phs
180
1/27

Postcard sent -

MASTER

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

UNIVERSITY of CALIFORNIA
LIVERMORE

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

H.C. \$3.00; MN 65

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

Lawrence Radiation Laboratory
UNIVERSITY OF CALIFORNIA
LIVERMORE

UCRL-7744-Rev II

**MAFCO — A MAGNETIC FIELD CODE FOR HANDLING GENERAL
CURRENT ELEMENTS IN THREE DIMENSIONS**

W. A. Perkins

J. C. Brown

November 9, 1966

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

MAFCO — A MAGNETIC FIELD CODE FOR HANDLING GENERAL
CURRENT ELEMENTS IN THREE DIMENSIONS

W. A. Perkins and J. C. Brown[†]

Lawrence Radiation Laboratory, University of California
Livermore, California

November 9, 1966

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

ABSTRACT

MAFCO, which is written in FORTRAN language, can be used on the IBM 7094 and CDC 6600 and other similar computers which will compile a machine language code from a FORTRAN deck. The purpose of this code is to take a given set of current-carrying elements of arbitrary geometry and calculate the magnetic field $\underline{B}$ at any

point in space and also the continuation of the magnetic field line (line of force) passing through any desired point in space. In practice, however, computer memory and available machine time usually require that most of the current-carrying conductors be approximated by straight lines, circular loops, and arcs of circles.

1. INTRODUCTION

MAFCO was written to solve some of the magnetic field problems that arise in plasma physics (although it could perhaps be useful in other areas). In particular the complex confining magnetic fields used in fusion research need to be calculated accurately and rapidly to facilitate design and use of these configurations. Methods for calculating magnetic properties of axially symmetric current system have

been discussed by Garrett¹ and some non-axially symmetric systems by Uo,² Balebanov *et al.*,³ Gibson *et al.*,⁴ and Larkin.⁵

In the MAFCO code it is assumed that the currents are dc and no permeable material is present. Winslow⁶ has written a two-dimensional code in which the field is calculated in the presence of permeable material. It is also possible to do some

[†]Now at Computer Science Corp., Los Altos, California.

axially symmetric calculations with this code.⁶ Sackett⁷ is now working on a modification of MAFCO to calculate fields in the presence of rectangular blocks of iron. (In this code⁷ the blocks are divided into smaller blocks which are assumed to behave as magnetic dipoles.)

In the MAFCO code the desired configuration of current-carrying conductors is approximated by a combination of the following: (1) Circular loops with any designated position and orientation in space. (2) Circular arcs with any designated position and orientation in space. (3) Helices along the Z-axis (in the cylindrical coordinate system) with any designated pitch, starting point, and ending point. (4) Straight lines with any designated starting and ending points in space. (5) General elements consisting of a list of points which the code connects by straight lines.

If the general current-carrying element is given by an equation, one could have another code calculate the points along the curve. Alternatively one could obtain the points along the curve from a graphic representation of the current element.

The most common current-carrying element in plasma physics research is a solenoidal coil. This can be approximated by one or more helices if it is positioned along the Z-axis. However, in general it is preferable to use circular loops because the field is calculated several times faster for them than for helices. For a coil with a small number of turns, each turn can be approximated by one circular loop. A many-turn coil can be approximated by a few loops appropriately spaced, with the current in each loop scaled up to account for the number of turns which it actually represents.

For the designated magnetic field configuration, the code will calculate the magnetic field $\underline{B}$ (B_R , B_θ , B_Z , $|\underline{B}|$) at rectangular grids of points. The code will also calculate field lines. Given some point (R, θ, Z) along the line S , it will trace out the line giving $\underline{B}$ and $\int dS/|\underline{B}|$ (which is useful in some plasma stability calculations) at designated intervals along the line. Another code, FORCE,⁸ is available which evaluates the magnetic force on a current element due to the presence of other current elements.

2. THEORY

A. Units

All distances are to be measured in centimeters, all angles in degrees, all currents in amperes. The magnetic field B will then be given in gauss.⁹ In these units, $\mu_0 = 4\pi \times 10^{-1}$.

B. Field from a CIRCULAR LOOP

(X, Y, Z) = coordinates of the center of the loop.

A = radius of loop.

α, β = Euler angles specifying orientation of loop.

I = current passing through loop; I is a positive number for the direction shown in Fig. 1.

(R, θ, Z_P) = coordinates of point P where the field is to be calculated.

The origin of the (X_0, Y_0, Z_0) coordinate system coincides with the center of the loop and is just translated from our (X, Y, Z) coordinate system. The orientation of the loop in this new coordinate system is shown in Fig. 1. The loop is first rotated through an angle α around the Z_0 -axis and then an angle β around the ξ -axis.

The equations for a circular loop in the (X_1, Y_1, Z_1) system are well known.¹⁰ Therefore, first of all, we must determine the coordinates of the point P in this system.

The coordinates of P in the (X_0, Y_0, Z_0) system are:

$$\begin{aligned} X_0 &= R \cos \theta - X, \\ Y_0 &= R \sin \theta - Y, \\ Z_0 &= Z_P - Z. \end{aligned} \quad (1)$$

The coordinates of this point in the rotated system are,¹¹

$$\begin{aligned} X_1 &= X_0 \cos \alpha + Y_0 \sin \alpha, \\ Y_1 &= -X_0 \sin \alpha \cos \beta + Y_0 \cos \alpha \cos \beta + Z_0 \sin \beta, \\ Z_1 &= X_0 \sin \alpha \sin \beta - Y_0 \cos \alpha \sin \beta + Z_0 \cos \beta. \end{aligned} \quad (2)$$

In cylindrical polar coordinates this point is

$$\rho = (X_1^2 + Y_1^2)^{1/2},$$

$$\tilde{Z} = Z_1,$$

$$\sin \tilde{\theta} = Y_1/\rho,$$

$$\cos \tilde{\theta} = X_1/\rho. \quad (3)$$

The magnetic field in this coordinate system (in which the loop lies in the XY plane with center at the origin) is calculated from¹⁰

$$B_\rho = \frac{\mu_0 I}{2\pi} \frac{\tilde{Z}}{\rho [(A + \rho)^2 + \tilde{Z}^2]^{1/2}} \left[-K + \frac{A^2 + \rho^2 + \tilde{Z}^2}{(A - \rho)^2 + \tilde{Z}^2} E \right]$$

for $k^2 > 10^{-3}$ and by $B_\rho = 0$ for $k^2 < 10^{-3}$.

$$B_{\tilde{\theta}} = 0.$$

$$B_Z = \frac{\mu_0 I}{2\pi} \frac{1}{[(A + \rho)^2 + \tilde{Z}^2]^{1/2}}$$

$$\left[K + \frac{A^2 - \rho^2 - \tilde{Z}^2}{(A - \rho)^2 + \tilde{Z}^2} E \right] \quad (4)$$

where K and E are the complete elliptic integrals of the first and second kind,

$$K(k) = \int_0^{\pi/2} (1 - k^2 \sin^2 \phi)^{-1/2} d\phi,$$

$$E(k) = \int_0^{\pi/2} (1 - k^2 \sin^2 \phi)^{1/2} d\phi, \quad (5)$$

where

$$k^2 = 4A\rho [(A + \rho)^2 + \tilde{Z}^2]^{-1}. \quad (6)$$

The elliptic integrals were calculated by the method described in ref. 12.

Transforming back to our original coordinate system in three steps,

$$\begin{aligned} B_{X1} &= B_\rho (X_1/\rho) - B_\theta (Y_1/\rho) \\ B_{Y1} &= B_\rho (Y_1/\rho) + B_\theta (X_1/\rho) \\ B_{Z1} &= B_{\tilde{Z}}, \end{aligned} \quad (7)$$

$$\begin{aligned} B_{X0} &= B_{X1} \cos \alpha - B_{Y1} \sin \alpha \cos \beta \\ &\quad + B_{Z1} \sin \alpha \sin \beta, \\ B_{Y0} &= B_{X1} \sin \alpha + B_{Y1} \cos \alpha \cos \beta \\ &\quad - B_{Z1} \cos \alpha \sin \beta, \\ B_{Z0} &= B_{Y1} \sin \beta + B_{Z1} \cos \beta, \end{aligned} \quad (8)$$

and finally in cylindrical coordinates, the components of the field at (R, θ, Z_P) are

$$\begin{aligned} B_R &= B_{X0} \cos \theta + B_{Y0} \sin \theta, \\ B_\theta &= -B_{X0} \sin \theta + B_{Y0} \cos \theta, \\ B_Z &= B_{Z0}. \end{aligned} \quad (9)$$

C. Field from a HELIX

A = radius of helix.

D = half the distance between turns in Z-direction.

ϕ_1 = angle between starting point and XZ plane.

ϕ_2 = angle at which helix ends = ϕ (see Fig. 2) at end of helix. $\phi_2 > \phi_1$. (Note that ϕ_2 will be greater than 360° in many cases.)

I = current in helix (plus if directed from 1 to 2).

Z_0 = distance that starting point is displaced from $Z = 0$ plane.

(R, θ, Z_P) = coordinates of point P where the field is to be calculated.

Figure 2 shows a diagram of the type of helix calculated. The pitch angle γ and length L of the helix are

$$\gamma = \tan^{-1} (D/\pi A), \quad L = D(\phi_2 - \phi_1)/180^\circ. \quad (10)$$

The field is calculated from the Biot-Savart law,¹³

$$\underline{B} = \frac{\mu_0 I}{4\pi} \int \frac{d\ell \times \underline{r}}{r^3}. \quad (11)$$

Putting the geometry of the helix into (11), the components of $\underline{B}$ are

$$\begin{aligned} B_R &= \frac{\mu_0 IA}{4\pi} \left[\left(Z + \frac{D\alpha_1}{\pi} \right) Q_1 + \frac{D}{\pi} (Q_3 - Q_2) \right], \\ B_\theta &= \frac{\mu_0 IA}{4\pi} \left[\frac{DR}{\pi A} Q_0 - \frac{D}{\pi} Q_1 \right. \\ &\quad \left. + \left(Z + \frac{D\alpha_1}{\pi} \right) Q_3 - \frac{D}{\pi} Q_4 \right], \\ B_Z &= \frac{\mu_0 IA}{4\pi} (AQ_0 - RQ_1), \end{aligned} \quad (12)$$

where

$$\begin{aligned}
 Q_0 &= \int_{\alpha_1}^{\alpha_2} \frac{d\alpha}{r^3}, \\
 Q_1 &= \int_{\alpha_1}^{\alpha_2} \frac{\cos \alpha d\alpha}{r^3}, \\
 Q_2 &= \int_{\alpha_1}^{\alpha_2} \frac{\alpha \cos \alpha d\alpha}{r^3}, \\
 Q_3 &= \int_{\alpha_1}^{\alpha_2} \frac{\sin \alpha d\alpha}{r^3}, \\
 Q_4 &= \int_{\alpha_1}^{\alpha_2} \frac{\alpha \sin \alpha d\alpha}{r^3}, \quad (13)
 \end{aligned}$$

and

$$\begin{aligned}
 Z &= Z_P - Z_0, \\
 \alpha_1 &= \phi_1 - \theta, \quad \alpha_2 = \phi_2 - \theta, \\
 r^3 &= \left\{ R^2 + A^2 - 2AR \cos \alpha \right. \\
 &\quad \left. + \left[Z - (D/\pi)(\alpha - \alpha_1) \right]^2 \right\}^{3/2}. \quad (14)
 \end{aligned}$$

The Romberg method¹⁴ of integration was used in the computer calculations of Eq. (13).

D. Field from a CIRCULAR ARC

(X, Y, Z) = coordinates of the center of imaginary loop formed by extending the arc.

A = radius of arc.

α, β = Euler angles specifying orientation of arc.

ϕ_1 = angle between starting point of arc and $X_1 Z_1$ plane (see Fig. 1b).

ϕ_2 = angle at which arc ends.

$\phi_2 > \phi_1$.

I = current passing through arc; I is positive for the direction shown in Fig. 1.

(R, θ , Z_p) = coordinates of point P where the field is to be calculated.

One transforms into the ($\rho, \tilde{\theta}, \tilde{Z}$) system in the same manner as with a CIRCULAR LOOP, except here we calculate $\tilde{\theta}$ as follows:

$$\text{For } X_1 > 0, \quad \tilde{\theta} = \tan^{-1} (Y_1/X_1), \quad (15)$$

$$\text{For } X_1 < 0, \quad \tilde{\theta} = \pi + \tan^{-1} (Y_1/X_1). \quad (16)$$

For $X_1 = 0$,

$$\tilde{\theta} = \begin{cases} -\pi/2 & \text{for } Y_1 < -10^{-4} |Z_p - Z| \\ 0 & \text{for } |Y_1| \leq 10^{-4} |Z_p - Z| \\ \pi/2 & \text{for } Y_1 > 10^{-4} |Z_p - Z| \end{cases}. \quad (17)$$

It is convenient to define two new angles:

$$\omega_1 = (\phi_1 - \tilde{\theta} - \pi)/2,$$

$$\omega_2 = (\phi_2 - \tilde{\theta} - \pi)/2. \quad (18)$$

For an arc with $D = 0$, Eq. (12) and (13) become, for $k^2 > 10^{-3}$,

$$\begin{aligned} B_\rho &= \frac{\mu_0 I \tilde{Z}}{4\pi} (A\bar{Q}_1), \\ B_{\tilde{\theta}} &= \frac{\mu_0 I \tilde{Z}}{4\pi} (A\bar{Q}_3), \\ B_{\tilde{Z}} &= \frac{\mu_0 I}{4\pi} \left[A (A\bar{Q}_0) \right. \\ &\quad \left. - \rho (A\bar{Q}_1) \right], \end{aligned} \quad (19)$$

and

$$\begin{aligned} (A\bar{Q}_0) &= \frac{1}{2\rho \left[(A + \rho)^2 + \tilde{Z}^2 \right]^{1/2}} \left(\frac{k^2}{1 - k^2} \right) \\ &\quad \left[E(\omega_2, k) - E(\omega_1, k) \right. \\ &\quad \left. - \frac{k^2 \sin \omega_2 \cos \omega_2}{(1 - k^2 \sin^2 \omega_2)^{1/2}} \right. \\ &\quad \left. + \frac{k^2 \sin \omega_1 \cos \omega_1}{(1 - k^2 \sin^2 \omega_1)^{1/2}} \right], \\ (A\bar{Q}_1) &= \frac{1}{\rho \left[(A + \rho)^2 + \tilde{Z}^2 \right]^{1/2}} \\ &\quad \left[F(\omega_1, k) - F(\omega_2, k) \right] \\ &\quad + \left(\frac{2 - k^2}{k^2} \right) (A\bar{Q}_0), \\ (A\bar{Q}_3) &= \frac{1}{\rho \left[(A + \rho)^2 + \tilde{Z}^2 \right]^{1/2}} \\ &\quad \left[(1 - k^2 \sin^2 \omega_1)^{-1/2} - (1 - k^2 \sin^2 \omega_2)^{-1/2} \right], \end{aligned} \quad (20)$$

where $F(\omega, k)$ and $E(\omega, k)$ are incomplete elliptic integrals of the first and second kind.¹⁵

$$\begin{aligned} F(\omega, k) &= \int_0^\omega (1 - k^2 \sin^2 \phi)^{-1/2} d\phi, \\ E(\omega, k) &= \int_0^\omega (1 - k^2 \sin^2 \phi)^{1/2} d\phi, \end{aligned} \quad (21)$$

where k is obtained from Eq. (6). Some useful properties are:

$$\begin{aligned} F(-\omega, k) &= -F(\omega, k), \\ E(-\omega, k) &= -E(\omega, k), \\ F(\pi/2, k) &= K(k), \\ E(\pi/2, k) &= E(k), \\ F(n\pi \pm \omega, k) &= 2nK \pm F(\omega, k), \\ E(n\pi \pm \omega, k) &= 2nE \pm E(\omega, k). \end{aligned} \quad (22)$$

For $k^2 < 10^{-3}$,

$$\begin{aligned} B_\rho &= \frac{\mu_0 I}{4\pi} \frac{\tilde{Z} A}{(A^2 + \tilde{Z}^2)^{3/2}} \\ &\quad \left[\sin(2\omega_1) - \sin(2\omega_2) \right], \\ B_{\tilde{\theta}} &= \frac{\mu_0 I}{2\pi} \frac{\tilde{Z} A}{(A^2 + \tilde{Z}^2)^{3/2}} \\ &\quad (\sin^2 \omega_1 - \sin^2 \omega_2), \\ B_{\tilde{Z}} &= \frac{\mu_0 I}{2\pi} \frac{A^2}{(A^2 + \tilde{Z}^2)^{3/2}} (\omega_2 - \omega_1). \end{aligned} \quad (23)$$

One transforms back to the original coordinate system with Eq. (7-9) as in Section 2B.

E. Field from a STRAIGHT LINE

Element

(X_1, Y_1, Z_1) = coordinates of one end of the line.

(X_2, Y_2, Z_2) = coordinates of the other end of the line.

I = current in line element (plus, if it is directed from (X_1, Y_1, Z_1) toward (X_2, Y_2, Z_2)).

(R, θ, Z_p) = coordinates of point P where the field is to be calculated.

The point where the field is to be calculated in rectangular coordinates is

$$\begin{aligned} X_0 &= R \cos \theta, \\ Y_0 &= R \sin \theta, \\ Z_0 &= Z_p. \end{aligned} \quad (24)$$

Integrating Eq. (11) for the straight line element gives¹⁶

$$\begin{aligned} B_X &= \frac{\mu_0 I}{4\pi} G \left[(Y_1 - Y_0)(Z_2 - Z_0) \right. \\ &\quad \left. - (Y_2 - Y_0)(Z_1 - Z_0) \right], \\ B_Y &= \frac{\mu_0 I}{4\pi} G \left[(Z_1 - Z_0)(X_2 - X_0) \right. \\ &\quad \left. - (Z_2 - Z_0)(X_1 - X_0) \right], \\ B_Z &= \frac{\mu_0 I}{4\pi} G \left[(X_1 - X_0)(Y_2 - Y_0) \right. \\ &\quad \left. - (X_2 - X_0)(Y_1 - Y_0) \right]. \end{aligned} \quad (25)$$

where

$$G = \frac{\rho_1 + \rho_2}{\rho_1 \rho_2 (\rho_1 \rho_2 + \underline{\rho}_1 \bullet \underline{\rho}_2)} \quad (26)$$

if

$$\left[\frac{\rho_1 \rho_2 + \underline{\rho}_1 \bullet \underline{\rho}_2}{\rho_1 \rho_2} \right] \geq 10^{-2}$$

and

$$G = \frac{(\rho_1 + \rho_2)(\rho_1 \rho_2 - \underline{\rho}_1 \bullet \underline{\rho}_2)}{\rho_1 \rho_2 (\underline{\rho}_1 \times \underline{\rho}_2)^2} \quad (27)$$

if

$$\left[\frac{\rho_1 \rho_2 + \underline{\rho}_1 \bullet \underline{\rho}_2}{\rho_1 \rho_2} \right] < 10^{-2},$$

with

$$\begin{aligned} \underline{\rho}_1 \bullet \underline{\rho}_2 &= (X_1 - X_0)(X_2 - X_0) \\ &\quad + (Y_1 - Y_0)(Y_2 - Y_0) \\ &\quad + (Z_1 - Z_0)(Z_2 - Z_0), \end{aligned} \quad (28)$$

$$\begin{aligned} (\underline{\rho}_1 \times \underline{\rho}_2)^2 &= \left[(Y_1 - Y_0)(Z_2 - Z_0) \right. \\ &\quad \left. - (Y_2 - Y_0)(Z_1 - Z_0) \right]^2 \\ &\quad + \left[(Z_1 - Z_0)(X_2 - X_0) \right. \\ &\quad \left. - (Z_2 - Z_0)(X_1 - X_0) \right]^2 \\ &\quad + \left[(X_1 - X_0)(Y_2 - Y_0) \right. \\ &\quad \left. - (X_2 - X_0)(Y_1 - Y_0) \right]^2, \end{aligned} \quad (29)$$

and

$$\rho_1 = \left[(X_0 - X_1)^2 + (Y_0 - Y_1)^2 + (Z_0 - Z_1)^2 \right]^{1/2}$$

$$\rho_2 = \left[(X_0 - X_2)^2 + (Y_0 - Y_2)^2 + (Z_0 - Z_2)^2 \right]^{1/2} \quad (30)$$

These are transformed into cylindrical coordinates by:

$$B_R = B_X \cos \theta + B_Y \sin \theta,$$

$$B_\theta = -B_X \sin \theta + B_Y \cos \theta. \quad (31)$$

F. Field from GENERAL CURRENT ELEMENT

(X_i, Y_i, Z_i) = coordinates of points along general current element with i running from 1 to n = total number of points.

I = current in general element (positive if directed toward increasing i).

(R, θ, Z_P) = coordinates of point P where field is to be calculated.

By use of the formulas of Sec. 2-E, one calculates the field of a straight line element with starting point (X_i, Y_i, Z_i) and ending point $(X_{i+1}, Y_{i+1}, Z_{i+1})$. By summing the components of B (i. e., B_X, B_Y, B_Z) for the $n - 1$ straight line elements formed by connecting the given points with straight lines, one obtains the approximate

field for the general current element. The approximation improves, of course, as the number of points representing the geometry of the current element is increased.

G. Total Field and Field Lines

Magnetic fields are additive vectorially. Therefore, the magnetic field at any point in space is determined by calculating the components of the fields (B_R, B_θ , and B_Z) at that point from each current element and adding them.

$$B_Z(\text{TOTAL}) = \sum_{j=1}^N (B_Z)_j (\text{CIRCULAR LOOP})$$

$$+ \sum_{j=1}^O (B_Z)_j (\text{CIRCULAR ARC})$$

$$+ \sum_{j=1}^M (B_Z)_j (\text{HELIX})$$

$$+ \sum_{j=1}^K (B_Z)_j (\text{STRAIGHT LINE})$$

$$+ \sum_{j=1}^G (B_Z)_j (\text{GENERAL ELEMENT}) \quad (32)$$

with similar expressions for B_R (TOTAL) and B_θ (TOTAL). The magnitude of the field at the point is given by

$$|B| (\text{TOTAL}) = \left\{ \left[B_R(\text{TOTAL}) \right]^2 + \left[B_\theta(\text{TOTAL}) \right]^2 + \left[B_Z(\text{TOTAL}) \right]^2 \right\}^{1/2} \quad (33)$$

The equation determining the field line (line of force) is¹⁷

$$\frac{dR}{B_R} = \frac{R d\theta}{B_\theta} = \frac{dZ}{B_Z}. \quad (34)$$

First, one calculates B_R , B_θ , and B_Z at the given point (R, θ, Z) along the field line. Then the next point is at a distance dS along the field line where

$$dS = [(dR)^2 + (R d\theta)^2 + (dZ)^2]^{1/2}. \quad (35)$$

Setting dS equal to Δ (delta), the given increment, one obtains the differentials by

$$dR = \frac{B_R}{|B|} \Delta,$$

$$R d\theta = \frac{B_\theta}{|B|} \Delta,$$

$$dZ = \frac{B_Z}{|B|} \Delta. \quad (36)$$

The new coordinates are now:

$$R(\text{NEW}) = R(\text{OLD}) + dR,$$

$$\theta(\text{NEW}) = \theta(\text{OLD}) + d\theta,$$

$$Z(\text{NEW}) = Z(\text{OLD}) + dZ. \quad (37)$$

The process is continued until for some number J , $J \Delta \geq L$ where L is the desired length for the calculation along the field line.

The integral $\int dS/|B|$ is approximated by

$$\int \frac{dS}{|B|} \approx \sum_i \frac{|\Delta|}{|B_i|}. \quad (38)$$

3. INPUT-OUTPUT

A. Program Cards

A binary program deck for the CDC 3600 and CDC 6600 and some other computers is available for use at the Lawrence Radiation Laboratory (LRL) in Livermore. At LRL this program can be run through the "monitor" system. A FORTRAN deck and listing of the code is available for other installations. At LRL the input tape is 2A and the output tape is 3A. Card numbers 181 (input tape number), 183 (output tape number) and 186 (number of lines available on the offline printer) may have to be changed for other installations.

B. Input Cards

In concise form, the input format is as given in Table I.

Integers less than 10 are to be placed in the last column on the right in the space allotted. Then integers greater than 10 overflow to the left. Ten columns are allotted for floating point decimal numbers, one of which is used for the decimal point; these numbers do not have to be right adjusted. How to use Table I will become clearer in the sample problems of Sec. 4.

The symbols for the five different types of current elements were explained in

Sec. 2. The units for the input and output quantities were discussed in Sec. 2-A.

Format (4F10.1, I5) means, for example, that the first 4 quantities are in floating point decimal form with 10 columns available for each; the I5 means that the next quantity is an integer placed in the next 5 columns (41-45, right adjusted) after the 4 floating point decimal numbers.

The increment Δ (delta) determines the distance over which the field line is approximated by a straight line. Smaller Δ 's give greater accuracy but are also more time-consuming. The desired size of Δ depends on how rapidly the field line is changing direction. For coils with a radius of 20 cm, $\Delta = 0.2$ cm was found to work very well for typical field lines. For a positive Δ the field line will start in the positive Z-direction from the given point (R, θ , Z). A negative Δ will cause the field line to start in the negative Z-direction. The printout spacing integer p causes the values of (R, θ , Z) and B to be printed out at spacings of $p\Delta$ instead of Δ as occurs if p is omitted.

The number of current-carrying elements of each type which can be used in one problem is as follows:

CIRCULAR LOOPS	200
CIRCULAR ARCS	200
HELICES	50
STRAIGHT LINES	300 (max)
GENERAL CURRENT ELEMENTS	100 (max), or 2400 points (max).

If no STRAIGHT LINES are to be calculated, the maximum number of GENERAL CURRENT ELEMENTS (different currents) must be ≤ 100 , and the total number of points for all these GENERAL CURRENT ELEMENTS must be ≤ 2400 . The STRAIGHT LINES and GENERAL CURRENT ELEMENTS use the same memory space, and the number of these different current elements must be ≤ 300 . Also $2 \times (\text{number of STRAIGHT LINES}) + (\text{number of points for all GENERAL CURRENT ELEMENT}) \leq 2400$.

The maximum number of each type of calculation that can be done for one problem is:

Grids of points for fields	100
Field lines	100.

C. Output

All output information is labeled. First, all the input information is printed out to identify the problem. Then columns are printed for "Fields along a line parallel to Z-axis" for $\Delta Z \neq 0$ and in increments ΔR (if any):

R θ Z B_Z B_R B_θ |B|.

If $\Delta Z = 0$, columns are printed for "Fields in a radial direction" (if any):

Z θ R B_Z B_R B_θ |B|.

and finally "Field lines" (if any):

S R θ Z B_Z B_R B_θ |B| $\int \frac{dS}{|B|}$.

The last column contains a running total of the integral $\int dS/|B|$ so that one can obtain the value of this integral between two points by subtracting the values at those points.

The coordinates are printed out as ordinary decimal numbers. However, the

magnetic fields are printed out in floating point form with the decimal point after the first digit and the power of 10 indicated at the end. For example, 1.2345678 E-02 would be 0.012345678 and 1.2345678 E 01 would be 12.345678.

4. SAMPLE PROBLEMS

A. Simple Helical Coil and Leads

Given a simple helical conductor of mean radius 15 cm, length 50 cm, 8-1/2 turns, and leads 70 cm long rising vertically, calculate the field in the vertical plane and a few field lines. For the helix, $A = 15$, $D = \frac{1}{2}(50/8.5) = 2.94$. Letting the XZ plane be the vertical plane, $\phi_1 = 90^\circ$, $\phi_2 = 315^\circ$, $I = 200$, and centering about YZ plane, $Z_0 = -25$. For the vertical leads $X_1 = 0$, $Y_1 = 15$, $Z_1 = -25$, $X_2 = 70$, $Y_2 = 15$, $Z_2 = -25$, $I = -200$; $X_1 = 0$, $Y_1 = -15$, $Z_1 = 25$, $X_2 = 70$, $Y_2 = -15$, $Z_2 = 25$, $I = 200$. The MAFCO input for this problem is shown below in Table II. The output is too voluminous to be printed here.

B. Magnetic Mirror Machine with Quadrupole Ioffe Coil¹⁸

Given the magnetic field configuration shown in Fig. 3 (i. e., two four-turn coils and four longitudinal bars with arcs connecting the ends), the problem is to obtain the isobars of $|B|$ and field lines in the

plane between bars. The mirror coils are approximated by eight CIRCULAR LOOPS; the three arcs, by CIRCULAR ARCS; the four bars, by four STRAIGHT LINES. MAFCO input for this configuration is given in Table III. The desired plot of isobars of $|B|$ and field lines is shown in Fig. 4. The code does not print out the isobars directly, but they can be obtained quickly from a grid of points calculated by the computer.

C. Bumpy Torus⁴ with Quadrupole Coil¹⁹

The given magnetic field configuration is a set of eight circular coils surrounding a torus with four circular loops (quadrupole) passing through the eight loops as shown in Fig. 5. The problem is to obtain some of the field lines for this configuration. Because of symmetry, one needs to calculate field lines for only one of the eight sections. The input data is given in Table IV and the resulting field lines are plotted in Fig. 5.

D. Corkscrew Coil

Given the corkscrew geometry shown in Fig. 6, calculate the field in the XZ plane and a field line. The helix changes pitch angle and radius uniformly, so that at the top end it has one-third the separation between turns and half the radius that it started with. The equations describing this geometry are

$$R = A(0) \left[1 - \frac{1}{2} (\phi - \phi_1) / (\phi_2 - \phi_1) \right],$$

$$Z = \frac{D(0)}{\pi} \left[1 - \frac{1}{3} (\phi - \phi_1) / (\phi_2 - \phi_1) \right] (\phi - \phi_1), \quad (39)$$

with $X = R \cos \phi$, $Y = R \sin \phi$, and $A(0) = 20$ cm, $D(0) = 10$ cm, $\phi_1 = 20^\circ$, $\phi_2 = 2130^\circ$.

By use of a hand calculator or a simple computer code one can obtain a set of points (X, Y, Z) along this helix. The geometry is then calculated as a GENERAL CURRENT ELEMENT. Input data with 50 points are shown in Table V. For the points P where the field was calculated

(see Table V), $|B|$ was obtained within 2.0% accuracy with 50 points, 0.3% accuracy with 100 points, and 0.003% accuracy with 1000 points, assuming that the value with 2000 points is exact. The end point of the field line that was calculated was displaced from the true point by less than 0.15 cm with 50 points, 0.035 cm with 100 points, and 0.005 cm with 1000 points.

E. Many-Turned Coil Arrangement

The problem here is to determine the magnetic field and some field lines for the coil arrangement of Fig. 7. Each coil has 144 turns and all coils are run at the same current, but coil number 4 has the current in the opposite direction so that coils 3 and 4 form a cusp arrangement. We shall use four CIRCULAR LOOPS to represent each coil (with current $I = 144/4 = 36$ A, so that B gives the gauss per ampere in the actual coils). Computer input for this problem is given in Table VI and the resulting field lines are plotted in Fig. 7.

ACKNOWLEDGMENTS

We are indebted to Dr. Dolores U. Olness for checking some of the calculations and Thomas N. Haratani for some debugging and processing. The first-named author would like to thank Dr.

Richard F. Post for his interest and encouragement throughout this work. The work was done under the auspices of the U. S. Atomic Energy Commission.

REFERENCES

- ¹M. W. Garrett, J. Appl. Phys. 34, 2567 (1963); Oak Ridge National Laboratory Rept. ORNL-3318 (1962).
- ²K. Uo, J. Phys. Soc. Japan 16, 1380 (1961).
- ³V. M. Balebanov, B. I. Volkov, V. B. Glasko, A. L. Groshev, V. V. Kuznetsov, A. G. Sveshnikov and N. N. Semashko, J. Nucl. Energy, Pt. C 5, 205 (1963).
- ⁴G. Gibson, W. C. Jordon, E. J. Lauer, and C. H. Woods, Phys. Fluids 7, 548 (1964).
- ⁵M. Larkin, Culham Laboratory Report CLM-R31 (1964).
- ⁶A. M. Winslow, Lawrence Radiation Laboratory (Livermore), Rept. UCRL-7784-T, Rev. 2 (1965).
- ⁷S. Sackett, Lawrence Radiation Laboratory, Livermore, California, Private Communication.
- ⁸C. D. Henning, Lawrence Radiation Laboratory (Livermore), Rept. UCRL-14917 (May, 1966).
- ⁹Strictly speaking, we should use "oersted" instead of "gauss" since these are vacuum fields. However, we shall follow the common practice of using the word "gauss".
- ¹⁰W. R. Smythe, Static and Dynamic Electricity (McGraw-Hill Book Co., New York, 1950), 2nd ed., pp. 270-271.
- ¹¹H. Goldstein, Classical Mechanics (Addison-Wesley, New York, 1953), pp. 107-109.
- ¹²C. Hastings, Approximations for Digital Computers (Princeton University Press, Princeton, N.J., 1955), pp. 172-175.
- ¹³See ref. 10, p. 275.
- ¹⁴F. N. Fritsch, Lawrence Radiation Laboratory Report (Livermore) UCRL-7569-T (1963).
- ¹⁵The code uses a subroutine written by R. L. Pexton to evaluate the incomplete elliptic integrals. See D. J. Hofsommer, R. P. van de Riet, Numerische Mathematik 5, 291-302 (1963).
- ¹⁶W. F. Gauster, ORNL-3652 Section 9.3, p. 118 (April 1964). Also W. J. Norris, Central Electricity Research Laboratory, Great Britain, Private Communication.
- ¹⁷See ref. 10, p. 7.
- ¹⁸Yu. T. Baiborodov, M. S. Ioffe, V. M. Petrov, and R. I. Sobolev, J. Nucl. Energy: Pt. C 5, 409 (1963).
- ¹⁹M. A. Levine, Bull. Am. Phys. Soc. 9, 335 (1964).

Table I. MAFCO Input.

First card contains the number of problems (integer, right adjusted in columns 1-5).

This next section of cards is repeated for each problem.

First card of this section contains in (right adjusted) columns:

- 1-5 Number of LOOPS.
- 6-10 Number of ARCS.
- 11-15 Number of HELICES.
- 16-20 Number of STRAIGHT LINES.
- 21-25 Number of GENERAL CURRENT ELEMENT groups.
- 26-30 Number of grids for calculating fields.
- 31-35 Number of calculations of field lines.

CIRCULAR LOOP cards (one for each loop in this problem) containing X, Y, Z, A, Alpha, Beta, I; Format (7F10.1).

ARC CARDS — (two for each arc in this problem) containing on card one X, Y, Z, A, Alpha, Beta, I; Format (7F10.1); and on card two Phi1, Phi2; Format (2F10.1).

HELIX cards (one for each helix in this problem) containing A, D (Z-distance of half-turn), ϕ_1 , ϕ_2 , I, distance from XY plane; Format (6F10.1).

STRAIGHT LINE cards (one for each straight line in this problem) containing X_1 , Y_1 , Z_1 , X_2 , Y_2 , Z_2 , current from 1 to 2; Format (7F10.1).

GENERAL CURRENT ELEMENT cards (one group for each element in this problem) containing on the first card, X, Y, Z of the first point, current along points, number of points; Format (4F10.1, I5).

On following cards, X, Y, Z of succeeding points; Format (3F10.1).

Range of points determining grid at which fields are to be calculated, containing RMIN, Delta-R, RMAX, Angle, ZMIN, Delta-Z, ZMAX; Format (7F10.1).

Calculation of field line cards (one for each line in this problem) containing R, θ , Z, Δ , total length of line, printout spacing integer (omit if 1); Format (5F10.1, I5).

Table II. Input data for problem A.

Column	5	10	15	20	30	40	50	60	70
	1 0	0	1	2	0	2	6	HELICAL COIL AND LEADS	
HELIX	15.0		2.94		90.0		3150.0	200.0	-25.0
STRAIGHT	0.0		15.0		-25.0		70.0	15.0	-25.0
LINES	0.0		-15.0		25.0		70.0	-15.0	25.0
Grids	1.0		1.0		8.0		180.0	-30.0	0.5
	0.0		1.0		8.0		0.0	-30.0	0.5
	2.0		0.0		0.0		-0.2	3.00	2
Field Lines	2.0		0.0		0.0		0.2	3.00	2
	4.0		0.0		0.0		-0.2	3.00	2
	4.0		0.0		0.0		0.2	3.00	2
	8.0		0.0		0.0		-0.2	3.00	2
	8.0		0.0		0.0		0.2	3.00	2

Table III. Input data for problem B

Column	5	10	15	20	30	40	50	60	70
	1								
	8	3	0	4	0	2	16	MIRROR AND QUADRUPOLE COILS	
CIRCULAR LOOPS	0.0			0.0	-23.0		20.0	0.0	0.0
	0.0			0.0	-24.0		20.0	0.0	0.0
	0.0			0.0	-25.0		20.0	0.0	0.0
	0.0			0.0	-26.0		20.0	0.0	0.0
	0.0			0.0	23.0		20.0	0.0	0.0
	0.0			0.0	24.0		20.0	0.0	0.0
CIRCULAR ARCS	0.0			0.0	25.0		20.0	0.0	0.0
	0.0			0.0	26.0		20.0	0.0	0.0
	0.0			0.0	40.0		16.0	0.0	0.0
	45.0		135.0						
	0.0		0.0		40.0		16.0	0.0	0.0
	225.0		315.0						
STRAIGHT LINES	0.0			0.0	-40.0		16.0	0.0	0.0
	135.0		225.0						
	11.3		11.3		-40.0		11.3	11.3	40.0
	-11.3		11.3		-40.0		-11.3	11.3	40.0
	-11.3		-11.3		-40.0		-11.3	-11.3	40.0
	11.3		-11.3		-40.0		11.3	-11.3	40.0
Grids	0.0		0.5		11.0		0.0	-24.0	0.5
	0.5		0.5		11.0		180.0	-24.0	0.5
	1.0		0.0		0.0		0.2	20.0	
	1.0		0.0		0.0		-0.2	20.0	
	1.0		180.0		0.0		0.2	20.0	
	1.0		180.0		0.0		-0.2	20.0	
Field Lines	2.0		0.0		0.0		0.2	20.0	
	2.0		0.0		0.0		-0.2	20.0	
	2.0		180.0		0.0		0.2	20.0	
	2.0		180.0		0.0		-0.2	20.0	
	4.0		0.0		0.0		0.2	12.0	
	4.0		0.0		0.0		-0.2	20.0	
	4.0		180.0		0.0		0.2	12.0	
	4.0		180.0		0.0		-0.2	20.0	
	8.0		0.0		0.0		0.2	6.0	
	8.0		0.0		0.0		-0.2	20.0	

Table IV. Input data for problem C.

Column	5	10	15	20	30	40	50	60	70
	1								
	12	0	0	0	0	0	14 BUMPY TORUS WITH QUADRUPOLE		
CIRCULAR LOOPS		50.0	0.0	0.0	0.0	20.0	0.0	90.0	1.0
		35.3	35.3	0.0	0.0	20.0	45.0	90.0	1.0
		.0	50.0	0.0	0.0	20.0	90.0	90.0	1.0
		-35.3	35.3	0.0	0.0	20.0	135.0	90.0	1.0
		-50.0	0.0	0.0	0.0	20.0	180.0	90.0	1.0
		-35.3	-35.3	0.0	0.0	20.0	225.0	90.0	1.0
		.0	-50.0	0.0	0.0	20.0	270.0	90.0	1.0
		35.3	-35.3	0.0	0.0	20.0	315.0	90.0	1.0
		.0	0.0	-11.3	61.3	0.0	0.0	0.0	1.0
		.0	0.0	11.3	61.3	0.0	0.0	0.0	-1.0
Field Lines		.0	0.0	-11.3	38.7	0.0	0.0	0.0	-1.0
		.0	0.0	11.3	38.7	0.0	0.0	0.0	1.0
		50.0	0.0	0.0	0.0	0.2	40.0		
		50.0	0.0	0.0	0.0	-0.2	35.0		
		40.0	0.0	0.0	0.0	-0.2	20.0		
		40.0	0.0	0.0	0.0	0.2	50.0		
		60.0	0.0	0.0	0.0	0.2	50.0		
		60.0	0.0	0.0	0.0	-0.2	15.0		
		48.0	0.0	0.0	0.0	0.2	40.0		
		48.0	0.0	0.0	0.0	-0.2	40.0		
		32.0	0.0	0.0	0.0	0.2	50.0		
		32.0	0.0	0.0	0.0	-0.2	15.0		
		45.0	0.0	0.0	0.0	0.2	50.0		
		45.0	0.0	0.0	0.0	-0.2	50.0		
		55.0	0.0	0.0	0.0	0.2	50.0		
		55.0	0.0	0.0	0.0	-0.2	20.0		

Table V: Input data for problem D.

Column	5	10	20	30	40	45
	1					
	0	0	0	0	1	CORKSCREW COIL
	18.792	06.840	00.000	1.0	50	
	8.968	17.647	02.376			
	-5.440	18.821	04.719			
	-16.650	09.932	07.030			
	-18.747	-04.068	09.308			
	10.802	-15.605	11.554			
	2.732	-18.575	13.767			
	14.515	-11.579	15.948			
	18.310	01.437	18.096			
	12.258	13.402	20.212			
	-1.191	17.958	22.295			
	-12.260	12.841	24.346			
	-17.522	00.999	26.364			
	-13.328	-11.103	28.349			
	-2.131	-17.009	30.302			
	9.936	-13.717	32.222			
	16.426	-03.198	34.110			
	14.012	08.769	35.965			
	4.157	15.777	37.788			
	-7.609	14.213	39.578			
	-15.071	05.123	41.336			
	-14.323	-06.463	43.061			
	-5.973	-14.313	44.753			
	5.337	-14.345	46.413			
	13.511	-06.745	48.041			
	14.282	04.239	49.636			
	7.437	12.672	51.198			
	-3.174	14.137	52.720			
	-11.802	08.047	54.225			
	-13.916	-02.148	55.689			
	-8.574	-10.911	57.122			
	1.167	-13.623	58.521			
	10.002	-09.019	59.888			
	13.263	00.236	61.223			
	9.382	09.086	62.525			
	.640	12.841	63.794			
	-8.167	09.663	65.031			
	-12.363	01.459	66.235			
	-9.865	-07.253	67.407			
	-2.217	-11.834	68.546			
	6.351	-09.988	69.653			
	11.262	-02.910	70.727			
	10.036	05.465	71.768			
	3.536	10.652	72.777			
	-4.604	10.012	73.754			
	-10.011	04.094	74.698			
	-9.919	-03.771	75.609			
	-4.582	-09.345	76.488			
	2.973	-09.761	77.334			
	8.660	-04.999	78.148			
Grid	0.0	1.0	6.0	0.0	0.0	2.0
Field Line	1.0	0.0	0.0	0.2	80.0	80.0

TABLE VI. Input data for problem E

Column	5	10	15	20	30	40	50	60	70
	1								
	16	0	0	0	0	3	4	MANY-TURNED COILS	
		.0	51.2		0.0	24.1	0.0	90.0	36.0
		.0	58.8		0.0	24.1	0.0	90.0	36.0
		.0	51.2		0.0	31.7	0.0	90.0	36.0
		.0	58.8		0.0	31.7	0.0	90.0	36.0
		.0	8.55	13.93		24.1	0.0	45.0	36.0
		.0	8.55	13.93		31.7	0.0	45.0	36.0
CIRCULAR LOOPS		.0	13.93	8.55		24.1	0.0	45.0	36.0
		.0	13.93	8.55		31.7	0.0	45.0	36.0
		.0	0.0	51.2		24.1	0.0	0.0	36.0
		.0	0.0	51.2		31.7	0.0	0.0	36.0
		.0	0.0	58.8		24.1	0.0	0.0	36.0
		.0	0.0	58.8		31.7	0.0	0.0	36.0
Grids		.0	0.0	91.8		24.1	0.0	0.0	-36.0
		.0	0.0	91.8		31.7	0.0	0.0	-36.0
		.0	0.0	99.4		24.1	0.0	0.0	-36.0
		.0	0.0	99.4		31.7	0.0	0.0	-36.0
		0.0	5.0	10.0		90.0	0.0	1.0	100.0
		5.0	5.0	10.0		270.0	0.0	1.0	100.0
Field Lines		0.0	1.0	70.0		90.0	-10.0	5.0	10.0
		70.0	90.0	5.0		-0.2	170.0	2	
		70.0	90.0	-5.0		0.2	170.0	2	
		70.0	90.0	10.0		-0.2	170.0	2	
		70.0	90.0	-10.0		0.2	170.0	2

Fig. 1. Position of circular loop in the different coordinate systems. (a) Coordinate system (X_0, Y_0, Z_0) is translated from the (X, Y, Z) (laboratory) system. The (ξ, η, ζ) system is obtained by a rotation through an angle α around the Z -axis. (b) The (X_1, Y_1, Z_1) coordinate system (in which the loop lies in the X_1Y_1 plane with center at the origin) is obtained by a rotation through an angle β around the ξ axis. The arrow shows the direction for positive current.

Fig. 2. Helix concentric about the Z-axis in cylindrical coordinate system.

Fig. 3. Two four-turn solenoidal (mirror) coils and quadrupole Ioffe coil. The arrows show the direction of the current in the quadrupole coil. The current in the mirror coils is in the positive direction (see Fig. 1).

Fig. 4. Isobars of constant $|B|$ and field lines in XZ plane for the current configuration of Fig. 3. The relative values of $|B|$ are given near each isobar. The heavy curves are field lines.

Fig. 5. Bumpy torus with quadrupole coil. The dots and crosses in Section AA' show the direction of the current in the four circular loops forming the quadrupole.

Fig. 6. Corkscrew coil. The current element starts in the XY plane at an angle $\phi_1 = 20^\circ$ and follows a helix which decreases in pitch angle and radius uniformly so that at the top end ($\phi_2 = 2130^\circ$) the separation between turns is one-third its initial value and the radius is one-half its initial value.

Fig. 7. Many-turned coil arrangement. Each 144-turn coil is approximated by four circular loops as shown. Coils 3 and 4 with currents in opposite direction form a cusp arrangement. The X-axis is pointing out of the paper.

DISTRIBUTION

LRL Internal Distribution

Michael M. May	
R. F. Post	
K. Moses	
A. Futch	
C. Damm	
S. Sackett	
C. Henning	
F. Coensgen	
R. Freis	
W. Nexsen	
J. Foote	
C. Taylor	
J. Osher	
C. Hartman	
T. Haratani	
A. Winslow	
D. Fuss	
E. Lauer	
C. M. Van Atta	
C. M. Van Atta, Berkeley	
R. K. Wakerling, Berkeley	2
K. Halbach, Berkeley	
W. A. Perkins	50
TID File	30

External Distribution

D. Baker
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

R. Briggs
Massachusetts Institute of Technology
Cambridge, Massachusetts

W. F. Gauster
M. W. Garrett
Oak Ridge National Laboratory
Oak Ridge, Tennessee

K. Wakefield
Plasma Physics Laboratory
Princeton, New Jersey

Dr. Amasa S. Bishop
Division of Research
U. S. Atomic Energy Commission
Washington, D. C. 20545

J. C. Brown
Computer Science Corp.
Los Altos, California

Division of Technical Information Extension
Oak Ridge, Tennessee

80

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.