X-325-67-70

NASA TM X-55790

MAGNETIC FIELD RESTRAINTS FOR SPACECRAFT SYSTEMS AND SUBSYSTEMS

GPO PRICE $ ____________

CFSTI PRICE(S) $ ____________

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

FEBRUARY 1967

NASA

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

N68-11295 (ACCESSION NUMBER)	(THRU)
94 (PAGES)	1 (CODE)
TMX #55790 (NASA CR OR TMX OR AD NUMBER)	30 (CATEGORY)

FF No. 602(A)

[redacted]

X-325-67-70

MAGNETIC FIELD RESTRAINTS FOR SPACECRAFT SYSTEMS AND SUBSYSTEMS

February 1967

Goddard Space Flight Center
Greenbelt, Maryland

X-325-67-70

MAGNETIC FIELD RESTRAINTS FOR SPACECRAFT SYSTEMS AND SUBSYSTEMS

Written by: ______________________
Charles A. Harris

Reviewed by: ______________________
C. Leland Parsons
(Head, Magnetic Test Section)

____
Dr. Norman F. Ness
(Project Scientist, IMP H & J)

Approved by: ______________________
John C. New
(Chief, Test & Evaluation Division)

MAGNETIC FIELD RESTRAINTS FOR SPACECRAFT SYSTEMS AND SUBSYSTEMS

ABSTRACT

Methods for limiting the magnetic fields generated by spacecraft systems and subsystems, are discussed in this report. Accepted practices useful in the design and fabrication of spacecraft systems, actual data related to the fields generated by individual components, and specific examples of field reduction techniques are furnished.

CONTENTS

MAGNETIC FIELD RESTRAINTS FOR SPACECRAFT SYSTEMS AND SUBSYSTEMS

INTRODUCTION

The problems associated with magnetic field restraints for components and spacecraft tend to vary according to the spacecraft program requirements. Those spacecraft which include magnetic field experiments; i.e., OGO, EPE-D, IMP*, and Pioneer must control and limit the magnetic field disturbance of the integrated spacecraft so that no undue magnetic field interference will occur at the flight sensor position. In the case of spacecraft which employ magnetic or gravity gradient attitude control systems, i.e., AE-B, ATS, DME & OAO, the magnetic field restraint problems are normally not as stringent; however, all satellite designers should avoid the use of components and sub-assemblies with significant magnetic dipole moments since these will increase magnetic torquing effects and place additional loads on the attitude control system. Thus, because of these requirements, information is presented pertaining to;

1. reduction of magnetic field disturbance magnitudes for spacecraft and spacecraft components and,

2. comparison of the magnitude of magnetic field to be expected for the various components; i.e., batteries, motors, relays, etc.

In the course of measuring the magnetic properties of the various sub-assemblies, a test procedure has been established which includes separate determinations of both the permanent and the stray field magnetization of the sub-assemblies since these two conditions represent the prominent sources of spacecraft magnetic field restraint problems. The stray field measurements are designed so that it is possible to differentiate between the power-on vs. power-off conditions of operation as well as the shifts in the stray-field levels during operation of the equipment. In the case of the permanent magnetization measurements, the following conditions or states are normally measured:

A. Initial Perm – "as received" magnetic state of item which provides the following information:

*Appendix A enumerates in detail the magnetic test program for IMP's H and J.

1. Indicates one possible level of perm which may exist for a newly manufactured item of the same design.

2. Indicates a relative magnitude of field which is used to determine the effectiveness of the deperm treatment.

3. Indicates stability of perm by initiating a record of its magnetic history.

B. Post Exposure – magnetic state of item after exposure to a 15 or 25 gauss D.C. magnetic field which represents the most probable maximum field to which the item is expected to be exposed during the environmental testing.

During the past and at the present time the exposure field magnitude has been maintained at a level of 25 gauss. This 25 gauss field corresponds to the field levels which were measured in the vicinity of shaker tables used during environmental testing. Subsequently, these shakers have been replaced with units which generate lesser fields, except for a large MBC 210 shaker which is primarily used for spacecraft testing. Furthermore, the tested assembly is mounted several inches above the top surface of the table which results in a further reduction of the field magnitude. As explained in the attached report (Appendix B, Review and Analysis of OGO-A and OGO-C S-49 and S-50, Experiment Assembly Magnetic Test Data) an exposure level of 15 gauss has been determined to be more realistic for depicting the "blackest picture" for the assembly. At the present time data are being acquired to provide for a correlation between these two levels of exposure. These data can then be incorporated with the presently available data which are displayed in Appendix B (Figure 6) and C (Figure 8) as well as Table I-2 of NASA TN D-3376.

C. Post Deperm – magnetic state of item after being demagnetized in a 50 gauss field (normally 60 Hz AC field). Appendix C provides further data related to methods of demagnetization and compares the results obtained.

For the purpose of uniformity, the enclosed tables of data relate the magnetic field magnitudes for the various components by indicating the magnetic field disturbance in gamma (10^{-5} oersted) at a distance of 12 inches from the center of the object. This magnitude has been either measured directly or extrapolated, (by inverse cube) from supplementary distance data. In many cases two or more identical items were measured to ensure more representative data; however, in these cases only the maximum value has been indicated. In the case of particular components which are required to be non-magnetic, i.e., resistors, connectors, the data is presented for the distance of 2 inches. Basically, these tables are intended to represent the various field levels to be expected from the object rather than representing an acceptable or nonacceptable parts list. This is the only recourse in view of the wide disparity in the design goals of the various programs in which the item might be utilized. Nevertheless the use of non-magnetic materials is especially desirable in the case of these spacecraft programs which include magnetic field experiments and in these cases it would be desired to select parts and accessories whose measured fields are less than 0.2 gammas at 2 inches (post exposure). As a criteria in the determination of suitable magnetic field restraint goals applicable in the selection of parts and accessories, one can refer to Table I. This table (I) indicates the design goal magnitudes established for a distance of 12 or 36 inches. For the purposes of comparison, these levels have been converted to magnetic moment magnitudes for the various systems of units*. Although the field restraint problems associated with the many various components can be quite similar, the components have been subdivided into separate categories as indicated in the table of contents.

Batteries

Information pertaining to the magnetic field characteristics of various types of batteries which are utilized in spacecraft has become of decided interest because of the varied magnetic field restraint requirements connected with the spacecraft programs. As a result, data has been obtained from tests of batteries associated with a number of these spacecraft programs (IMP, UK-2, OAO, and OGO), and is summarized in this section.

Permanent Magnetization

In the event a battery is being selected for use on a relatively non-magnetic spacecraft, i.e., spacecraft which contain magnetic field experiments, the recommended types of cells are those which utilize the nonmagnetic silver cadmium electrodes. The NICAD cells should be particularly avoided since these cells have substantial permanent magnetic field characteristics due to the presence of the nickel material. With the use of nickel, the magnitude of the permanent magnetization will vary according to the magnitude of field to which the cell has been exposed. While in the depermed state the field magnitudes might be substantially lower, under normal ambient field conditions this

*Since the data in the component tables represents the maximum radial component magnitude, conversion to a dipole moment magnitude is achieved by the following formula:

$$M = \frac{f_r \, r^3}{2}$$

TABLE 1

SPACECRAFT AND COMPONENTS – RADIAL COMPONENT AND MOMENT MAGNITUDES

	Program	Radial Component Magnitude-Gammas		Magnetic Moment Magnitudes Gamma – FT^3	Gauss-CM^3 (CGS) or pole – CM	Weber-Meter (MKS)
Spacecraft		3 feet	24 feet			
	ATS		0.5	3500	1000	130×10^{-8}
	RAE		0.3	2070	584	74×10^{-8}
	OGO		0.1	700	200	25×10^{-8}
	IMP	10		135	38	4.8×10^{-8}
	Pioneer*	5		68	19	2.4×10^{-8}
Components		12 inches	36 inches			
	ATS	710		350	100	10×10^{-8}
	RAE		20**	270	77	9.7×10^{-8}
	OGO	500		250	71	8.9×10^{-8}
	IMP		4**	54	15.2	1.9×10^{-8}
	Pioneer		2**	27	7.6	0.96×10^{-8}

*design goal 0.5 @ 80" **post exposure

magnitude could be expected to increase by at least a factor of three. In addition to the selection of the silver cadmium electrodes, the battery case should be nylon or polystyrene while the associated hardware would be composed of non-magnetic materials (i.e., brass, aluminum or copper). In the case of other spacecraft programs, where the nonmagnetic requirements are not quite as stringent, it might be more desirable to utilize the nickel cadmium cells due to preferred electrical characteristics. In this event, data has been gathered to show what field contributions the various spacecraft battery packs contained. From these magnetic moment (CGS units) magnitudes which have been presented in Table II it should be possible to establish an expected value depending upon the size and type of battery utilized. The permanent magnetic moment is listed for the initial, post exposure, and post deperm states. The induced moment data indicates the moment magnitude for an applied field of 0.26 gauss which is somewhat less than half that of earth's field (0.5 - 0.6 gauss) whereas the in-flight magnitude would depend upon the spacecraft orbital magnetic field. Table III presents data related to the magnetic field disturbance for numerous individual battery cells, while giving evidence to the possible variations in magnitude which might occur depending upon cell composition and structure.

Stray Field Magnetization

While the use of silver cadmium cells will minimize the permanent magnetic field disturbance, its use will not reduce the stray field disturbance which depends upon the current flow in the individual cells as well as the combined terminal connection arrangement. Reduction and cancellation of the stray field can be best achieved in those cases where an even number of cells have been combined to form the complete battery pack. Cancellation of the stray field, would be accomplished by combining the cells back to back in pairs so that the stray field of one cell effectively opposes that of the other. When an odd number of cells are combined, the stray field of the one unmatched cell can be cancelled by adding a supplementary loop of wire which generates a stray field in opposition to that of the single uncompensated cell. The size of this loop would depend upon the type of cell to be compensated; however, as a rough guide, the loop is generally slightly smaller than the cell to be compensated. An example of the stray field characteristics of a cell is shown in Figure 1, which indicates the magnitude (with direction) of the stray field from a Yardney silver cadmium cell when measured at 18 inches.

In addition, Figure 1 shows the stray field magnitude as measured at three inches, at various levels along the Y face of the cell in order to demonstrate the location of the area of maximum stray field. When the cells are combined and connected electrically to form a complete battery, the assembled unit tends to generate, when energized, a stray field which is caused by the current loop

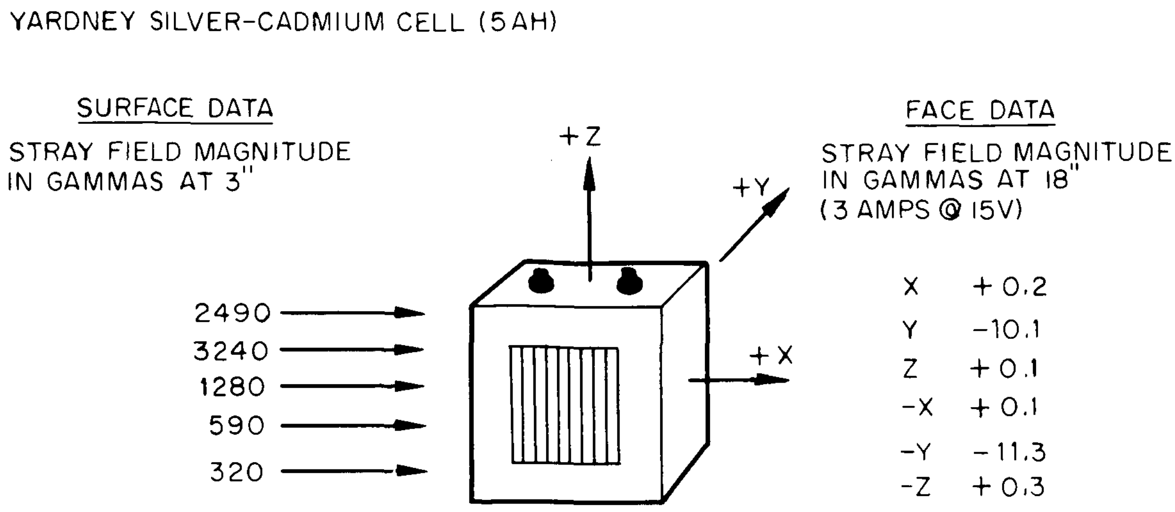

Figure 1–Single Cell Stray Field Magnetization

which the assembly forms when the cells are innerconnected. For effective cancellation, this stray field would require a single compensation loop which encloses the same area as the electrical connection arrangement of the battery and includes a current flow in the opposite direction. An example of the effectiveness of compensation is as follows: A 13 cell 5 AH circular battery pack, as utilized in the IMP spacecraft program, produced a stray field of 101.5 gammas at 18 inches without a compensation loop. With a single compensation loop, this magnitude was reduced to 15.1 gammas. By adjusting the size and position of this loop the field magnitude was further reduced to 7.6 gammas. Then after a small loop was added to the one uncompensated cell, this field was reduced 4.9 gammas. The net result was a 95 percent reduction in the stray field of tne battery. Although a 100 percent reduction might be expected, this is rather difficult since the size and positioning of the compensation loops become quite critical and if the loops are moved before or during the potting process, the stray field magnitude and direction will change. In the case where a 13 cell rectangular battery arrangement is utilized, the final results were comparable except that two small side loops were found to be more effective than a single one which had been utilized for the circular battery pack.

The results of various magnetic tests confirms that it is possible to have relatively non-magnetic batteries by proper selection of materials and the addition of stray field compensation loops. In the case of permanent field reduction, this is achieved by the selection of the SILCAD battery. Stray field reduction can be initiated in the laboratory but, for the final stages of compensation, a magnetically quiet test area is needed.

TABLE II
PERMANENT MAGNETIC MOMENTS OF BATTERIES

Spacecraft Program	Battery Type	Voltage and Current		No. of Cells	Initial Perm	Moment Magnitude in CGS Units			
		Volts	Amps			Post Exposure	Post Deperm	Induced (0.26Γ)	Stray Field
UK-2	Ni-Cad	1.3	–	10 cells	23	180	14	59	—
OAO	Ni-Cad	28	12	3 units	168	2521	49	401	679
OGO	Ni-Cad	28	–	22 cells	42 → 378	—	—	—	—
OGO	Sil-Cad	28	5		5	—	—	—	1106
IMP	Sil-Cad	13.5	3	13 cells	$\ll 1$	$\ll 1$	$\ll 1$	$\ll 1$	45(1)
IMP	Ni-Cad*	13.5	3	13 cells	19	1052	3	—	62
RAE (2)	Ni-Cad	14	4	12 cells	24	251	< 1	50	10
RAE (2)	Ni-Cad	16	4	12 cells	23	481	6	35	46
ATS	Ni-Cad	9	1.2		40	180	5	26	5

* Test unit
(1) <4 gammas compensated
(2) Both units contained 11 6AH Ni Cad cells but were from different manufacturers.

TABLE III
PERMANENT MAGNETIC FIELD OF BATTERY CELLS

Item	Type	Electrodes	Magnetic Field Magnitudes in Gammas at 12 inches		
			Initial	Post Exposure	Post Deperm
Electric Storage Battery Co.	5AH	SilCad	1.6	1.9	1.4
Yardney Electric Corp.	5AH	SilCad	<0.5	<0.5	<0.5
Gulton Industries, Inc.	4AG	NiCad	13.5	333.0	4.1
General Electric Co.	12AH	NiCad	333.6	864.0	14.4
General Electric Co.	4AH	NiCad	55.1	113.6	0.3
Sonotone Corp.	3AH	NiCad	6.8	171.7	0.6
Mallory Battery Corp.	1AH	Mercury (1)	70.0	217.5	<1.0
Mallory Battery Corp.	1AH	Mercury (2)	8.2	29.3	0.4

(1) 2.7 Volts
(2) 1.8 Volts

CAPACITORS

Normally, the permanent magnetic field disturbance of capacitors is sufficiently small, especially in a demagnetized state (≤ 0.2 gamma) so that their magnetic field characteristics are undiscernable when they are utilized in the construction of spacecraft assemblies. However, in the event spacecraft contain magnetic field experiments, even the use of a small quantity of capacitors can, when combined with otherparts, produce a significant field. As an example, Table IV indicates the permanent magnetic field disturbance magnitudes of various types of capacitors which, after exposure, vary from minimum of 5 gammas to a maximum of 130 gammas (distance - 12 inches). Two exceptions are the MLV and TE capacitors which utilize copper leads. The cross-section of a Sprague

TABLE IV
CAPACITORS

Manufacturer	Type	Value	Permanent Magnetic Field Magnetization		
			Magnitude in gammas at 12 inches		
		Mfd/Volts	Initial	Post Exposure	Post Deperm
Aerovox	P123ZNP	1 -200	4.5-37.2	130.1	1.2-2.8
		.47-200	12.8-30.0	122.3	0.1-0.5
Astron TES	CS 13AF	3.3 - 35	0.2- 1.0	4.6- 6.4	≤ 0.2
Erie	CS 13A	2.2 - 35	0.2- 1.0	4.6- 6.4	≤ 0.2
		6.8 - 35	1.0	12.8-16.2	≤ 0.2
General Instrument	CS 13A	0.33- 35	0.5- 2.3	14.0-12.5	≤ 0.2
		47 - 35	0.3- 1.0	19.8-24.3	≤ 0.2
	MLV*	50 - 50	≤ 0.2	≤ 0.2	≤ 0.2
GLP	CS 13A	35 - 10	15.5- 20.1	26.0	< 0.1
JFD	MC 604	6331	3.8	13.2	0.2
	MC 604	42	2.1	16.3	0.2
	MC 604	6502	3.8	15.2	0.2
	MC 613	6325	0.5	7.4	0.2
	VC 5	6403	12.4	19.8	0.2
	DS 453	DO	5.0	7.0	0.2
	MC 624	6452	6.0	9.4	0.3
Miniroc	CD	.01-100	< 0.1	< 0.1	< 0.1
Sprague	TE 1160*	50 - 15	< 0.1	< 0.1	< 0.1
	TE 1305*	20 - 50	< 0.1	< 0.1	< 0.1
	137D	70 - 15	1.5	26.0	< 0.2
		120 - 15	2.0	25.7	< 0.2
		220 - 8	2.0	28.4	< 0.2
		25 -125	0.0- 3.6	20.0-29.8	< 0.2
		560 - 6	0.9- 4.0	24.3-30.0	< 0.2
	150D	10 - 10	2.0- 5.5	18.0-19.5	≤ 0.2
		.01- 35	2.8	11.0-13.0	≤ 0.2
	150D	39 - 10	1.3	5.2	< 0.1
Westcap	CPO5A1	47 -400	4.3	130.5	0.2

type of solid tantalum electrolytic capacitor is shown in Figure 2. This type of capacitor contains a nickel anode lead (Kovar metal seal) as well as a copper-weld (copper plated steel wire) cathode lead. The three sources of magnetic field disturbance would then be the two leads plus the glass to metal seal material.

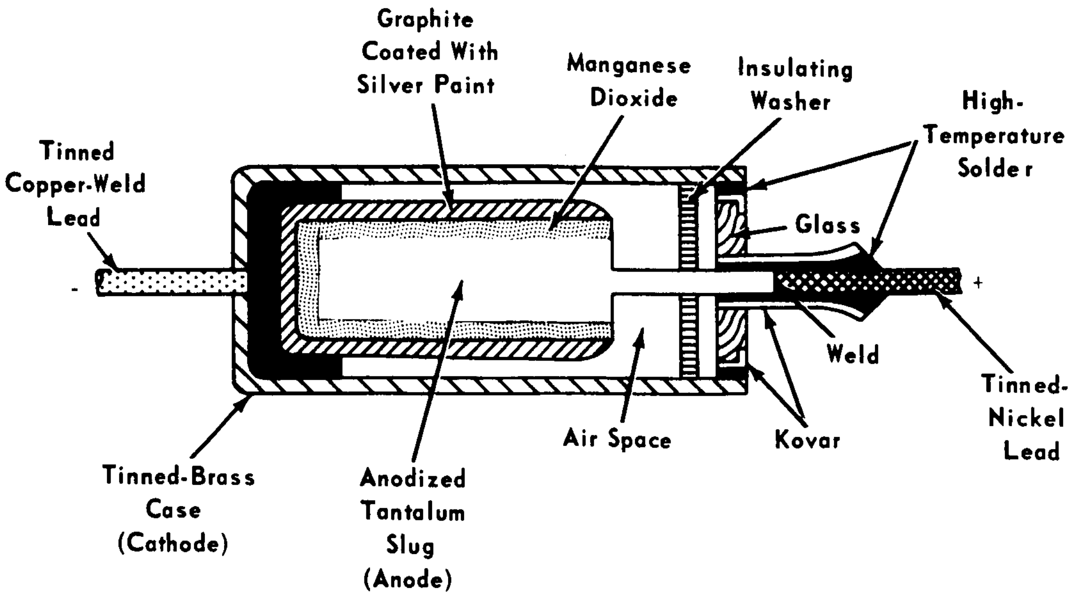

Figure 2–Construction Features of Sprague Type 150D Solid Tantalum Electrolytic Capacitor

To obtain a non-magnetic capacitor, it then would be necessary to replace these three items with non-magnetic materials or avoid capacitors which contain nickel, invar, 42 alloy, Kovar, dumet or copper weld materials. Another approach would be to minimize the effects of these materials by reducing lead lengths to less than 1/4 inch. When both leads cannot be shortened, a capacitor which contains a copper cathode lead should be selected so that this lead could be folded over while the anode is reduced to a minimum length. Table V cites specific examples of the reduction in field magnitudes which occur when the leads are shortened.

In comparing the two lead materials (copper weld and nickel) which the 150D capacitor contains, it is of interest to note the similarity in the measured post exposure magnitudes. For example, Figure 3 indicates the results of various levels of exposure which were obtained with 2 inch (length) samples of the two lead materials.

While there tends to be little difference between the two wires when exposed in zero background field a second test was performed to compare the effects of earth's field exposures. The two depermed wires ($<$ 0.1 gamma at 12") were

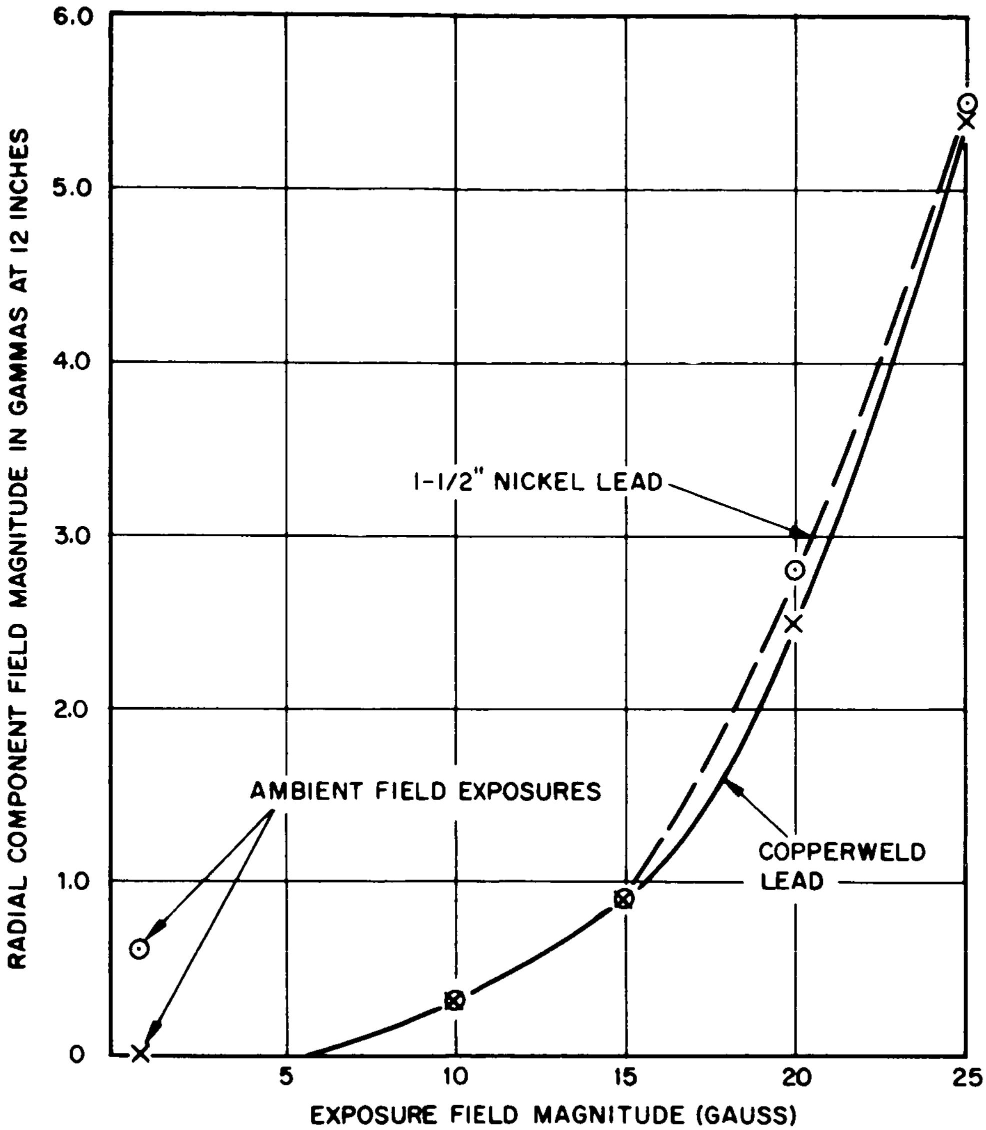

Figure 3—Magnetization Increase With Exposure Field Magnitude

placed in earth's field ($\leq$ 0.6 gauss) while being stressed and struck. As indicated in Figure 3, the copper weld (steel) wire remained in a depermed state while the softer nickel wire increased in magnitude to a level equivalent to a 12 gauss field exposure. Naturally, this effect would become negligible as the lead lengths are shortened but the fact that the stability of the deperm treatment can vary with the type of ferrous material is rather evident.

TABLE V
CAPACITOR FIELD REDUCTION RESULTS

CS 13A Capacitor	Field magnitudes in gammas at 12 inches			
Sample	Initial Perm	Post Exposure	Cathode Lead < 1/4"	Anode Lead < 1/4"
1. G.I.	1.0	19.8	< 6.4	≤ 0.2
2. G.I.	< 0.3	24.3	< 4.0	≤ 0.2
3. Erie	1.0	16.2	< 5.6	≤ 0.2
4. Erie	1.0	12.8	< 4.4	≤ 0.2

CONNECTORS

Magnetic field disturbance problems associated with connectors and junction boxes are generally minimized by obtaining the commercially designated non-magnetic units similar to the types which are listed in Table VI. By selecting the designated connectors which exhibit post exposure magnitudes below 3 gammas it is possible to avoid permanent field magnitudes in excess of 0.1 gamma at a distance of 6 inches. In the event connectors are to be placed in close proximity to actual magnetic field sensors, further careful testing of each individual connector, non-magnetic and otherwise, is recommended since even the designated non-magnetic connectors can be slightly magnetic at a distance of one or two inches. Normally, connectors which contain the white porcelain filler are the least magnetic primarily due to the fact that the pins and filler have fewer impurities. A suggested procedure for selection of suitable connectors for use near the magnetometers would be as follows:

1. Expose connector to a high field magnet (field strength from 100-500 gauss quite suitable).
2. Measure surface of connector to locate any "hot spots."
3. Deperm connector with a bulk tape eraser — deperm field magnitude from 800 — 1 K gauss recommended.
4. Repeat steps 1-3 using a 25 gauss exposure and 50 gauss depern (normal test procedure).

In the event the connector has some impurities, the high field deperm treatment provides effective demagnetization of the connector providing it is not re-exposed to a high field magnet. While the high field exposure will show if the connector contains impurities, the repeat exposure and demagnetization sequence is used to determine if the connector is usable if placed in a depermed state.

TABLE VI
CONNECTORS

Type	Quantity	Magnitude ranges in gammas at 2 inches		
		Initial	Post 25 gauss Exposure	Post Deperm
Cannon				
DAM				
11 WIS-NMC-2	1	0.4	0.4	0.2
15S-NM(R)*	15	0.4-1.2	0.6- 1.6	0.7
15P-NM(R)*	5	≤ 0.2	0.4	≤ 0.2
15S-NMC	11	0.3-0.5	0.5- 0.6	0.3-0.5
15P-NMC-1	9	0.1-0.5	0.3- 1.0	≤ 0.1
15S-NMC-2	10	≤0.2-1.6	≤ 0.2- 2.5	≤0.2-1.6
15P-NMC-2	6	≤0.2-0.7	≤ 0.2- 0.7	≤0.2-0.6
DBM				
13W3S-NMC-2	23	≤0.2-1.3	≤ 0.2- 1.4	≤0.1-0.5
13W3P-NMC-2	16	≤0.2-1.4	≤ 0.2- 1.6	≤0.1-1.0
21 WIS-NM(R)	4	≤ 0.2	≤ 0.2	≤ 0.2
25S NM(R)*	5	≤0.4-1.4	0.5- 2.0	0.4-1.3
25P NM(R)*	5	≤0.1-4.2	0.3- 4.6	≤ 0.4
25S-NMC-1	3	≤0.2-0.7	≤ 0.2- 0.7	≤0.2-0.6
25P NMC-2	13	≤0.2-1.4	≤ 0.4- 1.6	≤0.1-0.8
25S NMC-2	20	≤0.2-1.3	≤ 0.2- 1.4	≤0.1-0.5
DCM				
17W5P NMC-1	1	0.5	0.5	0.5
37S NM(R)*	15	0.2-0.7	0.2- 1.4	≤0.2-0.6
37P NM(R)*	9	0.2-7.2	0.2-27.4	0.2-1.5
37P NMC-2	3	0.1-1.4	0.1- 2.0	0.1-0.4
37S NMC-2	5	≤ 0.2	< 0.2	≤ 0.2
DDM				
11W1S NMC-1	2	0.2	0.2	0.2
24W7P NMC-2	3	0.3-0.7	0.3- 1.0	0.3-0.7
24W7P NMC-2	5	≤ 0.5	≤ 0.5	≤ 0.5
24W7S NMC-1	3	≤0.2-3.0	≤ 0.2- 3.2	≤0.2-3.0
24W7S NMC-2	6	≤ 0.5	≤ 0.5	≤ 0.5
25P-NMC-2	2	0.3	0.3	0.2

TABLE VI
CONNECTORS—Continued

Type	Quantity	Magnitude ranges in gammas at 2 inches		
		Initial	Post 25 gauss Exposure	Post Deperm
DDM (continued)				
36W4S-NMC-1	2	0.9	4.0	≤ 2.4
50P-NM(R)*	5	< 1.5	< 2.2	≤ 1.5
50S-NM(R)*	26	0.2-6.6	0.7- 7.7	0.2-5.0
50S-NM(R)	5	0.2-0.4	0.2- 0.4	0.2-0.4
50P-NMC-2	23	0.4-0.7	0.4- 0.7	≤ 0.4
50P-NMB-8	1	0.2	0.2	0.2
50S-NMC-2	1	0.4	0.4	0.4
DEM				
9S NM(R)	1	< 0.2	< 0.2	< 0.2
9S NMC-1	4	0.3-0.7	0.3- 0.7	0.2-0.6
9S NMC-2	11	≤ 0.3	≤ 0.4	≤ 0.3
9P NMC-2	2	0.3-1.1	0.3- 1.3	0.3-1.0
25P NMC-1	1	1.0	1.0	0.6
43W2P NMC-1	2	2.0	2.7	2.7
DEMF				
9S NMC-1	20	0.2-1.0	0.2- 1.0	≤ 0.3
9P NMC-1	3	0.2-1.0	0.2- 1.0	≤ 0.3
DDMF				
36W4P NMC-1	2	2.5	3.3	0.6
DMB				
17W2P NM*	1	2.0		
Cinch Jones DDM				
50S-NM C-1	10	1.2-6.6	1.5- 7.1	1.1-6.0
Amphenol				
14S 1P	1	≤ 0.2	≤ 0.2	≤ 0.2

TABLE VI
CONNECTORS–Continued

Type	Quantity	Magnitude ranges in gammas at 2 inches		
		Initial	Post 25 gauss Exposure	Post Deperm
General Radio				
874 QBP	2	1.0-9.5	1.0-10.0	1.0-9.5
Bendix				
PC02A 12-10P	2	0.5-1.0	0.5- 1.0	0.5-1.0
12-10S	2	< 0.1-0.7	< 0.1- 0.7	< 0.1-0.7
12-8P(SR)	1	0.2	0.2	0.2
Star				
UG-657/U	2	< 0.1	< 0.1	< 0.1
UG-260 D/U	2	< 0.1	< 0.1	< 0.1
UG-255/U	2	< 0.1	< 0.1	< 0.1
Amphenol (Parts)				
Terminals 2-1/2-4	20	1 -6.0	8-14.5	< 2.0
Minrac	Connector filler	0.6	0.6	0.6
	Body	4.2	4.3	3.8
	Pins	7.2	7.2	7.2
Cannon				
DM-053742-5000	1	2.0		
DM-053740-5019	1	2.0		
DM-051157	15	≤ 0.2	≤ 0.2	≤ 0.2
DM-S3740-5001	49	≤ 0.2	≤ 0.2	≤ 0.2
Deutsch				
RM54-328P	1	0.3	1.7	0.3
RM54-328S	1	186	2.5	172
Pin 28PCS	56	≤ 0.2	≤ 0.2	≤ 0.2
Continental				
NM 5-228	3	20	195	15
NM 14-8	5	15	36	12
NM 44-22		< 0.2	< 0.2	< 0.2

TABLE VII
CONNECTORS

Item	Type	Field in Gammas at 12 Inches		
		Initial	Post Exposure	Post Deperm
Connectors				
Bencix	JT07C-1098	8.8	39.6	0.9
El. Co.	30 Pin Female	0.2	0.2	0.2
Viking	VP4/4CE15	1.6	3.8	1.2
Deutsch	DS06-273	≤ 0.2	≤ 0.4	≤ 0.2
	DM-9700-3P	≤ 0.1	≤ 0.1	< 0.1
Cannon	DD-50 P,S	42.7	250.0	0.7
	DBA 70-19-OSN	< 0.3	2.1	< 0.1
	DBA 77-19-OPN	< 0.4	3.6	< 0.1
	KPT-100073-55	8.1	11.9	3.2
	DAM-7W2P NMC-1	≤ 2.0		
	XLR3-11C	8.0	44.2	0.6
	XLR-32	5.0	5.0	0.3
Amphenol	36-10S	1.5	1.7	1.0
	36-10P	2.5	2.5	1.0

Table VII has been included to show the various field levels the general type of connector contains. These measurements were performed at a distance of 12 inches from the center of the connector and vary in magnitude from < 0.1 to 250 gammas according to the connector and the magnetic state at the time. In conjunction with the stray field contributions connectors generate, this can be best avoided by minimizing possible current loops with the use of twisted pair wires and by avoiding large buss wire loops.

MATERIALS AND PRODUCTS

The listing of non-magnetic materials is sufficiently broad so that it is normally possible to obtain the required non-magnetic spacecraft fabrication materials except for certain items such as bearings and gears. At times, problems do occur when types of stainless steel, nickel coated brass, and other magnetic materials are inadvertently utilized in place of non-magnetic materials. Thus, where magnetic field restraints are required, it is essential that repeated magnetic checks be performed in order to ensure the use of the proper non-magnetic materials. As a word of caution, it would not be sufficient to obtain materials with low permeability such as ≥1.02, since materials in the permeability

TABLE VIII
MATERIALS AND PRODUCTS – GROUP A

Permanent Magnetic Field Magnetization

Material or Product	Description	Field in Gammas at 2 Inches		
		Initial	Post Exposure	Post Deperm
R.T.G. Comp.	Min-k-1301	< 0.2	< 0.2	< 0.2
Mica	Sheet	< 0.2	< 0.2	< 0.2
Bearing	Navajo	3.0	3.0	—
Titanium	Round Bar	< 0.2	< 0.2	< 0.2
	Hex Bar	< 0.2	< 0.2	< 0.2
	Self Locking Nuts	< 0.2	< 0.2	< 0.2
Magnesium	Rod	0.2	2.0	0.5
	Plate	< 0.2	< 0.2	< 0.2
	Plate Cu, Ni, Au plated	1.2	1.2	1.2
Aluminum Alloy	Bar	< 0.2	< 0.2	< 0.2
	Plate	< 0.2	< 0.2	< 0.2
Haynes #25	Rod Bar	1.2	6.0	0.7
	Weld Rod	0.2	0.3	< 0.2
	.065 Sheet	< 0.2	< 0.2	< 0.2
	.030 Sheet	< 0.2	< 0.2	< 0.2
Ni plated Brass	Screws 8/32 × 1/4"	2.3	3.0	2.0
Stainless Steel	Foil	< 0.3	< 0.5	3.0
	Screws	0.5	1.5	0.1
Epoxy-Ink	Humiseal (S-790) 5 and 1 mil	< 0.1	< 0.1	< 0.1
	Wornowick monc			
	5 mil	0.3	0.5	0.2
	1 mil	< 0.1	< 0.1	< 0.1
	Wornowick mon			
	5 mil	2.2	3.7	2.2
	1 mil	0.5	0.5	0.5
	Phillips			
	5 mil.	< 0.1	< 0.1	< 0.1
	1 mil	< 0.1	< 0.1	< 0.1

TABLE VIII (Continued)
MATERIALS AND PRODUCTS — GROUP A

Permanent Magnetic Field Magnetization

Material or Product	Description	Field in Gammas at 2 Inches		
		Initial	Post Exposure	Post Deperm
#25 Berylium Cu	Rod	< 0.1	< 0.1	< 0.1
Silicon bronze	Rod	< 0.1	< 0.1	< 0.1
Manganese bronze	Rod	< 0.1	< 0.1	< 0.1
Titanium	Rod	< 0.1	< 0.1	< 0.1

range ≤ 1.05 can have an equivalent magnetic field disturbance of approximately 60 gammas at distances of 6 inches. Even materials with 1.02 permeability can have a field magnitude of from 1/2 to 2 gammas at 12 inches. A series of tables have been prepared to serve as aids in the selection of preferred non-magnetic materials. Generally, those materials such as those listed in Table VIII would satisfy most non-magnetic requirements since the field levels at a distance of 2 inches are less than 1 gamma. The relatively more magnetic materials and samples are to be found in Table IX which indicates the expected field magnitudes obtainable at a distance of 12 inches from the center of the item. Table X. includes a separate listing specifically measured non-magnetic materials while Table XI lists general non-magnetic, feebly magnetic, and magnetic metals and alloys. While it is possible to differentiate between non-magnetic and highly magnetic materials, the "gray area" or feebly magnetic materials can change with fabrication and thermal treatment. The 300 series of stainless steels are a prime example of such materials. Although a material is non-magnetic, it is still possible that it may become contaminated by containing inclusions of ferrous materials as a result of the machining or manufacturing process. Thus, tests should be conducted at least after the item has been worked and treated. In the case, where steel tools are utilized even when working on spacecraft, it is possible to magnetize by contact, any ferrous materials which it might contain so that the magnetic state of an item can be changed. The possibility of such a change is another reason for avoiding the selection of ferrous materials. Referring to Table IX, it should also be mentioned that several of the materials listed as magnetic could also have been classified as non-magnetic under certain conditions; i.e., temperature, ambient field strength, and annealing process. As a result, rules governing the selection of materials can be expected to vary in

TABLE IX
MATERIALS AND PRODUCTS — GROUP B

Permanent Magnetic Field Magnetization

Material or Product	Description	Field in Gammas at 12 Inches		
		Initial	Post Exposure	Post Deperm
Hadfield steel	Rod	0.4	0.4	0.3
Stainless Steel	Rod	0.2	0.3	0.2
	Heat Treated	4.4	5.3	2.5
Stainless Steel 302	Plate	10.9	20.5	< 0.7
Minneapolis - Honeywell	Valve	14.5	24.9	15.4
	Valve Operator	436		
	Thermostat	26.8		
Memory Cores	Delta-max 50% Fe 50% Ni	< 0.3	< 0.3	< 0.1
Nickel	Ni-0-Nel 825 Rod	0.3	1.5	< 0.1
Starfinder Apogee Motor	Stainless Steel	89540	97740	27
Starfinder Apogee Bottle Nozzle	Stainless Steel	440	2063	32
Thiokol Retro Rocket Motor	TE-345			
	INERT Empty	1128	78336	73
	INERT Dummy	3321	81060	130
TEM	458 Squib S/N612	8.5	10.2	1.0
	458 Igniter S/N 51	9.2	15.6	2.0
TEM 458 Retro Motor	Titanium (inert)	< 0.1	< 0.1	< 0.1
SAE 1020	Rod 1/4 × 6"	1.9	3.0	1.6
SS 304	Rod 1/4 × 6"	< 0.2	< 0.4	< 0.2
Drill Rod	Rod 1/4 × 6"	8.3	180	7.8
Copperweld	#20 6" long	73.7	210	2.0
	#20 1-1/2" long	< 0.1	5.4	<0.1
	#20 2" long	< 0.1	9.6	<0.1

TABLE IX (Continued)
MATERIALS AND PRODUCTS — GROUP B

Permanent Magnetic Field Magnetization

Material or Product	Description	Field in Gammas at 2 Inches		
		Initial	Post Exposure	Post Deperm
Stainless Steel 304	Rod 1" × 6"	≤ 0.5	≤ 0.5*	≤ 0.5
K-500 Monel	Rod	0.3	0.6	< 0.1
K-500 Monel	Rod cold drawn - aged - scaled	100	100	100

* ≤ 0.1 after 800 gauss deperm.

TABLE X
NON-MAGNETIC METALS AND ALLOYS

Material	Permeability (0.5 oersted - 20°C) (2)	Maximum Field Magnitude at 2 Inches (Post 25 gauss exposure)(1)
Aluminum 7075, 5086, 6061	< 1.004	< 0.1
356	< 1.004	< 0.1
Beryllium Copper	< 1.004	< 0.1
Cartridge Brass	< 1.004	< 0.1
Silicon Bronze	< 1.004	< 0.1
Manganese Bronze	< 1.004	< 0.1
Copper Alloy 720	< 1.004	< 0.1
Haynes 25	< 1.004	< 0.1
Titanium	< 1.004	< 0.1
Magnesium Zk60A, AZ92	< 1.004	< 0.1
Magnesium AZ31B	< 1.004	< 0.5
K-500 Monel	< 1.004	< 0.1
Ni-0-Nel 825	< 1.008	< 0.1
Inconel X-750	< 1.004	< 0.1
Stainless Steel Alloy 310	< 1.004	< 0.1

(1) Surface data from 6" × 1" rods.

(2) Source—Dralle, A. V. and Moore, J., "Magnetic Properties of Materials," including references, GSFC Document X-100-65-407.

TABLE XI
GENERAL METALS AND ALLOYS

Non-magnetic	Feebly Magnetic	Magnetic
Alloy 30, 60, 90	Stainless Steel (μ)	
Beryllium	202 < 1.02	Cobalt
Germanium	302 < 1.02	Copperweld
Gold	303 < 1.02	Dumet
Lead	304 < 1.02	Electroloy
Manganin	310 1.01 - 1.004	Elinvar
Moleculoy	316 1.02 - 1.004	Fenicoloy
Molybdenum		Ferrites
Neutroloy	K-Monel 1.01 - 1.004	Gridaloy M, P
Nickel Silver	Elgiloy	Haynes Alloy #6
Silver	Alloy 720	Invar
		Mesoloy
Tantalum		Molypermalloy
		Mumetal
Tungsten		Nichrome
		Nickel, 200, 270
Zinc		Nickel iron
Zirconium		Platinum
		Pelcoloy
		Permalloy
		R Monel
		Remendur
		Rodar
		Stainless Steel
		403, 405, 410, 416, 430, 446
		Supermalloy
		Vicalloy
		426 Alloy
		430 Ti
		1008 Carbon Steel

accordance with the magnetic field restraint and design goals of each particular program.

MISCELLANEOUS PARTS

The enclosed list indicates the magnetic field disturbance magnitudes of parts which have been measured in conjunction with various spacecraft programs. Although the listing for parts of this type is far from complete, hopefully, the available information can be utilized in regard to problems associated with magnetic field restraints.

In the case of items which contain permanent magnets such as the traveling wave amplifier tube, the field magnitudes at 1 foot are in excess of 500 gammas; however, with compensation magnets, these magnitudes could be successfully reduced (refer to techniques discussed in relation to relay compensation). Various motors can have substantial fields and in addition present simulated stray field problems especially when a magnetic armature is rotated. As such, reduction by compensation would be difficult; however, by placing shielding material around the motor it is often possible to reduce the field at least 80%. It should be noted that; for example, in the case of stepping motors listed in Table XII certain types are somewhat less magnetic and would be preferred thus, by selecting a relatively low field motor and incorporating shielding, the effects of the magnet can be curtailed. For example, in one instance, a motor with a permanent field of 986 gammas at 12 inches was enclosed by various types and layers of cylindrical open ends shielding material. When the shielding consisted of two inner layers of netic and a single outer layer of co-netic material, the most effective results were obtained. With this type of shield, the resultant field magnitude at 12 inches was 15 gammas. As such, the initial field magnitude was reduced 98 per cent. When the same techniques were applied to a second motor with an initial perm field of 189 gammas, this magnitude was reduced to 35 gammas which resulted in an 82 per cent reduction of the magnetic field of the motor. Since both of these units were stepping motors, the utilization of shielding material alleviated the problems associated with a shifting of the perm field direction which occurred when the motor was activated.

Items which include leads i.e., photo-multiplier tubes, can also present problems if the leads are composed of magnetic materials. As indicated in Table IX, one type of pm tube with ferrous wire leads displayed a post exposure field magnitude in excess of 300 gammas at 1 foot. However, when the external leads were cut quite short, and the excess lead lengths were measured separately, they were found to be the primary source of field (measured magnitude - 241 gammas). Subsequent photo tubes which utilized non-magnetic materials indicated substantially lower magnitudes indicating that the lead problem can be resolved by careful selection of the proper non-magnetic materials.

TABLE XII
MSC PARTS

Permanent Magnetic Field Magnetization

Manufacturer	Type	Field in Gammas at 12 Inches		
		Initial	Post Exposure	Post Deperm
Erie	RF Filters			
	1206-051	<0.1	0.3	<0.1
	1212-051	<0.3	0.6	<<0.1
	1212-051	12.0	15.0	6.0
	Accelerometers			
Statham	A 69 TC-10-350	1.4	5.1	1.0
	A 402-10	9.5	9.5	6.1
	Model 303	1218	1230	1161
	Micro Switches			
Micro-Switch	1 LS5 (Modified with brass)			
	SN-3	0.1	0.1	0.1
	SN-2	0.8	0.8	0.8
	1 SEL-T	<<0.1	<<0.1	<<0.1
	Timers			
Hamilton	10,000 hr elapsed time indicator	2.4	7.8	1.0
	TE-12	45.0	54.4	43.9
Bulova	Accutron TE-12	41.2	53.1	42.6
	Transformers			
	14-107 63490	1.3	4.0	<0.1
Alladin (Pulse)	01-604 6219	<0.1	27.6	<0.1
UTC	DIT 25	3.5		
	DIT 23	19.0		
	DO-T4	6.4	37.0	0.2
	DO-T29	0.2	0.2	≤ 0.2
	SO-4	0.6	0.6	0.6

TABLE XII (Continued)
MSC PARTS

Permanent Magnetic Field Magnetization

Manufacturer	Type	Field in Gammas at 12 Inches		
		Initial	Post Exposure	Post Deperm
Thordarson	MIT 224	≤0.1	≤ 0.1	≤ 0.1
Halldorson	MI-T209	≤0.1	≤ 0.1	≤ 0.1
	MI-T219	≤0.1	≤ 0.1	≤ 0.1
	MI-T236	≤0.1	≤ 0.1	≤ 0.1
Burnell	Adjustoroid ATE-34	275	390	330
	<u>Other</u>			
General Time	Memory Cores Delta-Max	<0.1	< 0.1	< 0.1
Burr-Brown	Operational Amplifier	3.4	4.8	1.0
Vap-Air	Mercury Thermal Switch AA 20249110-11	<0.1	< 0.1	< 0.1
Astronic Inc. Delay line	22H2NS	<0.1		
	18 H 2NS	<0.1		
Westinghouse solid state circuits	(18 stacked)	0.1	8.0	<< 0.1
Keithley Electro-meter		15.2	96.8	4.0
Hughes Traveling Wave Amplifier Tube	384-HA	653.4	669.6	648.0
Mosfets	4 (row)	8.1	45.9	< 2.7
EMR Memory Unit	EMR 8	1.5	4.6	<0.1
Northern Engr. Labs	NE-18N 64,000 kc XTAL	0.2	6.0	< 0.1

TABLE XII (Continued)
MSC PARTS

Permanent Magnetic Field Magnetization

Manufacturer	Type	Field in Gammas at 12 Inches		
		Initial	Post Exposure	Post Deperm
Binary module		16.2	32.4	2.7
Sense amplifier	(2 modules)	15.6	19.4	13.6
Servonic Instr. Inc.				
Pressure Transducer	PN2091	2.0	11.0	1.5
	Power Supplies			
Matrix Research Corp.	81-6	2.7	95.5	1.6
	PS13	0.5	4.9	< 0.1
Philbrick Applied Research	PP-65A	6.5	20.3	1.6
Astronetics Model 596	PS13/1	13.0	30.8	1.0
Photo Multiplier Tubes ASCOP	543A210	59.6	130.0	11.9
	541A	6.0	19.1	3.3
	J01065	< 0.1	0.8	< 0.1
	J01120	0.3	1.0	< 0.1
	J01963	0.4	2.5	< 0.1
	———	151.2	308.0	26.4
	Ion Gauges			
Cooke Inc.	BA-60-TTK	0.3	0.3	≤0.1
NRC	551A	5.0	144	≤0.1
	Microswitches			
Klixon	AT85-1	1.1	1.1	1.1
Cemco	MAC 500-4	<0.1	< 0.1	<0.1

TABLE XII (Continued)
MSC PARTS

MOTORS

Initial Permanent and Stray Magnetic Field Magnetization

Manufacturer	Type	Field in Gammas at 12 Inches	
		Perm	Stray
American Electronics, Inc.	Stepping Motor	986	
American Electronics	851014-59	614	113
Cedar Engineering	Stepping Motor	27	
IMC Magnetics Corp.	Stepping Motor		
	Model 008-822	189	
	#1018	119	136
IMC Magnetics Corp.	Model 015-802	120	17
Sperry Farragut	Model 9738 Brushless	75	
Bendix	Model No. X1820359-1	52	≤1.6
Nash Controls	Motor	373	
Sterling Instruments	Magnetic Clutch T 9011-12	339	
Sterer Solenoid Valve	28410-1	89	702
	AF 42C-562	62	351
	AF 70C-11	41	392

In the event the stray magnetic field disturbance of an item is excessive, certain steps can be taken to avoid or reduce this field. As previously mentioned, shielding would be one solution but generally, compensation has proven to be more acceptable.

One example of the effectiveness of stray field compensation is evident in the case of the Matrix Power Supply. By winding compensation loops around the

TABLE XIII
RESISTORS — GROUP A

Permanent Magnetic Field Magnetization				
Manufacturer	Type	Field in Gammas at 2 Inches		
		Initial	Post Exposure	Post Deperm
Dale RH-50	20 W 1%	1.1	1.2	0.5
Dale NH-50	50 W 1%	0.4	0.4	0.4
Dale RS-2B-51	1 W 1%	<0.2	< 0.2	< 0.2
Dale NS-2-51	3 W 1%	<3.0	3.9	1.0
IRC RN65D	1/2 W 1%	<0.2	< 0.2	< 0.2
IRC RN65B	1/2 W 1%	<0.2	< 0.2	< 0.2
IRC RL07	1/2 W 5%	<0.2	< 0.2	< 0.2
IRC RN-55D	1/10 W 1%	<0.2	< 0.2	< 0.2
TI RN65B	1/2 W 1%	<0.2	< 0.2	< 0.2
CGW RN65B	1/2 W 1%	<0.2	0.5	< 0.2
MIL-R-11	2 W 5%	<0.2	< 0.2	< 0.2
MIL-R-11	1/2 W 5%	<0.2	< 0.2	< 0.2
Allen Bradley RC 08	1/10 W 10%	<0.2	< 0.2	< 0.2
Thermistor	YS1 44006	0.2	4.0	≤ 0.2

outsides of the unit it became possible to reduce the main component of the stray field at least 90%.

Transformers and coils which have iron cores and, in fact, any components with excessive amounts of ferrous materials are quite undesirable from the magnetics aspect and should be avoided.

RESISTORS

Although the permanent magnetic field disturbance of resistors is relatively negligible (refer to Table XIII) when resistors with tin, copper, brass or aluminum leads are selected, the flow of current through these resistors can generate

TABLE XIV
RESISTORS — GROUP B

Permanent and Stray Magnetic Field Magnetization					
Manufacturer	Type	Field in Gammas at 12 Inches			
		Initial Perm	Post Exposure	Post Deperm	Stray
	<u>Fixed Resistors</u>				
Dale	13ΩRH-50	< 0.1	< 0.1	< 0.1	19.3 (1a)
	50ΩNH-50	<< 0.1	<< 0.1	<< 0.1	
	55ΩRH-50	<< 0.1	<< 0.1	<< 0.1	5.5 (0.35a)
	13ΩNH-50	< 0.1	< 0.1	< 0.1	1.4 (1a)
	13ΩNHG-50-1 *	< 0.2	< 0.2	< 0.2	
	18ΩNH-50	< 0.2	3.0	< 0.2	
	32ΩNHG-25	< 0.2	2.7	≤ 0.1	
Sprague	50ΩNI-10	3.0	22.2	0.2	
Clarostat	15 VPR-10	7.1	16.4	3.4	
Ward Leonard F	50 VPR-10	0.2	0.2	< 0.1	
Tru-OHM FRL	1.2K 10	1.0	1.3	< 0.1	
OHMITE	40 10	0.2	0.8	< 0.1	
	<u>Variable Resistors</u>				
Bourns	3600S-1 10 Turn	0.2	1.0	<< 0.2	8.0 (17 ma)
Giannini	Mini-torque 85153	11.5	56.1	1.0	≤ 0.2 (0.5 ma)
Reon	50KΩ RJ6	< 0.2	< 0.2	< 0.2	
Mepco	30 P-90	0.4	1.7	< 0.1	
	40 P60-A	1.4	2.4	< 0.1	
Helipot	5712 R10K L-50	≤ 0.2	0.5	≤ 0.2	
Bourns	3250W-60-503 500K	1.9	4.0	< 0.1	
Dale	RT11C2P103 10K	2.6	1.3	0.3	
Spectrol	749-2-1-104 100K	≤ 0.1	1.2	≤ 0.2	

*Cu leads

troublesome stray magnetic field disturbances. The difference between the stray field magnitudes for the 2 Dale 13Ω resistors indicates (Table XIV) that by selecting an non-inductive type of resistor and in addition, avoiding large current loops, the stray field can be kept to a minimum. An example is the Dale 13Ω

NH-50 resistor which had a stray field of 0.4 gammas at 18 inches (1 amp of current) when the leads were twisted and brought up snug against the resistor. When the leads were expanded to form a 3 inch loop, the field magnitude increased to 7.7 gammas. In the event it became necessary to reduce the stray field of the spacecraft by compensation it would be a simple matter to expand the resistor circuit loop to the required size and then position for effective compensation. When resistors do have excessive perm fields, Table XIV, cutting the lead length to less than 1/4 inch can effectively reduce the problem. For example, the two Mepco wirewound resistors were remeasured after their lead lengths were reduced to 1/4 inch and the post exposure field magnitude was reduced to 0.5 gamma.

RELAYS

When it becomes necessary to incorporate relays in spacecraft subassemblies, especially those which have magnetic field restraints, the question immediately arises as to how effectively can the permanent and/or stray field disturbance of the relay be reduced to an acceptable level. The purpose of this section is to describe the possible means of achieving this reduction and to indicate the results which have been obtained. Since perm and stray field reduction problems are quite similar, the methods utilized in reduction of the perm field would also be applicable in the event stray field reduction also becomes necessary. The methods adopted, will normally depend upon requirements such as, magnitude of field reduction desired, quantity of relays,involved, electrical characteristics, size, weight, and physical arrangement. The three methods which have been successfully utilized in accomplishing this task are as follows:

1. compensation
2. shielding
3. replacement

The third method, relay replacement, can often solve the problem without much difficulty especially when just a few relays are involved. In fact, the problem might even be avoided in the event the proper relay could be selected during the preliminary design stages. Although there is no immediate means of knowing the field strength of any magnets which the relays might employ, it still is possible to separate relays on the basis of content of magnetic materials. For example, cases and contacts composed of non-ferrous materials would be preferred. Table XV indicates the permanent and stray magnetic field disturbance magnitudes for numerous relays and can, hopefully, serve as a guide in the selection of relays with low magnetic field properties. Although several types of relays do have low perm field magnitudes, the net magnitude can become appreciably high when a number of such relays are combined. Examples of

TABLE XV
TUNING FORKS AND RELAYS

Magnetic Field Magnetization			
Manufacturer	Type	Field in Gammas at 12 Inches	
		Permanent	Stray
Babcock	Relay 6405L	78	
	12633L	73	
	BR 5	2.4	
	BR 8	2.3	81 @ 28v
	BR 9 AX	37.6 → 76.5	
	BR 12K	4.5	42.6 @ 12v
	BR 16-190A1	< 1	28 @ 12v
	BR 75Z*	6.1	28.5 @ 6v
	PR 328-4 6405L	1.2	34 @ 12v
	BR 17A	21.0	
Couch Ordnance Company	Relay 2R02B440-A	1.5	140 @ 12v
CP Clare	Relay HF1201DC0	3.0	96 @26.5v
	RP 7614GA	1.1	178
	RP 764168	2.6	185 @ 12v
Filtor	PLR26H1M6A-1	130	18.9 @ 12v
	PL15C1M6A8	3.4	
General Electric	3S27916200A6*	9.7	64.2 @ 12v
	3SAE1236A1*	15	25 @ 12v
	3SAF1172	16.3	
	3SAF1333*	1-12	5-13 @ 12v
	3SAF1786A2	10.7	1.1 @ 15v
	3SAM1035 (Latching)	104-138	104 @ 12
	3SAV1012A1	0.8	133 @ 26.5
Gyrex	Tuning Fork #4896	8.0	
	Tuning Ford #63069	4.3	
Leach	M201A1-113	1.8	72.8 @ 12v
	M250A4-112	1.3	70 @ 26.5v

*Not recommended for cancellation.

TABLE XV (Continued)
TUNING FORKS AND RELAYS

Magnetic Field Magnetization			
Manufacturer	Type	Field in Gammas at 12 Inches	
		Permanent	Stray
Potter and Brumfield	Relay E6230K	152	18 @ 12v
	E6240L	259	16 @ 12v
	FC 11D (6058A)	134	55 @ 12v
	FL 11D (6442H)	104	50 @ 12v
	KHP 17D11	16	432 @ 12v
	MP 3-D	83.6	1315 @ 24v
	PW 5LS (6509L)	3.5	120 @ 12v
	SC 11DM	517	176 @ 12v
	SL 11D	200	307 @ 24v
	SL11DA(6446C)	266	125 & 250 @ 12v
	SL 11DB	199	165 @ 12v
	TL 17D	1322	
	TL 17DB	200	300 @ 24v 45 ma
	TL 17D-12	96-226	
Sigma	Relay 32R JK	242	294 @ 12v
Teledyne	821	8.4	4.1 @ 12v 1/2 a
	923	9.8	
	410U-1000	77*	3.2 @ 15v 1/2 a
Automatic Electric	V51	43.3	

*Magnitude reduced to 2 gammas by shortening lead lengths to 1/4".

this increase which occurred in the case of five types of relays are indicated in the following table.

In those instances where the relays are aligned with the individual moments oriented identically, the net magnitude was, as expected, approximately equal to the sum of the individual magnitudes. But, with random moment orientation, the net magnitude is approximately 1/2 of the sum of the individual magnitudes.

TABLE XVI
COMBINED RELAYS AND THE ACCUMULATED FIELD RESULTS

Relay	Quantity	Moment Orientations	Magnitude in Gammas at 12 Inches	
			Each	Total
P&B SL11DB	6	Identical	200	1512
GE 3SAF	12	Random	10.7	61.1
CP Claire R1764	40	Random	1.1	16.8
Filtor DJL26	10	Identical	15	175
P&B TL17D	4	Identical	160	570
P&B TL17D	5	Identical	160	720

Perm field reduction by compensation can be an effective means of reducing the magnetic field disturbance of relays to levels which ordinarily would be acceptable for most spacecraft programs. Field magnitudes of from 50 to 100 gammas (12 inches) can be readily achieved in the case of practically all the relays listed in Table XV, the identical types of relays are combined by alternating their moment directions. For example, 6 P&B SL110 relays (field magnitudes of 200 gammas at 12 inches) were combined to obtain a resultant field magnitude of 89.1 gammas. However, when perm field reduction to lower levels (1 to 50 gammas) is desired, the process becomes somewhat more involved. To effectively accomplish such a level of perm field reduction, the following step by step procedure is recommended:

1. Initially select relays which have low perm fields (refer to Table XV). Although some relays have low fields, they are not recommended for cancellation use since the moment directions and magnitudes tend to vary; i.e., General Electric 3SAF1333, 3SAF5176A2.

2. Measure the field magnitude on each face of the relay.

3. Combine the relays so that the faces tend to cancel (take into consideration desired physical arrangements).

4. Remeasure to determine results.

TABLE XVII
RELAY MAGNETIC FIELD COMPENSATION RESULTS

Relay Type	Combination	Magnitude in Gammas at 12"		% Compensation	Individual Moment Directions
		Separated	Compensated		
GE 3SAM1035	Pair	125,104	13	90	Identical
GE 3SAM1035	Pair	150,138	3	98	Identical
P&B SL11DB	Array of 6	256 (ea)	89	65	Identical
P&B KHP17D11	Pair	16 ea	4	75	Identical & off-axis
P&B SL11DA	Pair	265,231	25	91	Identical & off-axis
P&B FC11D, FL11D	2-Pair	100,134	28	79	Identical & off-axis
Babcock R6405L	Pair	83,82	5	94	Identical & off-axis
GE 3SAF 1333	Pair	5,7	4	43	Random
Babcock BR9-AX63VI	Pair	56,53	20	64	Random
Babcock BR9-AX63VI	Pair	77,64	39	49	Random
Babcock BR9-AX63VI	2-Pair	77,64	41	55	Random
Filtor DJL26C1P6A3	Array of 10	15 ea	34	93	Identical
	Pair	12,16	5	82	Identical
P&B TL17D	Four	120,140	30	95	Identical

Examples of the possible results which can be achieved when this procedure is followed are shown in Table XVII. It should be noted that the best results were obtained when the relays which had identical oriented moments were combined. In the case of the relays which had random oriented moments, the percentage compensation achieved was similar to that obtained when there had been no attempt to compensate (refer to Table XVI).

On the basis of the percentage compensation column it is possible to conclude that inherently better results can be obtained when relays with identical moments were paired. The miniature and sub-miniature relays are ideally suited for perm field cancellation because of their initial low field magnitudes. Table XVIII indicates the face magnitudes for 4 such types. It should be noted

TABLE XVIII
RELAY FACE MAGNITUDES — GAMMAS AT 12 INCHES

Relay	Designated Relay Face					
	X	Y	Z	-X	-Y	-Z
Babcock PR 328-4	1.0	0.0	-1.2*	-1.0	0.0	1.1
General Electric 3SAV1011241	0.8*	0.0	0.8	-0.7	0.0	-0.8
C. P. Clair HF 1201DCD	3.0*	0.0	-1.6	-2.8	0.0	1.7
Leach M25-A4-112	1.3*	0.0	0.4	-1.3	0.0	-0.3

*Peak magnitude

that the field at the base (-Y axis) of the relays is non-detectable at 12 inches so, ideally, groups of the individual relays could be placed side by side (alternating directions) for cancellation purposes without too much of a circuit layout problem.

Before the conclusion of the compensation tests, it would be advisable to actuate the relay especially since movement of the plunger and contact arms can charge the magnitude and direction of the relay field. In general, this need not require special attention except in those cases where the field disturbance magnitudes are crucial. For instance, latching relays with field magnitudes of less than 10 gammas at 12". The latching relay with a field magnitude in excess of 100 gammas would bear more consideration. In one case 5P&B TL-17D-12 relays were measured both before and after activation. Table XIX indicates the field magnitudes (12 inches) which were measured for the two latched positions of the individual relays. It is of interest to note that the minimum variation was 39

TABLE XIX
RELAY FIELD CHANGE WITH CONTACT POSITION

Relay Positions	Relay number and field magnitude in gammas at 12 inches					
	#1	#2	#3	#4	#5	1-5 Combined
1	133	186	96	184	132	720
2	226	145	136	121	171	637
Δ	93	-41	40	-63	39	83

gammas while the maximum case showed a 93 gamma variation between the two positions. With a wide change in magnitude such as this, it might be necessary to seek a compromise between the two contact positions. Shielding, would be an effective means of reducing the permanent and stray magnetic field of relays since both problems could be alleviated simultaneously. Table XX indicates the perm field reduction results which were obtained for relays which were enclosed by shielding material. Since these relays were not exceptionally large, it was a simple matter to fabricate external cover shields.

TABLE XX
RELAY MAGNETIC PERM FIELD REDUCTION BY SHIELDING

Type	Magnetic Field in Gammas at 12"		% Reduction of initial value
	Without shield	Shielded	
P&B SL 11DB 6240L	259	29	89
6230K	152	5	97
Babcock 6405L	83	<1	99
P&B KHP 17D11	16	3	81

A final item of further interest pertaining to relays concerns the possible effects of the deperming treatments. Tests were conducted on a group of P&B SL11D magnetic latching relays by measuring the magnetic field of the relay, deperming the relay, re-measuring and subsequently re-checking the holding power of the relay.* The relays were first depermed in a 50 gauss A.C. field (magnitude comparable to normal component deperm treatment) which resulted in; 1. no decrease in the holding power of the relay, and 2. no decrease in the magnetic field strength of the relay magnet.

As the relays were depermed in higher levels of field from 100 to 400 gauss, there was no greater than 5 percent decrease in the holding power of the magnet although when a 200 gauss field was applied, the relay reeds started to vibrate. In one instance, a relay was depermed in a field of greater than 1 Kilo gauss, which resulted in demagnetization of the relay magnet so that the relay no longer functioned. Similar tests also had been performed on a Gyrex tuning fork (field magnitude at 12 inches <10 gammas) which no longer functioned when exposed to

*The holding power of the relay was checked by measuring the coil current required to move the wiper arm from one contact to another.

a deperm field of 0.5 Kilogauss. From this stand point, although deperm field magnitudes from 50 to 200 gauss would be acceptable for deperming, caution should be observed when fields in excess of 500 gauss are utilized.

TRANSISTORS

Unfortunately, from the magnetic field aspect, several magnetic materials are utilized in the manufacture of transistors; i.e., kovar, nickel, and steel. As a result, transistors can contribute significantly to the magnetic field disturbance of an assembly when combined with other components. However, by obtaining transistors with aluminum, or gold leads and non-magnetic nickel-silver alloy cases this problem could be substantially reduced. Since generally non-magnetic transistors are not readily available, it often is desirable to obtain particular types which are somewhat less magnetic than others. Table XXI is a partial listing of various transistors which have been measured and indicates the magnitude of field that particular type of transistor can be expected to generate. With this and even more precise information, it is still difficult to select the most desirable and least magnetic transistors due to possible changes in the individual magnetic characteristics. Such a case in point occurred when a number of randomly selected 2N414A transistors (various manufacturers or part type) were found to differ widely in relation to their measured field magnitudes. To avoid this ocurrence repeated measurements would be advisable in order to insure selection of the least magnetic type. Furthermore when these transistors are mounted on the circuit board the recommended procedure is to minimize the lead length in order to remove as much of the lead material as possible before the transistor is wired into the circuit. An indication of the field magnitude which leads can contribute is demonstrated in the following table. Table XXII shows the field magnitudes which were obtained with 2N697 transistors containing either long or short leads and demonstrates the effectiveness of field reduction by making the leads as short as possible.

Although it was possible to deperm either of the two groups (long or short leads) to corresponding levels of magnitude, it should be noted that the group with the long leads had a considerably higher field magnitude after exposure. Normally, the transistors cannot be expected to remain in a completely demagnetized state because of ambient field exposure and the magnetizing effects of materials and tools. An example of the magnetizing effects of tools can be demonstrated by comparing the measured initial perm magnitudes of the two groups of 15 transistors. Since the short lead length units had been cut with diagonals and subsequently magnetized the initial perm magnitude was substantially higher than that obtained for the group with the longer leads. As a final step 15 additional short lead transistors were added to the original group of 15, which were then exposed, measured and then finally depermed. Although the post

TABLE XXI
TRANSISTORS

Permanent Magnetic Field Magnetization					
Manufacturer	Type	Case	Field in Gammas at 12 Inches		
			Initial	Post Exposure	Post Deperm
Bendix	2N301	T0-3	1.4	15.5	0.3
	2N24475A		2.8	5.0	0.8
	EM73327U		2.5		
	EM73327H		4.3		
	EM75069U		2.7		
	EM74808E		1.0		
	2N1653	T0-41	2.3		
Dickson	1N1521		11.0	43.0	1.8
	1N3020		4.8	35.5	0.8
Electronic Transistor Co.	2N123	T032	0.5	25.8	0.2
	2N360	T05	5.8	22.0	1.8
	2N1090	T0-9	0.7	29.8	0.2
Fairchild	SP-24 220		1.0	45.1	< 0.2
	D 400		0.5	24.0	< 0.2
	2N697	T0-5	5.3	7.2	1.3
General Electric	2N43A	R032	2.1	13.6	0.2
	2N335A	T0-5	3.0	18.7	0.2
General Instrument Co.	1N540		1.2	2.0	0.6
	2N414A(6428)	T0-5	2.3	12.7	1.0
	2N414A(6439)	T0-5	5.8	37.0	1.3
	1N 2069		≤ 0.1	≤ 0.1	≤ 0.1
Honeywell	2N2812		≤ 0.4	≤ 5.3	≤ 0.1
	HV83		≤ 1.0	≤ 15.0	≤ 3.5
	HM86-NM		≤ 0.5	≤ 3.9	≤ 0.1
IND	2N718	T018	1.7	5.0	
I.S.	2N1546		7.6	27.8	

TABLE XXI (Continued)
TRANSISTORS

Permanent Magnetic Field Magnetization					
Manufacturer	Type	Case	Field in Gammas at 12 Inches		
			Initial	Post Exposure	Post Deperm
Motorola	2N1924	T0-5	4.0	17.4	0.1
	2N2575		10.5	18.5	1.9
	1N720		1.1	8.0	< 0.1
	1N751	D0-7	0.5	9.0	< 0.1
	1N2620A	52	0.3	12.6	0.2
	1N2623	52	0.3	9.0	0.1
	1N3210	D0-5	<0.1	0.5	<< 0.1
	1N3210 w/hardware		0.6	1.0	0.4
	2N1175	T0-5	1.6	16.7	0.4
	2N1362	T0-3	12.8	16.0	2.0
	2N1530	T0-3	8.0	11.4	1.7
	2N3467		18.9	37.8	16.2
	2N2221	T0-18	2.0	4.8	<0.4
	MD981F		<0.1	<0.1	<0.1
	1N3340		0.7	1.7	0.3
	2N1011	T0-3	4.5	11.7	0.5
National Semi-conductor	2N330	T0-5	6.7	17.8	0.2
Raytheon	2N336	T0-5	1.8	9.9	<0.1
RCA	2N398(25)		0.2	30.0	<0.1
	2N277	T0-36	0.9	4.0	0.9
	2N301A	T0-3	1.3	4.4	1.3
	1N3253	T0-1	0.0	6.3	1.0
	2N1169		1.0	29.0	0.6
	2N1905	T0-3	4.4	29.7	1.3
	2N1226	T0-33	1.1	10.0	0.6
	2N1484	T0-8	0.4	4.0	<0.1
Solid State Products Inc.	2N2849-2		0.8	3.3	<0.2
	2N2845-1		2.0	28.1	<0.2

TABLE XXI (Continued)
TRANSISTORS

Permanent Magnetic Field Magnetization					
Manufacturer	Type	Case	Field in Gammas at 12 Inches		
			Initial	Post Exposure	Post Deperm
Sprague	2N240	T0-24	7.0	20.8	0.3
Standard Telephone and Cables	2N1724/1		7.8	8.1	0.3
	5553		1.6	4.4	0.7
S.T.C.	2N1485		0.1	2.0	
	2N2034	T0-5	0.3	7.0	
Sylvania	2N414A	T0-5	0.8	6.9	0.2
	2N709A	T0-18	0.5	1.1	0.2
	2N2784		0.5	1.2	0.3
Starkes-Tarzian	1N718A		1.6	8.4	≤ 0.1
Texas Instrument	2N1908	T0-3	11.2	54.8	1.3
	2N118	OV-6	4.2	7.7	0.3
	1N603A		12.8	72.0	0.6
	1N547		0.3	26.0	< 0.1
	2N388	T0-5	16.0	26.1	2.0
	2N1375	T0-5	7.7	33.0	1.4
	2N1374	T0-5	12.0	39.4	2.8
	2N337	T0-5	5.4	22.4	4.7
	2N1379	T0-5	3.8	25.3	0.3
	2N1600 (with mounting hardware)		0.4	0.7	0.4
	2N2906	T0-18	2.0	3.6	0.6
	1N253		< 0.1	1.9	≤ 0.1
	2N708		3.5	28.7	1.4
	2N871		2.0	15.2	0.3
	2N1595		≤ 0.1	26.7	≤ 0.1
T.I.	1N645		2.3	8.0	
	1N645 Leads folded			3.0	

TABLE XXI (Continued
TRANSISTORS

Permanent Magnetic Field Magnetization					
Manufacturer	Type	Case	Field in Gammas at 12 Inches		
			Initial	Post Exposure	Post Deperm
Transitron	2N886		0.8	5.6	< 0.1
	2N1595		2.7	43.8	0.5
	1N539		1.0	63.1	0.1
	2N1132		3.3	18.3	
	2N1132 Leads folded out			11.7	
Westinghouse	1N1342		0.2	2.3	<0.1
	1N1342 (with hardware)		4.2	7.6	4.2
	2N1016	MT-1	19.0		

TABLE XXII
TRANSISTOR MAGNETIC FIELD CONTRIBUTIONS

Quantity	Lead Length Inches	Magnitude in gammas at 12 inches		
		Initial Perm	Post Exposure	Post Deperm
1	1-1/2	5.3	7.2	1.3
1	3/8	2.1	3.0	0.9
15*	1-1/2	5.0	243.5	1.4
15*	3/8	24.7	32.9	1.5
30	3/8		41.8	3.5

*15 transistors were placed side by side (3 rows of 5 each)

deperm magnitude increased by a factor of 2 it is of interest to note that the post exposure magnitude increased by a factor of less than 1-1/2. Naturally, it is rather difficult to predict exactly how much the net field will increase or change when several of the same transistors are combined in a circuit, and this table can only serve as a rough guide.

Test equipment also can become the culprit for magnetizing the semiconductor leads. One such piece of equipment, a simple diode test fixture, employed a set of magnets which held the diode in place. When the holding magnets were measured with a gauss meter, a maximum field of 325 gauss was observed. A group of 6 diodes (initial perm magnitudes at 12 inches varying from 0.2 to 4.9 gammas) were in turn placed on the fixture, removed, and measured. After exposure to the magnets, maximum field magnitudes varying from 12 to 22 gammas were measured. This again points to the disadvantage of utilizing ferrous materials and components.

WIRING

In the magnetic testing of spacecraft and spacecraft assemblies, there will appear from time to time units which generate magnetic fields in excess of the design goal limits. When analysis and reduction tests are performed on these units a large percentage of the time, the primary source of the magnetic field disturbance has been found to be wire which contains ferrous materials. Such magnetic wire might be in the form of lead material, i.e., transistor and capacitor leads or just the inner connecting circuit wiring alone. The problems associated with magnetic wire can be compounded due to the fact that the magnetic state of the material can be changed during working by coming in contact with tools which have been previously magnetized. When two 1-1/2 inch lengths of lead material were depermed is zero field and then placed in earth's field (stressed and struck) the one steel copperweld wire remained in the depermed state while the other (nickel) increased in magnitude to a level equivalent to a post 10-15 gauss exposure (zero field). An example of the effects of the presence of ferrous wire upon the net moment of an assembly can be demonstrated by describing the results obtained with an Imp 1-1/2" thick × 9 inch long electronics card. One particular unit with ferrous wire generated a field of 66 gammas at 18 inches after a 25 gauss exposure. A similar unit with non-magnetic wire had a field magnitude of ≤ 0.5 gamma.

Since the undesirable effects of magnetic wire are common knowledge, the designer normally need only specify the use of non-magnetic wire to satisfy any magnetic field restraint requirements. Unfortunately, this does not resolve the problem for one must also perform follow-up checks to eliminate the possibility of inadvertent use of wire which contains any form of magnetic materials. These checks also ensure against the remote possibility that a spool of wire has been mislabeled or contains a mixture of both non-magnetic and magnetic wire. Circuit wiring which utilizes Kovar leads or ribbon should be avoided especially since nickel which has a low coercitivity can to some extent undergo perming under earth's field conditions. Table XXIII lists both magnetic and non-magnetic wires samples which were measured at 12 inches to show the possible field effects.

TABLE XXIII
WIRE SAMPLES

Permanent Magnetic Field Magnetization					
Manufacturer	Type	Length Inches	Radial Component Magnitude in Gammas at 12 Inches (1)		
			Initial	Post Exposure	Post Deperm
Alpha	#14 Stranded plastic	6	-	-	-
	#18 Mil-W-76C	6	-	-	-
	#20 Mil-W-76B	6	-	-	-
	60/40 alloy solder	6	-	-	-
Amphenol	#21 598 Coaxial	6	8.1	52.2	0.6 (2)
	RG 188 Coaxial Silver Plated Cu	6	41.9	92.2	0.3 (2)
Belden	RG 55/u #8245 #20 bare Cu	6	-	-	- (3)
	#20 Thermoplastic	6	-	-	-
	#20 Shielded ground wire	6	-	-	-
	#18 Mil-W-76B	6	-	-	-
	#14 Mil-W-76B shielded	6	-	-	-
	#20 Mil-W-76B	6	-	-	-
	#20 Tinned Copper	6	-	-	-
	#29 Tinned Copper	6	-	-	-
Federal	RG-62A/U +82879 Copperweld	6	73.7	21.0	2.0
Microdot	92 Ω Cable	6	-	-	-
Raychem	RG 188 Coaxial	6	-	-	-
	RG 178 Coaxial	6	4.7	32.3	< 0.1 (2)
	#26 (black)	6	0.2	67.0	0.1
	#22, 20, 28, 26 NM	6	-	-	-
	1/16 dia Havar	12	< 0.1	≤ 0.1	< 0.1
	1/16 dia Elgoy	18	< 0.1	< 0.1	< 0.1
	Protology (0.003")	-	< 0.1	< 0.1	< 0.1
Thermatics	#18 Mil-W-76A	6	-	-	-

(1) distance from center of wire

(2) when the outer shield and inner conductor were separated, the outer wire was found to be non-magnetic

(3) all wires which indicated no field at the 12 inch distance were remeasured at a distance of 2 inches and found to be non-magnetic (≤ 0.1 gamma).

Of note is the fact that the initial state magnitude can widely vary between the depermed and exposed levels depending upon exposure conditions. The wires which indicated no detectable field magnitude (≤ 0.1 gamma) at 12 inches were remeasured at 2" and could be classified as non-magnetic as the field level at this distance was ≤ 0.1 gamma. In selecting RG coaxial wire there is a series of wire types which use a copper weld (steel) inner conductor and should be avoided.* An example of this type of wire is the RG-62A/U wire sample.

Stray field problems associated with the use of wire are dependent upon either current flow or open loops which the circuit layout-forms. Thus, especially when currents exceeding 1 amp** are involved the following precautions should be observed:

1. Make all wires tightly twisted pairs (3-4 turns/inch) without any open loops.

2. Utilize single point grounds in the circuit layout.

3. Intra connecting wiring should be coaxial or twisted pair.

When these precautions are followed, it is possible to avoid the creation of magnetic interference problems which might be attributed to spacecraft and subassembly wiring.

In the course of measuring the stray field generated by the sub-assembly it often is not possible to supply the actual spacecraft power cabling. Under these circumstances it is important to avoid generating any erroneous fields with this external power cabling. The reason for following the procedure of step (1) for this external cable is evident when referring to Table XXIV which indicates the level of field generated by various types of conductors.

The data in Table XXIV indicates that under most circumstances twisted pair conductors would be adequate for reduction of stray fields; however, for critical applications, it might be more desirable to select the shielded twisted pair or the coaxial wire. It is also evident that little would be gained by using the more intricately woven cable.

---

* RG CUW, CUWAG Wire Nos. 6, 59, 62, 71, 79, 140, 141, 142, 143, 144, 174, 178, 179, 180, 187, 188, 195, 196, 210, 302, 303, 304, 316.

** A loop of wire 3 inches in diameter with one amp of current would generate a stray field magnitude of 25 gammas at a distance of 12 inches from the center of the loop.

TABLE XXIV
STRAY FIELD GENERATED BY PARALLEL CONDUCTORS

Type of Conductor	Current Flow	Magnitude in Gammas at 12 inches
1. Single wire	10 amps	6,560*
2. Parallel pair	10 amps	37.0
3. Twisted pair 3 turns/inch	10 amps	4.9
4. Shielded twisted pair	10 amps	1.4
5. Coaxial wire	10 amps	1.4
6. Inter-8 weave cable (4 conductors)	10 amps	1.3

*Computed

BIBLIOGRAPHY

1. Bastow, J. G., "Proceedings of the Magnetics Workshop" Technical Memorandum No. 33-216

2. Boyle, J. C. and Greyerbiehl, J. M., "A Method for the Measurement of Extremely Feeble Torques on Massive Bodies" NASA Technical Note D-3711

3. Bush, S., "Environmental Test Program of the Energetic Particles Explorer — D Satellite (EPE-D) For the Study of the Natural and Artificial Radiation Belts" GSFC Document X-326-65-293

4. Dralle, A. V. and Moore, J., "Magnetic Properties of Materials" "Final Report of the Goddard Summer Workshop Program in Analysis of Space Data and Measurements of Space Environments." GSFC Document X-100-65-407

5. Gebhardt, R. E. and Waidelich, D. L., "Coil Systems for Uniform Magnetic Fields" "Supplement to Final Report of the Goddard Summer Workshop Program in Analysis of Space Data and Measurement of Space Environments" GSFC Document X-100-65-407(S)

6. Hoggard, W. D., "Final Report on the Environmental Test Program for the Atmosphere Explorer-B Spacecraft" GSFC Document X-326-66-508

7. JPL "Final Report for a Study Program to Determine Magnetic Properties of JPL Spacecraft Electronic Components." JPL 1-61042-1

8. Lackey, Milton H., Jr., "Magnetic Moment Testing of Satellites NOL Technical Report 64-32

9. Ness, N. F., "Magnetic Fields: Reasons for Simulation and Methods Available" GSFC Document X-612-64-389

10. Ness, N. F., "Magnetic Field Restraints for Imp's F and G," GSFC Document X-672-64-167

11. Parsons, C. L. and Harris, C. A., "Imp-1 Spacecraft Magnetic Test Program NASA Technical Note D-3376

12. Parsons, C. L. and Harris, C. A., "Component Magnetic Test Facility Operations and Test Procedure Manual," GSFC Document X-325-65-312

13. Schutz, F. L. et al., "Mariner-Mars Science Subsystem NASA Technical Report No. 32-813

14. Watson, J. D., AC Demagnetization of Satellite Components "Final Report of the Goddard Summer Workshop Program in Measurement and Simulation of the Space Environment," GSFC Document X-320-63-264

15. "AIMP Operations Manual for Launch AIMP (D) Eastern Test Range Cape Kennedy" GSFC Document X-724-66-231

APPENDIX A

MAGNETIC FIELD RESTRAINT REQUIREMENTS FOR IMP'S H AND J

Introduction

The purpose of this Appendix is to present the magnetic field restraint requirements which pertain to Imp Spacecraft H and J. Whereas the design goal objectives contained within the main body of this report (Table I) are applicable to the needs of the previous Imp's, the enhanced sensitivity of the magnetic fields experiment requires that an updated and more stringent set of design objectives be adopted for the Imp's H and J. Achievement of these design objectives will ensure that the integrated spacecraft generates a net magnetic field disturbance of less than 0.125 gammas ($= 1.25 \times 10^{-6}$ oersted) from 0-25 Hz at the location of the magnetometer sensors. Under these conditions, the spacecraft field at the midway distance of 42 inches would be ≤ 1 gamma. Recognition should be given to the fact that the Imp spacecraft magnetic test program has included a well developed subassembly test procedure which has facilitated the construction of "magnetically clean" spacecraft. Continuous testing of the subassemblies and, when necessary, integral parts has permitted control, identification, and removal of magnetic field contamination sources before possible harmful integration of the unit within the spacecraft. As a result, design goals have been established to include both the integrated spacecraft as well as the individual sub-assemblies.

Fabrication Guidelines for Spacecraft and Sub-assemblies

Designers and fabricators connected with the Imp program should bear in mind that it is most desirable to avoid the use of components, parts or materials which have magnetic properties. Whenever possible, non-magnetic materials should be selected in preference to feebly or highly magnetic types. In those instances where this is not feasible, i.e., transistors and capacitors with nickel or kovar leads, the effects of the magnetic materials can be to some extent nullified by maintaining short lead lengths or inner-connecting wiring ($<$ 1/4 inch lengths). These and other procedures applicable in the case of sub-assemblies and components have been discussed in detail in the main text and hold true for the Imp program. However, application of shielding material is not recommended due to the unusual properties of the material itself and instead, it is recommended that established practices of field reduction by selection and intrinsic self-compensation be observed. The expanded sampling rate and increased frequency response (0-25 Hz) combined with the 0.125 gamma sensitivity of the magnetic fields experiment is ample reason for the establishment of a revised set of stray field design goal objectives for the Imp's H and J. Accordingly, closer attention should be devoted

TABLE I
SOURCES OF STRAY FIELD AND METHODS OF CONTROL

Sources	Remedies
1. Circulating currents in sub-assemblies and spacecraft.	1. Cancellation of current loops by utilization of twisted pair cabling.
2. Current loops formed by connectors and component wiring.	2. Close geometrical arrangement of connectors and leads.
3. Chokes and transformers.	3. Careful wiring to avoid leakage fields - use of toroids only.
4. Solar cell wiring.	4. Back wiring of individual solar cell groups to provide cancellation currents.
5. Areas of heavy power loads, solar cell power supply, batteries, converters, unloading circuits, spacecraft wiring harness.	5. Twisted pair wiring and, if necessary, compensation wiring to minimize current loops.
6. Circulating ground loops in spacecraft and subsystems.	6. Individual package grounds twisted with "hot" lead and common point grounding.

to pursuing the established practices of stray field reduction. Table I outlines specific problem areas and indicates accepted reduction techniques.

Magnetic Field Mapping of Integrated Spacecraft and Individual Subassemblies

Since coilless methods of magnetic field mapping for the Imp spacecraft are not sufficiently adequate to satisfy the Imp requirements, all test procedures discussed in this section pertain to mappings performed within a zero field coil system. In order to gain the most benefit and background information, the sub-assembly testing is begun in the early stages of the program while the sub-assemblies are mapped on a distinct single unit basis whenever possible. A complete magnetic history for these units and subsequently the integrated spacecraft is then obtained by measuring the permanent, induced, and stray field magnetization of the sub-assemblies prior to and after environmental testing. Resolution of the magnetic field disturbance generated by the Imp units at distances of 18 and 36 inches requires test magnetometers with 0.1 gamma resolution in addition to the zero ambient field conditions. By repeated measurements of the maximum radial component magnitudes at the two distances (18 and 36 inches) from the geometrical center of the assembly it is possible to determine the magnetic field disturbance or magnetic field moment generated by the unit for the following conditions:

Initial Perm

Determination of magnitude and direction of dipole moment prior to subjection to other test conditions. Second distance (36") measurements are included to verify whether dipole field approximation is valid for the particular package being measured.

Post 15 Guass Exposure

At the conclusion of the initial measurements, an exposure field of 15 gauss is applied along the direction of the previously determined moment. The exposure field magnitude of 15 gauss is more representative of the maximum expected level of magnetization during testing. This magnitude replaces the controlled level of 25 gauss which was used with earlier Imp spacecraft.

Post Deperm

Following the exposure and measurement sequence, a 50 gauss deperming field is applied to the assembly to reduce the remnant perm to a level below the initial level. Normally a 60 Hz a.c. field supplied by a coil and variac is slowly decreased in magnitude to a level of zero.

Stray Field

Measurements of the magnetic field, generated by the current flow within the assembly are made in a manner corresponding to the permanent field determination. These stray field measurements represent the difference between the power-off and power-on conditions of the assembly. In addition, a continuous monitoring of the field as the sub-assembly is cycled or pulsed through load changes or calibration sequences is necessary to detect any existing stray field differentials. This later type of measurement would require the use of test magnetometers with a minimum 0-40 Hz frequency response; or separate A.C. and D.C. magnetometers.

The previously listed measurements would then be performed to ensure that the sub-assemblies fulfilled the design goal requirements as indicated in Table II. In the event a subassembly exceeds the design goal requirements, immediate rework should be initiated before the design of the unit becomes fixed. Whereas the subassembly design levels are adequate for establishing the acceptability of

TABLE II

IMP'S H AND J SUB-ASSEMBLIES DESIGN GOAL REQUIREMENTS

	Magnetization	Background Field (gauss)	Maximum Magnetic Field disturbance (gamma)	
			18"	36"
1.	Initial perm	0	8	1
2.	Post 15 gauss exposure	0	32	4
3.	Post 50 gauss deperm	0	2	0.25
4.	Stray Field	0	2	0.25

the individual sub-assemblies, there is no guarantee that the design objectives for the integrated spacecraft will not be exceeded. A spacecraft integrated with sub-assemblies which fulfill the design goal objectives can still exceed the desired spacecraft levels when these units have moments which add vectorially. Separate mappings of the integrated spacecraft are therefore required to determine the actual magnetic field disturbance at the expected location of the sensor. This desired low level of field disturbance is ascertained by a mapping of the entire spacecraft at a distance mid way between the geometrical center of the spacecraft and the final position of the sensor. Furthermore the field change with distance along the length of the boom is determined to establish the rate of field change. Table III then represents the design goal levels for the mid way distance of 42 inches.

TABLE IV

DESIGN GOAL REQUIREMENT FOR IMP H AND J SPACECRAFT

Magnetization	Background Field (gauss)	Maximum Magnetic Field Disturbance (gamma) 42 inches
Initial Perm	0	1.0
Post 15 gauss Exposure	0	20.0
Post Deperm	0	1.0
Stray	0	1.0

APPENDIX B

Memorandum Report
No. 665-018
Date: June 16, 1966

To: Distribution

From: C. A. Harris
Functional Test Branch

Subject: Review and Analysis of the OGO-A and OGO-C (S-49 and S-50) Experiment Assembly Magnetic Test Data

ABSTRACT:

A final review and analysis of the OGO-A and C experiment assembly magnetic test data has been prepared to furnish comparative information relating to the testing of these assemblies. By utilizing the data obtained, it has been possible to determine the following conditions:

1. Relationship between measured and extrapolated field magnitudes.
2. Ranges in permanent, induced, and stray field magnitudes of assemblies in comparison with design goal values.
3. Perming effects of applied and ambient field exposures.
4. Effects of deperming and results obtained.

INTRODUCTION:

This report is a review and analysis of all OGO-A (S-49) and OGO-C (S-50) experiment assembly magnetic test data which have been acquired during measurements of these assemblies at the Components Magnetic Test Facility, GSFC.* In order to obtain a more complete representation of the typical spacecraft experiments both OGO-A and C test data have been included on the basis that a more diversified group of structures and materials have been utilized.** Although

---

* The assembly test data has been previously released in the following forms:
(1) preliminary report of environmental test (320–4)
(2) component magnetic test summary tables
(3) memorandum reports 634–029, 032, 034 and 655–002
(4) Observatory Magnetic Data Analysis (calculated field due to spacecraft assemblies)

** Since the experiments represent a combination of many items a more complex magnetic structure is involved than would be the case for individual parts and samples. Data relating to the magnetic field disturbance of various spacecraft components (OGO, IMP and other spacecraft programs) are presented in memorandum report 655–015 – spacecraft component magnetic field restraints.

the primary purpose of the magnetic testing is to provide control data pertaining to the magnetic field disturbance at the magnetometer sensor position, sufficient additional data were obtained to furnish pertinent information related to other phases of magnetic testing. As a result, a total of at least 350 magnetic tests* have been performed on the two spacecraft experiment assemblies.

The results of the review and analysis of these data have been formulated and are discussed in the following listed categories:

1. Measurement data and extrapolation results.
2. Magnetic field disturbance and design goal magnitudes.
3. Magnetic state changes resulting from environmental and applied field exposures.
4. Deperming (demagnetization) results and comparisons.

MEASUREMENT DATA AND EXTRAPOLATION RESULTS

Normally, the magnetic field disturbance of an OGO experiment assembly is determined by locating a detector at a distance from its geometrical center equivalent to 3 times the maximum linear dimension of the unit. The measured magnitude is subsequently extrapolated to the distance of 12 inches in order to obtain the desired design control data.** Provisions for obtaining fall-off data were also incorporated in the prototype assemblies tests by including second distance measurements of those units whose field magnitude at 12 inches exceeded 100 gammas. For these measurements the detector was placed a second distance away from the assembly (6 times maximum linear dimension). As a result, two distance measurements were performed on a total of 14 OGO-A and 17 OGO-C prototype assemblies. Comparing the fall-off rates of these 31 units, 11 were determined to have a fall-off in agreement with the established inverse cube rate while the remaining units had rates which varied as follows:

1. Inverse 2.5 to 2.8 a total of 5
2. Inverse 3.1 to 3.3 a total of 15

---

* Tests conducted and measurements performed are described in the following reports:
(1) Test and Evaluation Specifications S-4-101 and S-4-201.
(2) Component Magnetic Test Facility Operations and Test Procedure Manual X-325-65-312.

**$H_{12} = H_d \times \left(\frac{d}{d_{12}}\right)^3$

H_{12} = field at 12 inches
H_d = field at 3 × MLD
d = distance (inches)

A rate of other than inverse cube would be expected if, for example, the prominent dipole source were located off center or should the unit have second distance field magnitude of ≤ 1.0 gamma, which would be affected by the limits of measurement accuracy (±0.2 gamma). Since the combined assembly measurement results indicate that the rate of field change with distance corresponds to the conventional dipole field fall-off (inverse cube) this information has been utilized in determining the relationship between the following three forms of data:

1. Assembly measurements
2. Design control data (extrapolated 12 inch distance magnitudes).
3. Magnetic field disturbance magnitudes at flight sensor position (extrapolated 24 foot magnitudes).

The primary concern when analyzing the data and test results is that the net field contribution from all of the experiment assemblies be ≤0.1 gamma at the flight sensor position. If this condition is fulfilled, then one would not expect the corresponding magnitude at 12 inches to exceed 1382 gammas as indicated in figure 1. On this basis, it would then be desirable that the individual assemblies have a field magnitude at 12 inches ≤100 gammas in order to satisfy this requirement. In extrapolating these field magnitudes, no consideration was given to moment direction. Therefore, when the assembly data are combined (all moments oriented identically), the maximum condition would be established. This would not represent the true spacecraft condition since the combined assemblies in actuality have random moment orientations.

MAGNETIC FIELD DISTURBANCE AND DESIGN GOAL MAGNITUDES

The primary aim of the OGO experiment assembly magnetic test program has centered upon ensuring that the magnetic field disturbance generated by the assemblies does not exceed the design goal requirements.* Through a series of related assembly and spacecraft tests, it has been possible to confirm the achievement of this goal. Previously, the experiment assembly test results have been presented on an individual basis (summary tables or preliminary reports). However, in order to obtain the complete picture, the data have been combined and is now presented in the following manner as illustrated in figures 2 and 3:

1. Separate listings for prototype, flight-1 and flight-2 appendage and main body units

*For field magnitudes of less than 500 gammas at 12 inches, the extrapolated magnetic field disturbance at 20 feet would be less than 0.1 gamma as indicated in figure 1.

2. Each of 5 magnetic field states separately identified initial perm, post exposure, post deperm, induced and stray
3. Three ranges of field magnitudes (gammas at 12 inches) for each condition as designated by the following numbers: (1) 0-100, (2) >100 to <500 and (3) >500.

The combined experiment assembly test data which is presented in the two sets of graphs (figure 2 and 3) furnishes a clearer picture regarding the design goal limits and the extent to which the assemblies satisfy these requirements. Examining the data, it is apparent that at least 90% of the assemblies had initial perm, post deperm, induced and stray field magnitudes of ≤500 gammas while only 50% had post exposure magnitudes in excess of 500 gammas.* Thus, it can be concluded that the desired magnetic test results were achieved.** Since only one to two units exhibited initial or post deperm magnitudes >500 gammas (column 3 for each graph) it could be inferred that the net contribution from all the experiment assemblies would be <0.1 gamma at 24 feet.*** In those cases where excessive field magnitudes are measured extended efforts to reduce these fields proved successful especially since the exterimenter could take corrective action in the early stages of the program. The data obtained in these cases have been included in the summary tables. Referring to the ranges in magnitudes for the induced data, it is evident that the induced effects will be negligible due to the fact that the majority of the OGO-A&C assemblies indicated magnitudes of less than 100 gammas for an applied field of 0.26 gauss. In the event the induced field magnitudes were substantial (>500 gammas) then consideration should be given to the possibility of post deperm magnitude changes which occur when the assembly was exposed to earth's field. Since the assembly measurements, except induced, are performed in zero field, the perm field magnitudes would not include any induced field effects. The magnitudes of D.C. stray field which were measured for the assemblies are also ≤100 gammas at 12 inches in the majority of the cases. This provides evidence that the spacecraft stray field contribution from the assemblies would be small. While the stray field requirements have been fulfilled, details such as the possible post deperm magnitude change which might occur as a result of current flow in the experiment should also be considered.

---

* By exposing the assembly to an applied field of 25 gauss, it became possible to determine the extent of change (blackest picture) in the initial or post deperm magnitude which occur should the unit be exposed to a similar field in the course of the environmental testing.

** With an inverse cube rate of fall-off, a field magnitude of ≤100 gammas (12 inches) would diminish to a magnitude of <0.1 gammas at a distance of 10 feet. Thus, it would be possible to combine all the assemblies with this range of magnitudes and not generate a distinguishable field at 24 feet.

*** The one exception is the EP-4 appendage experiment which is 16.5 feet from the EP-6 sensor and should be considered separately.

Since pre and post stray perm field measurements were performed on the assemblies (post deperm — post stray perm) data are available indicating little or no perm change occurring for the majority of the units (refer to summary tables). This would be expected under normal circumstances since most of the experiments require less than an ampere of current. Examples of perm field changes which would or would not occur for various levels of current are presented in Table I.

TABLE I
PERM FIELD CHANGES FOR RELATED STRAY FIELD MAGNITUDES

Assembly	Current (amps)	Magnitude-Gammas at 12"		Percent Change	Stray Field
		Post Deperm	Post Stray		
OPEP-2	1.2	348	632	180	1337
5015	1.2**	62	54	8	1045
4909	0.16	257	1015	395	2565*
5001	0.16	289	286	-	11

*70ms pulse
** filaments off

MAGNETIC STATE CHANGES RESULTING FROM ENVIRONMENTAL AND APPLIED FIELD EXPOSURES

Provisions for a 25 gauss applied field exposure and subsequent deperm are incorporated in the OGO experiment assemblies test plan and serve as a means of further determining the nature of the magnetic field properties of the individual assemblies. The established exposure field level of 25 gauss is related to the D.C. field magnitudes, ranging from 1 to 25 gauss, which are encountered in the vicinity of the various exciter tables. Figure 4 has been included to show the measured field magnitudes at various distances above the center of the MB C-125 exciter. A second shaker table (MB C-126) which utilizes a compensation coil and has a correspondingly lower magnitude of field is illustrated in Figure 5. It is of interest to note the differences in the field magnitudes which were measured both above the center of the table and above the edge of the mounting plate on the MB C-126 exciter table. Since the maximum field level of 25 gauss was measured only within close proximity of the surface of the exciter table, this magnitude of field tends to represent maximum or "blackest picture" exposure field magnitude for the assembly. In this respect, Figure 6 is an example of the extent to which the permanent field of an assembly is increased when exposed to various levels of background or applied fields. While the initial magnitude of the unit increased by a factor of 4 with the 25 gauss exposure, at a level of 12 gauss which is more representative of the normal shaker table field, the magnitude was only twice the initial value. In order to avoid or remove the effects of the environmental test background exposure fields, the final tests are performed at the conclusion of these tests. Additional initial (pre-environmental) tests are therefore performed on those units having magnitudes in excess of 500 gammas to furnish the necessary design control data as well as useful pre and post environmental test data. Table II has been prepared to show the initial perm and post deperm (maximum and minimum) ranges in magnitudes for the assemblies prior to the environmental testing (pre-environmental) as well as the corresponding final test (post environmental) pre deperm ("as received state") magnitude. On the basis of this table alone it is apparent that the field of the assemblies had increased above the post deperm magnitude. Furthermore, many units had increased magnitude which exceeded the original initial perm value due to the environmental testing. Table III has been prepared in order to provide information regarding the amount of increase (factor) which occurred as a result of the environmental and applied field exposure. This table indicates the (maximum and minimum) ranges and average amounts by which the initial perm and post deperm magnitudes had increased after environment testing. An additional set of data is included to indicate the factor by which the post deperm magnitude increased as a result of the 25 gauss exposure. The date (Table III) provides evidence that the post deperm magnitude can be expected to increase by at least a factor of four during the environmental testing. In addition, the post environmental (pre deperm) measured magnitude tends to exceed the initial perm values thereby removing the effectiveness of the deperm treatment. Although the average deperm magnitude was quadrupled, this increase is considerably less than the increase which occurs as a result of the 25 gauss exposure where the minimum average increase was factor of 13. Two particular noteworthy examples of the perm changes which can occur have been prepared and tabulated in Table IV. The post environmental test increase is substantially above the expected average; however, the magnitudes are approximately 1/3 the post 25 gauss exposure magnitudes again indicating that the environmental exposure field magnitudes were appreciably less than 25 gauss.

As a result of the hundredfold increase in magnitude due to the 25 gauss exposure these two units would be classified as having a soft perm such that exposure fields of 1 to 2 gauss could also be expected to increase the perm field magnitude.* Accordingly, one would expect a slight change even when the units

*The post exposure graph in figure 6 shows a slight change in magnitude for field levels of 1–2 gauss in relation to a fourfold increase for a field of 25 gauss.

TABLE II
PRE AND POST ENVIRONMENTAL TEST PERM FIELD MAGNITUDE RANGES FOR OGO EXPERIMENT ASSEMBLIES

Spacecraft	Unit	No.	Pre-environmental Test		Post Environmental
			Initial Perm	Post Deperm	Pre Deperm
OGO-A	Prototype	21	18-755	6-563	37-608
	Flight 1	14	42-1056	22-354	30-1002
	Flight 2	14	23-451	1-373	18-772
OGO-C	Prototype	15	9-583	8-540	49-583
	Flight 1	13	14-778	8-410	5-2182
	Flight 2	10	8-556	8-543	46-591

TABLE III
RANGE AND AVERAGE PERM FIELD INCREASE RESULTING FROM EXPOSURE TO ENVIRONMENTAL (0.5-25 GAUSS) OR APPLIED (25 GAUSS) FIELD

Spacecraft	Unit	Environmental Field Exposure				25 Gauss	
		Initial Perm		Post Deperm		Post Deperm	
		Range	Average	Range	Average	Range	Average
OGO-A	Prototype	0.3-9.0	1.5	1-19	4	0.9-44	13
	Flight 1	0.2-1.5	0.8	1-4	2	2-77	24
	Flight 2	0.2-1.7	0.8	1-4	2	4-2150	115
OGO-C	Prototype	0.2-7.0	1.8	1-39	6	2-1080	112
	Flight 1	0.1-8.7	1.6	1-51	6	2-110	30
	Flight 2	0.2-2.9	1.2	1-7	2	1-92	26

TABLE IV
ENVIRONMENTAL FIELD EFFECTS PERM FIELD MAGNITUDE IN GAMMAS AT 12 INCHES

Experiment Assembly	Post Deperm	Post Environment	Post 25 Gauss Exposure
OGO-A	1	772	2030
OGO-C	11	340	1080

are exposed to earth's field (0.6 gauss). However, when the subsequent flight units of these two assemblies were measured (final test) one unit retained its post deperm magnitude of 11 gammas while the other had a field magnitude equivalent to 2/3 the original initial perm "as received" magnitude. While the data in Table IV indicates the adverse effects of environmental testing, the information from these other units is a favorable indication that the deperm treatment can establish and remain in a stable state.

DEPERMING (DEMAGNETIZATION) RESULTS AND COMPARISONS

Whereas the post 25 gauss exposure state represents the "blackest picture" condition and the initial perm state the "as received" condition, the post deperm state represents the lowest level of field the assembly can be expected to attain as a result of normal test conditions. The deperm or demagnetized state is on a smaller scale similar to the actual assembled spacecraft field where the individual dipole moments have a random orientation in contrast to the exposed state where the moments tend to align themselves in the direction of the exposure field. In order to determine the effectiveness of the deperm treatment, graphs have been prepared to illustrate the percentage reduction of either the initial or the post exposure field magnitude which occurred as a result of the deperm treatment. Figures 7 and 8 are graphs which indicate the OGO-A and OGO-C experiment assemblies results with separate columns for 6 separate ranges in percentages. This information is provided for both the prototype and flight units. Not only did the deperm reduce the post exposure magnitudes of 1/2 of the assemblies by 90% but it also reduced the initial perm magnitudes approximately 60% with the exception of a few assemblies which contained components such as permanent magnets. A further examination of the OGO-A deperm results in figure 7 is necessary in order to compare the various deperming processes which were utilized. Initially during the prototype tests, a 50 gauss D.C. linearly decaying (50 to 0.2 gauss during a period of 7 minutes) reversing polarity deperm field was employed. Near the conclusion of the prototype tests the deperm was changed from D.C. to 60 cycle A.C. with a magnitude of 42 gauss (RMS). Subsequently, the field magnitude was increased to the presently employed magnitude of 50 gauss (RMS). Table V is a comparison of the 3 deperm conditions and from all indications, the A.C. deperm seems to be slightly more effective than the type of D.C. deperm which was utilized.

An additional example of the A.C. vs D.C. deperm results is presented in figure 6 which primarily illustrates the relationship between the post deperm results and the level of D.C. deperm field applied.

TABLE V
OGO-A DEPERM RESULTS — PERCENTAGE
REDUCTION OF POST EXPOSURE MAGNITUDES

Unit	Deperm	< 70%	> 70%
Prototype	50 Gauss D.C.	4	21
Flight 1	42 Gauss A.C.	1	28
Flight 2	50 Gauss A.C.	0	27

CONCLUSION

Although there is a distinct difference between the OGO-A and OGO-C experimental assemblies in relation to size and composition, the magnetic test results obtained for these two spacecraft are similar. Accordingly, the relationships which have been established should be applicable for future OGO spacecraft providing components with permanent magnets (i.e., mass spectrometers, power relays, motors) are excluded. The following list summarizes the results and conclusions which have been derived from the available test data.

1. Deperming is an effective means of reducing the perm field magnitudes and, in addition, tends to remain stable providing the ambient field is controlled, i.e., fields not permitted to exceed 1 gauss.

2. Measurements of assemblies at distances equivalent to three times the maximum linear dimension of the item normally provide valid data for dipole moment computations. In those cases where magnetic field restrictions are critical, measurements at a further distance would be more appropriate.

3. Although the 25 gauss exposure represents a "blackest picture" condition, this perming provides useful design control data. However, since the actual exposure field during vibration tends to vary from <1 to no more than 15 gauss, the exposure field used for testing could be reduced accordingly. It is therefore recommended that the exposure level for future tests be reduced from 25 to 15 gauss.

4. Induced magnetic field magnitudes in an applied field of 0.26 gauss tend to fall within the <100 gamma category and generally can be disregarded. The induced field relationship can become important if the spacecraft is to fly in applied fields greater than 0.5 gauss.

5. The design goal of 500 gammas at one foot tends to be a realistic qualification providing the post exposure condition is not the controlling factor. Meeting this goal is not extremely difficult especially when testing can be performed in the early stages of design where alterations are still feasible.

6. In the event limited testing is to be performed, it is recommended that the measurements and deperm be performed at the conclusion of the environmental testing rather that at the beginning.

7. As the stray field magnitude increases above levels of 500 gamma (12 inches) consideration should be given to possible perming effects which might occur.

Whereas, for instance, the computed field disturbance of the combined OGO-C experiment assemblies was $<$ 0.1 gamma at 24 feet, it should not be overlooked that the net field of the spacecraft was $\leq$0.6 gamma and includes both the experiment and spacecraft assemblies. Since the spacecraft assembly tests were performed under the auspices of the OGO prime contractor while the experiment assemblies tests were performed at GSFC it has been more feasible to present the experiment assembly data separately.

/s/ C. A. Harris
C. A. Harris
Magnetic Test Section

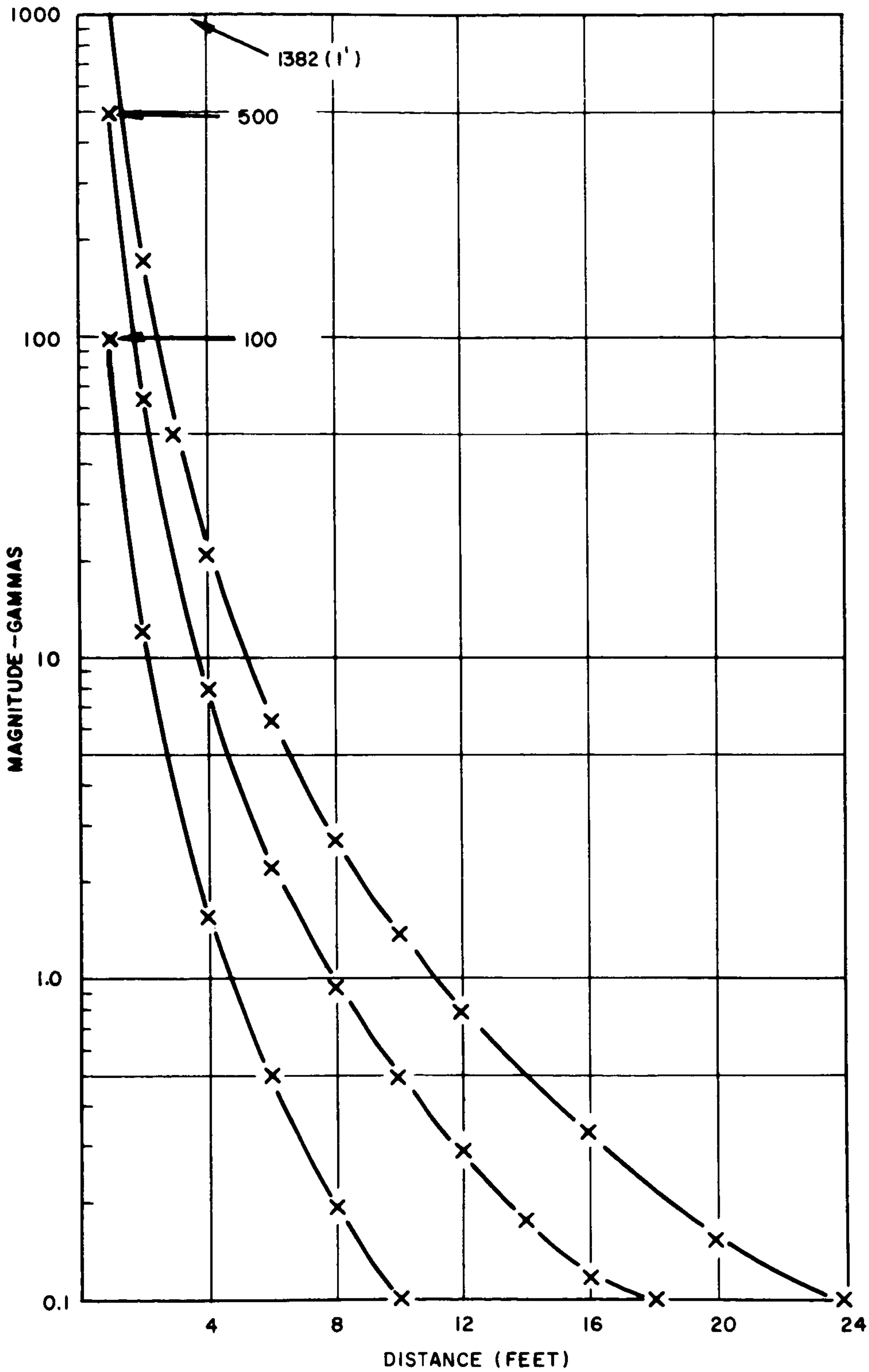

Figure 1–$1/r^3$ Extrapolated Field Magnitudes.

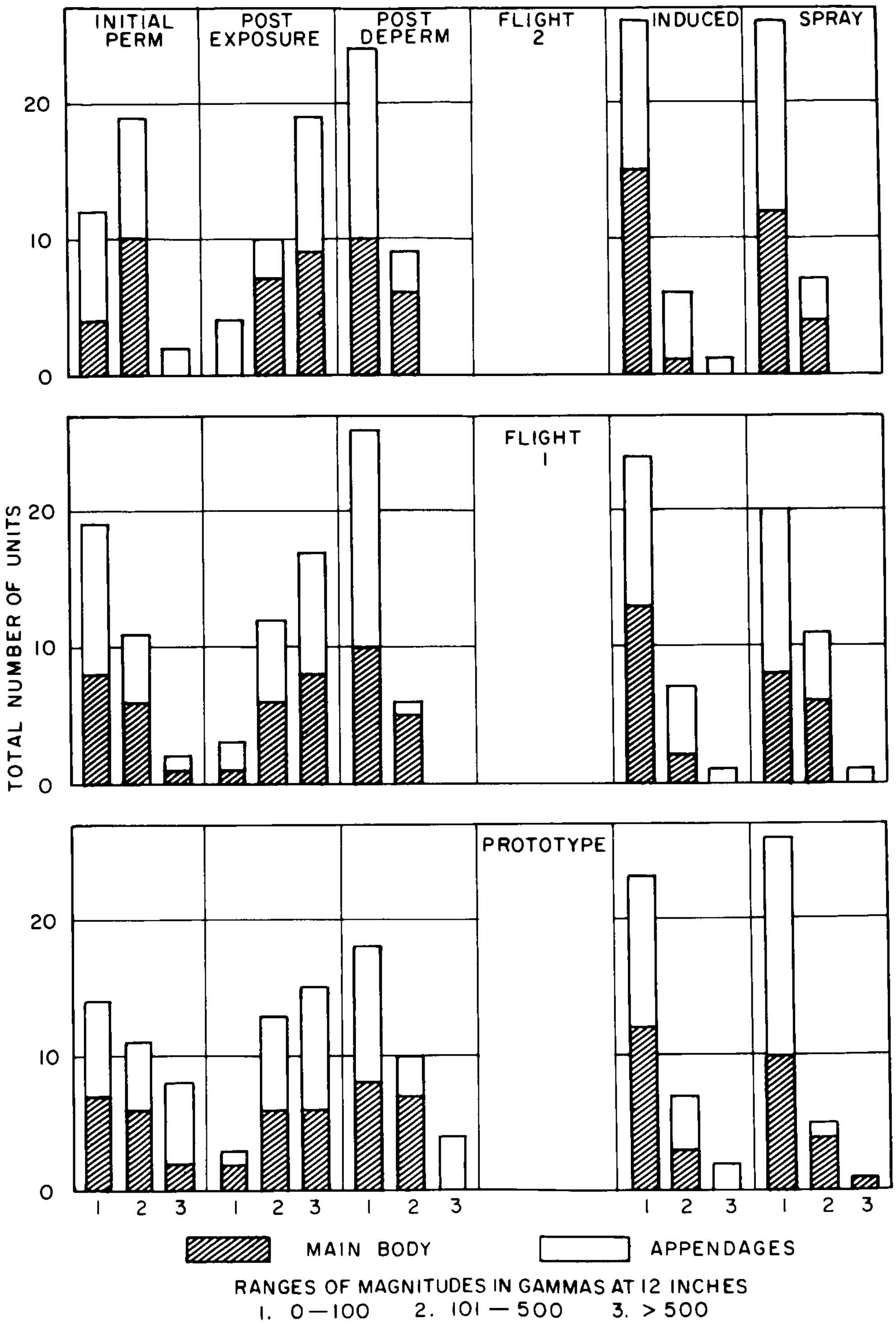

Figure 2–Distribution of Field Magnitudes for OGO–A Experiment Assemblies.

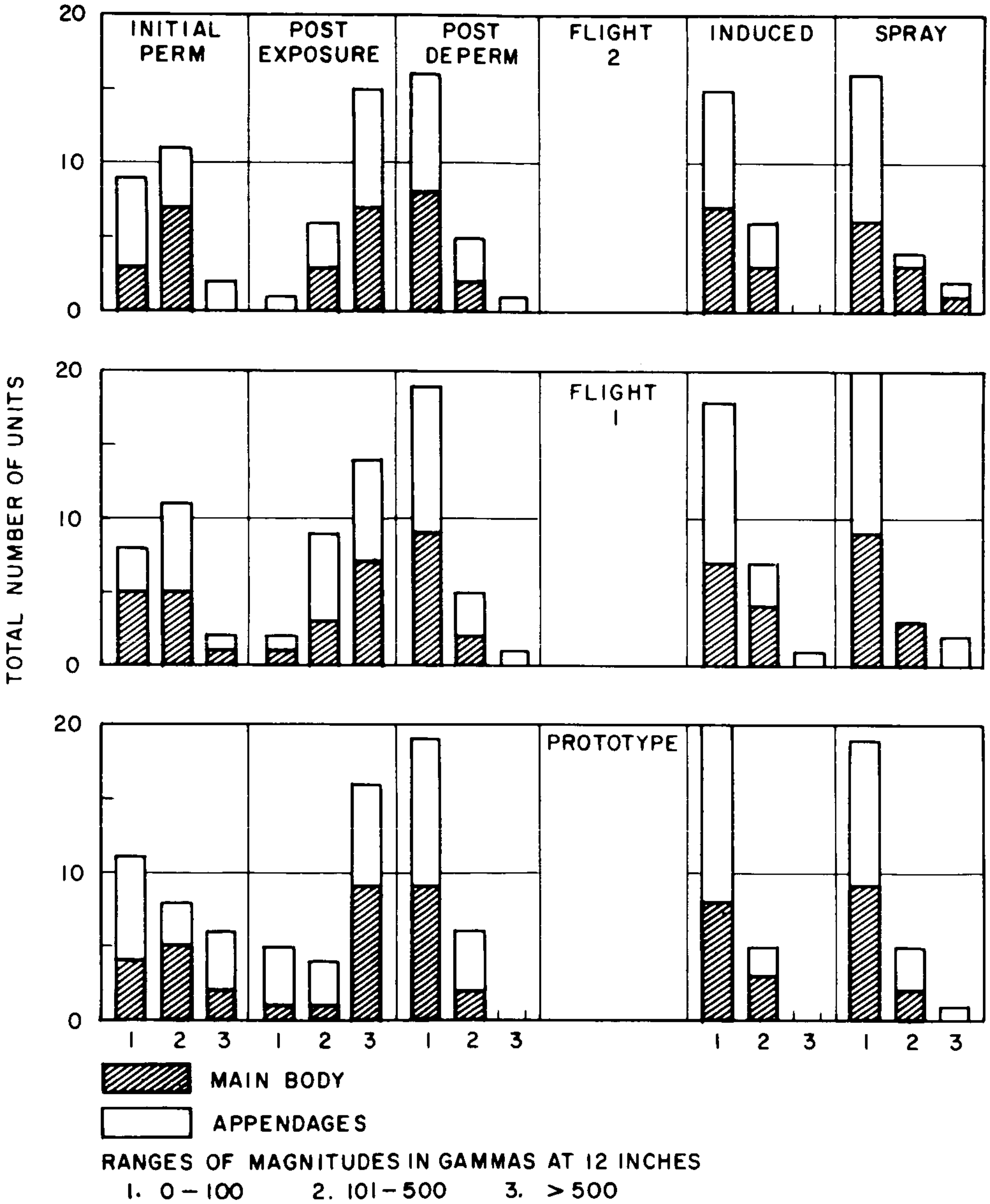

Figure 3–Distribution of Field Magnitudes for OGO–C Experiment Assemblies.

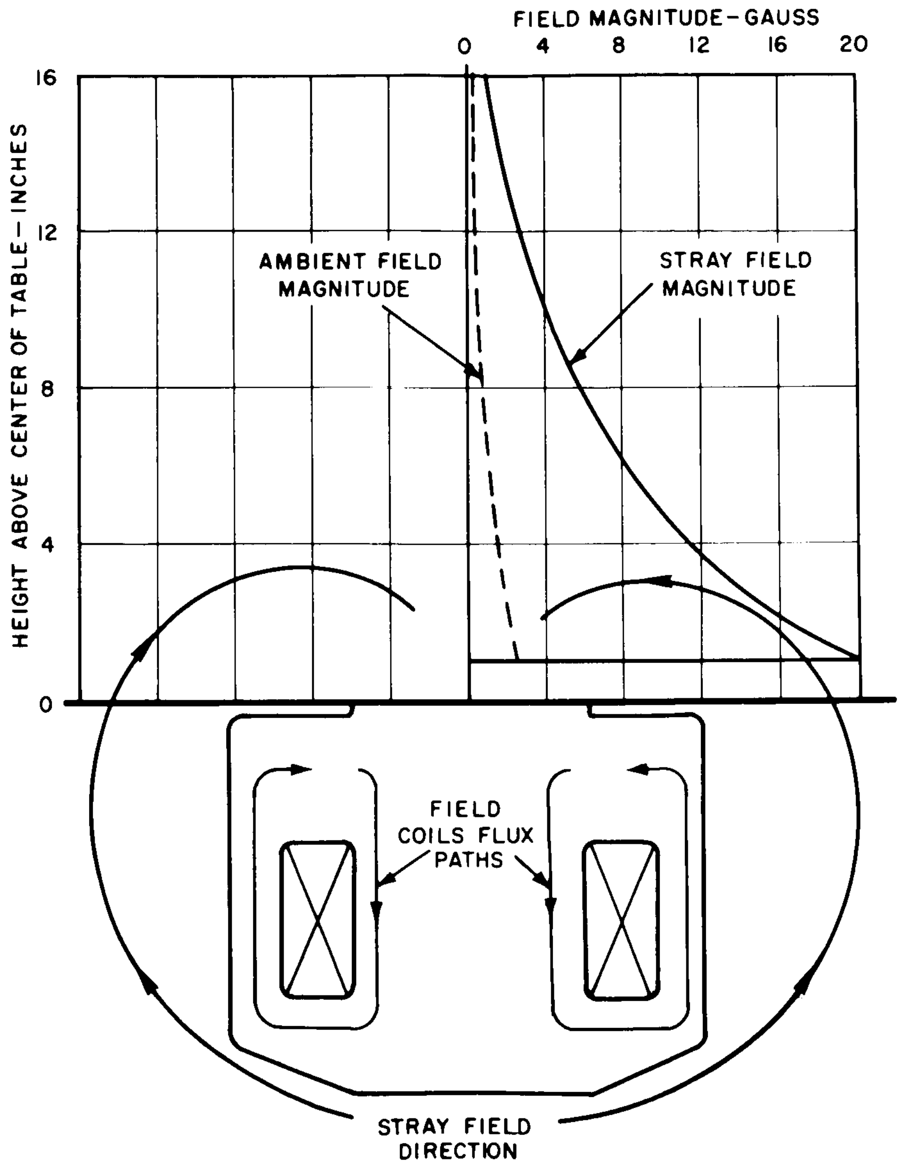

Figure 4–Exciter Table MB C–125 Magnetic Field Intensity.

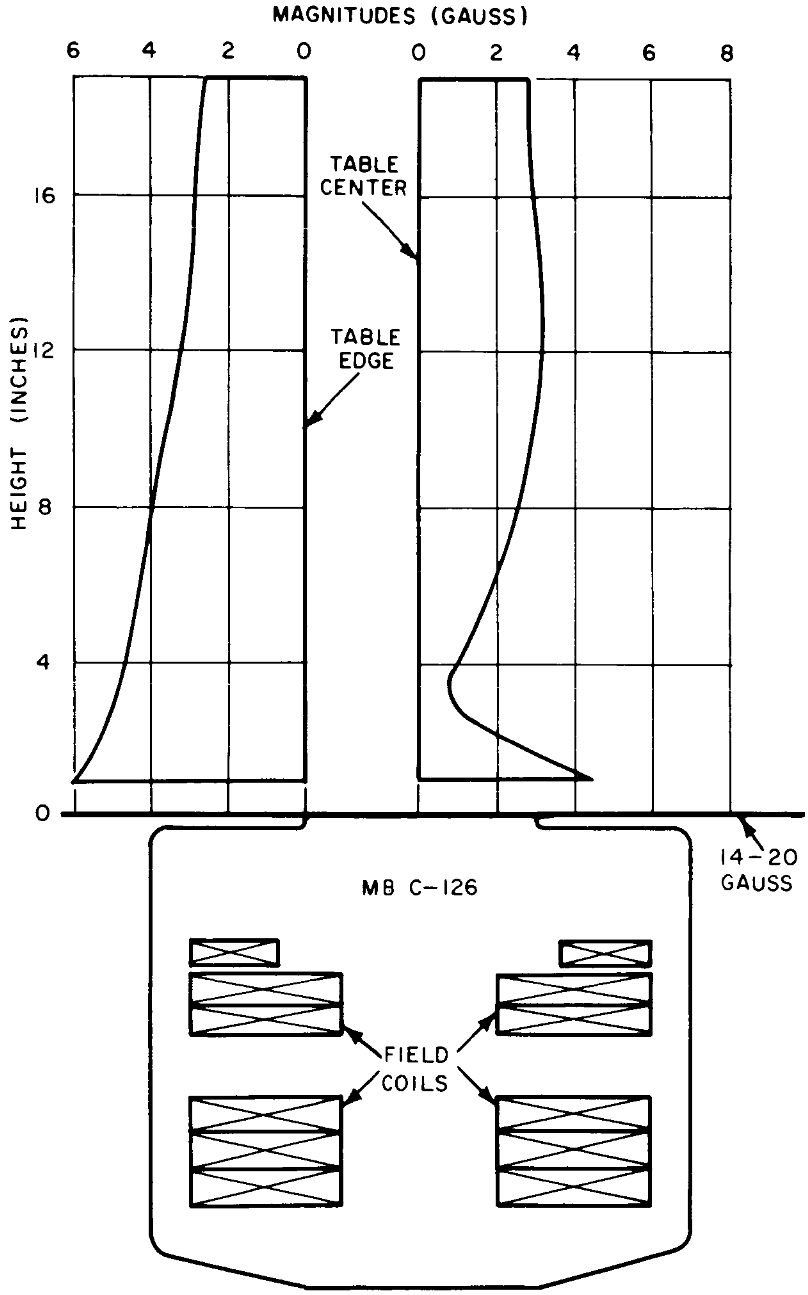

Figure 5–MB C–126 Exciter Table Magnetic Field Intensity.

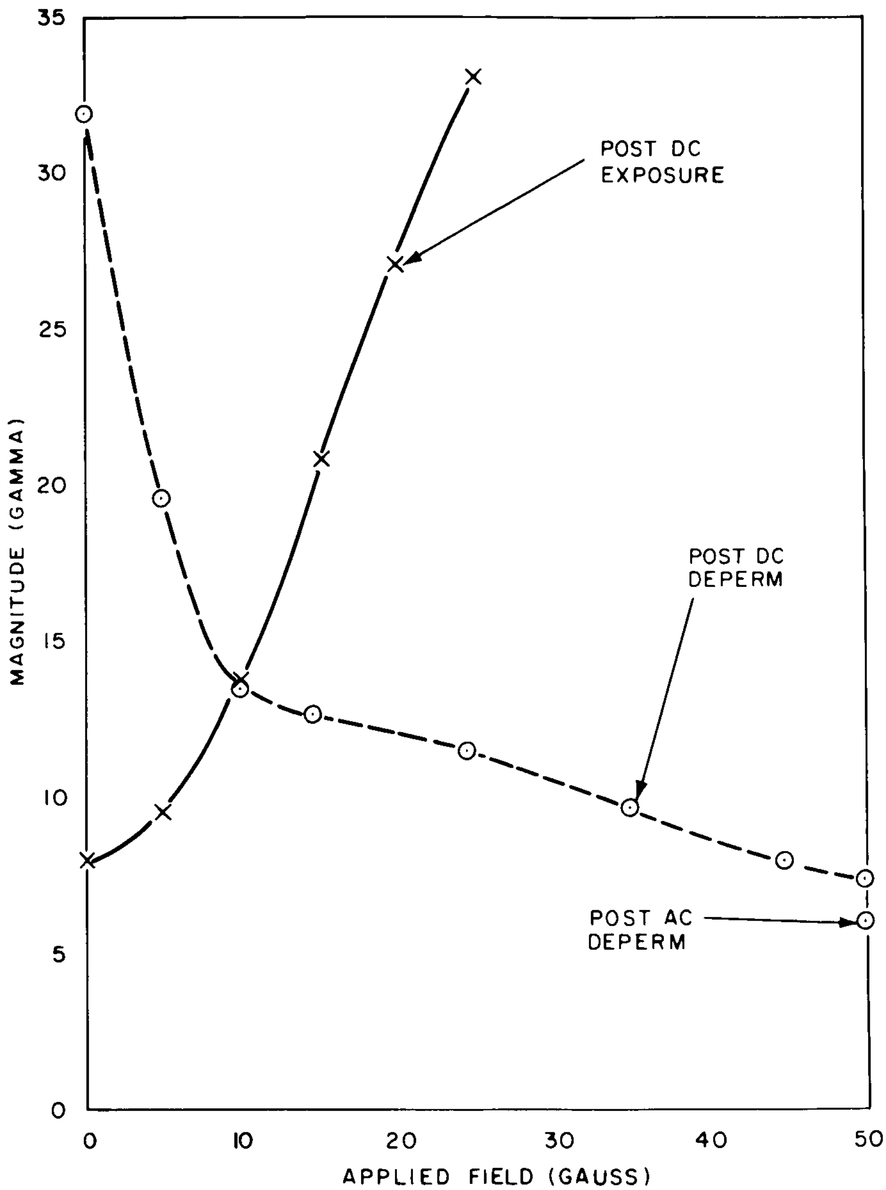

Figure 6–Assembly Magnitude Variation for Various Levels of Perm–Deperm Fields.

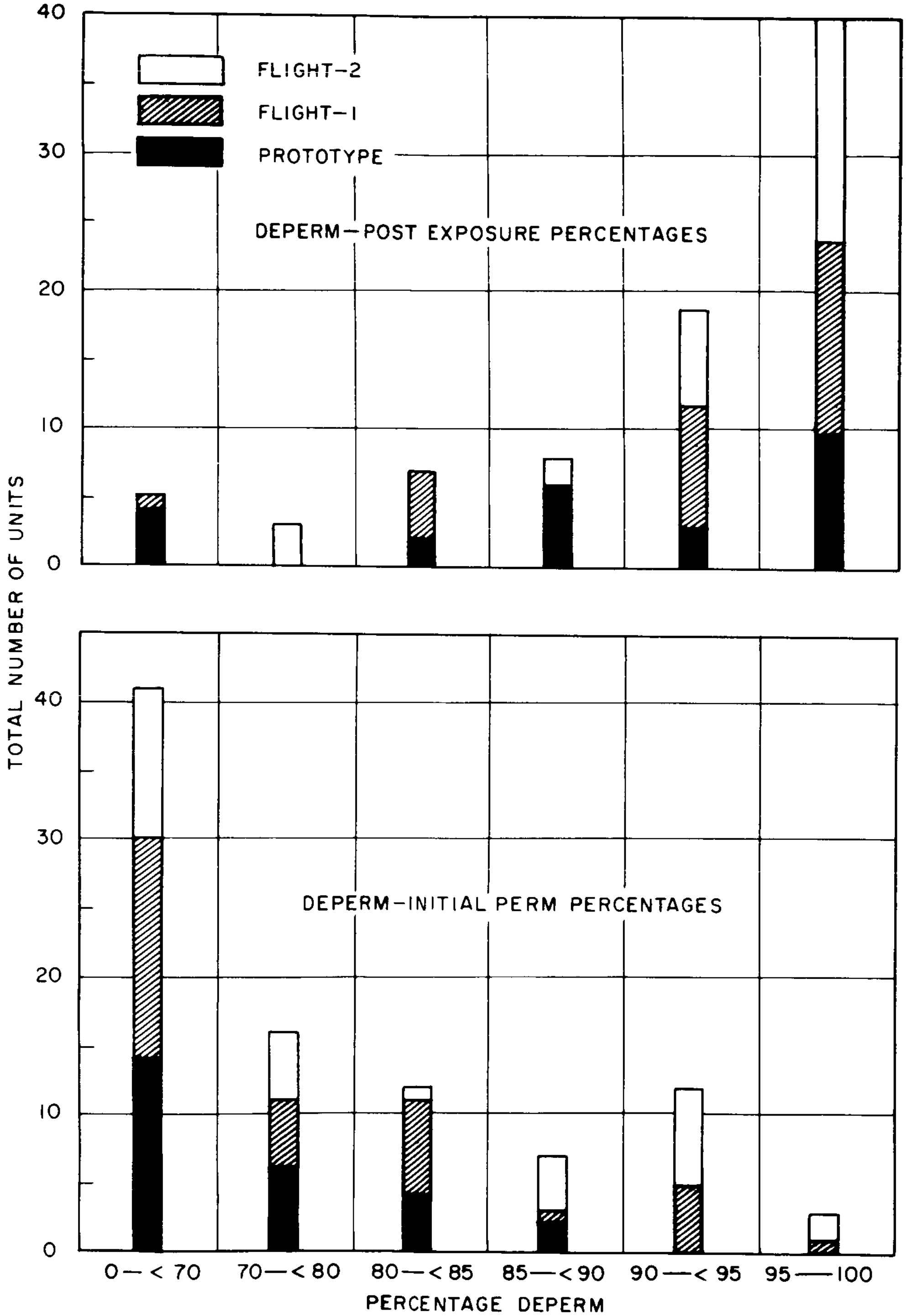

Figure 7–OGO–A Experiment Assemblies Deperm Percentage Results.

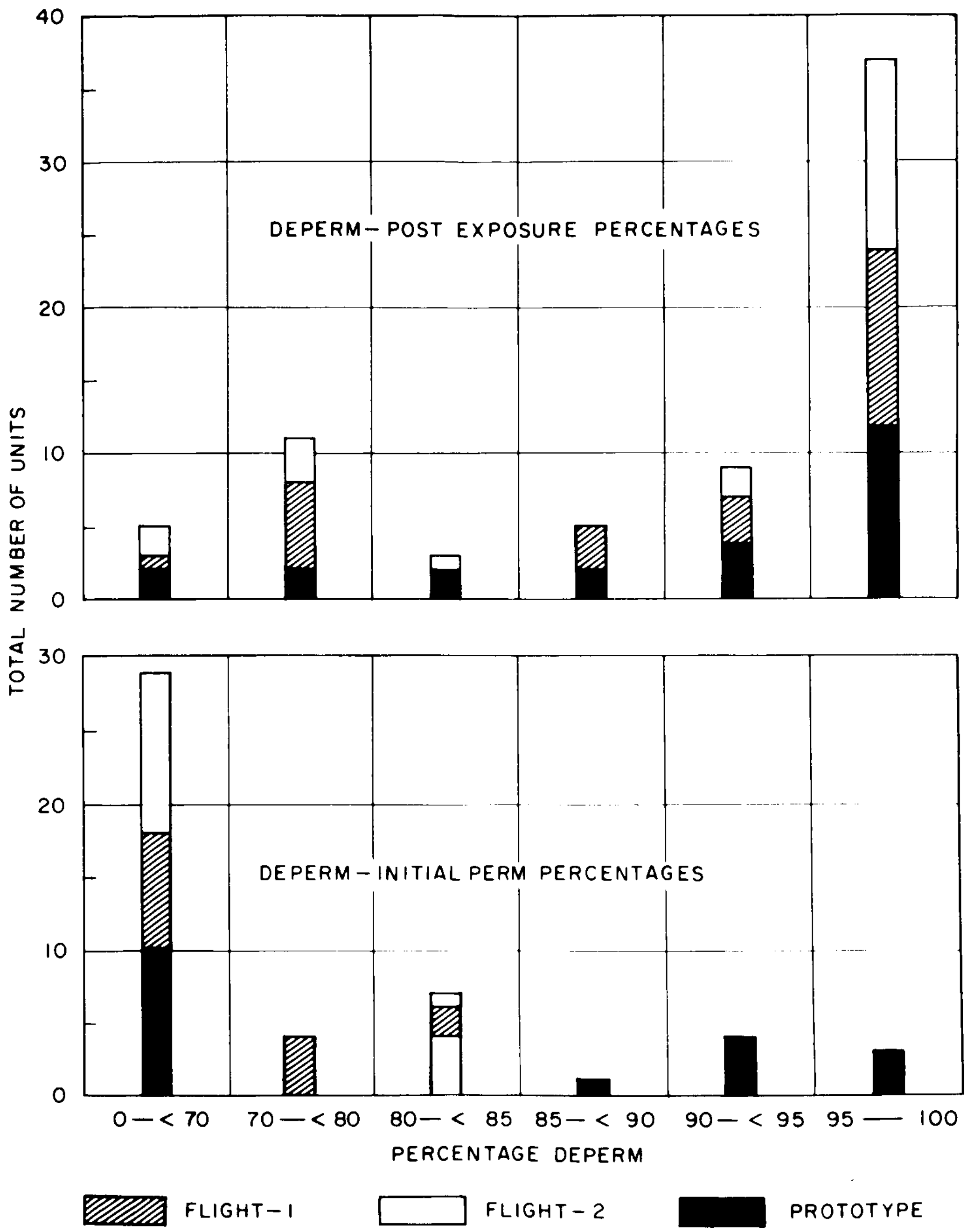

Figure 8–OGO–C Experiment Assemblies Deperm Percentage Results.

APPENDIX C

MEMORANDUM
REPORT NO. 665-021
August 19, 1966

To: Distribution

From: C. A. Harris
Test and Evaluation Division

Subject: Demagnetization Methods for Spacecraft Systems and Components — ART Deperm Experiments

ABSTRACT

This report evaluates the methods utilized in the demagnetization of spacecraft systems and components and proposes a technique of D.C. rotation deperm which would be particularly advantageous in the demagnetization of spacecraft.

INTRODUCTION

Since the commencement of the magnetic test programs for the IMP and OGO spacecraft systems and components, demagnetization has been employed as a means of restoring the object to a nearly zero virgin magnetic state. Between 1962 and 1963 D.C. demagnetization was employed at the Component Magnetic Test Facility (CMTF). More recently demagnetization has been performed by substituting a 60 cycle A.C. field for the D.C. schedule. Under normal conditions a ferromagnetic material can be demagnetized by the application of a demagnetizing force with an initial field strength amplitude equivalent to the coercive force of the material. A field of this magnitude would then ensure removal of the remanence resulting from prior saturation of the material.

However, in the testing of the spacecraft subsystems there are practical reasons why the demagnetization field magnitude has been maintained at a level of 50 Oersted or less. For example, facilities to generate more intense fields throughout large volumes are either very costly or are incompatible with requirements for generating gradient free low intensity fields (zero to a few gammas) needed for other magnetic tests. In addition, some spacecraft carry onboard permanent magnet devices (mass spectrometers, klystrons, compensating magnets) whose intended function would be impaired by even partial demagnetization. There is the possibility of inducing damaging mechanical and electrical forces with the spacecraft by exposure to very intense fields. Also, apart from the deliberate magnetization of permanent magnets and the magnetic inspection of components and welds, it is extremely unlikely that components or subassemblies will be exposed to magnetizing fields in excess of 10 or 15 Oersteds except under controlled test conditions. Therefore the 50 Oersted level of field should result in completely demagnetizing "soft" ferrous materials which have low coercivity and, in addition, reducing the field strength of "hard" ferrous materials which have not been magnetized with fields above this level. This will not reduce the moment of an ALNICO magnet however, and therefore will not alter the operating characteristics of components which include magnets. Figure 1, therefore presents examples of the hysteresis curves for both hard and soft ferrous materials and indicates the wide difference between the two saturation levels.

The sequential exposure of a component or assembly to a known magnetizing field followed by demagnetization provides a well defined magnetic history for the test item and is a means of establishing a relatively stable and predictable magnetic characteristic. Even if the exposure sequence is omitted, demagnetization alone can still be used to establish a relatively stable magnetically clean condition. Therefore there is a continuing need for improved methods to accomplish this task. As a result, a series of tests have been performed in order to compare the relative merits of A.C. and D.C. demagnetization techniques and to enable the selection of the method most suitable for demagnetization of spacecraft systems and components. In order to demagnetize materials properly, the following procedures should be included in the process.

1. Gradual and continuous reduction of the area under the hysteresis curve to zero by cycling through a series of gradually diminishing hysteresis loops.
2. Maximum amplitude of initial field strength equal to or in excess of the maximum coercivity of the material to ensure removal of the saturated remanence.
3. Return of object to a demagnetized isotropic condition similar to a virgin state by producing a scattering effect which in turn results in a completely random orientation of the domains in the material.

While the aforementioned requirements can be satisfied by either A.C. or D.C. demagnetization processes, a third method which does not satisfy these conditions can also be used for demagnetization. This technique, normally called the "recoil method," is not customarily employed since it actually results in a pseudo deperm by leaving the test item in an anisotropic condition. By trial and error the magnetization of "softer" elements is reversed to provide compensation for the remanence of the "harder" elements. The stability of such a multipole system comprising both soft and hard elements would then be uncertain. Therefore, only the A.C. or D.C. demagnetization processes have been investigated.

TEST OBJECTIVE

In order to evaluate the demagnetization techniques a series of tests was designed which would provide the following information:

1. Effectiveness of demagnetization process in reducing the residual field intensity.
2. Data to be used in comparing the results between 60 cycle A.C. and D.C. demagnetization.
3. Relationship between intensity of applied field and remanent magnetization of object.
4. Comparison between 3-axis and single axis (moment) demagnetization.
5. Feasibility of demagnetizing in earth's ambient field.
6. Other miscellaneous factors affecting the demagnetization process (L/D ratio, shape, eddy current loss).

Some of the problems and limitations of the two general categories (A.C. and D.C.) of demagnetization techniques involve:

1. Induction of large circulating currents within the spacecraft circuitry associated with 60 cycle ac.
2. High current switching requirements which are handled by relays for D.C. deperming.
3. Induced voltages which can affect cancellation coils.

While these problems are not insurmountable, it would appear that they should be taken into consideration and included in the actual demagnetization requirements. From the standpoint of the problems associated with (1) and (3) those demagnetization systems which include either A.C. or D.C. pulsing demagnetization are undesirable. A proposed solution would be to develop a D.C. rotation demagnetization capability which could be substituted for both the D.C. (pulsing) and A.C. systems. Whereas, the 60 cycle A.C. deperm can employ a variable autotransformer to vary the field, the D.C. — pulsing system requires a succession of field pulses of reversed polarity which can be diminished to a minimum field strength magnitude of zero. The sequence for such a system is displayed in Figure 2. The proposed D.C. — rotation method employs a diminishing D.C. field (refer to Figure 3) similar to the D.C. pulse deperm of Figure 2 but excludes the field reversal requirements. As seen by the test item, the D.C. field effectively becomes a low frequency A.C. field in view of the fact that the object is rotating in the applied D.C. field. There are several advantages to this system which make it more preferable to either the A.C. or D.C. pulsing systems; for example, power supply problems are simplified; ambient field effects are cancelled; there is greater uniformity and control of the deperming process; and though automatic controls are convenient, they are not mandatory. The last and final test objective then is to compare all three methods of demagnetization in order to determine if the D.C. rotation technique would indeed be practical.

TEST RESULTS

Prior to the actual deperm tests, consideration was given to the selection of test samples which might correspond to expected spacecraft components. Thus, one sample was obtained which represents an actual spacecraft electronics subassembly while the others were selected to represent various thicknesses and lengths of objects. The particular rods which were selected had approximate demagnetization factors which varied from 0.08 to 0.001 and contained low or moderate eddy current loss characteristics.

50 Gauss Deperm Results — Figure 4, is a comparison graph which indicates the percentage deperm results, obtained with the various samples for each of the three demagnetization states. In the case of four samples, each method of demagnetization reduced the remanent 25 gauss exposure field magnitude at least 90%. While there remained less than 5% difference between the three methods, the D.C. rotation system produced the most effective results in each case.

3.5 L/D Steel Rod — As depicted by Figure 4 which includes the demagnetization results for the various samples, only slight differences in the effectiveness of the three methods could be found. The one exception was the 3-1/2" length rod which had a much greater thickness (1 inch diameter). Here again the D.C. rotation method tends to prove slightly more effective than the 60 cycle A.C. and substantially more effective than the D.C. pulse demagnetization. In addition to the 50 gauss field results, treatments involving various field levels were also performed. Figure 5 has then been prepared to illustrate graphically the results obtained under these conditions. Although the A.C. method proves effective when the demagnetization field magnitude is less than 25 gauss, the D.C. rotation method becomes more effective as the magnitude is increased. Such a difference cah best be explained by examining the actual D.C. rotation deperm sequence illustrated in Figure 3. Unless the power supply programming rate is decreased or the rate of rotation of the item increased when demagnetizing at the lower levels of field magnitude only 1 to 3 field reversals will occur thus establishing too broad a decycling hysteresis curve pattern. Reexamining the results obtained with the 1" diameter rod, the following facts can be noted:

1. At levels of 50 gauss the D.C. rotation deperm was 2-3% more effective than the A.C. deperm.

2. Increasing the D.C. rotation magnitudes from 25 to 50 gauss resulted in a 10% improvement in the deperm results (81-85% reduction at 25 gauss and ≥95% at 50 gauss).

It is of particular interest to note the eddy current effects which are attributed to the less effective A.C. deperm. For example, as the diameter of a rod approaches and exceeds 1" the eddy currents generated by a 60 cycle field can become appreciable. In the case of a 1" diameter rod the ratio of field applied (H_a) to surface field (H_s) would be approximately 0.9. So for a 50 gauss 60 cycles A.C. field the rod will generate an opposition field of 5 gauss ($H_s = 45$ gauss). Furthermore, with a 2" diameter rod this ratio would approach 0.33 resulting in a 1/3 field reduction. These eddy current effects could be remedied by reducing the A.C. field frequency in which case the H_a/H_s ratio would diminish. However, this would require sources of controllable, high power, low frequency A.C. which are not readily available.

As a further note, there are instances where A.C. will not always result in an isotropic distribution of the material domains. This condition would prevail for a magnetic substance which had a cubic anisotropy. This material would be expected to have a domain distribution at the demagnetization state which would be confined to within 55° about the axis of the A.C. field. In order to eliminate this problem, a rotating field capability would be required.

Electronics Unit — The advantage of D.C. rotation demagnetization in relation to field magnitudes in excess of 25 gauss is illustrated in Figure 6 which displays the test results for the electronics unit. Although the composition of this spacecraft subassembly (Appendix A) is such that the three methods tested produce effective deperms there is still a decided difference between the results obtained with each method. In addition to the comparison data presented in Figure 6, the following tables summarize the A.C. and D.C. rotation test results. As evidenced by the hysteresis loop and normal magnetization curve for the unit (Figure 8), the 25 to 50 gauss exposure field magnitudes were not sufficient to saturate the item; therefore, if the item were exposed to fields above the maximum indicated level of 60 gauss (Figure 6) these curves would then have to be readjusted.

TABLE I

Summary of A.C. Test Results
1. By increasing the deperm magnitude by a factor of two (25 to 50 gauss) the remanent perm magnitude was reduced 60% (1.8 to 1.1 gammas). 2. By incorporating rotation of the assembly while deperming in earth's field results comparable to a zero (background) field deperm were obtained. 3. With the assembly and coil aligned east-west (D field magnitude zero) a satisfactory deperm could be obtained without rotation; however, the results were less effective than a zero field deperm (remanent field magnitude approximately twice as great). 4. Repetition of the deperm treatment (unit not re-exposed) results in slight reduction of remanent perm magnitude (5 to 10 percent reduction). 5. Application of the deperm field along three individual axes of the assembly resulted in a cleaner deperm than a single axis deperm (along moment). This included either a single axis (moment) or 3 axis exposure. Figure 7 indicates the results for the 3 axis exposure case.

TABLE II

Summary of D.C. Rotation Test Results
1. By comparison, the D.C. rotation method of demagnetization resulted in the most effective deperm (2-3% better than A.C.). 2. Although it was possible to vary the deperm cycle, effective results were obtained by employing the schedule indicated in Figure 3 (minimum of 7 to 10 complete field reversals). The actual demagnetization curve for this case with the 50 gauss field is presented in Figure 8. 3. A decidedly ineffective demagnetization treatment was obtained when the sweep rate was accelerated or diminished during the deperm sequence.

While the deperm sequence depicted in Figure 3 would prove effective when applied to most materials other combinations of field decrease and assembly rotation could be selected. In this particular case the speed of rotation for the assembly was 1 rpm which was identical to the power supply sweep drive rate. Variation of the deperm sequence could be accomplished by adjusting the rate of rotation of the assembly from 0 to 11 rpm and/or setting the sweep drive at 1 or 10 rpm. Thus, the deperm sequence could be shortened from a time interval of less than 7 minutes to just one minute if desired (rotation speed 10 rpm-sweep drive 10 rpm) while still obtaining the normal 7 field reversals. Obviously, these alternatives improve the versatility of the system as compared to the 60 cycle A.C. deperm. The selection of sequences which include fewer or more field reversals could be varied from test item to test item as necessary. Actual results which were obtained for various rotation and sweep rates, the corresponding number of full wave field reversals and the related increments of field magnitude between each cycle are presented in Table III. The data verifies the fact that little is to be gained from the efficiency standpoint by prolonging the deperm sequence unless there is a mechanical or other limitation on the rate of rotation.

TABLE III

D.C. ROTATION DEPERM SEQUENCE (50 GAUSS FIELD MAGNITUDE)

Assembly Rotation Speed (rpm)	Power Supply Sweep Drive Speed (rpm)	No. of Full Wave Field Reversals (shots)	Approximate Field Increment between shots (Gauss)	Percent Deperm Achieved
1	1*	7	8	97.5
2	1	14	4	97.6
11	1	75	1	97.7
1	10**	<1	50	0
5	10	3	14	95.4
7	10	5	10	97.5
11	10	7	7	97.5

* Total time required 6-2/3 minutes (identical to D.C. pulse deperm)

** Total time required 40 seconds (normal A.C. deperm <10 seconds)

CONCLUSIONS AND RECOMMENDATIONS

The demagnetization tests which were performed indicated the following:

1. Demagnetization with a pulsing D.C. field is the least effective of all three methods.
2. Rotation of the object is desirable when an earth's field deperm is attempted.
3. Although the results tend to favor the D.C. rotation deperm over the 60 cycle A.C., effective demagnetization of spacecraft subassemblies could be achieved by either method. When eight IMP or OGO spacecraft assemblies were demagnetized by both methods the maximum and minimum percentages of effective deperm were as follows:

   A. C. = 99 and 45

   D.C. rotation = 99 and 46

In view of the favorable deperm results obtained with the D.C. rotation method and especially because of the advantages of such a system, i.e., variable frequency rates, reduction of eddy current and rise time effects, and elimination of circuit breaking, it is recommended that this method be utilized in the demagnetization of spacecraft. Generation of a non-alternating D.C. field presents no difficulty and with the presently available Helmholtz coils and turntables the D.C. rotation method could be employed in the demagnetization of the IMP or ATS spacecraft in a facility such as the ACTF.

Now that the principle of demagnetization of spacecraft systems by the D.C. rotation method has proven effective it would be worthwhile to continue further investigations of demagnetization techniques utilizing this method. Three particular areas in which additional tests could be conducted would be as follows:

1. Random rotation of the object during the demagnetization process instead of the azimuth rotation which was employed in these tests.
2. Application of initial field strength amplitudes in excess of 50 gauss (100-200).
3. Substitution of exponential in place of linear D.C. field decay.

Additional tests, numbers 1 and 2, could be performed by utilizing the equipment designed for use in the Summer Workshop A.C. demagnetization tests which were performed in 1963 and would furnish additional comparative information relating

APPENDIX A

DESCRIPTION OF ELECTRONICS UNIT

Through the cooperation of the Fields and Plasma Branch (Code 612), it was possible to obtain the use of an actual EGO experiment electronics assembly (4911) as a test sample for the demagnetization tests. Because of the packaging density and variety of parts included within, this unit aptly represents the usual spacecraft subsystem components, i.e., converters, regulators, amplifiers. As shown in figure 1, the assembly contains a total of 15 electronic cards with innerconnecting wiring which occupy an approximate value of $(8)^3$ cubic inches and weighs a total of 11 pounds. In addition to the numerous circuit boards, resistors, and capacitors, the unit contains the following minimum totals of parts:

Transistors	300
Diodes	350
Connectors	37
Transformers (iron core)	30
Relays	4
Trim pots	40
Coils (iron core)	15

to A.C. and D.C. rotation demagnetization. There is the further possibility that this method would also be applicable in the demagnetization of materials which have been magnetized to saturation (applied fields greater than 25 gauss) by application of fields with initial strength in excess of 1 kilo gauss.

/s/ C. A. Harris
C. A. Harris
Functional Test Branch

Attachments — Appendix A, B
Figures 1 thru 8

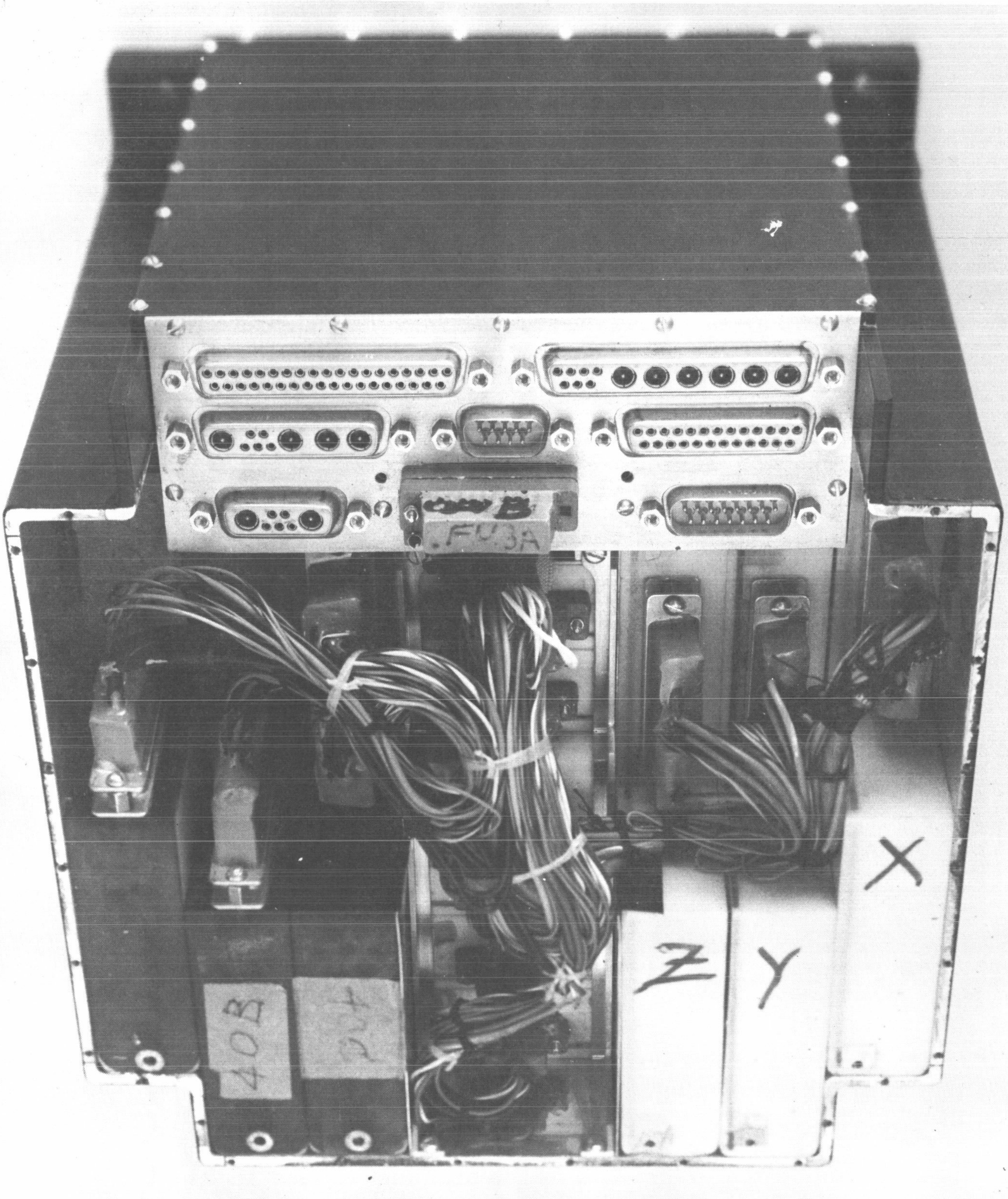

Figure 1–EGO (4911) Electronics Assembly

APPENDIX B

GLOSSARY OF MAGNETIC TERMS

Anisotropy - difference in magnetic properties as a function of direction of magnetization.

Coercive Force (H_c) - value of field intensity (H) required to reduce flux density from $B = B_r$ to $B = 0$.

Coercivity - value of coercive force (H_c) on a major hysteresis loop.

Demagnetization (deperm) - partial or complete reduction of residual induction.

Demagnetization curve - portion of the hysteresis loop which lies between B_r and H_c.

Dimension Ratio (L/D) - the ratio of the length of an object in the direction of its magnetization to its diameter.

Domain - small regions, each comprised of many atoms which compose a ferromagnetic material.

Eddy current - circulating currents set up in conducting masses or sheets by varying magnetic fields.

Ferromagnetic material (soft) - material for which the area enclosed by the demagnetization curve is small. In general $H_c < 10$ Oersteds.

Ferromagnetic material (hard) - area enclosed by demagnetization curve is large: $H_c > 10$ Oersteds.

Hysteresis - lag of induction (B) as the magnetic field intensity (H) is diminished to zero.

Magnetization curve - plot of the steady-state relation between magnetic induction in a material and the steady-state alternating magnetic field intensity that produces it.

Magnetic Saturation - a condition in which further increases in magnetizing field produce no increase in magnetization.

Permanent Magnets - strongly magnetized bodies whose magnetization is little affected by the action of internal or external magnetic fields.

Residual Induction or Remanence (B_r) - value of flux density when the magnetizing force (H) is decreased to zero.

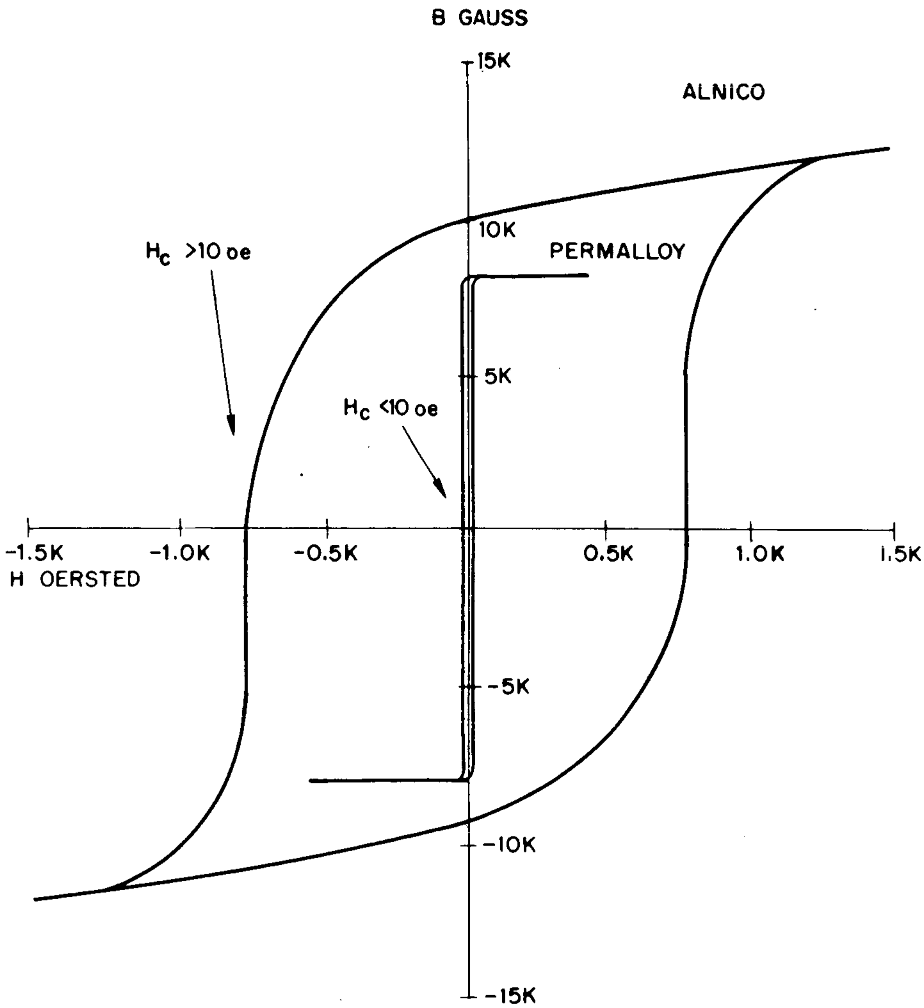

Figure 1—Hard and Soft Material Hysteresis Curves.

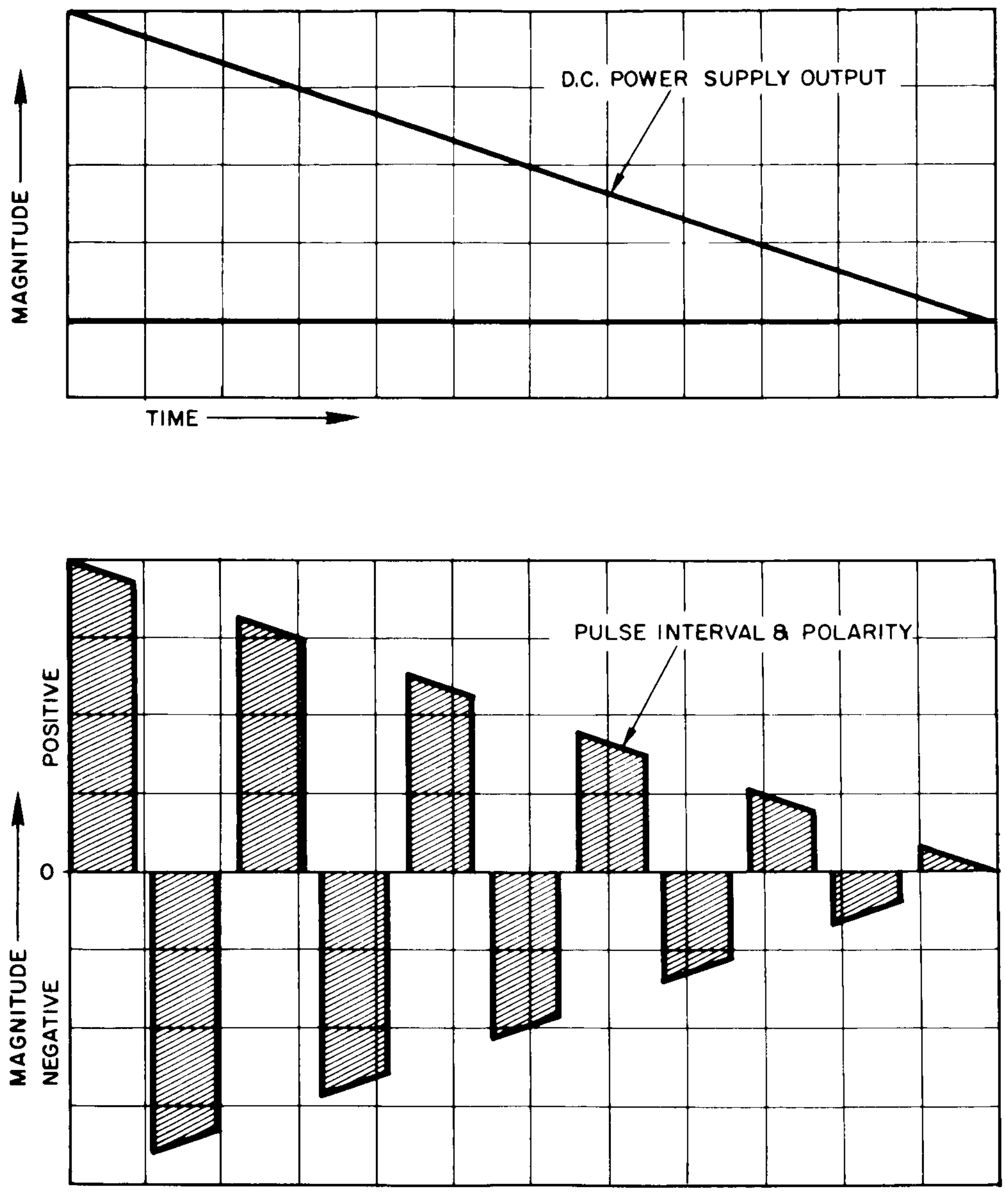

Figure 2–D.C. Pulse Demagnetization Sequence.

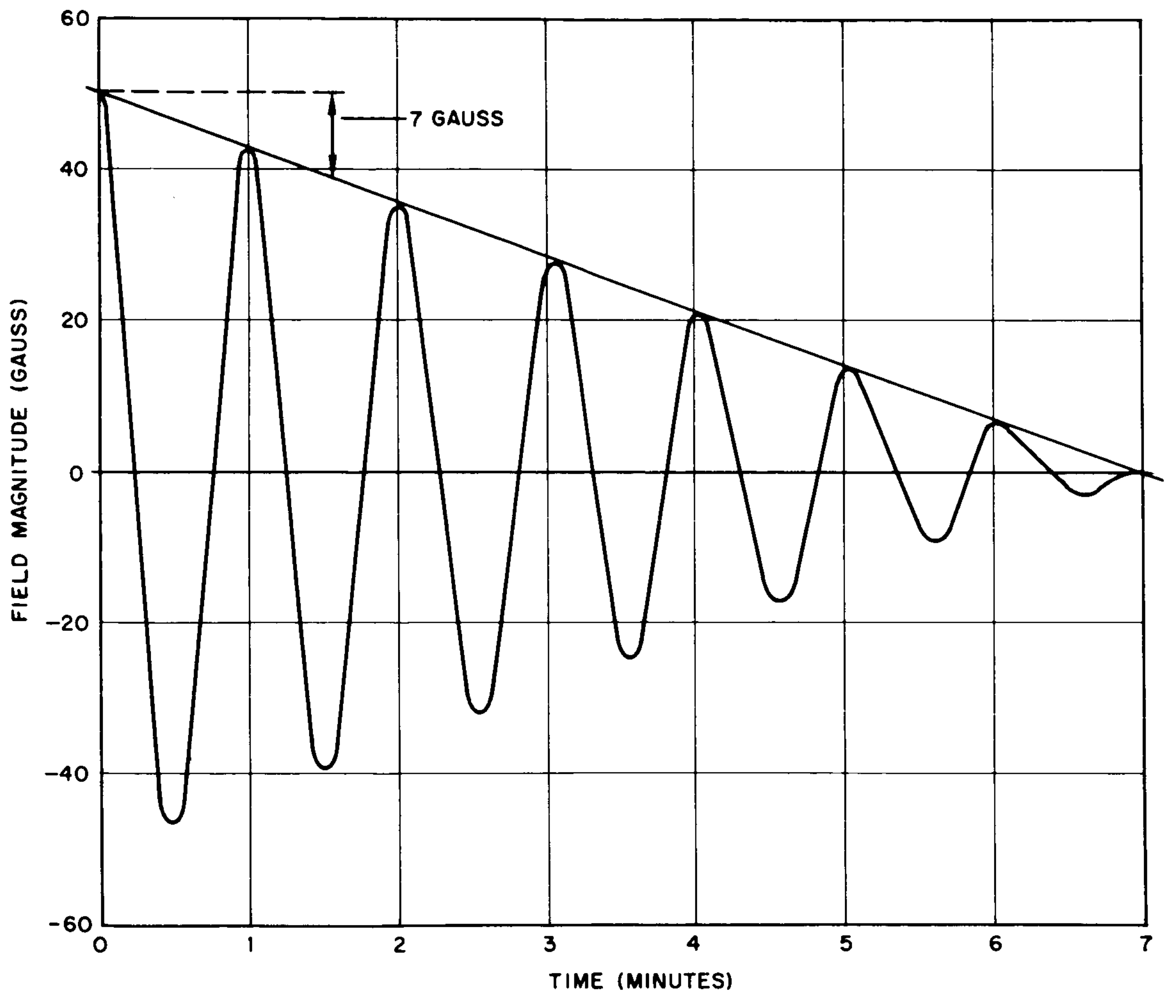

Figure 3–D.C. Rotation Deperm Sequence.

ITEM	L/D
ELECTRONICS UNIT	1
SAE 1020 ROD 3-1/2" x 1"	3.5
DRILL ROD 4" x 1/4"	16
SAE 1020 ROD 4" x 1/4"	16
STEEL ROD 12.5" x 1/4"	50

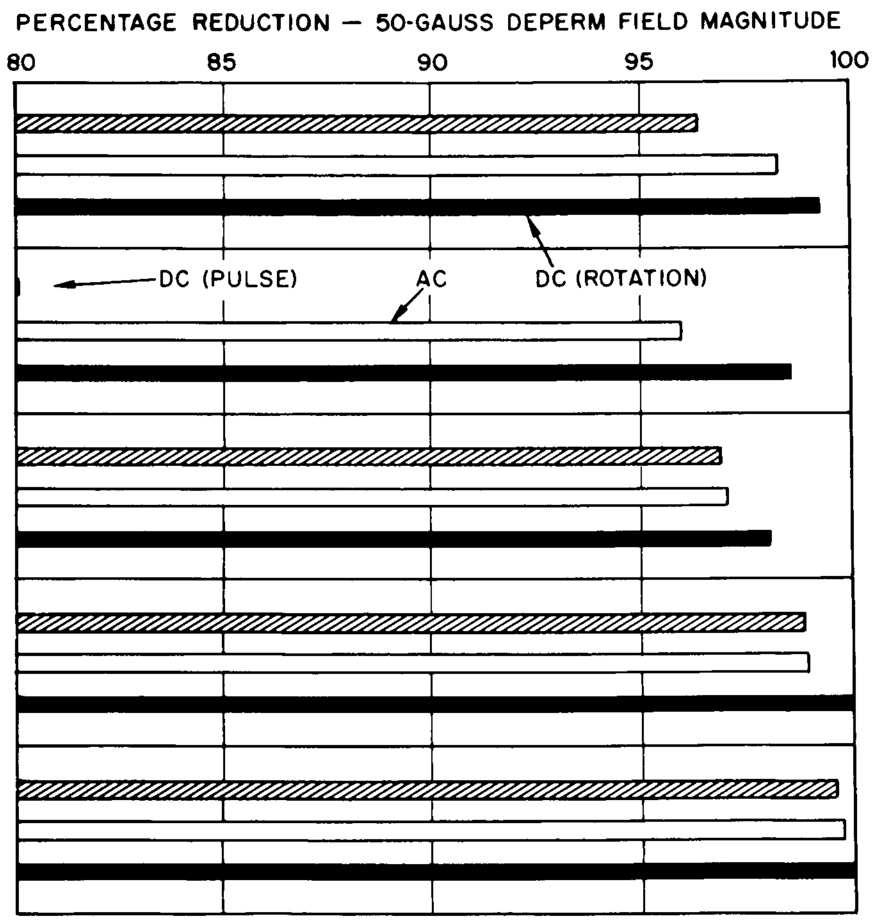

Figure 4–Deperm Test Results.

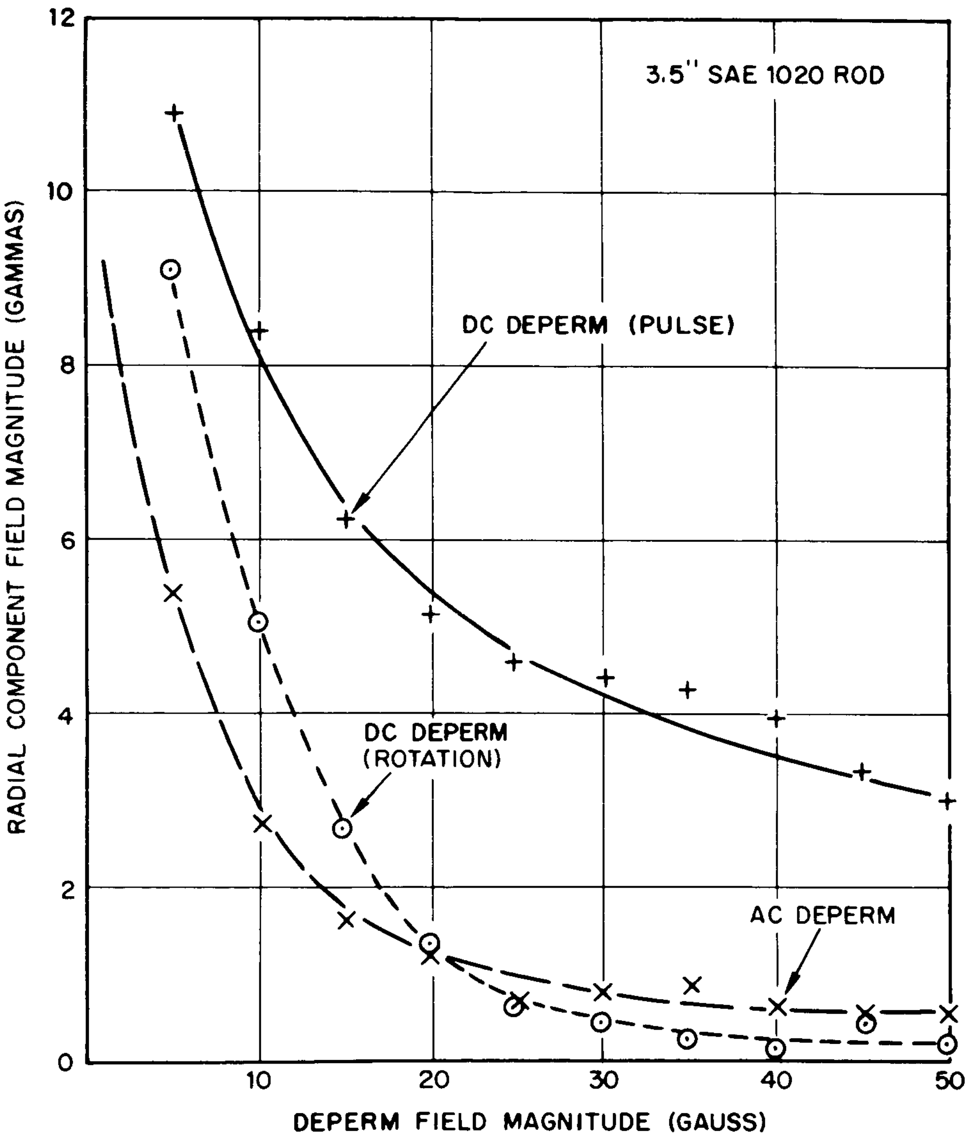

Figure 5–1" Diameter Rod Deperm Results.

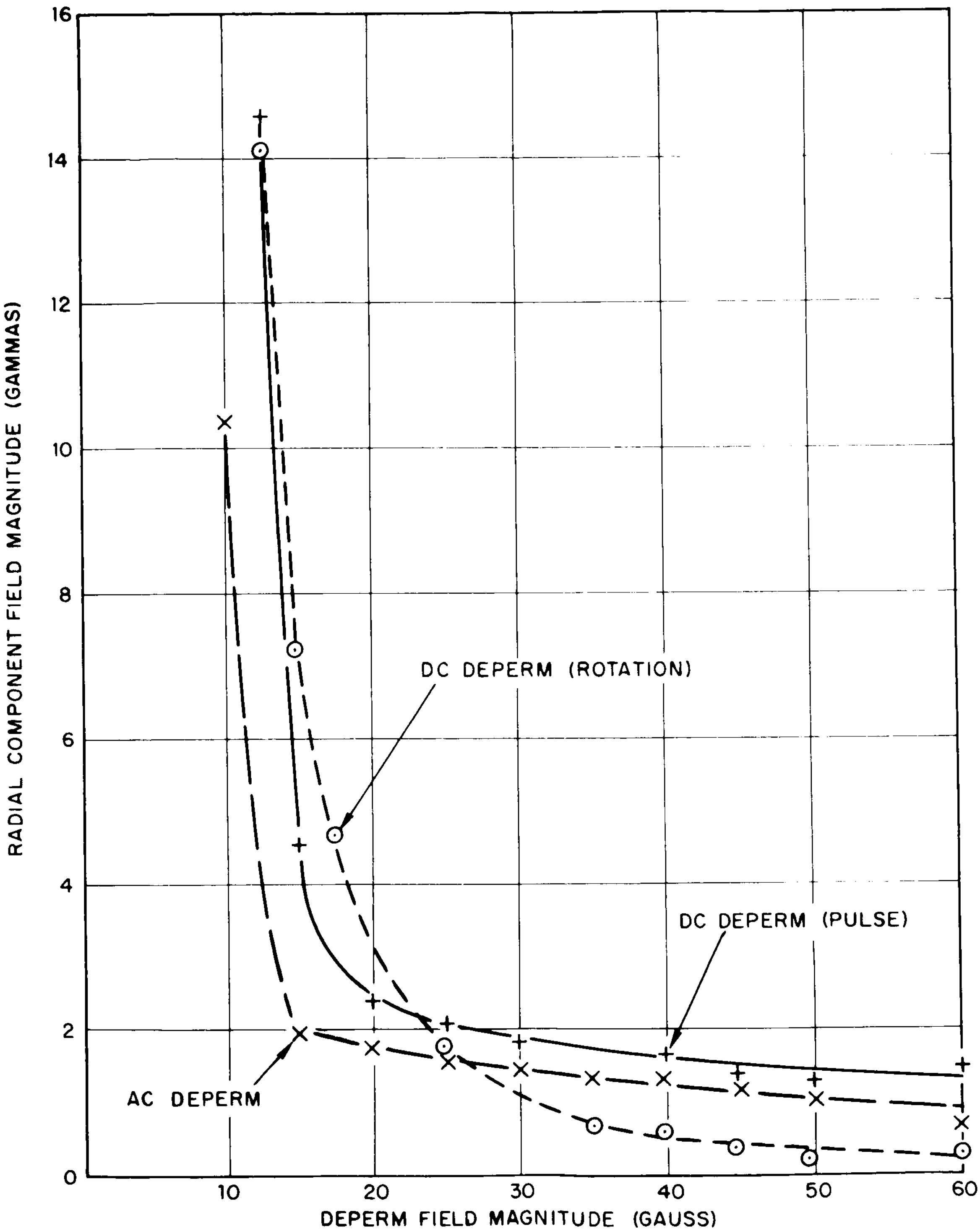

Figure 6–Electronics Unit Deperm Results.

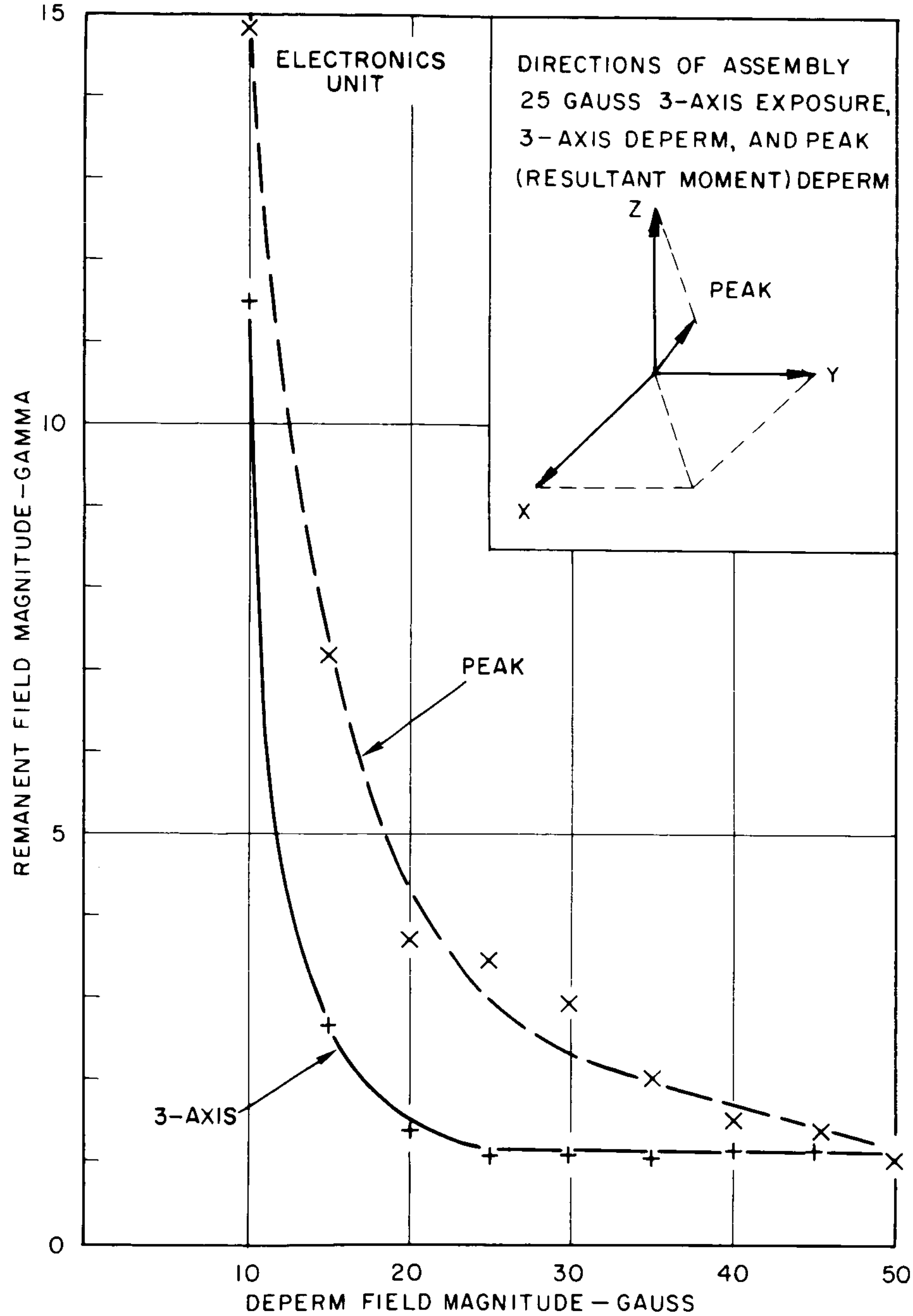

Figure 7–A.C. Deperm Comparison Data – Three Axis and Single Axis (peak) Demagnetization Results.

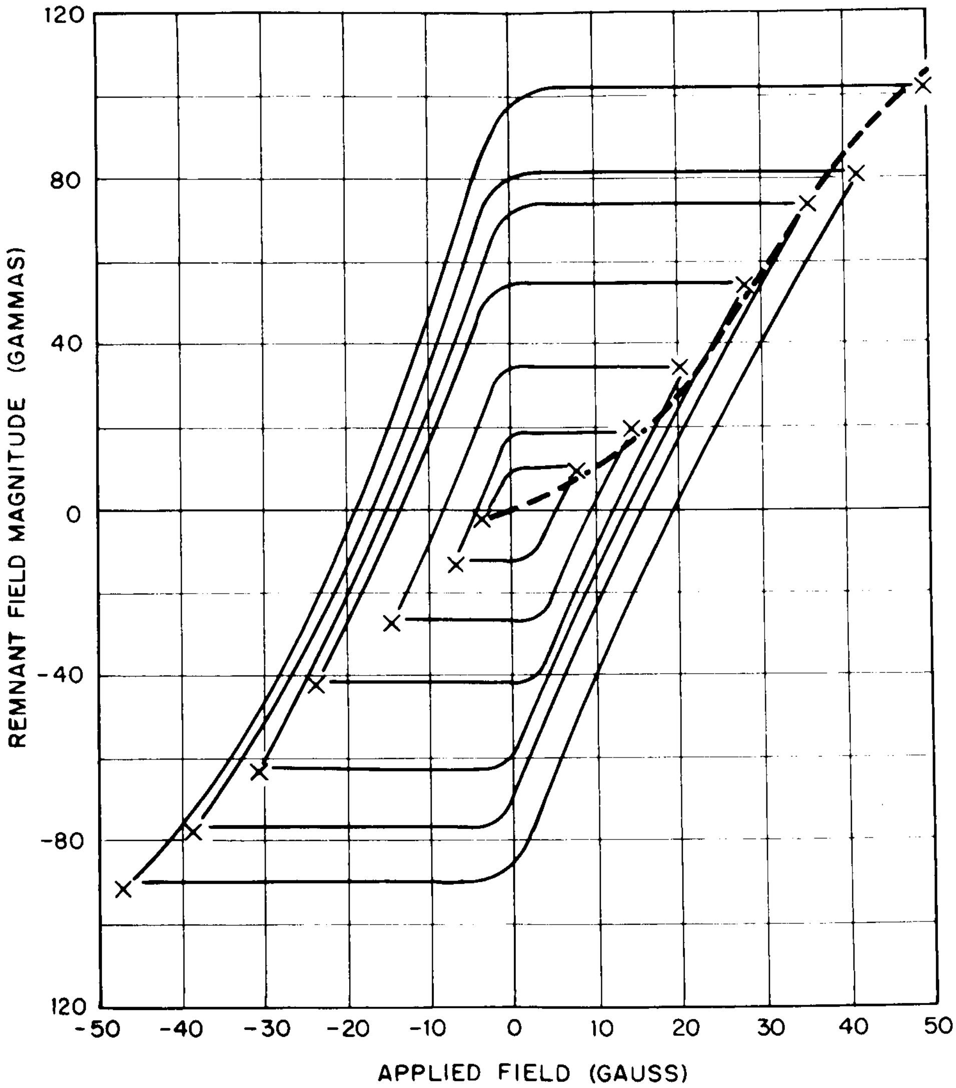

Figure 8—Electronics Unit Hysteresis Demagnetization Curve.