL CORE IN THE
TEST-SQ-S-D3 COIL ASSEMBLY (CONTINUED ON NEXT PAGE)
THERMAL TIME CONST: 132.207211
RESISTANCE @ S.S. TEMP: 99.6594453
CURRENT @ THAT TEMP: .0301025155
IDEAL FORCE @ THAT TEMP @ 3 VOLTS = 14.6520669

********** MAGNETIC DATA **********
TOTAL AMP-TURNS (ACTUAL): 30.5278593
TOTAL AMP-TURNS (AIR+IRON): 30.2013462
AMP-TURNS IN IRON: 12.2179572
AMP-TURNS IN AIR: 17.9833891
OERSTEDS IN IRON: 3.46969177
OERSTEDS IN AIR: 7532.86439
KILOGAUSSSES IN IRON: 7.59733031
KILOGAUSSSES IN AIR: 7.53286439
IRON SAT KILOGAUSS: 20.7

********** DESIGN CONSTRAINTS **********
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: .635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: .5
MIN CORE WIDTH: 0
MAX CORE DEPTH: .5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: .035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

DESIGN HINTS:
IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)
MATERIAL CHANGE OF THE TEST-SQ-S-D3 CORE TO Si-Strip

Pages 302 to 305 show the performance of the TEST-SQ-S-D3 coil assembly with an oriented 3% Si-Strip core. Several observations can be made when comparing it to the TEST-SQ-S-D3 assembly (pages 109 to 112), which is optimized for a solid 50/50 Ni-Fe core, and to the TEST-SQ-S-D5 coil (pages 306 to 309), which is optimized for the Si-strip.

1) The holding force at the design point of 3V and a 0.0015cm airgap is highest for each material in the coil assembly designed for that material and operating point. This also holds true for the 50/50 Ni-Fe trials not shown.

2) The dimensions for an optimized assembly are different for each set of constraints and material chosen.

3) Because the Si-strip is a high permeability material, when optimized at 3V, the force at higher voltages does not increase rapidly. This is because the optimized assembly is starting to saturate at the optimization point. In particular, compare the sensitivity graph on page 303 to the one on page 307. At 6V, the force developed in the coil with the larger core area is significantly higher. Choice of the design point, therefore, is important. It will affect the performance of the assembly at other operating points.
GAP AND VOLTAGE SENSITIVITY FOR TEST-SQ-S-D3S
WITH LISTING FOR FIRST GAP ONLY

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<th>IDEAL FORCE (OZ)</th>
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SAMPLE RUN FOR A SINGLE BOBBIN, RECTANGULAR CORE
SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

COIL NAME: TEST-SQ-S-D3S
COIL TYPE: SINGLE BOBBIN, RECTANGULAR CORE
OPERATING VOLTAGE: 3
CORE RESISTANCE: 85.7314358
CORE MATERIAL: ORIENTED 3% SI STRIP
THEORETICAL, NO LOSS HOLDING FORCE (OZ): 52.1778968
EXPECTED HOLDING FORCE (OZ): 33.3938539

**** PHYSICAL DIMENSIONS & CONSTANTS ****
OVERALL LENGTH: 2.01084969
OVERALL DEPTH: .635156443
OVERALL WIDTH: .998625621
FLANGE WIDTH: .0676721706
WINDING LENGTH: .76056841
BOBBIN WALL THICKNESS: .064
BOBBIN FLANGE THICKNESS: .15
ARMATURE/BOBBIN CLEARANCE: .285
WINDING CLEARANCE: .07
AIRGAP: 1.5E-03
STEEL PATH LENGTH: 4.42504373
CORE WIDTH: .33264064
CORE DEPTH: .371812102
CORNER RADIUS: 0
CORE PERIMETER: 1.40890548
CORE AREA: .123679816
AIRGAP AREA (FRINGING): .124738262
WINDING SURFACE AREA: 1.70080295

*************** WINDING DATA ***************
WIRE GAGE NUMBER: #41.4850841
 Turns SPECIFIED: 872.399078
 Turns POSSIBLE: 872.399069
 RANDOM WIND: 1
WINDING WIDTH: .0676721706
BARE WIRE DIA: 6.7237313E-03
OMMS/CM OF WIRE: .0485617446
EFFECTIVE INSUL.WG: 40.3370763
INSULATED WIRE DIA: 7.68097937E-03
THEORETICAL TURNS/SQ CM = 16949.8868
CURRENT AT 3 VOLTS: .0349929985
AVERAGE TURN LENGTH: 2.02362774
INDUCTANCE, HENRIES: .375456994
S.S.TEMP RISE, DEG C: 61.2650785

ANALYSIS LISTING FOR AN ORIENTED 3% SI-STRIP CORE IN THE
TEST-SQ-S-D3 COIL ASSEMBLY (CONTINUED ON NEXT PAGE)
SAMPLE LISTING CONTINUED

THERMAL TIME CONST: 132.207211
RESISTANCE @S.S.TEMP: 99.6594453
CURRENT @THAT TEMP: 0.0301025155
IDEAL FORCE @THAT TEMP @3VOLTS = 40.3779729

MAGNETIC DATA

TOTAL AMP-TURNS (ACTUAL): 30.5278593
TOTAL AMP-TURNS (AIR+IRON): 30.0295467
AMP-TURNS IN IRON: 1.20663438
AMP-TURNS IN AIR: 28.8229124
OERSTEDS IN IRON: .342663616
OERSTEDS IN AIR: 12073.3133
KILOGAUSSES IN IRON: 12.1766362
KILOGAUSSES IN AIR: 12.0733133
IRON SAT KILOGAUSS: 19.7

DESIGN CONSTRAINTS

MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: .635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: .5
MIN CORE WIDTH: 0
MAX CORE DEPTH: .5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: .035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 15.41

DESIGN HINTS:
IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

***Note: Strip stock is usually available in sheet form and used to make laminated cores, which would require the use of a stacking factor. It has been treated as a solid core, for this example only, to show the effects of using a higher permeability material than that used during the optimization process.

ANALYSIS LISTING FOR AN ORIENTED 3% Si-STRIP CORE IN THE TEST-SQ-S-D3 COIL ASSEMBLY (cont)
DESIGN REQUIREMENTS FOR TEST-SQ-S-D5
(IDENTICAL TO TEST-SQ-S-D3 WITH MATERIAL CHANGE)

OPTIMAL DESIGN FOR TEST-SQ-S-D5
NOTE DIFFERENCE IN CORE DIMENSIONS COMPARED TO TEST-SQ-S-D3
VOLTAGE AND AIR GAP SENSITIVITY FOR TEST-SQ-S-D5

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<th>IDEAL FORCE (OZ)</th>
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GAP AND VOLTAGE SENSITIVITY FOR TEST-SQ-S-D5
WITH LISTING FOR FIRST GAP ONLY
SAMPLE RUN FOR A SINGLE BOBBIN, RECTANGULAR CORE
SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

COIL NAME: TEST-SQ-S-D5
COIL TYPE: SINGLE BOBBIN, RECTANGULAR CORE
OPERATING VOLTAGE: 3
CORE RESISTANCE: 85.71988
CORE MATERIAL: ORIENTED 3% SI STRIP
THEORETICAL, NO LOSS HOLDING FORCE (OZ): 61.3016076
EXPECTED HOLDING FORCE (OZ): 39.2330289

*****PHYSICAL DIMENSIONS & CONSTANTS*****
OVERALL LENGTH: 2.01039033
OVERALL DEPTH: 0.635051052
OVERALL WIDTH: 0.996965227
FLANGE WIDTH: 0.095714184
WINDING LENGTH: 817853934
BOBBIN WALL THICKNESS: 0.064
BOBBIN FLANGE THICKNESS: 0.15
ARMATURE/BOBBIN CLEARANCE: 0.285
WINDING CLEARANCE: 0.07
AIRGAP: 1.5E-03
STEEL PATH LENGTH: 4.48020949
CORE WIDTH: 0.303768195
CORE DEPTH: 0.315622215
CORNER RADIUS: 0
CORE PERIMETER: 1.23878082
CORE AREA: 0.0958759906
AIRGAP AREA (FRINGING): 0.0968068433
WINDING SURFACE AREA: 1.83387069

************** WINDING DATA **************
WIRE GAGE NUMBER: #40.6562092
TURNS SPECIFIED: 1101.79546
TURNS POSSIBLE: 1101.79547
RANDOM WIND: 1
WINDING WIDTH: 0.095714184
BARE WIRE DIA: 7.40196674E-03
OMHS/CM OF WIRE: 0.0400701271
EFFECTIVE INSUL. WG: 39.5355543
INSULATED WIRE DIA: 8.42900021E-03
THEORETICAL TURNS/SQ CM = 14074.9827
CURRENT AT 3 VOLTS: 0.0349977158
AVERAGE TURN LENGTH: 1.94160039
INDUCTANCE, HENRIES: 0.45272374
S.S. TEMP RISE, DEG C: 57.5778289

ANALYSIS LISTING FOR AN OPTIMIZED COIL ASSEMBLY, TEST-SQ-S-D5
(CONTINUED ON NEXT PAGE)
(SAMPLE LISTING CONTINUED)

THERMAL TIME CONST: 181.28958
RESISTANCE @ S.S. TEMP: 98.4016397
CURRENT @ THAT TEMP: .0304872969
IDEAL FORCE @ THAT TEMP @ 3 VOLTS = 49.0676941

************ MAGNETIC DATA ************
TOTAL AMP-TURNS (ACTUAL): 38.5603248
TOTAL AMP-TURNS (AIR+IRON): 38.4332258
AMP-TURNS IN IRON: 2.97007462
AMP-TURNS IN AIR: 35.4631512
OERSTEDS IN IRON: .833065029
OERSTEDS IN AIR: 14854.77
KILOGAUSSES IN IRON: 14.9989939
KILOGAUSSES IN AIR: 14.85477
IRON SAT KILOGAUSS: 19.7

************ DESIGN CONSTRAINTS ************
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: .635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: .5
MIN CORE WIDTH: 0
MAX CORE DEPTH: .5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: .035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSS IN CORE: 19.7

DESIGN HINTS:
IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

***Note: This is an optimized coil assembly, which has the same physical constraints as the TEST-SQ-S-D3 coil, but a different core material. The physical dimensions are different, and the holding force at 3V is higher than when the ORIENTED 3% Si-Strip CORE is inserted in a TEST-SQ-S-D3 coil (pages 302-305).

ANALYSIS LISTING FOR AN OPTIMIZED COIL ASSEMBLY, TEST-SQ-S-D5 (cont)
**Design Requirements for Test-SQ-S-D7**

*Identical to Test-SQ-S-D3 with Material Change*

**Optimal Design for Test-SQ-S-D7**

Note difference in core dimensions compared to Test-SQ-S-D3

Also, FP had to be set to one in the coil design module.
VOLTAGE AND AIRGAP SENSITIVITY FOR TEST-SQ-S-D7

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GAP AND VOLTAGE SENSITIVITY FOR TEST-SQ-S-D7 WITH LISTING FOR FIRST GAP ONLY
SAMPLE RUN FOR A SINGLE BOBBIN, RECTANGULAR CORE
SUBJECT TO THE STANDARD LIMITS OF THIS PROJECT

COIL NAME: TEST-SQ-S-D7
COIL TYPE: SINGLE BOBBIN, RECTANGULAR CORE
OPERATING VOLTAGE: 3
CORE RESISTANCE: 85.7142732
CORE MATERIAL: COLD ROLLED STEEL
THEORETICAL, NO LOSS HOLDING FORCE (OZ): 22.6605943
EXPECTED HOLDING FORCE (OZ): 14.5027803

****PHYSICAL DIMENSIONS & CONSTANTS****
OVERALL LENGTH: 2.01042656
OVERALL DEPTH: .634860521
OVERALL WIDTH: .979841174
FLANGE WIDTH: .119167846
WINDING LENGTH: .881921078
BOBBIN WALL THICKNESS: .064
BOBBIN FLANGE THICKNESS: .15
ARMATURE/BOBBIN CLEARANCE: .285
WINDING CLEARANCE: .07
AIRGAP: 1.5E-03
STEEL PATH LENGTH: 4.52718881
CORE WIDTH: .271752741
CORE DEPTH: .268524829
CORNER RADIUS: 0
CORE PERIMETER: 1.08055514
CORE AREA: .0729723583
AIRGAP AREA (FRINGING): .0737845418
WINDING SURFACE AREA: 1.9679475

************ WINDING DATA ************
WIRE GAGE NUMBER: #40.1078283
TURNS SPECIFIED: 1308.07697
TURNS POSSIBLE: 1308.07697
RANDOM WIND: 1
WINDING WIDTH: .119167846
BARE WIRE DIA: 7.88787548E-03
OHMS/CM OF WIRE: .0352853871
EFFECTIVE INSUL. WG: 39.00527
INSULATED WIRE DIA: 8.96350274E-03
TEORETICAL TURNS/SQ CM = 12446.4211
CURRENT AT 3 VOLTS: .0350000051
AVERAGE TURN LENGTH: 1.85705583
INDUCTANCE, HENRIES: .28527687
S.S. TEMP RISE, DEG C: 54.3001689

ANALYSIS LISTING FOR AN OPTIMIZED COIL ASSEMBLY, TEST-SQ-S-D7
(CONTINUED ON NEXT PAGE)
(SAMPLE LISTING CONTINUED)

THERMAL TIME CONST: 219.528616
RESISTANCE @ S.S. TEMP: 97.2891317
CURRENT @ THAT TEMP: 0.0308359212
IDEAL FORCE @ THAT TEMP @ 3 VOLTS = 18.093319

************MAGNETIC DATA************
TOTAL AMP-TURNS (ACTUAL): 45.7827007
TOTAL AMP-TURNS (AIR+IRON): 45.2057641
AMP-TURNS IN IRON: 20.5085836
AMP-TURNS IN AIR: 24.6971805
OERSTEDS IN IRON: 5.69268198
OERSTEDS IN AIR: 10345.1308
KILOGAUSSES IN IRON: 10.4602723
KILOGAUSSES IN AIR: 10.3451308
IRON SAT KILOGAUSSE: 20.7

************DESIGN CONSTRAINTS************
MAX OVERALL LENGTH: 2.01
MIN OVERALL LENGTH: 0
MAX OVERALL DEPTH: .635
MIN OVERALL DEPTH: 0
MAX OVERALL WIDTH: 1.01
MIN OVERALL WIDTH: 0
MAX CORE WIDTH: .5
MIN CORE WIDTH: 0
MAX CORE DEPTH: .5
MIN CORE DEPTH: 0
MAX CORE CORNER RAD: 0
MIN CORE CORNER RAD: 0
MAX CURRENT @ 3 VOLTS: .035
MAX WIRE GAGE NUMBER: 45
MIN WIRE GAGE NUMBER: 35
MAX KILOGAUSSES IN CORE: 20.7

DESIGN HINTS:
IF ANY FINAL DIMENSIONS ARE AT OR NEAR THEIR LIMITS, THEN CHANGING THOSE LIMITS MAY CHANGE THE FINAL SOLUTION.
TEMPERATURE RISE CAN BE REDUCED BY INCREASING THE SURFACE AREA (OR LX)

***Note: This is an optimized coil assembly, which has the same physical constraints as the TEST-SQ-S-D3 coil, but a different core material. The final physical dimensions are different, and the holding force at 3V is higher than when the COLD ROLLED STEEL core is inserted in the TEST-SQ-S-D3 coil (pages 298-301).

ANALYSIS LISTING FOR AN OPTIMIZED COIL ASSEMBLY, TEST-SQ-S-D7 (cont)
REFERENCES

2. Plonus, p.408.
4. Roters, Chapter VII.
5. Greenwood, p.31.
6. Jorgensen, pp.34-44.
7. Roters, p.156.
8. Lowdon, p.11.
10. Durkee
11. Roters, p.139,149.
BIBLIOGRAPHY


