Measurement Notes

Note 26

Summary of Cable Response Experiments

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ABSTRACT

Experiments to investigate the radiation response of various types of cables are described; the experiments were performed at The Aerospace Corporation from 1973 to date. The photon sources used were the Mk IV and V dense plasma focus devices. Measured responses of cables used on the DSP, FSC, GPS, and DMSP satellites, and in laboratory and underground test instrumentation, are summarized. The responses of various types of cables (braid-shielded multiconductor, braid-shielded single conductor, hollow dielectric semirigid, solid dielectric semirigid, and multiconductor flat ribbon cable) are given and compared. Experiments that examined cable response mechanisms, such as effect of metal-dielectric gaps, air effects, effect of applied potential bias, and emission from cable materials, also are described. The initial cable response of a shielded conductor was deliberately examined; no anomalous first-exposure response was observed. Designs for minimum-response cables that employ Kel F dielectric and aluminum shield and conductor are proposed. A complete list of references to published and internal Aerospace literature describing this effort is included.

CONTENTS

APPENDIX

TABLES

FIGURES

I. INTRODUCTION

Radiation responses of many of the cables used in several current satellites have been measured. The X-radiation sources used were The Aerospace Corporation Mk IV and Mk V dense plasma focus (DPF) devices. These response measurements, extrapolated to threat radiation levels, are being used to compute the expected magnitudes of signals generated within the cables in satellite survivability analyses. These signals, if sufficiently large, can damage or destroy electronic and electrical systems. To ensure survival of these systems, protective devices (Zener diodes, filters, etc.) designed to bypass these signals are inserted between the cables and the vulnerable components. In addition, radiation responses of several cables used in laboratory and underground nuclear test instrumentation and signal transmission have been measured. These measurements permit selection of the optimum cable for a given test application and allow an estimate of the cable radiation noise under given irradiation.

These response measurements have been reported in the published literature and in internal Aerospace Corporation correspondence. The objective of this report is to summarize, in one document, the cable response measurements and experiments performed to date at The Aerospace Corporation. This summary gives an indication of the various types of cabling being used on current satellites and the general magnitude of the radiation response associated with these cables. This summary also describes experiments directed toward relating cable response to cable characteristics. This report therefore provides insight into the solution of the problem of radiation effects response reduction.

Section II of this report summarizes response data for cables irradiated by filtered DPF X-ray fluence. Experiments that were conducted to examine mechanisms affecting cable response are described in Section III. Section IV briefly describes studies implemented to investigate photoemission from various dielectrics and metals, which bears directly on cable response. Section V shows data obtained in an experiment conducted to examine the initial response of a shielded cable, a controversial aspect of cable response. Section VI concludes the report by discussing possible new designs that would reduce the radiation response in cables.

II. CABLE RESPONSE MEASUREMENTS

All cable radiation response measurements given in this report were obtained at the DPF facility. The DPF devices, the test arrangement, the measurement procedure, and the incident X-ray spectrum have been described (Refs. 1 through 3) and are briefly covered in Appendix A. Cable response is reported in units of coul/rad(Si)-cm [= amp/(rad(Si)/sec)-cm], indicating normalization to dose in silicon. Numerical factors for conversion to response normalized to incident fluence (cal/cm^2), for the various DPF spectra specified by given filtration, are also given in Appendix A.

Since 1973 several Aerospace Corporation investigators have examined numerous cables for radiation response. These cables include many being used in current satellites (DSP, FSC, GPS, and DSAP)*, common laboratory cables, and semirigid coaxial cables used in AFWL underground test EMP sensors. To give some order to this large number of measurements, the response measurements have been divided into six categories — four associated with specific satellites, one with laboratory cables, and one with solid dielectric coaxial cables. Similar types of cables have been grouped together within each category. These measurements are given in Tables 1 through 6 with a brief description of the cable, the irradiation spectrum, and the reference number. (More detailed characterization of each cable is given in Appendix B.) These measurements are also plotted in Figures 1 through 6.

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[1] M. J. Bernstein, Radiation-Induced Currents in Subminiature Coaxial Cables," IEEE Trans. Nucl. Sci. NS-20 (December 1973).

[2] R. L. Fitzwilson, M. J. Bernstein, and T. E. Alston, "Radiation Induced Currents in Shielded Multiconductor and Semirigid Cables," IEEE Trans. Nucl. Sci. NS-21 (December 1974).

[3] F. Hai and P. A. Beemer, Cable-Sensor Test and Development Program, TOR-0076(6501)-1, The Aerospace Corporation, El Segundo, California (15 January 1976),

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*See Glossary

Table 1. Response of DSP Satellite Cables

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF* Source & Filter	Reference
1	Sh 28, PT3-33G Wire braid shielded, 28 ga multi-strand conductor	$-1.7 \pm 0.3 \times 10^{-14}$	Mk IV 3 mm Al	4
2	PT3-33 Wire braid shielded, 28 ga multi-strand conductor	$-2.5 \pm 0.7 \times 10^{-14}$ $-5.0 \pm 1.0 \times 10^{-14}$	Mk IV 3 mm Al 0.3 mm Cu	5
3	Wire Sh 28 Wire braid shielded, 28 ga multi-strand conductor	$-2.4 \pm 0.7 \times 10^{-14}$ $-4.6 \pm 1.0 \times 10^{-14}$	Mk IV 4 mm Al 0.3 mm Cu	6
4	Ribbon Sh 28 Ribbon braid shielded, 28 ga multi-strand conductor	$-1.6 \pm 0.5 \times 10^{-14}$ $-2.3 \pm 0.7 \times 10^{-14}$	Mk IV 4 mm Al 0.3 mm Cu	6
5	PT3-59 Double ribbon braid shielded 93 Ω cable	$+7.0 \pm 0.6 \times 10^{-14}$	Mk IV 0.3 mm Cu	5
6	PT3-29 Hollow semirigid cable	$-1.6 \pm 0.4 \times 10^{-13}$	Mk IV 0.3 mm Cu	5
7	Gold braid Gold coated Ni braid shielded wire	$-2.8 \pm 0.5 \times 10^{-14}$	Mk IV 3 mm Al	4
8	Gold braid Gold coated Ni braid shielded wire	$-4.2 \pm 0.7 \times 10^{-14}$ $-4.5 \pm 0.7 \times 10^{-14}$	Mk IV 3 mm Al 0.3 mm Cu	5

*dense plasma-focus

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[4] M. J. Bernstein, "Measured Responses of Miniature Cables to Pulsed Photon and Photoelectron Irradiation," IEMP Symposium, DNA 3098P (6 February 1973) p. 13-1.

[5] M. J. Bernstein Memorandum to I. M. Garfunkel, Subject: Coaxial Cable Irradiation Results, The Aerospace Corporation, El Segundo, California (19 March 1973).

[6] M. J. Bernstein Memorandum to I. M. Garfunkel, Subject: Additional Irradiation Results for Subminiature Coaxial Cables, The Aerospace Corporation, El Segundo, California (12 July 1973).

[7] M. J. Bernstein and R. H. Vandre, Radiation Responses of AESC Prototype Multiconductor Ribbon Cables, ATM 75-5409-03-3, The Aerospace Corporation, El Segundo, California (16 October 1974).

Table 1. Response of DSP Satellite Cables (Continued)

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF Source & Filter	Reference
9	Gold braid Gold coated Ni braid shielded wire	-3.0×10^{-14}	Mk V 4 mm Al 0.3 mm Cu	7
10	Al shielded multiconductor ribbon (positive second pulse)	-7.0×10^{-15} alternate conductor grounded	Mk V 4 mm Al 0.3 mm Cu	7
		-1.3×10^{-14} alternate conductor floating	4 mm Al 0.3 mm Cu	
11	No shield multiconductor ribbon	-7.0×10^{-15} alternate conductor grounded	Mk V 4 mm Al 0.3 mm Cu	7
		-1.2×10^{-14} alternate conductor floating	4 mm Al 0.3 mm Cu	
12	Au shielded multiconductor ribbon	-6.0×10^{-15} alternate conductor grounded	Mk V 4 mm Al 0.3 mm Cu	7
		-8.0×10^{-15} alternate conductor floating	4 mm Al 0.3 mm Cu	
		-4.0×10^{-15} all conductor floating except signal	4 mm Al 0.3 mm Cu	
13	Aluminized multiconductor ribbon	$+3.0 \pm 0.8 \times 10^{-15}$	Mk V 3 mm Al	8
		$+5.5 \pm 1.5 \times 10^{-15}$	3 mm Al 0.5 mm Cu	

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[8] M. J. Bernstein, Radiation Responses of Aluminized Multiconductor Ribbon Cables, ATM 76(6409)-1, The Aerospace Corporation, El Segundo, California (1 July 1975).

Table 2. Response of FSC Satellite Cables

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF Source & Filter	Reference
1	PT3-59-93 Braid shielded, foamed dielectric coax	$+2.48 \pm 1.24 \times 10^{-14}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
2	PT3-49-50 Double braid shielded coax	$-1.76 \pm 0.53 \times 10^{-14}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
3	PT3-33N-24 Braid shielded coax	$-3.31 \pm 0.99 \times 10^{-14}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
4	PT3-33E-28 Braid shielded coax	$-2.91 \pm 0.58 \times 10^{-14}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
5	PT3-33N-22 Braid shielded coax	$-3.70 \pm 1.1 \times 10^{-14}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
6	PT3-53RR-18 Braid shielded 3 inner conductor coax	$-3.54 \pm 0.71 \times 10^{-13}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
7	PT3-33P-20 Braid shielded 2 inner conductor coax	$-2.88 \pm 0.86 \times 10^{-13}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
8	PT3-33F-26 Braid shielded 2 inner conductor coax	$-1.54 \pm 0.31 \times 10^{-13}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9

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[9] R. L. Fitzwilson Memorandum to F. Kahn, Subject: Radiation Response of Flt. Sat. Com. Cables, The Aerospace Corporation, El Segundo, California (23 October 1973).

Table 2. Response of FSC Satellite Cables (Continued)

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF Source & Filter	Reference
9	PT3-33S-20 Braid shielded 4 inner conductor coax	$-3.36 \pm 1.0 \times 10^{-13}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
10	PT3-33R-20 Braid shielded 3 inner conductor coax	$-2.76 \pm 1.38 \times 10^{-13}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
11	PT3-33P-24 Braid shielded 2 inner conductor coax	$-1.57 \pm 0.31 \times 10^{-13}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
12	PT3-29-4 Cu/Cu semirigid coax	$<1 \times 10^{-15}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
13	PT3-29-6 Al/Cu hollow semirigid coax	$-3.10 \pm 0.93 \times 10^{-14}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9
14	PT3-29-8 Al/Cu hollow semirigid coax	$-1.55 \pm 0.47 \times 10^{-13}$	Mk IV, V 4 mm Al 0.3 mm Cu	2, 9

Table 3. Response of GPS Satellite Cables

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF Source & Filter	Reference
1	RG - 400/U Double braid shielded coax	$-3.2 \pm 0.4 \times 10^{-14}$	Mk V 2.1 mm Al 0.25 mm Cu	10
2	RG - 316 Single braid shielded coax	$-3.6 \pm 0.8 \times 10^{-14}$	Mk V 2.1 mm Al 0.25 mm Cu	10
3	Braid shielded twisted pair	$-1.4 \pm 0.5 \times 10^{-13}$ (both wires)	Mk V 0.5 mm Cu	11
		-1.05×10^{-13} (one wire)		
4	Braid shielded, coaxially shielded triple	$-2.0 \pm 0.4 \times 10^{-13}$ (3 wires-terminated)	Mk V 2.1 mm Al 0.25 mm Cu	10
		$-2.3 \pm 0.6 \times 10^{-13}$ (3 wires-unterminated)	Mk V 2.1 mm Al 0.25 mm Cu	
		$-6.5 \pm 0.7 \times 10^{-14}$ (2 wires-grounded)	Mk V 2.1 mm Al 0.25 mm Cu	
5	Ribbon shielded single wire (old sample)	$-5.0 \pm 3.0 \times 10^{-15}$	Mk V 0.5 mm Cu	11
6	Ribbon shielded single wire (old sample)	$-9.6 \pm 2.8 \times 10^{-15}$	Mk V 1.52 mm Al	12

[10] M. J. Bernstein and P. A. Beemer Memorandum to S. P. Bower, Subject: Radiation Response of Additional GPS Cables, The Aerospace Corporation, El Segundo, California (9 December 1975).

[11] M. J. Bernstein Memorandum to S. P. Bower, Subject: Radiation Response of Cables, The Aerospace Corporation, El Segundo, California (3 July 1975).

[12] F. Hai and P. A. Beemer Memorandum to E. L. Katz, Subject: Radiation Response of GPS Solar Cell Cables, The Aerospace Corporation, El Segundo, California (30 June 1976).

Table 3. Response of GPS Satellite Cables (Continued)

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF Source & Filter	Reference
7	Solar Cell Cable Ribbon braid shielded single wire (new sample)	$+2.5 \pm 1.2 \times 10^{-14}$	Mk V 1.52 mm Al	12
8	Solar Cell Cable Ribbon braid shielded single wire (new sample)	$+3.5 \times 10^{-14}$	Mk IV 1.52 mm Al 0.025 mm Cu	13
9	Solar Cell Cable Ribbon braid shielded single wire (new sample)	$+2.6 \times 10^{-14}$	Mk IV 1.52 mm Al 0.025 mm Cu	13
10	Solar Cell Cable Ribbon braid shielded single wire (new sample)	$+2.2 \times 10^{-14}$	Mk IV 1.52 mm Al 0.025 mm Cu	13
11	Solar Cell Cable Ribbon braid shielded single wire (new sample)	$+3.1 \times 10^{-14}$	Mk IV 1.52 mm Al 0.025 mm Cu	13
12	Solar Cell Cable Ribbon braid shielded single wire (new sample)	$+1.7 \times 10^{-14}$	Mk IV 1.52 mm Al 0.025 mm Cu	13

[13] K. W. Paschen and F. Hai Memorandum to R. M. Cooper, Subject: Radiation Response of Virgin Cables, The Aerospace Corporation, El Segundo, California (22 July 1976).

Table 4. Response of DSAP Satellite Cable

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF Source & Filter	Reference
	Super cable Composite - braid shielded (18 insulated wires, 5 shielded wires, and 1 shielded twisted pair)		Mk IV 4 mm Al 0.25 mm Cu	14
1	Shielded wire	-4.0×10^{-15}	Mk IV 4 mm Al 0.25 mm Cu	14
2	Shielded pair	-1.4×10^{-14} (both wires)	Mk IV 4 mm Al 0.25 mm Cu	14
3	Insulated wire	Ringing $> 4.0 \times 10^{-15}$	Mk IV 4 mm Al 0.25 mm Cu	14
4	RG 174 Reference	$-2.1 \pm 0.6 \times 10^{-14}$	Mk IV 4 mm Al 0.25 mm Cu	14

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[14] M. J. Bernstein Memorandum to D. A. McPherson, Subject: Measured Responses of Super Cable, The Aerospace Corporation, El Segundo, California (22 October 1973).

Table 5. Response of Braid Shielded Coaxial Cables

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF Source & Filter	Reference
1	Microdot 250-3804	-1.0×10^{-15}	Mk IV 4 mm Al	1,6
		-2.8×10^{-15}	4 mm Al 0.3 mm Cu	
2	RG - 196 A/U	$-4.5 \pm 1.5 \times 10^{-15}$	4 mm Al 0.3 mm Cu	1,6
3	RG - 188 A/U	$-9.0 \pm 3.0 \times 10^{-15}$	4 mm Al 0.3 mm Cu	1,6
4	RG - 58/U	$-2.4 \pm 0.6 \times 10^{-14}$	4 mm Al 0.3 mm Cu	1,6
5	RG - 174/U (Amphenol)	$-1.9 \pm 0.5 \times 10^{-14}$	4 mm Al	1,6
		$-2.7 \pm 0.7 \times 10^{-14}$	4 mm Al 0.3 mm Cu	1,6
6	RG - 174/U (Surco)	$-2.0 \pm 0.5 \times 10^{-14}$	4 mm Al	1,6
		$-2.8 \pm 0.6 \times 10^{-14}$	4 mm Al 0.3 mm Cu	1,6
7	Rg - 174/U (Beldon)	$-2.9 \pm 0.7 \times 10^{-14}$	4 mm Al	1,6
		$-5.3 \pm 1.0 \times 10^{-14}$	4 mm Al 0.3 mm	1,6
8	RG - 174/U (ITT)	$-5.0 \pm 1.2 \times 10^{-14}$	4 mm Al	1,6
		$-8.9 \pm 2.0 \times 10^{-14}$	4 mm Al 0.3 mm Cu	1,6

Table 6. Response of Solid Dielectric Semirigid Cables

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF Source & Filter	Reference
1	Al/Al 0.100 50Ω (AFWL)	-2.5×10^{-17}	Mk V 1.52 mm Al	3
		$+5.5 \times 10^{-17}$	1.52 mm Al 0.13 mm Cu	
		$+1.2 \times 10^{-16}$	1.52 mm Al 0.25 mm Cu	
2	Al/Al 0.100 100Ω (AFWL)	$+7.5 \times 10^{-17}$	1.52 mm Al	3
		$+1.7 \times 10^{-16}$	1.52 mm Al 1.55 mm Al	
		$+2.5 \times 10^{-16}$	1.52 mm Al 0.13 mm Cu	
		$+3.15 \times 10^{-16}$	1.52 mm Al 0.25 mm Cu	
		$+2.3 \times 10^{-16}$	1.52 mm Al 0.51 mm Cu	
3	Al/Al 0.085 50Ω	$+9.0 \times 10^{-17}$	1.52 mm Al 1.55 mm Al	3
		$+1.0 \times 10^{-16}$	1.52 mm Al 0.51 mm Cu	
4	Al/Al 0.141 50Ω	-2.8×10^{-16}	1.52 mm Al 1.55 mm Al	3
		-4.3×10^{-16}	1.52 mm Al 0.51 mm Cu	

Table 6. Response of Solid Dielectric Semirigid Cables (Continued)

No.	Designation & Description	Response (coul/rad(Si)-cm)	DPF Source & Filter	Reference
5	Al/Cu 0.141 50Ω	$+1.8 \times 10^{-15}$	1.52 mm Al 1.55 mm Al	3
		$+5.6 \times 10^{-15}$	1.52 mm Al 0.51 mm Cu	
6	Cu/Cu 0.085 50Ω	$+1.4 \times 10^{-16}$	1.52 mm Al	3
		$+8.0 \times 10^{-16}$	1.52 mm Al 0.13 mm Cu	
		$+1.55 \times 10^{-15}$	1.52 mm Al 0.38 mm Cu	
7	Cu/Cu 0.141 50Ω	-1.8×10^{-16}	1.52 mm Al	3
		-4.3×10^{-16}	1.52 mm Al 0.13 mm Cu	
		$+7.6 \times 10^{-16}$	1.52 mm Al 0.38 mm Cu	
		$+9.3 \times 10^{-16}$	1.52 mm Al 0.51 mm Cu	

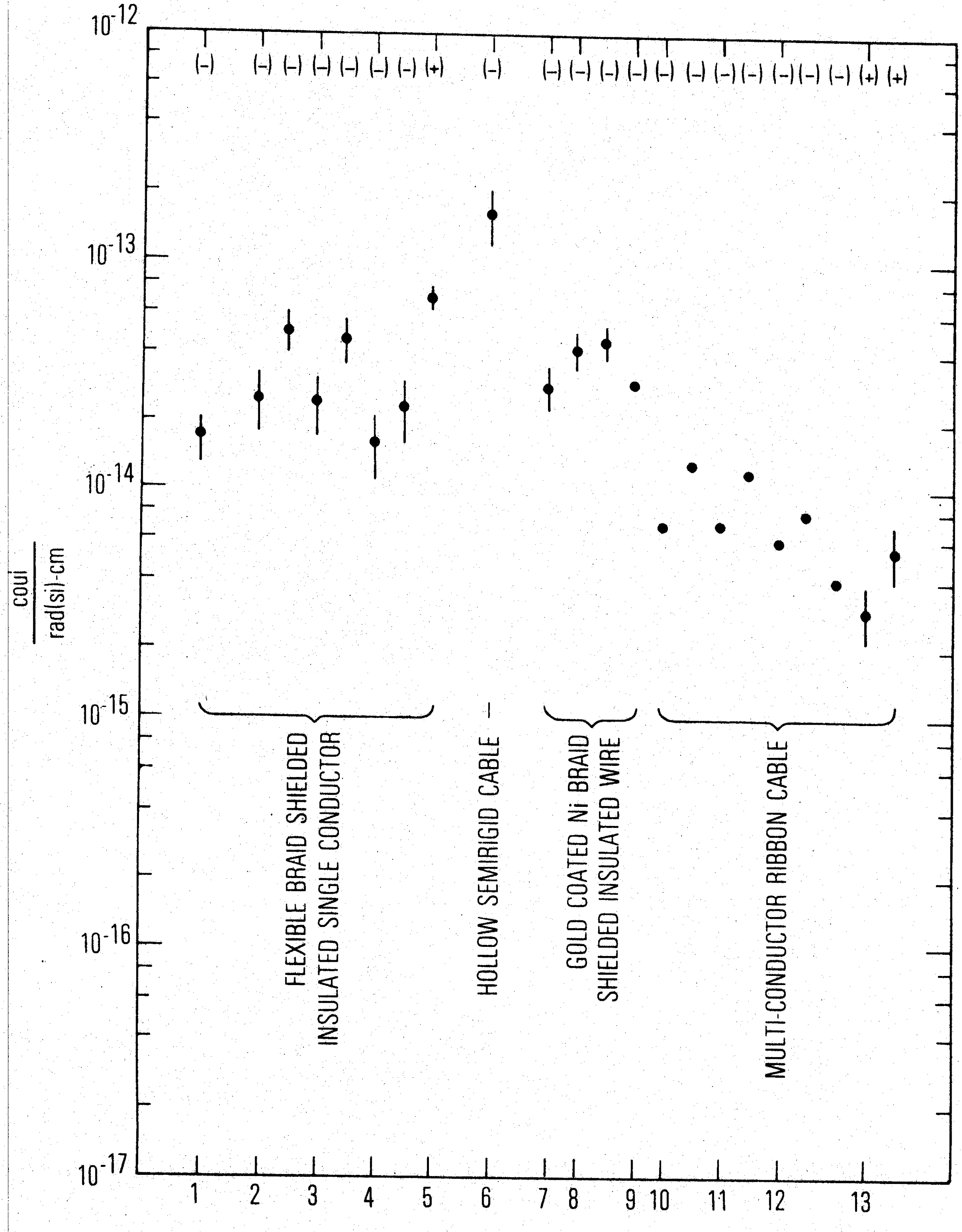

Figure 1. Response of DSP Cables

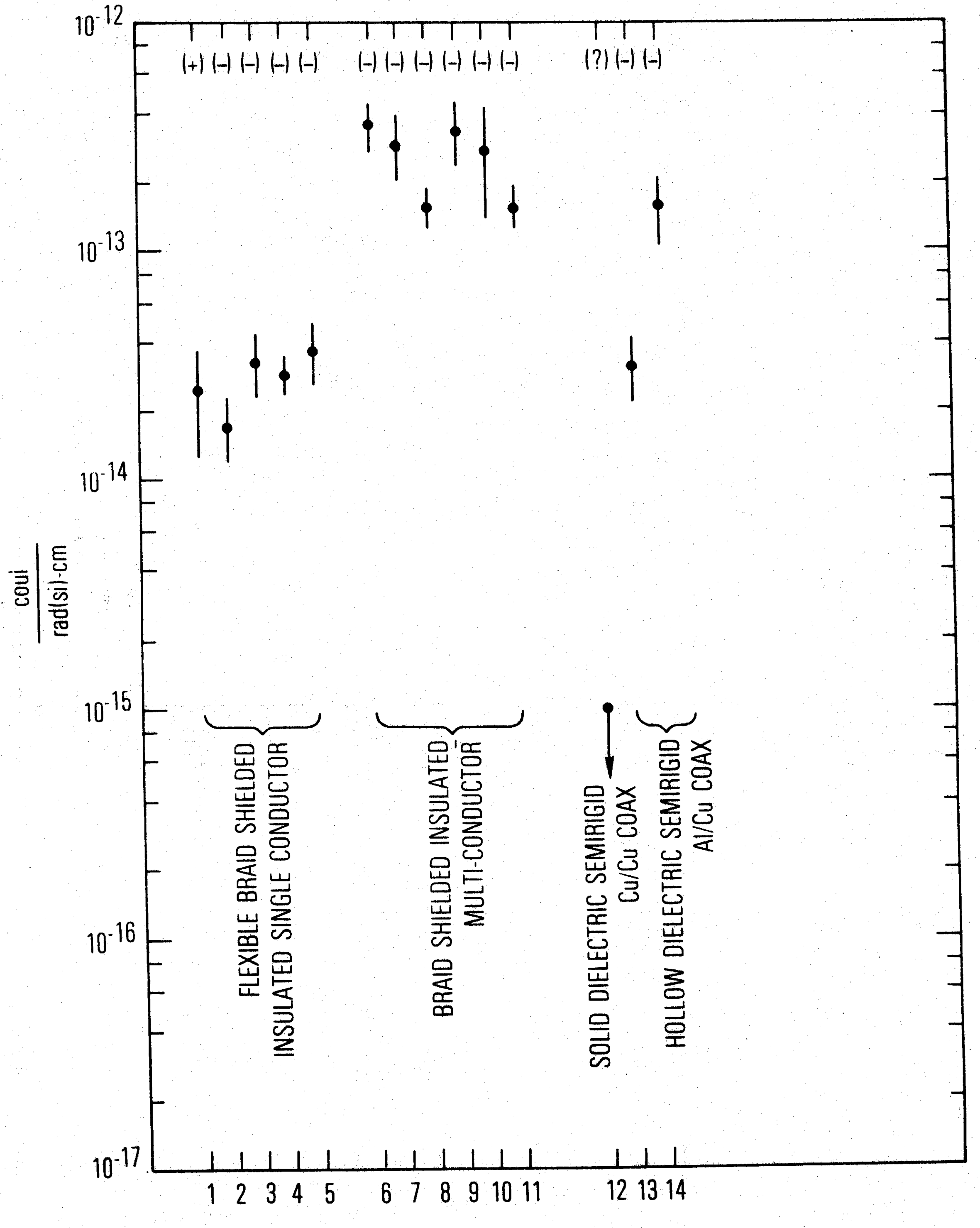

Figure 2. Response of FSC Cables

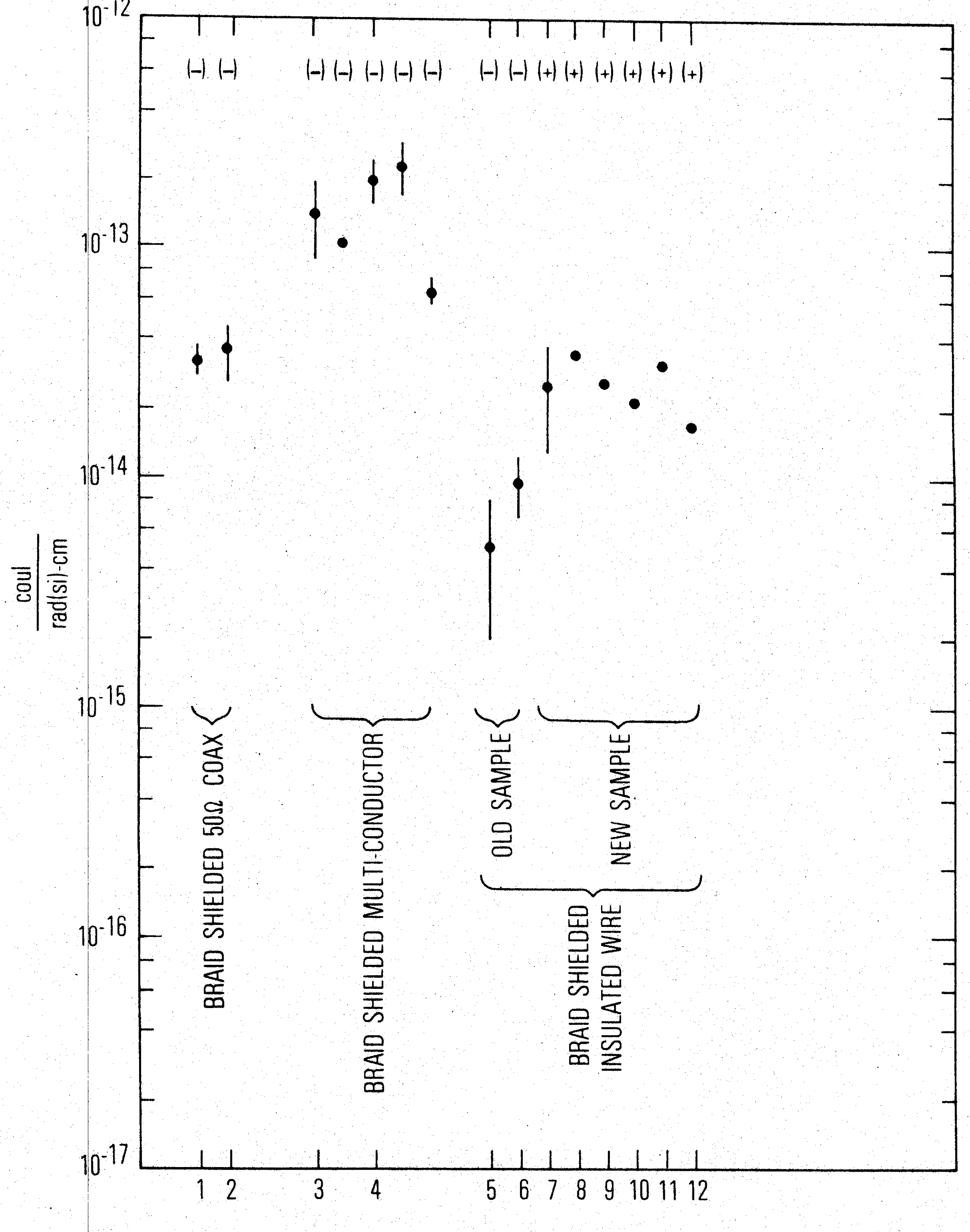

Figure 3. Response of GPS Satellite Cables

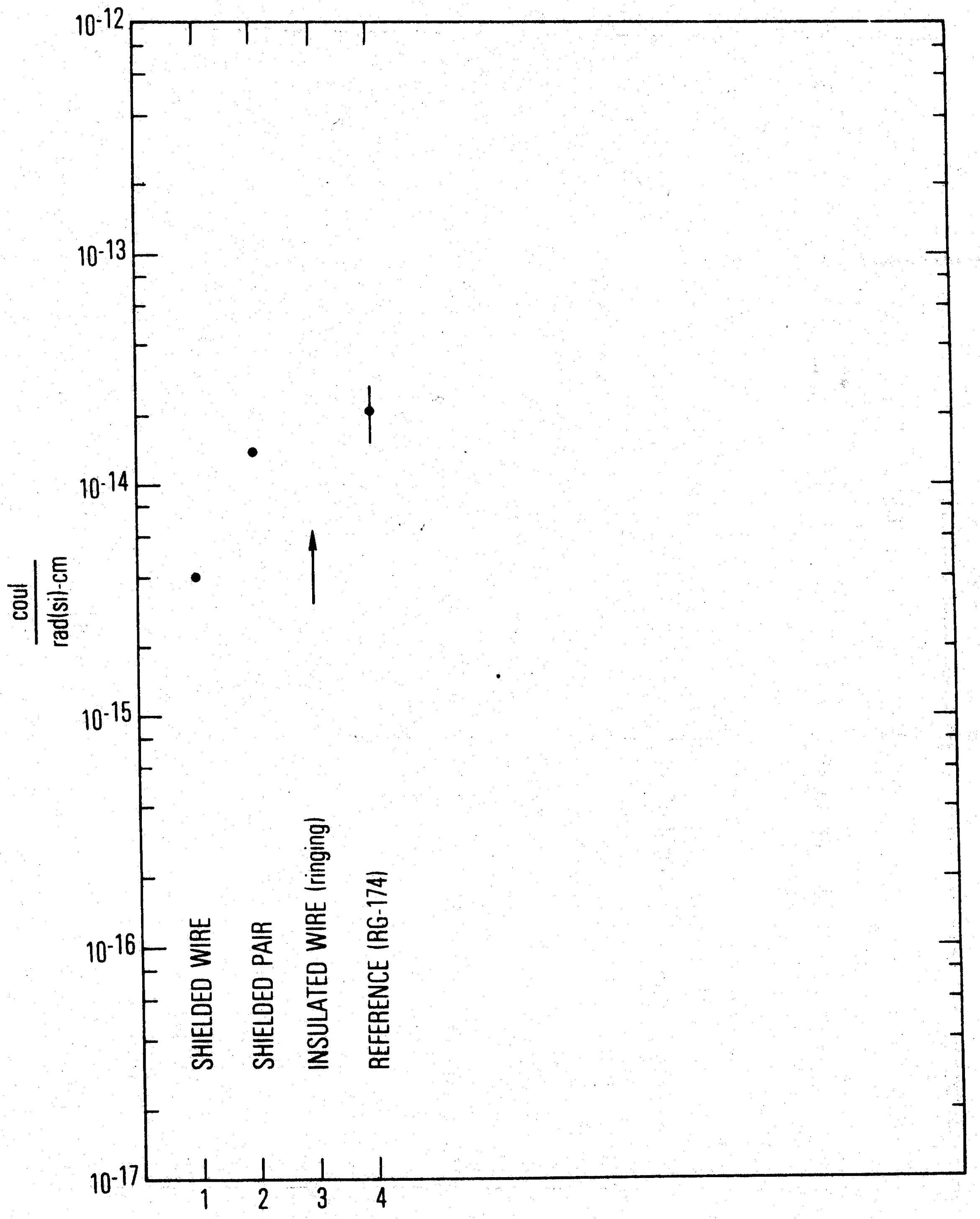

Figure 4. Response of DSAP Satellite Cable

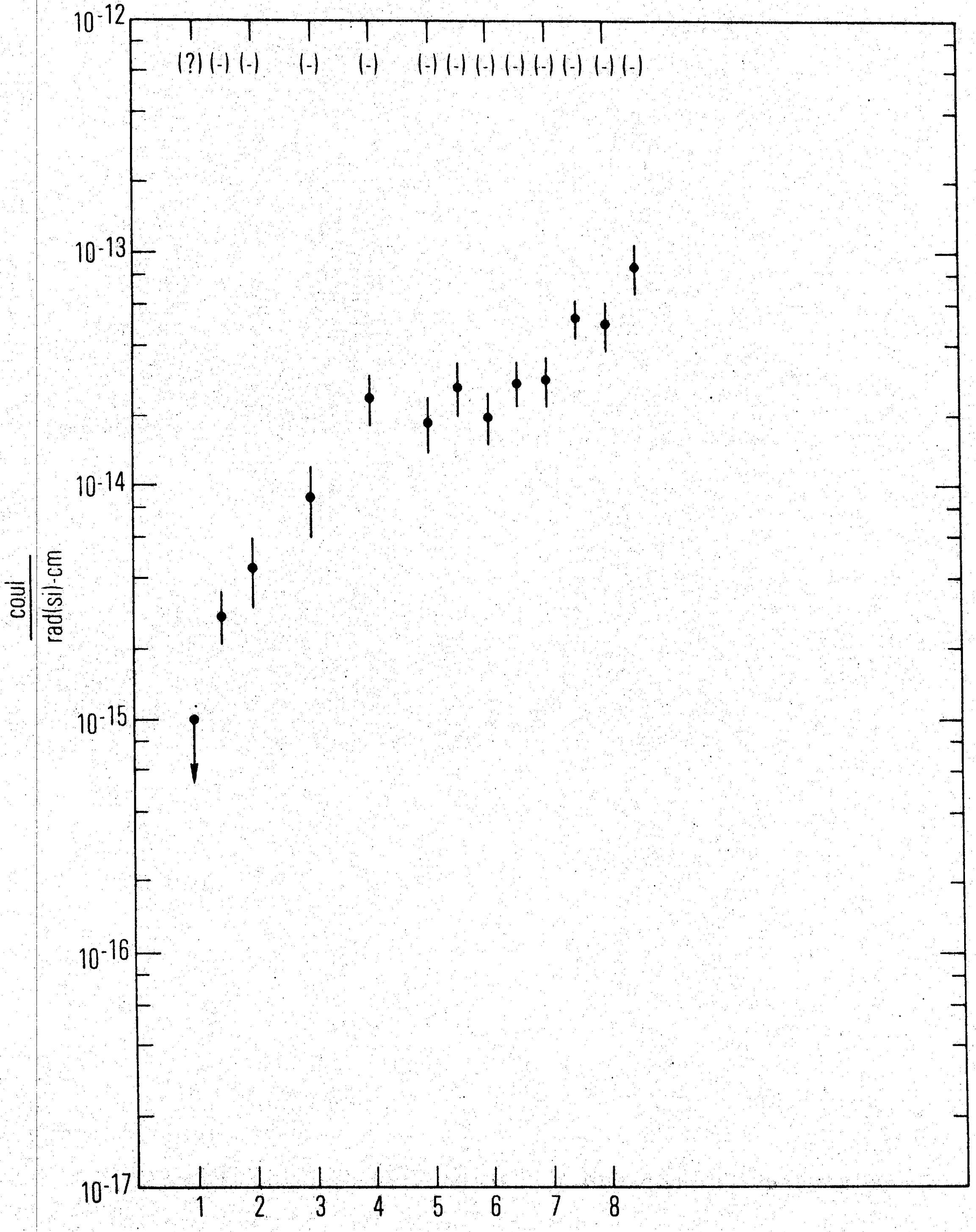

Figure 5. Response of Braid Shielded Coaxial Cables

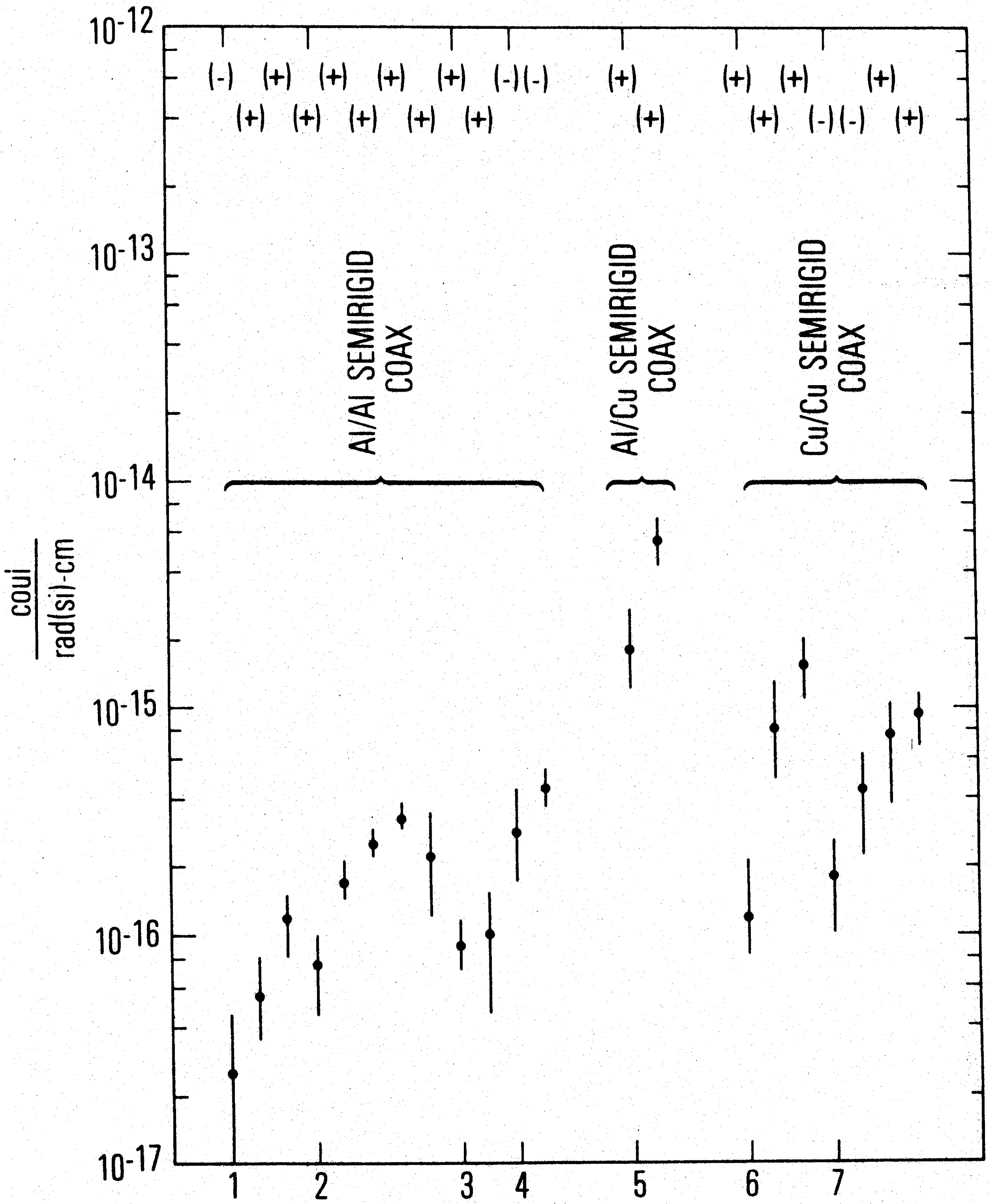

Figure 6. Response of Solid Dielectric Semirigid Cables

Examination of the data in the tables and the figures indicates the following:

a. The responses of flexible, braid-shielded single conductor wires used on DSP, FSC, and GPS satellites range from $\sim 10^{-14}$ to 10^{-13} coul/rad(Si)-cm. The signs of these responses were mostly negative, corresponding to an effective net charge transfer from the shield to the center conductor. This transfer is associated mainly with the effect of large gaps between the shield and the dielectric. However, positive responses were also observed. One (response 5, Figure 1) was attributed to a loose center conductor, and another (response 1, Figure 2) to voids in the foamed dielectric around the center conductor.

b. The responses of the braid-shielded multiconductor cables in FSC and GPS satellites are $\gtrsim 10^{-13}$ coul/rad(Si)-cm and reflect the large, nonuniform gaps between the outer braid and the insulation of the conductors. Also, these responses are large because the measurements were made with the conductors tied together. As expected, these responses were all negative.

c. The responses of braid-shielded RG type cables with specified impedance $\sim 50\,\Omega$ range from $\sim 10^{-15}$ to 10^{-13} coul/rad(Si)-cm. All observable responses were negative. Only two responses were significantly below 10^{-14}. These were attributed to a tight wrap of the braid about the insulation (response 2, Figure 5) and to the filling of the braid gaps by some conductive material (response 1, Figure 5).

d. The responses of hollow (spline type) semirigid cables range from 10^{-14} to above 10^{-13} coul/rad(Si)-cm. These relatively large negative responses are associated with the large regular voids between the outer conductor and the dielectric.

e. The relatively large positive response of the solid dielectric Al/Cu semirigid coax (response 5, Figure 6) is attributed to large outward emission from the Cu center conductor, relative to the inward emission from the Al outer conductor. (Emission from Cu relative to that from Al is discussed in Section IV.)

f. The only cable currently used on a satellite that exhibits a response $\lesssim 10^{-15}$ coul/rad(Si)-cm is the Cu/Cu solid dielectric semirigid coax. The response of this cable is a factor of ~ 10 below that of most braid-shielded cables.

g. The response of the Al/Al solid dielectric semirigid cables is nearly equal to that of the Cu/Cu cables for soft incident spectra, but it is a factor of about 5 below for the hard spectra (as indicated in Figure 6). This variation occurs because, for the hard spectra, almost equal fluences reach the metal-dielectric interfaces in the two cables; however, the response of the Al/Al cable is lower than that of Cu/Cu because of the better match in emission between Al and teflon compared to that between Cu and teflon (shown in Section IV). For the soft spectra, the fluence is significantly attenuated by the Cu shield, thereby reducing the response of the Cu/Cu cable to nearly equal the low Al/Al cable response.

h. The replacement of the gold braid shielded wires by the aluminized multiconductor ribbon cable in DSP has reduced this special function cable response by a factor of ~ 10.

i. In the investigation of the response of a composite cable, only one of a large number of possible wiring configurations was examined. The response of the shielded twisted pair was larger than that of the shielded wire. This difference was attributed to larger gaps between the shield and the twisted pair. In addition, the response of the shielded wire was significantly below that of the reference cable. This low response was associated with fluence attenuation by the composite cable shield and the other cables.

The cables examined at Aerospace Corporation are listed in order of decreasing radiation responsivity, as follows: Braid-shielded insulated multiconductor cables (conductors tied together), hollow dielectric semirigid cables, braid-shielded insulated single conductor cables, RG type braid-shielded cables, Al/Cu semirigid coaxes, Cu/Cu semirigid coaxes, and Al/Al semirigid coaxes.

The above observations suggest that the response of cables being used in satellites and in experimental testing can be reduced by (a) minimizing the photon fluence reaching the metal-dielectric interfaces by providing maximum radiation shielding, (b) minimizing the metal-dielectric gaps by embedding the metal in the dielectric, filling the gap with suitable material, or coating the metal with an equivalent dielectric, and (c) minimizing the effective net charge transfer through the selection of metal and dielectric matched to one another in electron emissivity. These requirements of a low response cable are further considered in the following sections.

III. MECHANISMS AFFECTING CABLE RESPONSE

The primary objective in most of the cable experiments has been the determination of the radiation response in vacuum. However, in many of the experiments, additional measurements were made either to verify proposed mechanisms producing the vacuum response or to examine other mechanisms affecting cable response. The former measurements were associated primarily with determining the effect of shield-insulator or insulator-conductor gaps on the response of the cable. The latter were concerned with the effect of air in these gaps or the effect of a potential difference between the shield and the conductor.

The initial experiments mainly investigated the response of braid-shielded cables. Early in the experiments it was recognized that response in these cables was primarily produced by gaps between the metal braid and the dielectric insulator (Ref. 4). Analysis showed that the effective charge transfer for electrons traversing a vacuum gap of width G and deposited at one electron range d in the insulator was increased above that for electrons deposited in only the insulator (no gap) by $\sim KG/d$, where G is usually greater than d and K is the dielectric constant of the insulator (Ref. 1). This mechanism was experimentally confirmed by filling various cables with oil and measuring the change in their response. The PT3-33, Sh 28, RG 174, and RG 196A cables decreased in response by a factor of four to six when filled with oil (Refs. 1 and 5).

This gap effect can occur not only in braid-shielded cables but also in tube-shielded solid dielectric semirigid cables. Because of lax tolerances in the fabrication of the Al/Al 0.100 50 Ω semirigid cable, a gap occurred between the center conductor and the teflon insulator. Filling this gap with silicon oil reduced the positive cable response by only 25 percent (Ref. 3). The existence of this gap was confirmed by monitoring the cable response as a function of air pressure. The initial positive response became negative as the pressure in the test cavity was increased. This technique was used earlier in examining the response of a piece of bent semirigid cable (PT3-29-4) (Ref. 9). Here the initial very low response increased in the positive direction as the pressure was increased, indicating a gap between the outer shield and the insulator. These cable response variations can be explained by the discussion given below.

Air effects in cables occur only in the presence of gaps between the metal and the dielectric. These effects occur essentially as follows. High energy photo-Compton electrons are generated by high energy X-rays interacting with the walls of the gap. These electrons, in traversing the gap, ionize the air and create ion-electron pairs. In the current cables (consisting of a high Z, high electron emissivity metal, and a low Z, low emissivity dielectric), a net surplus of electrons is deposited in the dielectric giving rise to an electric field. This field acts on the low energy electrons released by air ionization, driving these electrons in the direction opposite that of the field generating photo-Compton electrons. (The ions, because of their large mass, react more slowly to this field and, therefore, do not contribute significantly to the measured transient response.) Consequently, the response of a cable in a vacuum primarily produced by photo-Compton electrons is severely changed if air is present in the gaps.

This change usually appears as a change in sign and magnitude of the response pulse. However, a bipolar pulse is also possible, depending upon such experimental and cable parameters as gap width, gap material, photon energy spectrum, air pressure, and RC time constant of the cable and its termination. Furthermore, subsequent irradiations of the cable can produce additional changes.

An experimental investigation of the effect of air in gaps on cable response in several of the FSC satellite cables has been conducted (Ref. 2). These air effects were further examined in irradiated parallel plate geometries connected to shielded external circuitry (Refs. 15 and 16). The effects of other gases were also examined in one of these studies. Both studies were supported by detailed analyses, taking into consideration air and dielectric conductivity in one case and the microscopic properties of the plasma in the other.

Several FSC cables were examined to determine the effects of a potential difference between the shield and the center conductor (Ref. 2). Both positive and negative bias potentials up to 20 volts magnitude were applied to the center conductor; the shield remained grounded. Under vacuum conditions, the changes from zero bias response were less than 20 percent. However, the response changed significantly in an air environment, depending upon the gap characteristics of the cable and its previous conditioning. This was expected because of the presence of a large number of low energy plasma electrons, which are affected even by the relatively small applied electric fields. Effect on the response of one conductor of a braid-shielded three conductor cable when the other two conductors were biased at ± 68 volts was studied (Ref. 10). Again, the major change in response occurred with the cable in air.

Both of the above studies were concerned with the effect of the applied potential on the low energy electrons in the gaps in the cable. In a well-constructed, undeformed semirigid coaxial cable, there are no gaps. However, an applied potential on the center conductor can still affect the cable response; the mechanism operating, in this case, is that of dielectric conductivity. The response of an Al/Al 0.085 50 Ω semirigid cable changed from

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[15] L. D. Singletary, L. C. Nielson, D. M. Clement, C. E. Wuller Jr., and R. L. Fitzwilson, "Replacement Currents in Irradiated Multilayer Structures," IEEE Trans. Nucl. Sci. NS-21 (December 1974).

[16] E. D. de Plomb, R. Fitzwilson, and P. Beemer, "Analytical Modeling and Experimental Testing of Pressure Effects in Small Cavities Coupled to Circuitry," IEEE Trans. Nucl. Sci. NS-21 (December 1974).

$+5.5 \times 10^{-16}$ to -1.6×10^{-16} coul/rad(Si)-cm when the bias potential was varied from -400 to +200 volts (Ref. 3). This small change in response arising from dielectric conductivity is probably not detectable in braid-shielded cables where the change is dominated by low energy secondary electrons in the gaps, even under vacuum conditions.

IV. PHOTO-COMPTON EMISSION FROM METALS AND DIELECTRICS

Several experiments were performed to examine the photoemission of electrons from various metals and dielectrics. An early emission study was conducted using the DPF as the radiation source (Ref. 17). The emission geometry used was dual parallel plate diodes. Emissions from various polymers and several metals relative to that from aluminum were measured.

Two additional experiments were conducted investigating photoemission from materials (Refs. 18 and 19). The radiation source used was a 100 keV X-ray tube with various filters to harden the radiation spectrum. Emissions relative to those from aluminum for various materials were computed from these data and are plotted in Figure 7, together with those from the earlier study. For comparison with analytical predictions, the photoemissions computed by Dellin and MacCullum (Ref. 20) normalized also to aluminum over the energy range from 20 to 150 keV are also shown. Close correlation exists between the experimental data and the analytical code predictions.

Figure 7 shows a very large difference (over a factor of 10) between emission from Cu and that from the low Z cable dielectrics: teflon, kapton and polyethylene. This difference is increased if the Cu is coated with Sn or

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[17] F. Hai and M. J. Bernstein, "Photoemission from Polymers," IEEE Trans. Nucl. Sci. NS-18 (December 1971).

[18] M. J. Bernstein and K. W. Paschen, "Forward and Backward Photoemission Yields from Metals at Various X-Ray Angles of Incidence," IEEE Trans. Nucl. Sci. NS-20 (December 1973).

[19] M. J. Bernstein and K. W. Paschen, X-Ray Photoemission from Coated Surfaces, SAMSO-TR-75-302, The Aerospace Corporation, El Segundo, California (19 December 1975).

[20] T. A. Dellin and C. J. MacCallum, A Handbook of Photo-Compton Current Data, SCL-RR-720086, Sandia Laboratories, Albuquerque, New Mexico (December 1972).

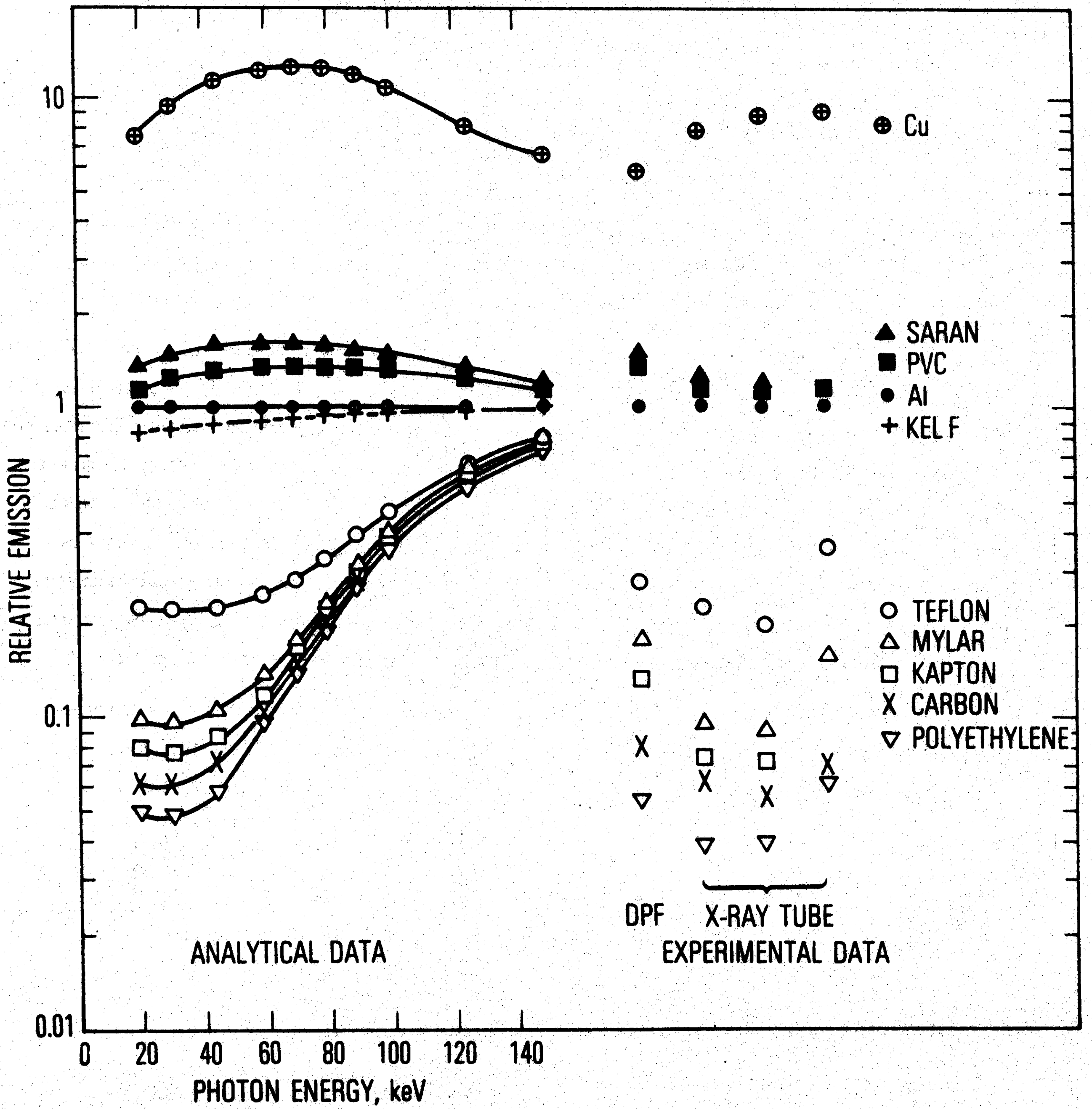

Figure 7. Relative Emission from Metals and Dielectrics

Ag. (Coated Cu is commonly found in braid shields and center conductors of cables as shown in Appendix B). If the Cu is replaced by aluminum, this difference is still significant (over a factor of 3 for teflon). However, several polymers not used for cable insulation are closely matched to aluminum in emission, e.g., PVC and saran. Another closely matched polymer is Kel F; Kel F has not been examined experimentally, but has been examined analytically with respect to emission (Ref. 3). Emission from Kel F computed from the data of Dellin and MacCullum is also shown in Figure 7.

V. THE INITIAL CABLE RESPONSE

A current controversy in regard to cable response is whether the initial response is significantly different from or quite similar to the succeeding responses in a sequence of exposures to radiation. The initial response can be quite different from succeeding responses if the cable dielectric contains substantial trapped or polarization charge. Otherwise, the initial response should be equal to the other responses, except for the effect of charge buildup in the dielectric that results from many high fluence exposures in a short time span.

A recent experiment was conducted to directly examine the initial response of a cable of current interest — the solar cell cable used on GPS (Ref. 13). Short sections of this cable and a reference section were exposed to DPF radiation. (This reference section had been previously exposed and was kept as a reference for the entire series of measurements.) Response measurements were made in vacuum and in air. The values for the initial vacuum responses for the various sections are given in Figure 3 (responses 8 through 12). When normalized to the incident fluence, the initial and succeeding responses for a given section showed a large variation (±50 percent of the mean value) also observed in the earlier measurement (response 7, Figure 3). These variations were attributed to fluctuations in the radiation spectrum. When normalized to the reference cable response, the initial and succeeding responses were more nearly alike as shown in Figure 8. Although the responses of the sections of cable differ from one another by as much as a factor of two, no significant difference is observed between the initial response and the following responses in vacuum for the same section of cable. In air, large changes from response to response are observed.

The variations in Figure 8 show that the initial cable response does not differ from the subsequent responses, at least for the cable sections examined in vacuum, indicating no significant amount of trapped or polarization charge.

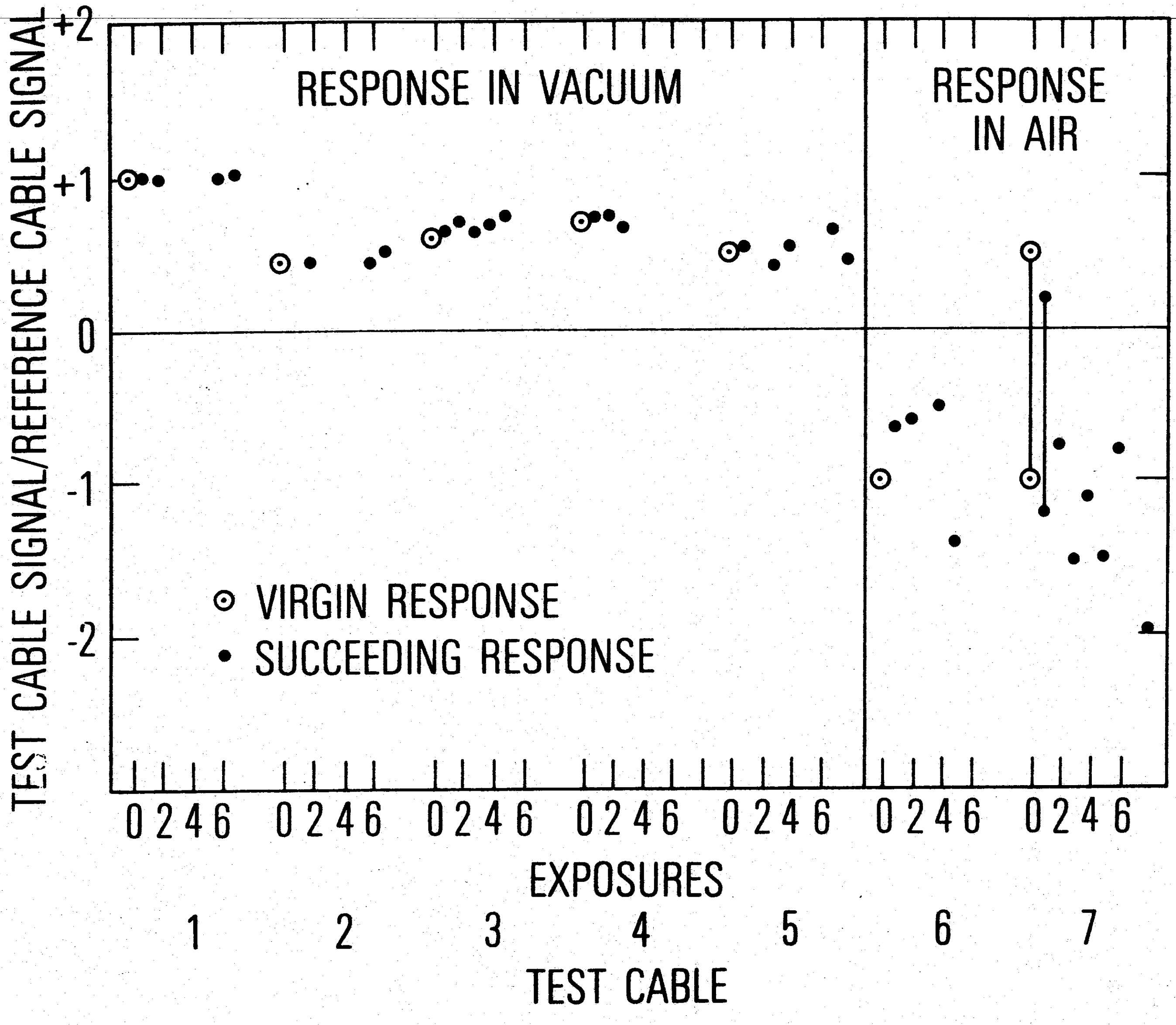

Figure 8. Ratio of Test Cable Response to Reference Cable Response

VI. MINIMUM RESPONSE CABLE DESIGN

The cables examined for radiation response in the series of experiments summarized in this report consist of several basic types: the braid-shielded multiconductor, the braid-shielded single conductor, the hollow dielectric, the solid dielectric, and the multiconductor flat ribbon. New designs to reduce radiation response will be discussed for all except the flat ribbon cables.

Radiation response reduction in cables can be separated into three steps, as indicated in Section II and in the simple analytical treatment of response in a coaxial cable given in Reference 3. These steps are: (a) minimizing the incident fluence, (b) minimizing or eliminating all gaps, and (c) matching electron emission between the dielectric and the metal.

Minimizing response through reduction of the fluence by means of shielding is an obvious step. However, this step can be applied only if the cable weight, size, and flexibility requirements can be fulfilled with the added shielding.

Minimizing or eliminating metal-dielectric gaps has been the most frequently recommended (Ref. 21) and applied (Ref. 22) technique of response reduction. To eliminate the gaps, it has been recommended that the dielectric be extruded onto the multistrand center conductor, the center conductor be coated with a low Z dielectric, or the conductor be a single wire so that it can be sleeved with a tight fitting dielectric. To eliminate the braid-shield/dielectric gap, a tight weave of the braid about the dielectric or filling the braid with a suitable conducting material has been suggested.

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[21] M. J. Bernstein Memorandum to D. A. McPherson, Subject: Development of Cables with Reduced Radiation Response, The Aerospace Corporation, El Segundo, California (24 Septemebr 1973).

[22] E. P. Chivington, Radiation Induced Response of Shielded Cables, Report 99994-6329-RU-00, TRW, Redondo Beach, California (18 May 1976).

Some of the above techniques have been applied to a braid-shielded multiconductor cable (Ref. 22). In this study, coating of the conductors with a polyimide film reduced the response by a factor of three. In another experiment, the difference in response between an old sample and a new sample of shielded wire was attributed partially to a visible coating on the conductor of the old sample (Ref. 23). A measurable difference in emission from the center conductor was experimentally observed.

Response reduction by selection of cable materials matched in electron emission has been proposed by numerous investigators. However, no cable based on this approach has been designed, fabricated, or tested to date.

Application of this approach requires finding a suitable dielectric matched to the high conductivity metal. The metal used in most cables is copper. A match to this relatively high Z metal requires adding high Z materials to the usually low Z dielectric. This particular approach was examined wherein $PbWO_4$ was added to polyethylene (Ref. 24). This new compound was not examined for its electrical properties and was not used in the fabrication of a cable. Several low Z dielectrics currently used in cables can be matched to alloys of Be (Ref. 3). However, because of the undesirable physical properties of Be alloys and their high cost, this combination has not been considered further. Finding a suitable dielectric equivalent to copper in electron emissivity and having the appropriate electrical and physical properties appears to be a costly and long-term project.

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[23] P. A. Beemer and F. Hai, Shielded Wire Response Experiments, ATM-76(6124)-8, The Aerospace Corporation, El Segundo, California (26 July 1976).*

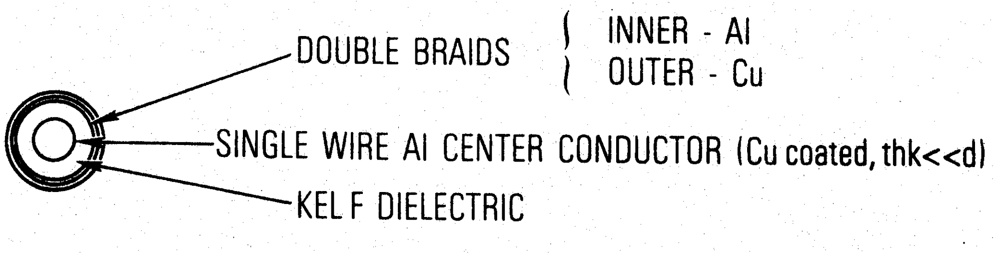
[24] T. M. Flanagan, R. E. Leadon, and C. E. Mallon, Investigation of Cable Response to X-Radiation, AFWL-TR-73-295, IRT Corporation, San Diego, California (November 1974).

*Not available for external distribution.

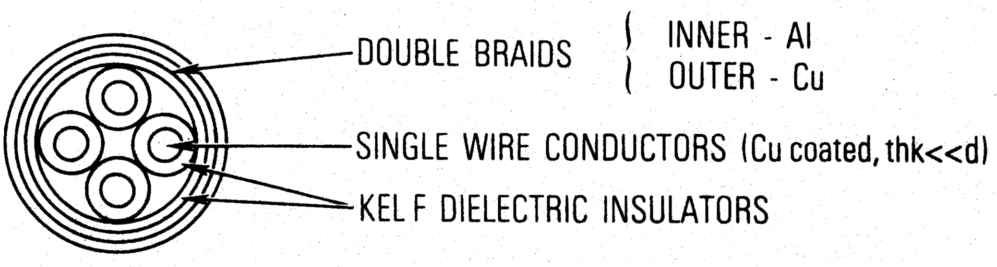
An approach which would require minimum cost, and permit almost immediate cable fabrication and testing, is that directed toward selection of an available dielectric equivalent to aluminum. Examination of Figure 7 indicates that Kel F is a suitable match for aluminum. The electrical and physical properties of Kel F are well documented and it can be used in cable fabrication. The unfavorable characteristic of Kel F is its high dissipation factor associated with polarization losses in the dielectric at high-signal frequencies. Even through the dielectric had this property, a cable fabricated with Kel F may be acceptable in certain applications requiring minimum radiation response. Other available dielectrics matched to aluminum are saran, PVC, and durasan. The properties of these dielectric materials should be examined prior to consideration of their usage in cables.

Cable designs based on a Kel F dielectric and aluminum shield and conductor are shown in Figure 9. Shielding to reduce soft incident fluence and gap elimination, or minimization, are applied where possible. The response of each these proposed cables should be significantly below that of existing cables of the same general design but of different dielectric and the metal. This prediction indicates that the response of the new solid dielectric (Kel F) semirigid cable would be less than that of the current Al/Al semirigid cable (dielectric-teflon), i.e., $< 10^{-16}$ coul/rad(Si)-cm. Cables with responses in this range would be highly useful in hardened satellites.

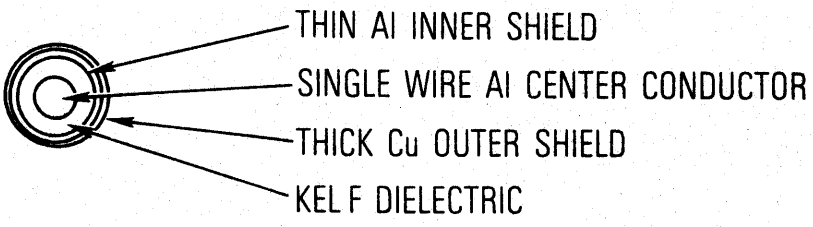
DOUBLE BRAID SHIELDED SINGLE CONDUCTOR CABLE



DOUBLE BRAID SHIELDED MULTICONDUCTOR CABLE



SOLID DIELECTRIC SEMIRIGID CABLE



HOLLOW DIELECTRIC SEMIRIGID CABLE

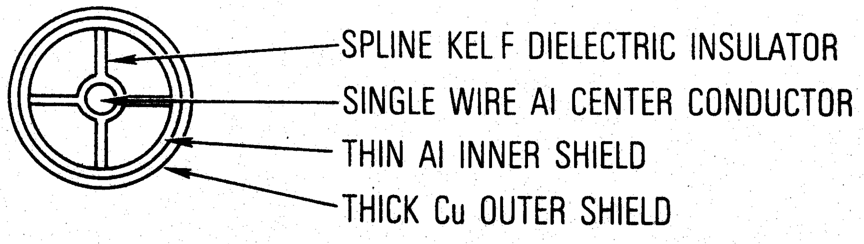


Figure 9. Minimum Response Cable Designs

APPENDIX A

DPF RADIATION TEST FACILITY

The cable response measurements were obtained on The Aerospace Corporation's dense plasma focus devices — intense pulsed sources of X-radiation ranging from ~ 5 to well over 100 keV. These cable experiments were conducted either on the Mk IV device (Refs. 1 and 2) or on the Mk V device (Refs. 2 and 3). Using either device, the test cable was separated from the radiation source by a window of aluminum, Mg, and/or Be. This window protected the cable sample from damage caused by anode debris and from pressure effects produced by the plasma discharge. This window also determined the low photon energy limit of the test spectrum.

The cable test sample was contained in an aluminum cavity evacuable to ~ 10 μm. The vacuum measurements were obtained at this pressure, and the air measurements were conducted at pressures ranging from this lower limit to one atmosphere. For irradiation of long samples ($\gtrsim 100$ cm), the cable was bent into a zigzag pattern (Ref. 1) or coiled in the form of a spiral (Ref. 3). The cable was tested almost always with one end of the cable open and the other end attached to a 50 Ω signal cable terminated in 50 Ω at the oscilloscope or to a 50 Ω resistor in parallel with the signal cable giving an effective 25 Ω impedance. The signal cable was located behind lead shields in the test cavity and then in a solid copper conduit between the cavity and the screen room. In the latter, the signals were monitored on Tektronix 555 oscilloscopes in the early experiments and on Tektronix 7904 and 7844 in the more recent experiments. In the tests of very low response cables (e.g., Al/Al semirigid coaxes), wide bandwidth high frequency amplifiers were used just outside the test cavity to amplify the small response signal prior to its transmission to the screen room (Refs. 2 and 3).

The radiation incident on the test cable was monitored by either 125 or 20 μm Si PIN diode detectors. These detectors were calibrated to give dose rate directly in silicon (rad(Si)/sec). The X-ray pulse varied from discharge to discharge, exhibiting both single- and multiply-peaked pulses. The pulsewidth ranged from ~10 to over 100 nsec, exhibiting risetimes as short as a few nanoseconds on some discharges. The dose rate ranged to slightly over 10^9 rad(Si)/sec.

The X-ray spectrum of the two DPF devices have been measured with the Ross filter-TLD technique, providing a time integrated energy distribution (Refs. A1 and A2). The spectrum for the Mk V device (Ref. 3) is slightly harder than that for the Mk IV device (Ref. 1), probably because the Mk V is the higher energy device of the two. This difference is shown in Figure A-1, wherein the filtered spectra for the Mk IV have been superimposed on those for the Mk V.

The conversion factors for changing cable response normalized to dose in silicon to response normalized to energy density are given in Table A-1 for the MK IV and Mk V filtered spectra.

[A1] H. L. L. van Paassen, R. H. Vandre and R. S. White, "X-Ray Spectra from Dense Plasma Focus Devices," Phys. Fluids 13 (1970) 2306.

[A2] H. L. L. van Paassen and R. H. Vandre, Description and Operation of the Mk 1B (V) Plasma Focus Radiation Facility, TR-0076(4124)-1, The Aerospace Corporation, El Segundo, California (November 1973).

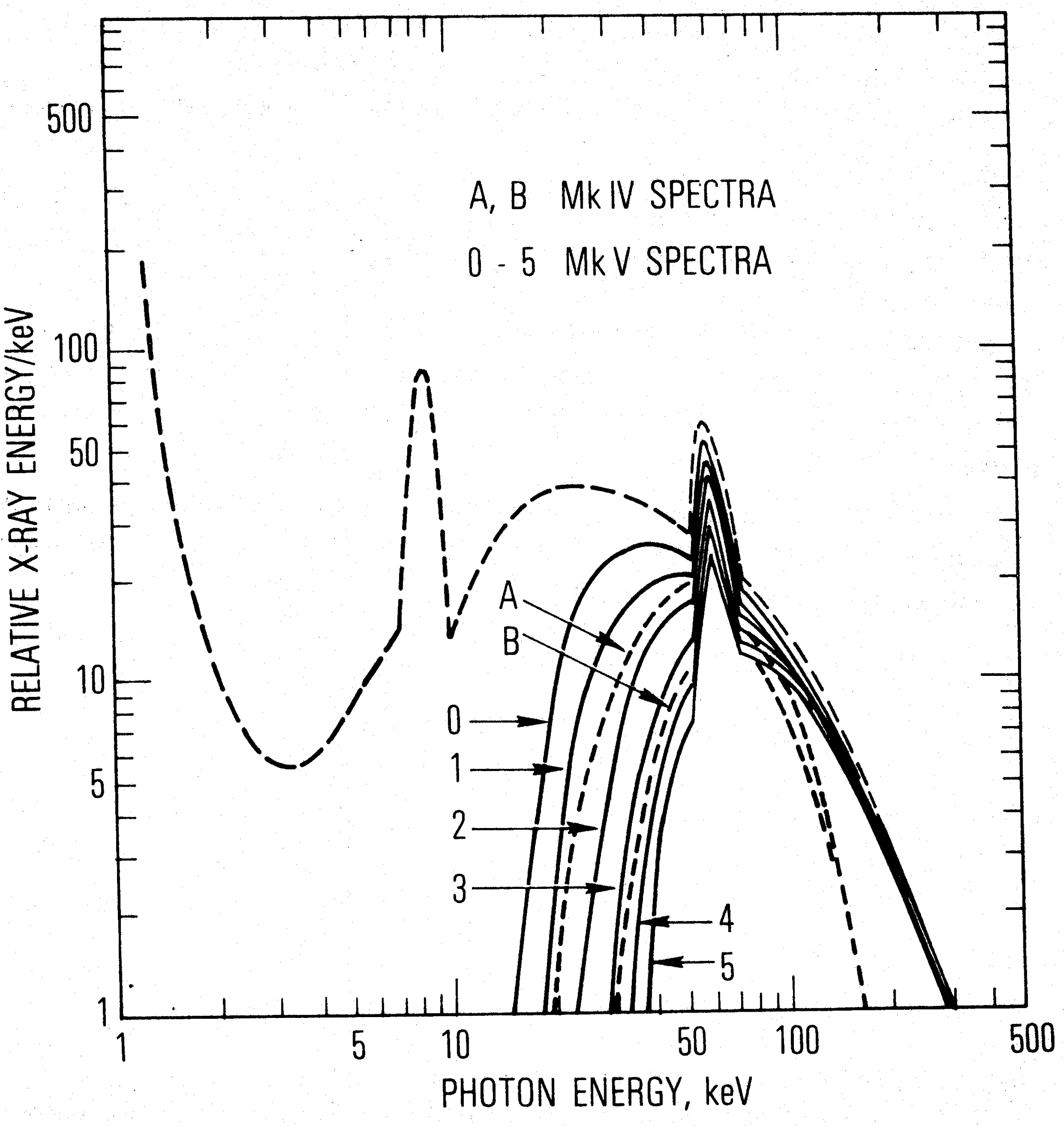


Figure A1. Dense Plasma Focus Spectra

Table A-1. Conversion Factors for Normalization to Incident Energy Density

DPF Spectrum Designation	Filter	Factor (rad(Si)/cal/cm^2)	Factor (rad(Si)/joules/m^2)
0	1.52 mm Al	2.46×10^5	5.89
1	1.52 mm Al 1.55 mm Al	9.6×10^4	2.30
2	1.52 mm Al 0.13 mm Cu	6.2×10^4	1.48
3	1.52 mm Al 0.25 mm Cu	4.6×10^4	1.10
4	1.52 mm Al 0.38 mm Cu	3.9×10^4	0.93
5	1.52 mm Al 0.51 mm Cu	3.4×10^4	0.81
A	4.0 mm Al	9.34×10^4	2.23
B	4.0 mm Al 0.3 mm Cu	4.83×10^4	1.15

APPENDIX B

ADDITIONAL CABLE CHARACTERISTICS

Additional cable characteristics of interest, which were not listed in Tables 1 through 6, are given in Tables B-1 through B-6. These data include the manufacturer of the cable and the material and dimension of shield, dielectric, and conductor. All these data were not given in the listed references. Data acquired through other means (conversation with satellite program personnel, cable maufacturers, examination of the test sample, etc.) are indicated by parentheses, and missing data are indicated by dashes. Some types of data not shown in the tables (e.g., gap widths and code predictions of cable response) may be available in the references.

The following abbreviations are used in Tables B-1 through B-6.

Cable Shield and Conductor

CCS - copper covered steel
SC - silver coated copper
SPC - silver plated copper
SPCW - silver plated copper-clad steel
SCCS - silver covered copper covered steel
TC - Tin covered copper
GN - Gold coated nickel

Cable Dielectric

PE - polyethylene
PO - polyolefin (polyalkene)
PVF_2 - Kynar (polyvinylidene and polyolefin)
PTFE = TFE - polytetrafluoroethylene

Table B-1. DSP Satellite Cable Characteristics

No.	Designation	Shield ID (cm)	Thickness (cm)	Dielectric Thickness (cm)	Conductor Diameter (cm)	Manufacturer
1	PT3-33G	TC 0.077	0.017	--- 0.021	TC 0.036	(Raychem)
2	PT3-33	0.077		0.021	0.036	(Raychem)
3	Wire Sh 28	TC 0.077	0.014	--- 0.0195	TC 0.038	(Raychem)
4	Ribbon Sh 28	TC ---	---	--- ---	TC ---	(Raychem)
5	PT3-59	--- ---	---	--- ---	--- ---	(Raychem)
6	PT3-29	--- ---	---	--- ---	--- ---	(Raychem)
7	Gold Braid	GN 0.058	0.011	--- 0.017	GN 0.025	---
8	Gold Braid					
9	Gold Braid					
10	Al Sh Ribbon	Al	---	Teflon 0.005 x 0.3	Ni (10 wires) 0.003	---
11	No Sh Ribbon	---		Teflon 0.005 x 0.3	Ni (10 wires) 0.003	---
12	Au Sh Ribbon	Au		Teflon 0.005 x 0.3	Ni (10 wires) 0.003	---
13	Al Mc Ribbon	Al 4 x 10^{-5}		Teflon 0.015	GN 0.0054 Au 4 x 10^{-5} thk	---

Table B-2. FSC Satellite Cable Characteristics

No.	Designation	Shield ID (cm)	Thickness (cm)	Dielectric Thickness (cm)	Conductor Diameter (cm)	Manufacturer
1	PT3-59-93	TC 0.279	0.018	Foamed PO 0.103	SC 0.0382	(Raychem)
2	PT3-49-50	SC 0.295	0.0559	TFE 0.0901	SC 0.102	(Raychem)
3	PT3-33N-24	Cu 0.0990	0.0076	PVF_2 0.0140	Cu 0.0660	(Raychem)
4	PT333E-28	Cu 0.0736	0.0076	PVF_2 0.0140	Cu 0.0406	(Raychem)
5	PT3-33N-22	Cu 0.117	0.0076	PVF_2 0.0114	Cu 0.0838	(Raychem)
6	PT3-55RR-18	TC 0.394	0.0317	PVF_2 0.0307	Cu 0.229	(Raychem)
7	PT3-33P-20	Cu 0.224	0.0076	PVF_2 0.0234	Cu 0.147	(Raychem)
8	PT3-33F-26	Cu 0.131	0.0076	PVF_2 0.0219	Cu 0.0750	(Raychem)
9	PT3-33S-20	Cu 0.320	0.0076	PVF_2 0.0330	Cu 0.208	(Raychem)
10	PT3-33R-20	Cu 0.313	0.0076	PVF_2 0.0285	Cu 0.1802	(Raychem)
11	PT3-33P-24	---		---	---	---
12	PT3-29-4	Cu 0.246	0.0294	TFE 0.0774	SC 0.0916	(Uniform Tubes)
13	PT3-29-6	Al 0.566	0.0356	TFE 0.0381	SC 0.224	(Precision Tube)
14	PT3-29-8	Al 0.864	0.0660	TFE 0.0432	SC 0.345	(Precision Tube)

Table B-3. GPS Satellite Cable Characteristics

No.	Designation	Shield ID (cm)	Thickness (cm)	Dielectric Thickness (cm)	Conductor Diameter (cm)	Manufacturer
1	RG 400/U	(SC) (0.295)	---	(PTFE) (0.0984)	(SPC) (0.0978)	(Time Wire & Cable)
2	RG 316	(SC) (0.1524)	---	(PTFE) (0.0507)	(SCCS) (0.0511)	(Time Wire & Cable)
3	Br Sh Pair	--- ---	--- ---	(Polyarylene) ---	--- ---	(Raychem)
4	Br Sh Triple	--- ---	--- ---	(Polyarylene) ---	--- ---	(Raychem)
5	Rib Sh Wire	(TC) (0.109)	(0.0076)	(Polyarylene) (0.0127)	(TC) (0.084)	(Raychem)
6	Rib Sh Wire	(TC) (0.109)	(0.0076)	(Polyarylene) (0.0127)	(TC) (0.084)	(Raychem)
7	Rib Sh Wire	(TC) (0.109)	(0.0076)	(Polyarylene) (0.0127)	(TC) (0.084)	(Raychem)
8	Rib Sh Wire	(TC) (0.109)	(0.0076)	(Polyarylene) (0.0127)	(TC) (0.084)	(Raychem)
9	Rib Sh Wire	(TC) (0.109)	(0.0076)	(Polyarylene) (0.0127)	(TC) (0.084)	(Raychem)
10	Rib Sh Wire	(TC) (0.109)	(0.0076)	(Polyarylene) (0.0127)	(TC) (0.084)	(Raychem)
11	Rib Sh Wire	(TC) (0.109)	(0.0076)	(Polyarylene) (0.0127)	(TC) (0.084)	(Raychem)
12	Rib Sh Wire	(TC) (0.109)	(0.0076)	(Polyarylene) (0.0127)	(TC) (0.084)	(Raychem)

Table B-4. DSAP Satellite Cable Characteristics

No.	Designation	Shield ID (cm)	Thickness (cm)	Dielectric Thickness (cm)	Conductor Diameter (cm)	Manufacturer
1	Sh Wire	---		---	---	Westinghouse
2	Sh Pair	---		---	---	Westinghouse
3	Ins Wire	---		---	---	Westinghouse
4	RG 174	(TC) 0.152	0.0250	(PE) 0.0520	(CCS) 0.048	Amphenol

Table B-5. Braid Shielded Coaxial Cable Characteristics

No.	Designation	Shield ID (cm)	Thickness (cm)	Dielectric Thickness (cm)	Conductor Diameter (cm)	Manufacturer
1	Microdot 250-3804	(SC) 0.097	0.0205	--- 0.0345	(SC) 0.028	Microdot
2	RG 196A/U	(SC) 0.092	0.0170	(PTFE) 0.0308	(SCCS) 0.0305	---
3	RG 188A/U	(SC) 0.152	0.0195	(PTFE) 0.0515	(SCCS) 0.049	---
4	RG 58/U	(TC) 0.295	0.0275	(PE) 0.102	(TC) 0.091	Amphenol
5	RG 174/U	(TC) 0.152	0.0250	(PE) 0.0520	(CCS) 0.048	Amphenol
6	RG 174/U	(TC) 0.152	0.0250	(PE) 0.0520	(CCS) 0.048	Surco
7	RG 174/U	(TC) 0.152	0.0250	(PE) 0.0520	(CCS) 0.048	Beldon
8	RG 174/U	(TC) 0.152	0.0250	(PE) 0.0520	(CCS) 0.048	ITT

Table B-6. Solid Dielectric Semirigid Coaxial Cables

No.	Designation	Shield ID (cm)	Thickness (cm)	Dielectric Thickness (cm)	Conductor Diameter (cm)	Manufacturer
1	Al/Al 0.100 50	Al 0.203	0.0254	TFE 0.0706	Al 0.0602	Uniform Tubes
2	Al/Al 0.100 100	Al 0.203	0.0254	TFE 0.0922	Al 0.0188	Uniform Tubes
3	Al/Al 0.085 50	Al 0.168	0.0241	TFE 0.0584	Al 0.0508	Uniform Tubes
4	Al/Al 0.141 50	Al 0.302	0.0279	TFE 0.1054	Al 0.0914	Uniform Tubes
5	Al/Cu 0.141 50	Al 0.302	0.0279	TFE 0.1054	SPCW 0.0914	Uniform Tubes
6	Cu/Cu 0.085 50	Cu 0.168	0.0241	TFE 0.0584	SPCW 0.0508	Phelps Dodge
7	Cu/Cu 0.141 50	Cu 0.302	0.0279	TFE 0.1054	SPC 0.0914	Phelps Dodge

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