~~APPROVED FOR RELEASE~~

TID--25769

DOC. NO. 6300-237

JUNE 15, 1967

RECEIVED BY DTIC AUG 1 1967

**FINAL REPORT
FOR
MAGNETIC FIELD MEASUREMENT
AND ANALYSIS
PART 1
SNAP-27 PROGRAM**

ADVANCED NUCLEAR SYSTEMS OPERATION

GENERAL ELECTRIC

**MISSILE AND SPACE DIVISION
Valley Forge Space Technology Center**

P.O. Box 8661-Philadelphia 1, Penna.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

FINAL REPORT
FOR
MAGNETIC FIELD MEASUREMENT
AND ANALYSIS
PART 1
SNAP-27 PROGRAM

(Contract AT(30-1)-3535)

Prepared for:

U.S. ATOMIC ENERGY COMMISSION
ALBUQUERQUE OPERATIONS OFFICE
P.O. BOX 5400
ALBUQUERQUE, N. M. 87115

Prepared by: Gerald Wouch
G. Wouch, Physicist
Environmental Analysis

Approved by: R. T. Frost
Dr. R. T. Frost, Manager
Space Physics Operation

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or 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.

TABLE OF CONTENTS

Section		Page
1	INTRODUCTION	1-1
2	COORDINATE SYSTEMS	2-1
3	DEPERMING THE MOD 8B	3-1
4	MAGNETIC FIELD OF THE RTG AFTER PERMING IN A 15 OERSTED FIELD DIRECTED ALONG THE +X AXIS	4-1
	4.1 Measurements and Data	4-1
	4.2 RTG Field Analysis	4-1
5	MAGNETIC FIELD OF THE RTG AFTER PERMING IN A 15 OERSTED FIELD DIRECTED ALONG THE -Y AXIS	5-1
	5.1 Measurements and Data	5-1
	5.2 RTG Field Analysis	5-1
6	INDUCED MAGNETISM IN THE RTG	6-1
	6.1 Measurements and Data	6-1
	6.2 Analysis of Data	6-1
7	STRAY FIELD	7-1
	7.1 Measurements and Data	7-1
	7.2 Analysis of Data	7-1
8	INITIAL PERM AS RECEIVED IN EARTH'S AMBIENT FIELD	8-1
	8.1 Basic Measurements and Data	8-1
	8.2 Analysis of Data	8-7
9	INITIAL PERM AS RECEIVED IN ZERO FIELD ENVIRONMENT	9-1
	9.1 Basic Measurements and Data	9-1
	9.2 Analysis	9-2
10	CONCLUSIONS	10-1

LIST OF ILLUSTRATIONS

Figure	Title	Page
2-1	Package Coordinate System	2-1
2-2	Initial Alignment of Package Coordinate System and Coil System Coordinates	2-2
2-3	Package Coordinates Rotated by Rotation in Zenith Angle	2-3
2-4	Package Coordinates Rotated by Rotation in Azimuth	2-3
4-5	Package Coordinate System with Dipole $\vec{M}$	4-7
6-6	Maximum Dipole Moment	6-7

PREFACE

Part I of the SNAP-27 Engineering Report contains all of the magnetic field analysis which is usually performed in estimating the acceptance of a package. Part II will be an elaboration of Part I which will go much beyond this usual analysis. Part II will evaluate performance of degaussing loops based on a spherical harmonic analysis of data on the stray fields. Part II will also contain elaboration of all data and more plots and tables of data.

page blank

FINAL REPORT FOR
MAGNETIC FIELD MEASUREMENT AND ANALYSIS
PART I

SECTION 1
INTRODUCTION

RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG)

The Engineering Model 8B Generator Assembly was subjected to various magnetic environments described below and the magnetic field from the RTG as a result of these environments was measured in the Component Magnetic Test Facility at the Goddard Space Flight Center. This test facility is completely described in Reference 1.

The test objectives were:

- 1) To insure that the SNAP-27 RTG will satisfy the LSEP Magnetic Field Specification
- 2) To obtain data on the magnetic field of the RTG for evaluation of its utility in other space applications

The test plan is described in Reference 2 and will be discussed only briefly as required.

The RTG magnetic field was measured under the following conditions:

- 1) As received in the Earth's ambient field
- 2) As received in zero field environment
- 3) Depermed in zero field environment
- 4) After perming with a 15 oersted field
- 5) Rotating in a field of 0.26 oersteds
- 6) With selected currents flowing in the generator in a zero field environment with the generator depermed before the test

Analysis of the data was performed and the results of the field model achieved from data analysis checked to insure that the model fitted the measured data.

SECTION 2

COORDINATE SYSTEMS

The RTG was set into a fixture which enabled it to be clamped in the gimbal of the Component Test Facility coil system without damage to the RTG. The RTG in its fixture will be referred to as the "package" in the following description. The package coordinate system adopted is shown in Figure 2-1 with the origin, "0", at the package center.

Figure 2-1. Package Coordinate System

The coil system coordinates are the primed cartesian coordinates $X'Y'Z'$ with X' the vertical axis, Y' parallel to the detector boom, and Z' perpendicular to X' and Y'

In the reference position the initial alignment of the package coordinate system and the coil system coordinates are as shown in Figure 2-2. The angles are those that correspond to the coil system axes and the arrows show the initial zenith and azimuth readings in the reference position.

Figure 2-2. Initial Alignment of Package Coordinate System and Coil System Coordinates

A rotation in zenith angle alone, from the reference position, rotates the package coordinates as in Figure 2-3.

Figure 2-3. Package Coordinates Rotated by Rotation in Zenith Angle

A rotation in azimuth alone, from the reference position, rotates the package coordinates as in Figure 2-4. The construction of the experimental gimbal dial was such that its reading gave directly the azimuth defined in this manner.

Figure 2-4. Package Coordinates Rotated by Rotation in Azimuth

SECTION 3

DEPERMING THE MOD 8B

The Mod 8B RTG was depermed twice by the procedure of the test plan, Reference 2. After deperming the following fields were detected:

R	B_R
24"	$< 1 \gamma$
36"	$< 0.4 \gamma$
48"	$< 0.4 \gamma$
72"	$< 0.4 \gamma$

At $R = 24"$ the peak positive field was 1.1γ at the zenith $\theta = 270^\circ$, azimuth $\phi = 90^\circ$ and the peak negative field was -0.8γ at zenith $\theta = 60^\circ$, azimuth $\phi = 90^\circ$. The maximum peak field before deperming was 87.8γ so that the maximum peak was reduced to 1.27% of its previous value. The values at distances in terms of values before deperming were:

R	% Previous Max.
24 "	1 %
36 "	2 %
48 "	3 %
72 "	No detectable field Readings vary at noise level

Thus the Mod 8B can be reduced to better than 95% of its maximum peak for initial perm. Every time the mod 8B was depermed in the tests discussed below, better than a 95% reduction in peak was observed.

SECTION 4

MAGNETIC FIELD OF THE RTG AFTER PERMING IN A 15 ORSTED FIELD DIRECTED ALONG THE+ X AXIS

4.1 MEASUREMENTS AND DATA

The Radioisotope Generator was permed along the X axis of the generator with the field pointing in the +X direction. Then the generator was returned to the reference position and rotated to find the peak radial field at 0.6096 meters. Next, starting with the generator at the reference position, the RTG was rotated about the Z axis and radial field versus zenith angle recorded. Similarly with the RTG at the reference position initially, rotation about the X axis was performed and radial field versus azimuth recorded. This was repeated for 0.9144, 1.2192, and 1.8288 meters.

Examination of this data showed that the peak positive and peak negative radial fields fall on the X axis for the permed generator. The positive and negative peaks are 180° apart, the positive peaks falling on the +X side and the negative peaks on the -X side. A plot of the + and - peaks versus distance is shown in Figure 4-1. The slope of both lines is -3.06 or ~ -3 . Plots of the variation of radial field component with zenith angle are shown in Figure 4-2.

4.2 RTG FIELD ANALYSIS

4.2.1 BASIC THEORY

Within the limits of the coil system the measured field of the RTG is due only to the magnetized material in the RTG after perming the RTG in a 15 oersted field. The magnetic field due to a volume containing magnetized material can be expressed as the gradient of a scalar magnetic potential, V , in the region external to the volume containing the magnetized material. We can express the scalar potential in terms spherical coordinates (see Figure 4-3); λ , δ , R where λ is the colatitude or the complement of the zenith angle which is read from the reference position shown in Section 2. The coordinate R is read from the center of the package 0.

PEAK RADIAL FIELD MAGNITUDE VS DISTANCE FROM CENTER OF ROTATION
(FIELD DIRECTION IS IN POSITIVE X DIRECTION)

Figure 4-1

RADIAL FIELD VS ZENITH ANGLE
(15 OE PERM ALONG POSITIVE X DIRECTION)

Figure 4-2

Figure 4-3

Then the scalar potential external to an imaginary sphere of radius $a = \ell/2$, where ℓ = the maximum linear dimension of the package (RTG in the fixture) is just

$$V = a \sum_{n=1}^{\infty} \sum_{m=0}^n \left(\frac{a}{R}\right)^{n+1} P_n^m(\cos \lambda) \left\{ g_n^m \cos m \delta + h_n^m \sin m \delta \right\}$$

Examination of the data, as can be observed in Figure 4-4, shows that within the assumed measurement error of $\pm 1/2 \gamma$, there is symmetry in ϕ and therefore in δ . Within experimental limits, then, only the terms in $P_n^0(\cos \lambda)$ are required and V can be expressed entirely in zonal harmonics

$$V = a \sum_{n=1}^{\infty} \left(\frac{a}{R}\right)^{n+1} g_n^0 P_n^0(\cos \lambda)$$

Figure 4-4

As the distance from the package center increases the higher order terms become less important until only the first few terms of the series are needed and in this region which is approximately $R = 3 \ell$

$$V = \frac{a^3}{R^2} g_1^0 \cos \lambda + \frac{a^4}{R^3} g_2^0 (3/2 \cos^2 \lambda - 1/2)$$

where the second term is a quadrupole term.

In this region

$$B_R = -\partial V / \partial R = 2 \left(\frac{a}{R}\right)^3 g_1^0 \cos \lambda + 3 \left(\frac{a}{R}\right)^4 g_2^0 (3/2 \cos^2 \lambda - 1/2)$$

For $\lambda = 0$ in this region

$$B_{R_+} = 2 \left(\frac{a}{R}\right)^3 g_1^0 + 3 \left(\frac{a}{R}\right)^4 g_2^0$$

and for $\lambda = \pi$

$$B_{R_-} = -2 \left(\frac{a}{R}\right)^3 g_1^0 + 3 \left(\frac{a}{R}\right)^4 g_2^0$$

In a region where the dipole term predominates $\log |B_R|$ versus $\log R$ should yield a straight line of slope -3 and looking at Figure 4-1 this is observed to occur at 36 inches. Then the region starting at 36 inches is the dipole region. Looking at Figure 4-1 the following facts are observed $|B_{R_-}| > |B_{R_+}|$ and B_{R_+} is positive.

This means that g_2^0 is a negative number; $g_2^0 = -K$ where K is a positive number.

Then

$$B_{R_+} = 2 \left(\frac{a}{R}\right)^3 g_1^0 - 3K \left(\frac{a}{R}\right)^4$$

$$B_{R_-} = - \left\{ 2 \left(\frac{a}{R}\right)^3 g_1^0 + 3K \left(\frac{a}{R}\right)^4 \right\}$$

It is possible to transform to a new position on the X axis where $K = 0$. This may increase the other terms of the expansion, but in the dipole region where $\log |B_R|$ versus $\log R$ gives a line of slope -3 these terms are so small as not to contribute much to the field. At this position then, on the X axis,

$$B_{r_+} = 2 \left(\frac{a}{r}\right)^3 G_1^0 = \frac{2M}{r^3}$$

$$B_{r_-} = -2 \left(\frac{a}{r}\right)^3 G_1^0 = -\frac{2M}{r^3}$$

and with respect to a new origin the field at $R > 36''$ can be expressed as a dipole field of moment M . Since $|B_{R_-}| > |B_{R_+}|$, the new origin must be a distance below the package center on the X axis, so that in the package coordinate system the dipole $\vec{M}$ can be drawn as shown in Figure 4-5 in the X Y plane. Since there is symmetry about the X axis, any meridian plane having an azimuth angle δ in the package coordinate system will have the same field as $P(R, \lambda)$ or $P(r, \Theta)$.

Figure 4-5. Package Coordinate System with Dipole $\vec{M}$

The total field with respect to the dipole origin is $\vec{B} = \frac{M}{r^3} (2 \cos \Theta \hat{r} + \sin \Theta \hat{\Theta})$

The field measured by the magnetometer was B_R and

$$B_R = \vec{B} \cdot \hat{R} = \frac{M}{r^3} 2 \cos \Theta \cos (\lambda - \Theta) + \sin \Theta \sin (\lambda - \Theta)$$

This formula can be used to check the above model after the dipole moment M and the displacement from the package coordinate origin 0 is determined.

4.2.2 LOCATION OF THE DIPOLE CENTER

All measurements of distance have been taken with respect to the RTG center. Thus the positive peak on the X axis is a distance $R + d$ from the dipole axis and the negative peak a distance $R - d$ from the dipole center for a measured distance R , so for the peaks on the X axis

$$\left| \frac{B_{R_+}}{B_{R_-}} \right| = \frac{\frac{2M}{(R+d)^3}}{\frac{2M}{(R-d)^3}} = \frac{(R-d)^3}{(R+d)^3}$$

or since it is preferred to work with logarithms > 1

$$\left| \frac{B_{R_-}}{B_{R_+}} \right| = \frac{(R+d)^3}{(R-d)^3}$$

$$\text{Then } \left\{ \left| \frac{B_{R_-}}{B_{R_+}} \right| \right\}^{1/3} = \frac{R+d}{R-d} \text{ and letting } \left\{ \left| \frac{B_{R_-}}{B_{R_+}} \right| \right\}^{1/3} = A$$

$$AR - Ad = R + d \text{ or } (A-1)R = (A+1)d \text{ or } d = \frac{(A-1)}{(A+1)} R$$

For $R = 48''$ or 1.22 meters

$$\left| \frac{B_{R_-}}{B_{R_+}} \right| = \frac{23.68}{19.87} = 1.19$$

and solving for d gives $d = 1.4$ inches or 0.036 meters

at $R = 72''$ or 1.8288 meters

$$\left| \frac{B_{R_-}}{B_{R_+}} \right| = \frac{6.55}{5.95}$$

and solving for d gives $d = 1.16$ inches or 0.029 meters

At $R = 36''$ or 0.9144 meters $d = 1.7$ inches and since $36''$ is not 3 x the Maximum Linear Dimension of $18''$ the average d was obtained by averaging $d_{48''}$ and $d_{72''}$ obtaining

$$d_{ave} = 1.28'' \text{ or } 0.0324 \text{ meters}$$

Thus the dipole is located 0.0324 meters below the center of the package (RTG in its fixture).

4.2.3 THE DETERMINATION OF THE DIPOLE MOMENT

The determination of a dipole moment at each distance is as follows. Having computed d ,

$$B_{R_+} = \frac{2M_+}{(R+d)^3} \text{ or } M_+ = \frac{(B_{R_+})(R+d)^3}{2}$$

and

$$M_- = \frac{|B_{R_-}| (R-d)^3}{2}$$

at $48''$ or 1.2192 meters with $B_{R_+} = 19.87 \gamma$

and

$$|B_{R_-}| = 23.68 \gamma$$

$$M_+ = 19.63 \gamma \text{ m}^3$$

$$M_- = 19.63 \gamma \text{ m}^3$$

and $M_{ave_{48''}} = 19.63 \gamma \text{ m}^3$

at 72" or 1.8288 meters with $B_{R_+} = 5.95\gamma$ and $|B_{R_-}| = 6.55\gamma$

$$M_{ave_{72''}} = 20.69 \gamma m^3$$

At 36" $M_{ave} = 19.56 \gamma m^3$ so even with the variance of d , M_{ave} does not vary much from 36" to 72".

Averaging $M_{ave_{48''}}$ and $M_{ave_{72''}}$

$$M_{ave} = 20.16 \gamma m^3$$

Having computed the average dipole moment and the average displacement of the dipole we can construct Figure 4-6 for zenith rotation

Figure 4-6

A rotation of the RTG through a zenith angle θ results in an angle, between the radial vector $\hat{r}$ and the dipole axis, of Θ .

Since $\frac{d}{R} = \sin \lambda \cot \Theta - \cos \lambda$ and $\lambda = \pi/2 - \theta$

with $d = d_{ave}$ and λ determined from the zenith rotation, Θ can be computed.

Then using $r = \left[\frac{\sin \lambda}{\sin \Theta} \right] R$, r can be determined

$$\text{and } B_R = \frac{M}{r^3} \left[2 \cos \Theta \cos (\lambda - \Theta) + \sin \Theta \sin (\lambda - \Theta) \right]$$

can be used to get B_R which is the value the detector would read for the zenith rotation θ . This method has been used to check the fit of the assumed dipole to the data with the following results shown in Figure 4-2. On Figure 4-2 the fitted data is plotted as well as the measured data. It can be seen that the measured data is fitted by the dipole to within the noise level of $\pm 5\gamma$ present in the coil system. At 48" and 72" the maximum deviation is about 1γ from the plotted measured data points.

Thus the assumption of the dipole described above fits the field data gathered on the RTG assembly. Since the RTG center in the fixture is only 0.2" below the center of rotation and $\frac{0.2''}{24''} = \frac{20}{24} \%$ or $< 1\%$ error at the minimum distance the difference between RTG center and assembly center can be neglected for engineering computations. A plot of the actual field magnitude with respect to the dipole origin versus polar angle between dipole and radial vector from dipole origin is shown in Figure 4-7. The equation with respect to the dipole origin is

$$\vec{B} = \frac{M}{r^3} \left\{ 2 \cos \Theta \hat{r} + \sin \Theta \hat{\Theta} \right\}$$

so

$$B = \frac{M}{r^3} \left\{ 4 \cos^2 \Theta + \sin^2 \Theta \right\}^{1/2}$$

and the plot is made for $r^3 = 1$ so to get the value of the field at any distance from the dipole origin at any angle, take the value at the angle on the plot and divide by the cube of the distance. Since the value of B is invariant under a coordinate transformation this is also the value for a distance R from the package center and an angle λ between the radial vector $\hat{R}$ and the X axis which can be obtained by using the relations above.

TOTAL FIELD AT 1 METER
AFTER 15 OERSTED PERM IN POSITIVE X DIRECTION

Figure 4-7

SECTION 5
MAGNETIC FIELD OF THE RTG AFTER PERMING IN
A 15-OERSTED FIELD DIRECTED ALONG THE-Y AXIS

5.1 MEASUREMENTS AND DATA

The RTG was permed along the Y axis of the generator in the -Y direction with a 15 oersted dc field. Then the generator was returned to the reference position and rotated to find the peak radial field at 1.2192 meters. Next, starting with the RTG in the reference position, the RTG was rotated about the X axis to get radial field versus azimuth angle and about the Z axis to get radial field versus zenith angle. One distance was taken since the purpose of the crosswise perm is to show that the maximum remenance is obtained for perming along the X axis. Figure 5-1 is a plot of radial field versus azimuth. The zenith measurements show considerable noise.

5.2 RTG FIELD ANALYSIS

5.2.1 BASIC THEORY

The peak radial fields for both zenith rotation and azimuth rotation fall on the Y axis and the positive and negative peaks are 180° apart. The radial field in zenith and azimuth is roughly the same and the peaks differ by at most 0.4γ which is within the accuracy of the measurements.

The analysis of the dipole field for the crosswise perm is similar to that of the lengthwise perm. The negative peak for an azimuth angle of 90° is higher than the positive peak for an azimuth angle of 270° so the dipole is displaced along the Y axis a distance d toward the detector with the dipole vector pointing away from the detector in the reference position, as shown in Figure 5-2.

For an azimuth φ the position of the dipole is as shown in Figure 5-3, and the azimuth φ has the relation to λ

$$\varphi + \lambda = \frac{3\pi}{2}$$
$$\text{or } \lambda = \frac{3\pi}{2} - \varphi$$

and by this choice

$$B_R = \frac{M}{r^3} \left\{ 2 \cos \Theta \cos (\lambda - \Theta) + \sin \Theta \sin (\lambda - \Theta) \right\}$$

as before.

5.2.2 LOCATION OF THE DIPOLE CENTER

The + peak occurs at $\varphi = 270^\circ$ or $\lambda = 0$. When $\lambda = 0$ $\Theta = 0$, so

$$B_{R+} = \frac{2M}{(R+d)^3}$$

and the negative peak occurs at $\varphi = 90^\circ$ or $\lambda = \pi$ where $\Theta = \pi$ and $B_{R-} = -\frac{2M}{(R-d)^3}$

so $\sqrt[3]{\frac{|B_{R-}|}{|B_{R+}|}} = \frac{R+d}{R-d}$ and letting $\sqrt[3]{\frac{|B_{R-}|}{|B_{R+}|}} = A$

$$d = \frac{(A-1)}{(A+1)} R$$

From the data, $A = \sqrt[3]{\frac{4.2}{3.656}} = 1.149$ and with $R = 48$ inches

$d = 1.11''$ or 0.0282 meters.

5.2.3 VALUE OF THE DIPOLE MOMENT

$$M_2 = \frac{|B_{R-}| (R-d)^3}{2} = \frac{(4.2) (1.164)^3}{2} = 3.312 \gamma m^3$$

$$M_1 = \frac{B_{R+} (R+d)^3}{2} = \frac{(3.656) (2.07)^3}{2} = 3.78 \gamma m^3$$

and $M_{ave} = 3.56 \gamma m^3$.

Having computed the displacement of the dipole and the dipole moment, one can compute B_R as a check to see how well the assumed model fits the data. This has been done with the following results shown in Figure 5-1. Thus the assumed dipole model fits the data within experimental limits.

RADIAL FIELD VS AZIMUTH ANGLE AT 48 IN.
(15 OE PERM ALONG NEGATIVE Y DIRECTION)

Figure 5-1

Figure 5-2. Dipole Vector Pointing away from Detector

Figure 5-3. Position of Dipole for Azimuth ϕ

The assumption of the above dipole at the dipole position fits the data. The zenith angle data is fitted also. A plot of the actual field magnitude with respect to the dipole origin versus polar angle between dipole and radial vector from the dipole origin is shown in Figure 5-4. The equation with respect to the dipole origin is

found by
$$\vec{B} = \frac{M}{r^3} \left\{ 2 \cos \Theta \hat{r} + \sin \Theta \hat{\Theta} \right\} \text{ and the plot is for } r^3 = 1. \text{ B at any point can be}$$

$$B = \frac{M}{r^3} \left\{ 4 \cos^2 \Theta + \sin^2 \Theta \right\}^{1/2} \text{ and the geometry can be used to put this in terms}$$

of R and φ or R and θ .

Comparing the moment obtained from lengthwise perming with the moment obtained by crosswise perming

$$\frac{M_{\text{long}}}{M_{\text{cross}}} = \frac{20.16}{3.55} = 5.66 \sim 6$$

and the displacements from the center are about the same. This clearly shows that the worst case perming is along the +X axis.

Figure 5-4

SECTION 6

INDUCED MAGNETISM IN THE RTG

6.1 MEASUREMENTS AND DATA

A dc field of 0.26 oersteds was applied in the +Y' direction of the coil system coordinates and the field due to the RTG measured as the RTG was slowly rotated in the field. Figures 6-1 and 6-2 show the radial field detected as the device was rotated in the zenith and then in azimuth. It is found that the peak radial fields fall on the X axis and that the peak positive* fields are 180° apart from the peak negative* fields. The positive peak is obtained when the +X axis is aligned with the +Y' axis of the coil system so that the top of the package is pointing directly at the detector. The negative peak is obtained when the -X axis is aligned with the +Y' axis so that the bottom of the RTG points directly at the detector. Both fields are positive directed, however, since the direction of the inducing field does not change as the RTG is rotated. The peak fall-off with distance is plotted in Figure 6-3. The slope of the + peak radial field and the - peak radial field curve is -3.38 or approximately -3, which is a dipole field characteristic.

6.2 ANALYSIS OF DATA

6.2.1 BASIC THEORY

The RTG is rotated slowly enough so that magnetic domains can keep pace with the field change. Thus, as the device is rotated, the value read at the detector on the Y axis represents the induced magnetism of the RTG for a field directed at an angle $\pi/2 + \theta$, for zenith angle rotation, to the X axis and at an angle $\pi/2 - \phi$ to the -Y axis for azimuth rotation as can be seen in Figures 6-4 and 6-5.

The data at 48" shows that for a field of 0.26 γ there is no best crosswise direction of magnetization and for a field of 0.26 γ the direction of maximum induction is lengthwise or along the X axis.

*Note: Although for induced magnetism both peaks are positive directed it is convenient to retain the nomenclature used in Section 5 for purposes of identification and differentiation between 2 peaks obtained for rotation at a given distance.

Figure 6-1

Figure 6-2

Figure 6-3

Figure 6-4

Figure 6-5

The maximum induced moment can be considered as a dipole moment displaced from the package center as in the permanent moment case. The two peaks for induction are both positive for induced magnetism since rotating the device 180° in zenith is the same as reversing the direction of the field by 180° that is causing the induced moment. The origin of the moment will not change if the field reversal was slow enough, but its direction will change 180° . Since the induced moment for the field in the +X direction is smaller than the induced moment for the -X direction, the dipole must be displaced toward the bottom of the RTG along the -X direction from the package center. The displacement can be determined by taking the ratio of the peaks.

6.2.2 DISPLACEMENT OF THE INDUCED DIPOLE MOMENT

$$\text{At } 48'' \quad B_{R_{+x}} = 1.3 \gamma = \frac{2M}{(1.2192 + d)^3}$$

and

$$B_{R_{-x}} = 1.6 \gamma = \frac{2M}{(1.2192 - d)^3}$$

or

$$\frac{B_{R_{-x}}}{B_{R_{+x}}} = \frac{1.6}{1.3} = \frac{(48 + d)^3}{(48 - d)^3} = 1.231, \text{ using inches instead of meters}$$

and

$$1.0717 = \frac{48 + d}{48 - d}$$

and

$$d = 1.66 \text{ inches or } 0.0422 \text{ meters.}$$

6.2.3 VALUE OF THE DIPOLE MOMENT

$$M_{+x} = \frac{(R + d)^3 B_{R_{+x}}}{2} = \frac{(2.01)(1.3)}{2} = 1.307 \gamma m^3 = 1.31 \gamma m^3 \text{ to 2 places accuracy}$$

at $R = 48''$ and

$$M_{-x} = \frac{(R - d)^3 B_{R_{-x}}}{2} = \frac{(1.6)(1.631)}{2} = 1.305 \gamma m^3 = 1.31 \gamma m^3 \text{ to 2 places accuracy}$$

and

$$M_{ave} = 1.31 \gamma m^3$$

Then the maximum induced moment is along the X axis and for the field directed in the +X direction the maximum dipole moment can be drawn as shown in Figure 6-6.

Figure 6-6. Maximum Dipole Moment

Figure 6-7 is a plot for $r^3 = 1$ of the total field of the maximum induced moment.

TOTAL FIELD AFTER DEPERMING IN THE PRESENCE OF A 0.26
GAUSS INDUCING FIELD IN THE POSITIVE Y DIRECTION FOR $r=1$ METER

Figure 6-7

SECTION 7

STRAY FIELD

7.1 MEASUREMENT AND DATA

The field due to currents flowing in the RTG (stray field) was measured for currents of 1, 3, 4, 6, 8 amperes. Figures 7-1 through 7-6 are plots of the fall-off of stray field with distance from package center for each package axis (+X, -X, +Y, -Y, +Z, -Z). The peaks for 36", 48", 72" for current ≥ 3 amp all occur at about (330° zenith, 40° azimuth) for the + peak and (180° zenith, 110° azimuth) for the -peak. Since the fields are very small for a current of 1 ampere and even for 3 amperes, a measurement error of 10° at 3 amps can be due to noise and therefore disregarded. This occurred for the peak at 72" at 3 amperes where the + peak read (350° , 60°) and the - read (180° , 120°). The + peak here was 0.7γ and the - peak, -0.8γ , and these are small enough so that a measurement error of 0.5γ can have serious consequences. At 1 ampere the peaks are so small as to be easily subject to the measurement error and there the angles read were + peak (305° , 50°) and the - peak was not taken. The fall-off of peak field with distance is plotted in Figure 7-7. It is important for proper orientation to keep in mind that to get to each peak first rotate the package in azimuth, then in zenith. The reverse will not give the same orientation.

For this measurement tightly twisted pairs were used in the cable and it was carefully determined that the cable was not affecting the measurements. Full details on the measurement procedure can be obtained in Reference 2.

7.2 ANALYSIS OF DATA

Referring to Figures 7-1 through 7-6 the curves for the +X and -X axis all have slopes which can be rounded off to -4 while the curves for the +Y, -Y, +Z, -Z axis have slopes which can be rounded off to -3. Also, the ratio of values of the +X, -X fields to +Y, -Y, +Z, -Z fields at 2 meters are about $1/9$. This indicates that the degaussing loops are indeed suppressing the dipole field along the X axis as they were designed. The field along the X axis has a quadrupole fall-off $\sim 1/r^4$, while along the Z and Y axes a dipole fall-off $\sim 1/r^3$.

The peak fall-off of stray field with distance goes as $1/r^3$ since the slope of $\log |B_R|$ versus LOG R is $-2.9 \sim -3$ along the + peak axis and the - peak axis. If the + peaks and the - peaks

Figure 7-1

Figure 7-2

Figure 7-3

Figure 7-4

POSITIVE Z AXIS STRAY
FIELD RADIAL COMPONENT
(POSITIVE Z DIRECTION)

Figure 7-5

NEGATIVE Z AXIS STRAY
FIELD RADIAL COMPONENT
(FIELD IN POSITIVE Z DIRECTION)

Figure 7-6

Figure 7-7

fall roughly on a straight line, then we can make an identification of a dipole moment along this line.

Consider the X axis. If the positions of the X axis differ by 180° for the + and - peaks, then the peaks are on the same line.

An azimuth angle rotation of φ as azimuths are defined in Section 2 is equivalent to rotating the Z, Y axes to Z_1 Y_1 , at an angle of $\delta = \pi/2 - \varphi$ from the Z', Y' axes respectively as shown in Figure 7-8. The rotation matrix for this rotation is

$$\begin{pmatrix} \cos \delta & \sin \delta & 0 \\ -\sin \delta & \cos \delta & 0 \\ 0 & 0 & 1 \end{pmatrix} = R_1$$

and $R_1 \begin{pmatrix} Z' \\ Y' \\ X' \end{pmatrix} = \begin{pmatrix} Z_1 \\ Y_1 \\ X_1 \end{pmatrix}$

Figure 7-8

so the angle between the peaks is $\cos^{-1} \left(-\frac{\sqrt{3}}{2} \right)$ which is 150° which means that the + and - peaks are not exactly on a straight line. The picture obtained is as shown in Figure 7-9.

Figure 7-9

The difference in alignment between the peaks can be interpreted as follows. The field falls off as a dipole along the Y and Z axis of the package; and if the angle in Figure 7-9 were 180° there would be a true dipole lying in the YZ plane having its origin at the package center. This would be the case if the degaussing loops were functioning perfectly. The field falls off roughly as a quadrupole along the X axes showing that the degaussing loops are working. The misalignment of the peaks is probably due to the not perfect cancellation of the dipole field from the end loop segments of the RTG by the degaussing loops along directions other than the X axis. This problem will be considered carefully by a spherical harmonic analysis at a later time. There is a rough net dipole moment, however, which can be determined approximately by taking the peak fall-off with distance as follows.

A rotation in zenith about the Z_1 axis has the rotation matrix

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} = R_2$$

Then any point on the RTG at coordinates $\begin{pmatrix} Z' \\ Y' \\ X' \end{pmatrix}$ are rotated to $R_2 R_1 \begin{pmatrix} Z' \\ Y' \\ X' \end{pmatrix} = \begin{pmatrix} Z \\ Y \\ X \end{pmatrix}$

for an azimuth rotation followed by a zenith rotation. In the reference position the X axis of the package is aligned with the X' axis of the coil coordinate system. A rotation to azimuth of $\varphi = 40^\circ$ gives $\delta = 50^\circ$. The rotation of a point $\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$ on the X axis in the reference position through $\varphi = 40^\circ$ and then $\theta = 330^\circ$ gives

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos 330^\circ & \sin 330^\circ \\ 0 & -\sin 330^\circ & \cos 330^\circ \end{pmatrix} \begin{pmatrix} \cos 50^\circ & \sin 50^\circ & 0 \\ -\sin 50^\circ & \cos 50^\circ & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} Z \\ Y \\ X \end{pmatrix}$$

or

$$\begin{pmatrix} Z \\ Y \\ X \end{pmatrix} = \begin{pmatrix} 0 \\ -1/2 \\ \sqrt{3}/2 \end{pmatrix}$$

A rotation to $\varphi = 110^\circ$ followed by a rotation to $\theta = 180^\circ$ gives

$$\begin{pmatrix} Z \\ Y \\ X \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$$

The dot product of these two vectors is the cosine of the angle between them since they are unit vectors so

$$(0 \ 0 \ -1) \begin{pmatrix} 0 \\ -1/2 \\ \sqrt{3}/2 \end{pmatrix} = -\frac{\sqrt{3}}{2}$$

If the peaks were the peaks of some dipole of moment M , then the radial field read by the detector, when the package is rotated until the peaks are encountered at a distance R , would be

$$B_R = \frac{2M}{R^3} \text{ at the + peak and } B_R = \frac{-2M}{R^3} \text{ at the - peak.}$$

The fact that the peaks

are only 150° apart, however, means that the field is not a true dipole field, but the facts that the peaks are equal but of opposite sign and fall off as $1/R^3$ means that to a small but important correction factor we are close to the actual peaks of the dipole field. Therefore, we can solve the above equations to get M at each current. So solving for M using data from Figure 7-7 for B_R ;

$$M = \frac{B_R R^3}{2} \text{ and at 1 meter the following results are obtained.}$$

R	Current	Moment
1	8 amps	$6.5 \gamma m^3$
1	6 amps	$5 \gamma m^3$
1	4 amps	$3.5 \gamma m^3$
1	3 amps	$2.4 \gamma m^3$

These moments scale linearly with current since

I_1	I_2	I_1/I_2	M_1	M_2	M_1/M_2
8	6	1.333	6.5	5	1.3
8	4	2	6.5	3.5	1.86
8	3	2.67	6.5	2.4	2.71

This result of the dipole moment M being proportional to the current indicates that the field from the current configuration does not appreciably perm the generator or else nonlinear scaling with current would be obtained in comparing the dipole moment.

Summing up, then, a rough dipole moment having its origin at the package coordinate system origin (approximately center of RTG) can be used to estimate field magnitudes at distances $> R = 36''$ for the stray field. A better moment will be obtained when the spherical harmonic analysis is performed. This analysis may also permit an improvement in design of the degaussing system.

SECTION 8

INITIAL PERM AS RECEIVED IN EARTH'S AMBIENT FIELD

Although these were the first measurements taken chronologically, the following two sections are here given last, since these measurements are considered to be of lesser significance than those described in preceding sections. The presently described measurements do, however, reflect the magnetic history of the MOD 8 components during manufacture and assembly. Comparison of the results from the following two sections gives some indication of the high degree of stability of the generator magnetic properties.

8.1 BASIC MEASUREMENTS AND DATA

With the coil system inoperative and the magnetometer nulled by its internal null, the MOD 8B was rotated to find the + peak radial field point and the negative radial field point. Then the MOD 8B was rotated from the reference position in zenith angle and the field plotted with an X-Y chart recorder. Returning the MOD 8B to the reference position, it was then rotated in azimuth and the field plotted with an X-Y chart recorder.

It is found that the positive peaks are obtained with the zenith angle about $\theta = 140^\circ$ and the azimuth $\phi = 90^\circ$, while the negative peaks are obtained for approximately $\theta = 265^\circ$, $\phi = 90^\circ$. The position for the + peak is shown in Figure 8-1 and the negative peak in Figure 8-2. The + and - peaks are only 125° apart.

Plots of the fall-off with distance of the peak positive and negative radial fields are given in Figure 8-3. Plots of the fall-off with distance of the radial field along the +X, -X, +Y, -Y, +Z, -Z axes are given in Figure 8-4, 8-5 and 8-6.

The slope of the curve of log peak negative radial field versus log distance has a slope of -3.3 and the slope of log + peak radial field versus log distance is -2.5 so that the peak radial fields are falling off with distance roughly as $1/R^3$.

The slope of the log radial field magnitude versus log distance along the -X axis is -3.38 or approximately -3 and along the +X axis -3.38 or approximately -3. The slope along the Y axis is -3.46. The slope along the Z axis is -4.1. Along the X axis the field reverses sign from the +X axis to the -X axis as the package is rotated from +X to -X axis while the field does not reverse sign as the package is rotated in azimuth.

Figure 8-1

Figure 8-2

Figure 8-3

Figure 8-4

Figure 8-5

Figure 8-6

8.2 ANALYSIS OF DATA

As the package is rotated from its reference position, the detector sees a net field due to two moments, the permanent moment of the package and the induced moment due to the earth's ambient field. As the device is rotated in azimuth the direction of the field does not change. As the package is rotated in zenith, the field reverses sign showing the presence of a permanent moment directed such that it has a large component in the +X direction. This means that it must only be slightly misaligned from the X axis.

Rather than define moments for the results given above, it is better to use the curves to define the radial fields measured with distance. The random perming the device has seen, the presence of the ambient field, etc. , make it unrealistic to treat the package as a bar magnet in this case. Comparing these curves with the curves in Section 9 will provide a measure of the stability of the total moment and better define what permanent moment is really there.

SECTION 9

INITIAL PERM AS RECEIVED IN ZERO FIELD ENVIRONMENT

9.1 BASIC MEASUREMENTS AND DATA

With the coil system operative, the package was rotated to find the peak + and peak - radial fields. Then the package was rotated in zenith 360° and then in azimuth 360° to get the field variation with zenith and the field variation with azimuth. The distances at which this was done was $R = 24''$, $36''$, $48''$, and $72''$. The variation in zenith and azimuth was plotted on the X-Y recorder.

The peak + field at $R = 72''$ is located at $\theta = 120^\circ$, $\varphi = 90^\circ$ and the peak - field at $\theta = 270^\circ$, $\varphi = 90^\circ$. The peak + fields at $R = 48''$ and $36''$ are located at $\theta = 135^\circ$, $\varphi = 90^\circ$, and the peak - fields at $\theta = 270^\circ$, $\varphi = 90^\circ$. The peak + field at $R = 24''$ is located at $\theta = 150^\circ$, $\varphi = 90^\circ$, and the peak - field at $\theta = 275^\circ$, $\varphi = 90^\circ$. The peak positive fields then roughly line up at $\theta = 135^\circ$, $\varphi = 90^\circ$ with a variation of 15° or $15/360 = 0.0415$ or $4.15\% \sim 4\%$ and the peak negative fields line up at $\theta = 270^\circ$, $\varphi = 90^\circ$. These positions are sketched in Figures 9-1 and 9-2.

Figure 9-1

Figure 9-2

This is roughly the same as the peaks measured for the package in the ambient field with at most a shift of 5° or 0.014 or 1.4% in zenith and azimuth.

The fall off of peak radial field with distance is given in Figure 9-3. The slope of $\log B_R$ versus $\log R$ where B_R = radial field, R = distance from package center is $-3.38 \sim -3$. The variation of B_R with R along the $+X$, $-X$, $+Y$, $-Y$, $+Z$, $-Z$ axes are given in Figures 9-4, 9-5 and 9-6. The slope of $\log B_R$ versus $\log R$ along the $+X$ axis is -2.43 and along the $-X$ axis is -3.53 . These can be averaged to give roughly -3 so along the X axis the dipole field still dominates but higher order fields are contributing. The slope of $\log B_R$ versus $\log R$ along the $-Y$ axis is $3.4 \sim -3$ and since there are only two acceptable data points for the $+Y$ axis a best fit line was drawn there and is roughly parallel to the $-Y$ axis line. The slope along the $+Z$ and $-Z$ directions is -3.54 .

9.2 ANALYSIS

The change in environment from earth ambient to zero field environment has not affected the measured field of the package to any appreciable degree except along the X axis and this

Figure 9-3

RADIAL FIELD VARIATION
WITH DISTANCE ALONG X AXIS

Figure 9-4

Figure 9-5

Figure 9-6

could be due to removal of the ambient field or some other factor such as measurement error. The results of Sections 8 and 9 show, however, that the initial perm of the package is a permanent magnetic configuration. The random magnetic history of the device makes it difficult to interpret the field in any dipole moment sense, however. The failure to obtain a field reversal upon rotation in azimuth is not due to an induced moment as could have been the case in Section 8. The random perming of each hotshoe and Kovar headers is simply such as to produce this field at the measurement-distances. For the as-received state, then the curves are the only means of specifying the observed fields and stating field magnitudes with distance. As the measurements proceeded however, as described in the previous sections, by removing this random history and substituting a known history the worst case dipole moments have been determined.

SECTION 10

CONCLUSIONS

The MOD 8B RTG differs from the flight RTG insofar as disposition of ferrous material. Ten internal iron constantan thermocouples were located within the MOD 8B are situated as in Figure 10-1. The iron used in these thermocouples is situated toward the base of the RTG and as can be seen in the figure the bulk is between fins 4 and 6, or on the -Y side of the generator. The Kovar headers are at the base of the generator and one is located on the centerline of fin 4 and the other a little to the right of it toward fin 3. This unequal weighting of ferrous material explains to a large extent the shift in dipole moment from the package center which is at most 0.2" from the MOD 8B center to a point about 1.2" down from the center toward the base when permed lengthwise in a 15 oersted field. The amount of ferrous material around fins 4 and 6 is about a total of 52 inches length of soft iron from the thermocouples plus the amount of ferrous material in the Kovar headers. This explains why on perming the MOD 8B crosswise the dipole origin is not at the package center but displaced some 1.11" along the Y axis in the -Y direction.

Since the iron hotshoes are distributed symmetrically on the surface of a cylinder with axis along the X axis and the wires are parallel to the X axis the greater moment on perming would naturally occur for lengthwise perming. For random perming a large moment located almost on the X axis would be expected and this is observed.

The worst case field for the generator can be obtained for several situations and these are:

- 1) permed lengthwise and stray
- 2) permed crosswise and stray
- 3) induced and stray

The procedure is to use the package center as the origin and locate the dipole origin of either the permanent moments or the maximum induced moment with respect to the package center. The angle between the dipole and the radial vector can be determined as has been shown above. The field at the point in question can be determined from the dipole field formulas given. If the point is on axis the actual stray field magnitude should be added. If it is off axis the approximate dipole moment for the stray field should be used.

BOTTOM VIEW OF MOD 8B GENERATOR ASSEMBLY

LENGTH OF 2 IRON LOADS AT 13°	IS 9.55 IN.
LENGTH OF 2 IRON LOADS AT 40°	IS 14.27 IN.
LENGTH OF 2 IRON LOADS AT 120°	IS 8.26 IN.
LENGTH OF 2 IRON LOADS AT 225°	IS 8.26 IN.
LENGTH OF 2 IRON LOADS AT 332°	IS 2.25 IN.

Figure 10-1

SYMBOLS USED IN THIS DOCUMENT

1. θ = zenith as defined in Section 1.
2. φ = azimuth as defined in Section 1.
3. Θ = angle between dipole vector and radial vector from dipole center to field point as defined in each section for each fitted dipole moment.
4. R = distance from package (generator assembly in the fixture) center to field point.
5. r = distance from the fitted dipole to field point.
6. d = displacement of dipole from package center.
7. $\hat{R}$ = unit radial vector along R .
8. $\hat{r}$ = unit radial vector along r .
9. $\hat{\theta}$ = unit polar vector in direction of increasing θ .
10. $\hat{\Theta}$ = unit polar vector in direction of increasing Θ .
11. B_R = radial field along R in gammas and is the field actually measured by magnetometer.
12. B_r = radial field in gammas along r .
13. B = total field in gammas.
14. $\overrightarrow{B_R}$ = vector radial field along $R = B_R \hat{R}$.
15. $\overrightarrow{B_r}$ = vector radial field along $r = B_r \hat{r}$.
16. $\overrightarrow{B}$ = total vector field and for a dipole field
$$\overrightarrow{B} = \frac{B}{\sqrt{4 \cos^2 \Theta + \sin^2 \Theta}} \left\{ 2 \cos \Theta \hat{r} + \sin \Theta \hat{\Theta} \right\}$$
17. M = dipole moment in γ meters³.

REFERENCES

1. Parsons, C. L. and Harris, C. A., "Component Magnetic Test Facility Operations and Test Procedure Manual", Goddard Space Flight Center, Greenbelt, Maryland, July 1965, NASA X-325-65-312.
2. Test Plan for Model No. 8 Generator Assembly, Magnetic Evaluation Test, SI249167, Advanced Nuclear Systems Operation, General Electric Missile and Space Division.