AN INTERACTIVE CODE FOR OPTIMIZATION OF THE DESIGN OF WATER-COOLED CONDUCTORS*

Kenneth M. Thompson
Argonne National Laboratory
Argonne, Illinois 60439

Abstract

A code has been developed to aid in the optimization of the design of water-cooled conductors which are to be used in conventional magnet designs. The code is intended to be used in a Wang 720B-702 programmable calculator system in such a mode as to allow the operator to interact with the program during the calculation process. The results of the computations as well as all input and auxiliary parameters are printed out along with the parameter titles and associated units. The philosophy of this code is discussed as well as the available options and safeguards which permit an individual with no experience in coil design or calculator operation to perform useful calculations. The use of this code in the design of conventional water-cooled coils is discussed.

Introduction

The designs of conventional magnets using hollow conductors are often complicated by the limitations which are set by the proposed operating conditions. Some of these conditions have limits which cannot be exceeded. The power supply, for example, which will be used to excite the coil has a limited voltage range over which it can properly regulate and has a maximum current capability. Also the system used to supply the coolant has a maximum pressure gradient that it can supply across the coil and a minimum supply temperature.

Besides these fixed constraints there are those conditions which may have preferred characteristics that can be altered slightly for the benefit of a workable design. These include the size of the magnet gap and the size of coil pack. There will also be a maximum temperature at which the preferred insulating media retains its desirable mechanical and electrical properties. This will put an upper bound on the temperature gradient in any of the cooling circuits but may be changed by a different choice of insulation.

There are also considerations of economics that should be included in the design of these magnets. Here it would be desirable to minimize the amount of steel and the amount of conductor used in the design while also minimizing the amount of coolant and electrical power needed in the operation of the magnet. Of course, these cannot be simultaneously realized. It is necessary, therefore, to make compromises on these desires.

It soon becomes evident in the construction of conventional magnet coils that there are a large number of interacting parameters that must be dealt with by the designer. As a result he may never be able to truly optimize the design. The term to optimize is intended here to indicate that a design has been found for which the necessary compromises have been defined and accepted.

Some of the equations used in the analysis of coolant circuits can become rather complex. As a result, they can lead to errors in their manual application. It seems, therefore, that there is a need for a computer code to aid the designer. This code, however, must allow him to interact with the calculations directly in order for him to incorporate and understand the compromises. It must give the solution to a given set of parameters in a time that is short enough to allow him to complete, in an acceptable period, the large number of cases necessary to provide him with an understanding of the effects of changes in the critical parameters. Such a code should also allow an individual with no experience in magnet coil design to do a useful calculation. In addition, it should provide a hard copy of all the input and calculated parameters in a given problem. These parameters should be listed along with their associated units in such a way as to facilitate the distinction between input and calculated values. Finally, the parameters of one case should be capable of being reused in a succeeding case without having to be re-entered and the list of parameters for this new case should be presented in an adjacent column to the preceding case to allow for a visual comparison of the results of the two calculations. Such a code has been written for a Wang 720B Programmable Calculator using a Wang 702 Printer/Plotter. This code will be discussed in the following sections.

Hard Copy Features

The output of this code can be printed by the Wang 702 Printer/Plotter on standard paper sizes that are 11 inches high. The present version is

*Work performed under the auspices of the U. S. Atomic Energy Commission.

formated to enter the results on standard ANL-145 and ANL-145A engineering note sheets. This includes the printing of the operators name, division, and the date at the top of the page. The code has been written in two versions. One is to be used for running the first case which includes the printing of all parameter names and units; the second can be used for all succeeding cases with the output of each printed in the column to the right of that containing the results of the preceding case.

For any given case there are a total of 57 parameters–either input, taken over from the preceding case, or calculated. These are listed on 63 lines with each value that is manually entered being underlined; all other values are not. The designer has the option in many cases to choose to input a particular variable or not. If he does not, the code, in general, will continue or may assume a value consistent with previous magnet designs. Depending on the circumstances in each case there may be certain parameters which cannot be calculated from those values already entered or from succeeding quantities or cannot be extracted from a previous case. If this variable is necessary for the code to be able to provide a useful calculation, the code will underline the space for that variable before it stops to wait for input. If the designer fails to enter a value, the code will not continue but will redemand it.

All parameters that can be calculated from previously listed quantities cannot be input, but rather, the calculated value is printed in the appropriate spot. If at any time there is any undefined parameter that can be calculated using a succeeding value that has been listed, the code will automatically evaluate it and list it in the designated location. By this system of input, calculation, and reuse of the parameters the list of values printed for each case is as complete as possible. In addition, the listed quantities, in general, form a self-consistent set. If there is any inconsistency in the list, the code will mark it with an asterisk (*) to bring it to the attention of the designer. Such problems may occur, for example, when the calculated pressure gradient across a water circuit or the voltage drop across the total coil is greater than the maximum allowable values which were input.

All quantities calculated after the conductor dimensions have been listed and which depend on these dimensions are listed in a different form. These quantities may be very sensitive to the variations in conductor size due to mill tolerances. Therefore, these results are listed as two quantities, one resulting from the conductor dimensions which give a maximum conductor area and one resulting from those that give a minimum area.

During the execution of this code there may occur a combination of parameters that will result in unreal solutions or program errors resulting in a program stoppage causing some frustration and delay for the designer. To minimize such problems, there are sections incorporated into the program to anticipate these occurrences. The code may terminate the calculation but will often provide the designer with sufficient results to localize the cause of the difficulty.

Code Sections

The parameters are listed in seven sections as shown in Figure 1. Each section will be discussed below and the special features of each will be pointed out. Consider the outputs shown in Figure 1 as examples when needed for clarification in the discussion that follows.

Magnet Type

There are four general classifications of magnet geometries that can be handled by this code. The first input parameter is an integer from one to four each unequally representing one of the magnet types. Before continuing, the code guarantees that this variable is one of these integers no matter what number was input.

Septum magnet. This magnet type is defined to consist of a coil with each turn made from two conductor sizes. The resulting coil can be pictured as consisting of two hydraulically independent coil halves, the septum coil made from a small high current density conductor and the return coil made from a larger size conductor with a smaller current density. The resulting coil is assumed to fit between the poles of the magnet and extend through the median plane of the magnet gap. The width of the septum coil is considered to be limited but that of the return coil is not. A complete coil requires two successive runs to finish. Certain parameters are assumed not to change between these two cases and are printed automatically for the second case - the operating current, for example. Other parameters are assumed to accumulate between the two cases - the total coil voltage or the total water flow through the complete coil. The total accumulated values are printed in the results for the second case.

Picture frame magnet. This type of magnet is defined to have a coil which again is required to fit between the poles but the geometries of the coil packs located on the sides of the gap are identical.

In this case, however, an acceptable width of the coil packs is assumed to be unlimited.

H frame magnet. This magnet type is considered by this code to imply no limitations on the coil pack size except that it is to have uniform cross section. This coil is also assumed to be split into two separate coil halves, one located above and the other below the median plane of the gap.

Quadrupole magnet. The above magnet types are all bending magnets. The quadrupole magnet is of a completely different geometry. The preliminary parameters to be input to the code will differ somewhat but eventually the required ampere turns is defined and the succeeding calculations are essentially identical to those for the bending magnets.

In the listing of the variable names there are some differences depending on what type of magnet is under consideration. For brevity, however, the details of these differences will not be presented and only the picture frame magnet will be implied in the discussion contained in the remainder of this paper. Refer to Figure 1 in the following sections to clarify those parameters of special interest which are reviewed and to exemplify the parameters which are not mentioned.

Particle Parameters

When a bending magnet is required, the primary requirement that must be met is often specified in terms of having to bend a charged particle beam with a given momentum or energy through a given angle. In this program section these parameters may be entered. Either the momentum or energy can be entered here while the other is calculated and listed by the code using the relativistically correct relation

$$P = (E^2 + 2\,Em_oc^2)^{1/2} \qquad (1)$$

where E = particle kinetic energy (GeV)
m_oc^2 = particle rest mass energy (GeV)

The code assumes the charged particle is the frequently occurring proton.

Magnet Gap Parameters

The integrated field required can be input if it cannot be calculated from the particle parameters that have been input. The resulting figure that is listed is the required integrated field along a straight line parallel to the Z-axis of the magnet gap and not that along the curved arc of the beam trajectory. This result is more closely related to the minimum physical length of the magnet core that will be required. If you consider the particle beam as crossing the width of the gap and returning while it is in transit along the length of the gap, the equation for the integrated field as defined above is

$$\int B d\ell = B_o L_{eff} = 2625 \frac{P}{Z} \sin\frac{\theta}{2} \qquad (2)$$

where L_{eff} = effective length (in.)
Z = particle charge number (assumed as 1)
θ = particle bend angle (degree)

Coil Parameters

The ampere turns that must be supplied by the coil can be input if there is insufficient data for it to be calculated. If the data is complete, however, this parameter will be calculated using the following equation derived from the application of Ampere's Law to a simple solenoid coil.

$$NI = 2.021 \times 10^5\, B_o H/\epsilon \qquad (3)$$

where H = gap height (in.)
ϵ = magnetic efficiency (%)

The magnetic efficiency is related to the leakage field from the magnet geometry and core saturation effects. If this quantity is not entered, it will be defined by the code at a value depending on past trends for the magnet type being studied.

For a quadrupole magnet the ampere turns per pole is defined by

$$NI = 2.021 \times 10^5\, \bar{B}_o R/\epsilon \qquad (4)$$

where $\bar{B}_o$ = average field strength in the magnet bore disregarding the sign (kG)
R = bore radius (in.)

The total allowable voltage across the coil and the current through each coil winding must be input. These parameters depend only on the power supply chosen to drive the magnet. The coil layer and turn numbers must also be entered in this section. This is one area where the interaction of the designer and the code is very important. There is often a large number of possible combinations of these variables that would be acceptable for a mathematical solution but only a few that would be acceptable for a practical solution. For this reason it is left to the designer to decide the exact turn configuration for a given solution.

The maximum coil size may be input or may be left to be calculated from the conductor size, row and layer numbers, minimum insulation thicknesses, and coil-to-core clearance. These last parameters are assumed to be 0.010 inch if they are not input.

Hydraulic Parameters

The supply temperature of the coolant and the maximum available pressure gradient that can be developed across the cooling circuits will depend on the cooling system which will be used. These parameters must be defined before the code will continue. If they are not input, the code will define them according to the typical parameters at the ZGS Complex of Argonne. The temperature gradient developed across a coolant circuit must also be input. Here again the designer has much freedom in adjusting this temperature according to numerous criteria. The hydraulic bend factor is related to the length which is added to the actual coolant circuit length due to the bends in the circuit. This is typically around a value of 1.1, and, therefore, if it is not input, the code will assume this value.

Conductor Parameters

The average length of an electrical turn and of a hydraulic circuit must be defined. They are interrelated, however, by the parameter for the ratio of one to the other. Two of these three variables must be input while the third is calculated. If the ratio is calculated, the code assumes it to be the integerized value of the exact ratio. If the ACS conductivity is not input, the code assumes a value of 100%.

The conductor dimensions are the last to be input. If the first of these is entered, the code assumes the rest are to be entered and will not continue until all have been defined. If the tolerance values are not entered, the code will automatically define them to be consistent with those appearing in Ref. 1.

With the conductor dimensions defined, the code can calculate the remaining undefined parameters which appear in the list. During these computations, values for several temperature dependent quantities will be required. These include the conductor resistivity and the coolant density, viscosity, and heat conductivity. The temperature dependence of the resistivity is handled in the standard way. The coolant parameters, however, are defined from second degree equations. These equations were found by performing a least squares fit to the tabulated data over a temperature range from $32^{\circ}F$ to $212^{\circ}F$ appearing in Ref. 2 and Ref. 3. The standard errors between the resulting equations and the associated data is from 0.05% to 0.54%. The average temperature of the conductor is determined by an iterative procedure. It is assumed to be equal to the average temperature of the coolant to start. The temperature gradient between coolant and conductor is then found using the equation[4]

$$\Delta t_f = 23.04\,\overline{P}^{.2}(\Delta t)^{.8}\,d^{.8}\mu^{.467}/L_H k^{.667} \quad (5)$$

Using the result of this equation, the average conductor temperature can be adjusted and a new $\overline{P}$ can be determined leading to a new Δt_f. This is continued until the average conductor temperature has sufficiently converged.

Other parameters that are found by use of complex equations[5] are the Reynolds number, N_{re}, and the pressure gradient across the hydraulic circuit. The first is defined by the equation

$$N_{re} = 52.145\,\overline{P}/\mu\,\Delta t\,d \quad (6)$$

The pressure gradient is defined by the equation

$$\Delta p = 0.22046 \times 10^{-9}\,(N_{re})^{1.8}\mu^{2}\,a\,L_H/d^{3}\gamma \quad (7)$$

Another useful equation is used in this code to determine the flow required in the coolant circuit. Assuming that water is the coolant used,

$$Q = 0.4256\,\overline{P}/\Delta t\gamma \quad (8)$$

Completed Coil Parameters

The results in this section are listed to provide that information which has often been required in the past during the design, fabrication, testing and actual operation of the completed magnet. A few of these need some explanation. The required magnetic efficiency gives the designer an indication of how he has met the required number of ampere turns for the coil. A number too close to or greater than 100% or a number too small may indicate that there are problems in the design.

The electrical power required to pump the coolant through the coil is calculated in order to give the designer a more accurate figure of the total power requirements for the operation of the completed magnet. This result depends on pump efficiency, assumed to be 70%, and is defined by the equation

$$P_C = 0.6214\,\Delta p\,Q \quad (9)$$

where P_C = power (W)

and Δp is set at the maximum available pressure gradient that was input to the code, Δp_{max}. The coolant flow through the coil while at 68^oF and operating at zero power is calculated using the equation[6]

$$Q = 539.5 \left[\frac{\Delta p_{max} d^{4.865}}{L_H \gamma}\right] N_H \qquad (10)$$

where N_H = number of coolant circuits in the coil

This result is useful during flow tests near room temperature.

Another parameter that is calculated by the code and needs an explanation is the orifice diameter. The code assumes that the magnet will always have a coolant pressure gradient available that is equal the maximum value input. If a lesser gradient is actually needed for a satisfactory design, a throttling device must be put in one of the coolant lines feeding the magnet. One such device is an orifice inserted in the return line. The size of the hole in an orifice with a beveled hole is found using the equation[7]

$$d_{or}^2 = 0.6957 \times 10^{-2} \, Q_T / \left[(\Delta p_{max} - \Delta p)/\gamma\right]^{1/2} \qquad (11)$$

where d_{or} = orifice diameter (in.)
Q_T = the total coolant flow through the coil (gpm)

The final parameter listed for each case is the transverse force on the coil due to the interaction of the current and the magnetic field in the coil pack. The equation used to approximate this parameter is

$$F = 5.71 \times 10^{-4} \, NIL\overline{B}_o / H_c \qquad (12)$$

where F = force per in^2 on the coil surface parallel to the magnetic field (psi)
L = the length of the conductor in the field = 1 inch
$\overline{B}_o$ = average magnetic field inside the coil, assumed to be $B_o/2$
H_c = height of the coil pack

Coil Optimization

Due to the fact that this code can do a fairly complete calculation on a given coil geometry in a short time compared to a manual solution, the designer can try to meet all the goals of the problem by manually changing the input parameters. In order to aid in this process, there is included in this code the capability of determining the conductor dimensions from the coil parameter limits listed earlier in the calculation. In this process it is assumed that the resulting voltage and pressure gradients across the coil are to be as close as possible to the maximum limits that were input. There are two different types of problems that must be considered. First, there are those cases where the outside dimensions of the conductor are uniquely determined by the maximum coil dimensions and the numbers of layers and rows listed earlier under the Coil Parameters. If both the maximum coil dimensions are not defined, however, one or both of the conductor outside dimensions is free to be chosen. This constitutes the second type of problem.

For the first type of problem the inside hole diameter must be determined such that the voltage drop is not more than the maximum allowable, V_{max}. The maximum voltage drop across a coil with the conductor at a mean temperature, $\overline{T}$, is

$$V_{max} = \rho L_e NI / A_{min} \qquad (13)$$

where ρ = resistivity of the conductor at a maximum temperature, $\overline{T}_{max}$
A_{min} = minimum conductor area corresponding to a maximum inside diameter, d_{max}

But,

$$\rho = C_2 + C_1(\overline{T}_{max} - 68^oF) \qquad (14)$$

$$A_{min} = A_{min}(d{=}0) - \frac{\pi}{4} d^2_{max}$$
$$= C_3 - C_4 d^2_{max} \qquad (15)$$

with water as the coolant

$$\overline{T}_{max} = \overline{T}_{H_2O} + \Delta t_f^{max} \qquad (16)$$

where C_1 and C_2 depend on the conductor type contained in the code. All C values are constants which do not change during the solution process. Combining Eqs. 13, 14 and 15 results in

$$\frac{V_{max}}{L_e NI} = C_5 = \frac{C_2 + C_1(\overline{T}_{max} - 68)}{C_3 - C_4 d^2_{max}} \qquad (17)$$

Combining this with Eq. 16 and solving for Δt_f^{max} gives

$$\Delta t_f^{max} = \left(68 + \frac{C_5C_3 - C_2}{C_1} - \overline{T}_{H_2O}\right) - \frac{C_4C_5}{C_1} d_{max}^2$$

$$= K_1 - K_2 d_{max}^2 \qquad (18)$$

Since $\overline{P} = V_{max} I/N$ = constant, Eq. 5 can be rewritten as

$$\Delta t_f^{max} = K_4 d_{max}^{.8} \qquad (19)$$

Combining this with Eq. 18 results in one equation with one unknown, d_{max},

$$\frac{K_1}{K_4} - \frac{K_2}{K_4} d_{max}^2 = d_{max}^{.8} \qquad (20)$$

The code solves this equation and determines the pressure drop across the resultant coolant circuit. It compares the result with the maximum allowed. If it is smaller than the maximum, the hole diameter is decreased in an iterative process until the two pressure gradients are equal. Having completed this gives a coil that will operate at less of a voltage than that which is available.

For the second type of problem, one or both of the outside dimensions of the conductor are adjustable. If it is remembered that $\overline{T}_{H_2O}$ is defined for each problem, Eq. 6 and Eq. 7 can be combined and solved for the hole diameter,

$$d = K_6 \frac{\overline{P}^{.375}}{(\Delta p)^{.208}} \qquad (21)$$

The code uses $\Delta p = \Delta p_{max}$ and $\overline{P} = \overline{P}_{max}$ to find a hole diameter. The minimum required conductor area can then be found by solving for C_3, defined in Eq. 15, using Eqs. 17 and 19 and the results for d found above. The outside dimensions of the conductor can then be found being careful to satisfy any limitations set by the coil parameters listed earlier in the calculation. If there are no such limitations, the code assumes the conductor has an outside shape that is square.

The resultant conductor shape has the minimum allowable hole diameter associated with the maximum allowable pressure gradient. This is not an absolute minimum, however, since d_{min} is associated with $\overline{P} = \overline{P}_{min}$ and not $\overline{P} = \overline{P}_{max}$. The absolute minimum diameter is found by an iterative procedure using Eq. 7 and adjusting d starting at the value determined above. The outside shape is also adjusted in the same manner as described above.

It often happens in this procedure that a mathematical solution produces a conductor with a maximum hole diameter larger than the smallest outside dimension. When this occurs, the code will reduce the maximum allowable voltage by 10% and recalculate the problem. This will be repeated until a real solution is found.

One must realize that there are certain combinations of parameters that will not yield to a real solution. This code tries to allow for these situations and will indicate problems with an asterisk (*). It will try to continue in the calculation, however, but will normally terminate the calculation if it cannot. By this process the program code still has control and the designer has enough results in many cases to see where the problem lies. If he has some experience in coil design, he will be able to continue to the next case in a normal fashion and will probably be able to enter a set of parameters that will give a valid solution.

Conclusions

The present code has been used successfully at Argonne to study the designs of several magnets. In those designs requiring the calculation of conductor dimensions the time required to run a single case from start to finish is around 20 minutes. The less involved cases typically require from 3 to 5 minutes to execute.

In the design of a single coil there have been 30 to 50 cases run to establish the final geometry and final operating conditions. The entire process has required 10 to 12 uninterrupted hours to complete. The method of approach to each new magnet has been similar and has pursued the scheme that follows. The intended use of the magnet has defined the gap parameters, the coil parameters, the coolant supply temperature, the coolant maximum pressure gradient, and conductor circuit lengths. From previous coil designs, a feasible operating temperature gradient was chosen. From these and other values that were set by the code a usable conductor size was found through a series of solutions.

Conductor sizes that were on hand at ANL and standard conductor sizes listed in Ref. 1 were then considered. A size was sought that was close in size to the results of the first series. A second series of cases was run on the candidates found in these already purchased or readily available sizes. If no suitable size could be found, a final shape was determined and the resulting final operating conditions were found in a third series of computations.

All conductor shapes cannot be easily made by the conductor fabricators. Using past experience and conversations with conductor fabricators, changes were made in the final conductor shape and a fourth series of cases was run to verify that the resultant shape provided an acceptable set of operating conditions.

There have been other areas where this code has been found to be useful. It is often quite beneficial to compare the calculations against actual operating conditions. This can easily be done after the magnet has been built and operated and the operating parameters measured. Using this code the temperature and pressure gradients can be measured and can then be calculated. The code does the same calculation each time it is used on a given collection of parameters no matter what the exact values may be. The designer can, therefore, gain much insight into the accuracy of his calculations by the comparison of the measured and calculated figures without a fear of unreproducible errors entering. It is very easy to do the calculations since all of the parameters used in the code are controllable by the designer.

One final area of usefulness has been found in the application of this code to an existing magnet that is desired to be operated at a point outside of the original limits. It is a simple and rather quick matter to determine if the new operating limits will damage the coil or to find acceptable upper limits for operation.

The code described here has not evolved to its final version. In its present state, however, it has proven to have met most of the original goals and has greatly simplified the design of conventional magnets at Argonne. In the future, modifications will be implemented to incorporate an additional magnet type and to permit the code to operate faster. It will, therefore, become more responsive to the designers wishes and will be even more useful in the design of water-cooled conductors.

Definitions of Symbols

The following list includes definitions for those symbols which appear in more than one equation.

a = correction factor for bends in the coolant circuit

B_o = central magnetic field strength (kG)

d = inside diameter of hollow conductor (in.)

k = heat conductivity of the coolant (Btu/hr-ft-^oF)

I = operating current in each turn (A)

L_e = length of the conductor per electrical turn (in.)

L_H = length of the a coolant circuit (in.)

N = total number of turns in the coil

$\overline{P}$ = electrical power to be dissipated in the coolant circuit (W)

Δp = pressure gradient across a coolant circuit (psi)

Q = coolant flow through a coolant circuit (gpm)

Δt = temperature gradient across a coolant circuit (^oF)

Δt_f = temperature gradient across the interface between the conductor and the coolant (^oF)

γ = coolant density (lb/ft^3)

μ = coolant absolute viscosity (lb/hr-ft)

References

1. Anaconda American Brass Company, "Hollow Copper Conductors", Technical Publication 56, 1968.
2. Handbook of Chemistry and Physics, 41st ed., Chemical Rubber Publishing Co., 1960.
3. Machinery's Handbook, 17th ed., The Industrial Press, 1964.
4. I. Pollack, Proc. of the International Symposium on Magnet Technology, 1965, H. Brechna and H. S. Gordon, Editors, p 349.
5. I. Pollack, "Methodical Selection of Water-Cooled Conductors for DC Magnets", Argonne National Laboratory, Accelerator Division, Report IP-1(January 11, 1965).
6. Cameron Hydraulic Data, Edited by G. V. Shaw and A. W. Loomis (Ingersoll-Rand Company, New York, 1951), p. 27.
7. Ibid, p. 67.

ARGONNE NATIONAL LABORATORY ENGINEERING NOTE	DIVISION HEF/MVE	PROJECT	FILE NO.	PAGE 1/1
SUBJECT Sample Calculations on a Small Picture Frame Magnet	NAME K THOMPSON			
	DATE 9/ 6/72	REV. DATE		

No.	Parameter	Units	[Try # 1]	[Try # 2]
1	Magnet type;1-Septum,2-<u>Pic frame</u>,3-H frame,4-Quad(INPUT 1,2,3,or 4)			
	Particle Parameters;			
3	Particle momentum	(GeV/c)=	1.0900	1.0900
4	Particle energy	(GeV)=	.5000	.5000
5	Particle bend angle	(Deg)=	4.4000	4.4000
	Magnet Gap Parameters;			
7	Field integral along Z axis	(kG-in)=	109.8417	109.8417
8	Gap effective length	(in)=	22.0000	22.0000
9	Gap central field	(kG)=	4.9928	4.9928
10	Gap height	(in)=	1.2500	1.2500
11	Magnetic efficiency	(%)=	98.0000	98.0000
	Coil Parameters;			
13	Ampere turns	(kAmperes)=	12.8705	12.8705
14	Maximum coil voltage	(Volts)=	15.0000	15.0000
15	Maximum coil current	(Amperes)=	1500.0000	1500.0000
16	Nominal coil current	(Amperes)=	1287.0487	1287.0487
17	Total number of turns	=	10.0000	10.0000
18	Total number of layers	=	5.0000	5.0000
19	Total number of rows	=	2.0000	2.0000
20	Maximum coil width	(in)=	.4300	.5080
21	Maximum coil height	(in)=	1.2400	1.2400
22	Minimum ground insulation	(in)=	.0100	.0100
23	Minimum turn insulation	(in)=	.0100	.0100
24	Minimum coil-to-core clearence	(in)=	.0100	.0100
25	Space factor	(%)=	70.9/66.6	68.8/64.6
	Hydraulic Parameters;			
27	Coolant supply temperature	(°F)=	100.0000	100.0000
28	Coolant or conductor temp. gradient	(°F)=	40.0000	20.0000
29	Maximum pressure gradient	(psi)=	120.0000	100.0000
30	Hydraulic bend factor	=	1.1000	1.1000
31	Power per circuit	(kW)=	1.72/1.93	1.46/1.64
32	Reynold's number	(thousands)=	25.3/26.0	27.9/29.3
33	Pressure gradient per circuit(OP)	(psi)=	120/96.7	62.6/56.4
34	Coolant flow per circuit(OP)	(gpm)=	.296/.333	.504/.564
	Conductor Parameters;			
36	Conductor average temperature	(°F)=	128/ 129	116/ 117
37	Average length per electrical turn	(in)=	51.0000	51.0000
38	Electrical turns per hydraulic circuit	=	1.0000	1.0000
39	Average length per hydraulic circuit	(in)=	53.0000	53.0000
40	Conductor ACS conductivity	(%)=	100.0000	100.0000
41	Conductor height	(in)=	.2210	.2210
42	Conductor height tolerance	(in)=	.0030	.0030
43	Conductor width	(in)=	.1820	.2210
44	Conductor width tolerance	(in)=	.0030	.0030
45	Conductor hole diameter	(in)=	.0678	.0940
46	Conductor hole tolerance	(in)=	.0030	.0030
47	Conductor corner radius	(in)=	.0300	.0300
48	Conductor corner tolerance	(in)=	.0100	.0100
49	Conductor section area	(sq in)=	.038/.034	.043/.039
50	Turn resistance(OP)	(milliOhms)=	1.04/1.17	.884/.989
51	Conductor current density	(kAmperes/sq in)=	34.1/38.2	29.7/33.2
	Completed Coil Parameters;			
53	Required magnetic efficiency	(%)=	98.0000	98.0000
54	Conductor resistance @ 68°F (ZP)	(Ohms)=	.009/.010	.008/.009
55	Operating voltage	(Volts)=	13.4/15.0	11.4/12.7
56	Coil power dissipation	(kW)=	17.2/19.3	14.6/16.4
57	Coolant pump power	(kW)=	.221/.248	.313/.350
58	Coolant flow(OP)	(gpm)=	2.96/3.33	5.04/5.64
59	Orifice diameter for dP=dP(MAX)	(in)=	1.06/.038	.045/.047
60	Coolant flow @ 68°F (ZP) & dP=dP(MAX)	(gpm)=	2.57/3.24	5.68/6.72
61	Conductor length	(ft)=	44.1667	44.1667
62	Conductor weight	(tons)=	.003/.003	.004/.003
63	Transverse force on coil	(psi)=	29.5906	29.5906

ANL-145 (5-66)

Figure 1