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Technical Memorandum 33-623

Electromagnetic Interference of Power Conditioners for Solar Electric Propulsion

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PREFACE

The work described in this document was performed by the Propulsion and Project Engineering Divisions of the Jet Propulsion Laboratory.

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ABSTRACT

Electrical, multikilowatt power conditioning (PC) equipment needed on board a spacecraft utilizing solar electric propulsion creates an electromagnetic environment that is potentially detrimental to the science, navigation, and radio communication hardware.

Within the scope of the solar electric propulsion system technology program at JPL, three lightweight, 2.5-kW PCs were evaluated in terms of their electromagnetic characteristics. It was found that the levels of radiated and conducted interference exceeded the levels anticipated for a solar electric propulsion mission. These noise emissions, however, were the result of deficient interference design in these models, rather than a basic inability to control interference in this type of PC.

It is essential that PC design specifications clearly define the electromagnetic interference (EMI) and electromagnetic compatibility requirements, that milestones of design evaluation be established, and that the quality assurance plan includes provisions for satisfying the EMI design requirements as well as an EMI test to verify adequacy of the design.

I. INTRODUCTION

The use of solar electric propulsion for the sophisticated deep-space missions has long been advocated and promoted (Refs. 1 and 2).

To convert the unregulated solar array power to the levels necessary to operate an ion thruster, it is necessary to incorporate electrical, multi-kilowatt power conditioning equipment on board a spacecraft. This equipment creates an electromagnetic environment that is potentially detrimental to the mission; science, navigation, and radio communication hardware could be affected and therefore must be protected.

To achieve the required compatibility, two alternatives are available: first, the hardware can be immunized; second, the intensity of the electromagnetic interference (EMI) can be reduced. In both cases, the levels and characteristics of the EMI environment must be identified.

Within the scope of the solar electric propulsion system technology (Ref. 1) program at JPL in the 1971-1972 period, three lightweight, 2.5-kW power conditioners (PCs) were evaluated in terms of their electromagnetic characteristics. This document summarizes the findings and proposed cures of the observed electromagnetic compatibility (EMC) problems.

II. PROGRAM DESCRIPTION

A. General

The EMI characteristics of the PCs were studied by separating the effort into three tasks: (1) define the test requirements, (2) measure and evaluate the EMI generated by the PCs and (3) perform an EMI design analysis of the circuitry. Because of the time constraints, these tasks were executed in parallel.

The activity first was rather general, then focused on those areas that appeared most important in the search for compatibility. As a result, this report stresses the different areas to different levels of detail, but it is felt that this approach yielded the maximum amount of information to aid future designs for compatibility.

B. Test Requirements

Baseline EMI requirements were established for the solar electric propulsion (SEP) spacecraft. These requirements are similar to the requirements established for other JPL flight projects. The Viking Orbiter (VO-75) EMC requirements and Mariner-Jupiter-Saturn 1977 (MJS-77) electromagnetic control requirements as reported in Section III of this document, with minor exceptions, are considered applicable at this time, with the understanding that they will be subject to change in accordance with SEP spacecraft and payload definitions.

It has subsequently been concluded that the MIL-STD-461/462 EMC specifications provide a good base for requirements over selected frequencies; that base should consequently be supplemented by a careful analysis of mission-particular requirements.

C. Test Scope

Tests were performed in a manner compatible with the established JPL-EMC test standards. Conducted and radiated emissions from the power conditioner were measured. Susceptibility testing of the power conditioner was not performed because of the time constraints on the program and because of previous work on noise immunization of the PC logic while integrating the SEPST III thrust subsystem (Ref. 3). Measurement of the static magnetic fields was considered a separate task and the results of that investigation are not part of this report. Details of the tests performed are reported in Sections IV and V of this document.

D. Design Analysis

In the course of this assignment, an attempt was made to identify the major sources of EMI and the mechanisms of noise coupling. This led to an investigation that made use of blueprints, electrical schematics, and a physical examination of the power conditioner. The circuitry, grounding, wiring, and packaging all received scrutiny. Details of this study are presented in Section VI of this document.

III. TEST REQUIREMENTS

A. General

The EMI and EMC control requirements for the SEP spacecraft should be realistic and based on mission requirements. These requirements can be formulated only when the design of the SEP spacecraft proceeds to such a level that all the scientific and operational payloads are fully defined in terms of susceptibility and location. At that time, detailed compatibility design tradeoffs can be made and a suitable EMC document generated.

To make the present investigation meaningful, two presently available EMC documents were used for evaluation of the test results: the existing VO-75 specification and the proposed requirements for the MJS-77 spacecraft prior to experiment selection. The requirements for VO-75 and MJS-77 are discussed in paragraphs B and C of this Section.

In those cases where the above specifications did not provide sufficient guidance, MIL-STD-461-462 specifications were consulted.

B. VO-75 Baseline

The baseline for the Viking Orbiter 1975 spacecraft EMI control is on-board compatibility. The relatively insensitive experiments and spacecraft subsystems do not require stringent EMI controls. Radiated noise limit and immunity requirements are imposed only out of consideration for communications with the Lander and with Earth stations. Conducted noise limits and immunity requirements are on a subsystem basis and concern only data and control circuits that interface with other subsystems. Ground line noise limits and immunity requirements are imposed to assure equipment safety for continued operation after mild transients are experienced between circuit common and chassis. Magnetic fields, both static and dynamic, are of minor concern because there is no magnetic field experiment on the spacecraft. The VO-75 requirements are listed in Table 1.

Additional general requirements and design guidelines not detailed here are imposed, i.e., electrical grounding, electrical bonding, interface circuit treatment, wire treatment, and transient suppression devices.

C. MJS-77 Baseline

The baseline for the MJS-77 EMI control is that all interference within certain bounds is detrimental because of the extreme sensitivity of the scientific instruments. Even though electromagnetic and magnetic interference cannot be completely eliminated, any reduction is beneficial. The Table 1 levels have been established as the maximum acceptable noise generation based on the minimum acceptable immunity limits that will allow meaningful data to be gathered by the science payload.

IV. TEST CONDITIONS

A. General

In keeping with the intent of this program, all tests were performed in the electric propulsion test facility, which contained all the support equipment for operating the power conditioners. The facility contributed to an ambient environment that sometimes impeded measurements.

B. Test Environment

No attempt was made to control the electromagnetic environmental effects of the equipment such as those associated with a thermal-vacuum chamber, a machine shop, electronic hardware, and miscellaneous other tests. The EMI test data were obtained while the power conditioner was both energized and de-energized to verify that local ambient levels did not interfere with the gathering of data.

C. Test Samples

Two versions of the power conditioner were evaluated: a breadboard (BB-1M) and two experimental (EX-1 and -2) models. Detailed descriptions of both can be found in Refs. 3 through 8. The input power leads to all modules were collectively shielded with aluminum foil as were the remaining telemetry, command, and internal low-voltage interconnecting leads. The two shielded harnesses were routed together; they were unshielded and grouped together only at the various module connectors.

D. Test Configuration

The power conditioners were tested in two phases, and in two different configurations. The first phase of testing was performed on the BB-1M power conditioner unit (Fig. 1), and the second phase was conducted on a "SEP mockup" containing the EX-1 and EX-2 power conditioner units (Fig. 2).

Figure 3 depicts the test configuration for the BB-1M unit. All ground references were made at the control console frame, which was in turn referenced to facility ground. Several ground loops were in existence and reference ground wires carried intentional current; both are considered undesirable from an EMI point of view.

Figure 4 depicts the test configuration for EX-1 and EX-2 units. Figure 5 depicts the ground reference tree and load bank return connections for the SEP mockup. A single ground reference point was established within the SEP mockup for all ground referenced circuits and structures.

Both configurations suffered from excessive lengths of interconnecting cables as well as many open, unterminated leads that contributed to a high ambient radiated electromagnetic environment. An effort was made to eliminate or reduce the effects of cable radiation by covering all interconnecting cables with zipper tube shielding. Only ground referencing wires (chassis and signal common and power output return) were left unshielded.

E. Test Operating Modes

Two operating modes of the thruster were simulated during the test program: one, the normal mode, where the thruster operated undisturbed within specified margins; the other, where the operation was perturbed by simulating arcing between the grids of the thruster. Most of the testing was performed in the normal mode.

F. Power Source

The solar array simulator (SAS) was a Hewlett-Packard HP-6475A SCR power supply capable of delivering 10 kW of dc power, with the nominal output voltage adjusted to 60 V.

Because of the nature of the control of the power, this supply generated a considerable amount of conducted interference that prevented evaluation of the conducted interference generated in the dc-input lines by the power conditioner. The power lines between the SAS and the power conditioners were shielded, and the radiated EMI was contained to minimize the effects on other measurements.

G. Load for Power Conditioners

Resistive loads were used to simulate the thruster load. Arcing of the thruster was simulated by means of firing thyratrons or closing the contacts of load relays. Cables connecting the power conditioners to the above loads were run as a single bundle; a shield was wrapped around that bundle to minimize the radiated EMI. The length of the cable used ranged from 6 to 15 m; the excess length was coiled and placed on the floor behind the PC.

H. Control and Monitoring

The control and monitoring of the power conditioner operation was usually executed from a control console having the capability of sending commands and reference levels, and monitoring all telemetry channels.

I. Test Instrumentation

Specialized EMI measurement equipment and standard electronic measurement equipment were utilized to obtain data. Most of the data were obtained via amplitude-versus-frequency or amplitude-versus-time displays. The oscilloscope and spectrum analyzer utilized had the capability of storing information captured during a single scan. Sensors utilized in gathering data were current probes, voltage probes and antennas. Isolation transformers, ground planes and other miscellaneous equipment were also utilized as necessary. Table 2 lists all test equipment utilized.

V. TEST RESULTS

A. General

The radiated and conducted EMI generated by the test samples was measured, varying numerous parameters. The results are reported herein.

B. Radiated Interference

1. BB-1M. Radiated interference from the BB-1M operating in the normal mode was measured as shown in Figs. 1 and 6. Results of the measurements from 15 kHz to 100 MHz are shown in Figs. 7 and 8. The results at selected frequencies above 100 MHz are listed in Table 3.

BB-1M radiated noise was also measured in the "arcing" mode. Interference in this mode extended to 40 MHz. The noise, which was broadband in nature, ranged from 10 to 20 dB above the normal operate levels.

It was possible (Fig. 9) to lower the normal mode radiated levels 10 dB by covering the component side with a perforated, metallic screen (Fig. 9b); additional 5-dB reduction was obtained by mounting a solid aluminum foil cover (Fig. 9c). It is expected that arcing noise would be reduced the same amount at the same frequencies.

2. SEP Mockup. Radiated interference from the SEP mockup in the normal operating mode was measured. Figures 7 and 8 show the SEP radiated interference from 15 kHz to 100 MHz. Note that BB-1M and the SEP mockup had essentially the same emission characteristics. Both exceeded the proposed MJS-77 limits by 50 dB at the lower frequencies. Measurements taken at various locations around the SEP mockup showed similar radiation characteristics.

The ground reference for the SEP mockup was changed to determine its effects on radiated emissions. Figures 10 and 11 show the measured data from 15 kHz to 30 MHz. Although the EMI levels changed as much as 20 dB at some frequencies, the basic shape of the spectrum remained unchanged. The grounding change was not always beneficial. This illustrates the fact that the general effect of grounding cannot necessarily be predicted. Any spacecraft will have to work out the best grounding for its particular configuration.

C. Conducted Interference

Conducted interference was measured on telemetry lines and reference and command lines. Most measurements were made in the normal operating mode, but the effect of arcing was also investigated. Most measurements of conducted interference were performed in the time domain using an oscilloscope with differential voltage probes.

1. Telemetry Lines. The power conditioner telemetry (TM) system consisted of 15 individual channels representing ten output currents and five output voltages. Each channel carried an analog signal of the level from 0 to 5 V. A single TM-common return wire was used between the PC and the TM console. Figure 12 illustrates a typical telemetry circuit in the power conditioner and shows typical measurement points. Figures 13 and 14 show the test configuration for BB-1M and the SEP mockup respectively.

Table 4 lists noise voltage amplitudes as measured at the test points of Fig. 12 for both BB-1M and the EX-1 and EX-2 mounted in the SEP mockup, operating in the normal mode. The "As is" columns list noise voltages as normally configured. The "High wire removed" columns list noise voltages appearing across a 100-k Ω resistor temporarily attached to the telemetry module output with the long "high" wire to the test console removed. The noise consisted of transients recurring at a rate that identified the source as the 5-kHz heater power inverter. The transients rang at a rate of 0.5 to 2 MHz and decayed to 0 V in 5 to 20 μs.

From the lower noise voltage in the "High-wire-removed" configuration it was concluded that the noise originated in the wiring and/or grounding scheme rather than the telemetry modules themselves. This item receives more attention in paragraph C of Section VI.

The noise caused by the arcing mode of operation was larger than the noise from 5-kHz inverters and ranged as high as 10-V peak, corresponding to the maximum of 7 V on BB-1M at the measurement point 1 of Fig. 12.

The noise voltages of the Table 4 "As is" columns greatly exceed the MJS-77 requirements of 50 mV and the VO-75 requirement of 300 mV for intersubsystem quiet circuits. The large reduction shown in the "High wire removed" columns indicate that the noise present could be reduced by a large amount and possibly meet the requirements if the telemetry circuitry and wiring were independent and isolated from other wiring. See paragraph C, Section VI, for details.

2. Reference and Command Circuits. The power conditioner utilized two external analog 0 to 5 Vdc reference sources to maintain control of the beam and arc power. These beam and arc reference control circuits were isolated from each other within the power conditioner but were common in the command and control console at the signal source return. The beam

reference had an isolated return within the power conditioner; the arc reference return was common with signal and the digital command return carrying the signals from the control console.

The power conditioner utilized five command lines that activated latching relays. The command circuits were activated from a 28-Vdc source.

Figure 15 shows the interference monitoring points. Table 5 shows the results. As in the case of telemetry, the noise was short duration transients occurring at the 5-kHz inverter rate. It can be seen that these amplitudes also exceed the "quiet circuit" requirements of 50 mV for MJS-77 and 300 mV for VO-75. Because the command control circuits have the same common ground as the reference circuits they were considered to be quiet circuits. If the command circuits utilized an independent ground circuit reference, they would be classified as "noisy circuits."

VI. DESIGN ANALYSIS AND RECOMMENDATIONS

A. General

As measurements were being made, the reason for interference was traced, where possible, and several areas of design were observed to be contributing to the radiated and conducted interference from the power conditioner. Generally, the areas of design contributing most to interference can be classified under the headings waveform control, common impedances and grounding, wiring, and packaging, each of which is discussed in the following paragraphs.

B. Waveform Control

The greatest single source of conducted and perhaps radiated noise is the 5-kHz inverter that supplies heater power to the thruster. The specific mode of noise coupling (e.g., wire cross-talk, and common ground) could not be identified. Improved grounding and wiring as discussed in subsequent paragraphs would provide a partial solution. It is felt that, more than anything else, the control of the waveform generated by this inverter would contribute to a sharp reduction of the system noise.

The waveform of the 5-kHz inverter is shown in Fig. 16. It is a square wave whose amplitude is 200 V p-p with an additional overshoot of 120 V.

The rise and fall times are less than one μs, generating high-frequency components in the radiated spectrum as shown in Fig. 17, curve A (a rough approximation of measured noise). Elimination of the overshoot would reduce the level of EMI by an estimated 3 to 6 dB, as illustrated in curve B. Slowing of the rise time (t_r) would result in a lowering of the cutoff frequency as estimated in curve C. A sine wave source (with some harmonic content) further trims the bandwidth of radiated noise as estimated in curve D. Conducted interference in the time domain is illustrated in Fig. 18 for the same source waveforms; it shows measured noise (curve A) and estimated reduced noise (curves B, C, and D).

Most of the auxiliary outputs energized from the 5-kHz inverter are of a regulated type. A magnetic amplifier (MA) is inserted between the source and the load; control consists of suppressing the initial portion of the waveform. To assess the EMI characteristics of the MA controlled outputs, a bench test was performed. A 5-kHz power wire was run near another wire simulating a TM circuit. The power source in one case was a square wave inverter and in the other case a sinusoidal source. In both cases they were controlled by magnetic amplifiers. The noise pickup on the adjacent wire was measured in the same manner as that on the PC circuits. Figures 19 and 20 show the results. The top trace of the picture shows the waveform of the current in the power line, the bottom trace the noise coupled into an adjoining telemetry line. The time scale for both figures is about the same, but the vertical scale of the bottom trace of Fig. 20 is one-tenth of that of Fig. 19. In Fig. 19 it can be seen that the MA controlled rise time has been slowed down and this part of the waveform no longer generates EMI. The same cannot be said about the fall times as they are determined by the source. Figure 20 shows the effect of MA control on a sinusoidal source. Figures 19 and 20 show a reduction of telemetry line noise in this example from 500 mV, due to the square wave source, to 60 mV, due to the sinusoidal source.

The circuit designer should strive to:

(1) Reduce overshoot on waveforms (e.g., by means of zener diodes).

(2) Increase the rise and fall time of square wave technology (reduce dV/dt) or use sinusoidal technology for power conversion.

C. Common Impedances and Grounding

Figure 21 shows an example of wiring that contributes to conducted noise transients on telemetry lines. Note the wire A-B, in a typical magnetic modulator module, that serves as a return for both the housekeeping power and the telemetry signal. Noise transients as described in subparagraph V-C-1 were measured on the return wire A-B on several modules. The transients typically ranged from 400 to 700 mA and were as high as 4.5 V measured from point A to point B. The resultant voltage also appears on the telemetry lines because they share the one return wire.

The source of these transients was identified as the housekeeping power supply in an experiment. It was possible to separate the telemetry ground A (Fig. 22) and the housekeeping power ground C in one module. The measured noise in the telemetry wire A-B dropped from 500 mA to 30 mA and from 3 to 0.8 V, identifying the housekeeping power as the principle source of transients.

The recommended grounding configuration for EMI control is shown in Fig. 23. The following rules are applicable:

(1) The telemetry ground A and the housekeeping power ground C are electrically isolated in the module.

(2) The telemetry high and return wires are equal.

(3) The telemetry and housekeeping power have ground reference wires A-B and E-B, respectively, which do not carry current.

Note in Fig. 24 that D-B and C-B provide acceptable alternate ground references. However, leaving both A-B and D-B connected provides a "ground loop" that is unacceptable from an EMI standpoint.

Figures 25 and 26 show present configuration and possible implementation of isolation for ac- and dc-telemetry signals, respectively.

In general, it is recommended that the following groups of circuits be electrically isolated in each module, and have one ground reference to the central ground point so that no ground loops are created:

(1) Input power.

(2) Telemetry.

(3) Internal power "housekeeping."

(4) Command and control.

(5) Output power.

D. Wiring Harness

Designing a harness for minimal pickup of interference is a formidable task of its own. Because of the common grounds and common returns used extensively in the power conditioner, the wiring was not sufficiently segregated for interference control.

If possible, the wiring should be in segregated harnesses comprised of:

(1) Input power.

(2) Input control signals.

(3) Output telemetry signals.

(4) Output power.

(5) Internal power.

(6) Internal signals.

The degree of isolation by the use of separate circuit commons will dictate the degree of harness segregation that is possible.

The following guidelines should be adopted:

(1) Route wire harnesses near the frame to take advantage of its shielding effect.

(2) Route a given wire harness in its own connectors.

(3) Route high and return wires as close to each other as possible.

(4) Have an equal length of high and return wires.

(5) Separate the different wire harnesses, especially the high-level (power) and low-level (telemetry) circuit wiring.

(6) Twist and/or shield high and return wires.

E. Packaging

The attainment of high-efficiency power conversion through the application of squarewave technology requires the use of submicrosecond circuit switching. The effects of fast rise-time current and voltage pulses must be confined to their functional area and not allowed to propagate to other non-required areas. This confinement requires compartmentalization through the application of shielding and filtering. Only those circuits required to process the fast rise-time pulses should be allowed to experience the high-level electromagnetic environment produced by the fast rise-time pulses. All circuits that enter and/or exit the confined area may require filtering to remove conducted interference acquired through conduction and/or radiation while within the confined area.

Figure 27 depicts one interference containment scheme that could be utilized by the power conditioner. Each of the five major sources of interference are housed in individual shielded compartments as are all associated power processing components. All primary power input lines are filtered as are all dc outputs. A shielded interconnect system is utilized to contain all ac - and pulsating-power transmission. The ac output power lines are also shielded.

This type of individual compartmentalization should be given preference in lieu of the overall shield concept as presently attempted. Individual shielded compartments and local filtering reduces the exposure of interconnect wiring to the electromagnetic environment.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

It was found that the levels of radiated and conducted interference exceeded the levels desired for a solar electric propulsion mission. Fortunately, the noise emissions were due to a deficiency in interference control design in these models, rather than a basic inability to control interference in this type of power conditioner.

The prime objectives that guided the designers of the power conditioners in question were to achieve a minimum weight, maximum efficiency configuration that would perform reliably in vacuum over the specified interval of time. The EMI considerations, though recognized as existing, were viewed to be of secondary importance. The designs used to achieve the above prime objectives in many instances were contrary to basic EMI control concepts. The analysis of this design indicated it should be comparatively easy, on future designs, to improve the EMI characteristics greatly, at a modest penalty to the prime objectives.

B. Recommendations

This study and experience from other space programs have shown that the EMI control is essential.

EMC can be most economically and efficiently implemented if started as early in the initial design concepts as possible and carried through the development and test phases. Prompt application of necessary corrective actions, when needed, will minimize costly delays due to last minute "fixes."

It is, therefore, essential that the power conditioner design specifications clearly define the EMI/EMC requirements and establish milestones of design evaluation. It is also important that the quality assurance plan includes provisions for satisfying the EMI design requirements, and calls for an EMI test of the first engineering model to verify the adequacy of the design.

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Table 1. Electromagnetic compatibility requirements for VO-75 and MJS-77 spacecraft[a]

Environment	Design requirement	
	VO-75	MJS-77
Conducted noise generation		
Intersubsystem quiet circuits	300 mV (p-p)	<50 mV (p-p)
Intersubsystem noisy circuits	None	<100 mV (p-p)
Direct access or umbilical	1000 mV (p-p)	<100 mV (p-p)
Circuit common to chassis[b]	1000 mV (p-p)	<100 mV (p-p)
Radiated noise generation (measured at 1 m)		
Magnetic fields		
1 Hz to 10 Hz	None	<72 dBpT/$\sqrt{\text{Hz}}$
10 Hz to 1 MHz	None	<72 to 22 dBpT/$\sqrt{\text{Hz}}$
Electric fields		
30 Hz to 200 kHz (BB)	None	<+15 to -23 dBμV/m/$\sqrt{\text{Hz}}$
15 kHz to 40 MHz	None	<45 to 25 dBμV/m
200 kHz to 40 MHz (BB)	None	<0 to -15 dBμV/m/$\sqrt{\text{Hz}}$
350 MHz to 450 MHz	-9 dBV/m	None
2.1 GHz to 2.3 GHz	<-24 dBμV/m	Same as VO-75
5.5 GHz to 5.8 GHz	<76 dBμV/m	Same as VO-75
Conducted transient noise immunity		
Intersubsystem interfaces (Centaur)	None	<±2 V or ±200 mA
Intersubsystem interfaces	<±1 V or ±100 mA	Same as VO-75
Direct access or umbilical	<±3 V or ±300 mA	Same as VO-75
Circuit common to chassis[c]	<±3 V or ±5 mA	Same as VO-75
Radiated RF power immunity		
350 to 450 MHz	3 W/m^2 average	None
2.1 to 2.3 GHz	10 W/m^2 average	Same as VO-75
5.5 to 5.8 GHz	600 W/m^2 peak	Same as VO-75
8.3 to 8.5 GHz	0.5 W/m^2 average	Same as VO-75
Magnetic control		
Maximum radial magnetic field[d]		
Bus-mounted subsystems	5000 nT	<40 nT at 1 m
Scan platform instruments	5000 nT	<30 nT at 1 m
All other assemblies	5000 nT At surface[e]	<5 nT at 1 m

[a]Assumed a 16-m boom to magnetometer with a 0.03 nT sensitivity.

[b]2 m of No. 24 AWG wire.

[c]Not commonly connected to chassis.

[d]Hardware demagnetized by 4 mT (max).

[e]Science instruments within 0.5 m from surface.

Table 2. Test equipment

Parameter to be measured	Equipment
Radiated noise	Empire Model NF105 noise and field intensity meter, with the following accessories: TX NF105 plug-in TA NF105 plug-in T-1 NF105 plug-in T-2 NF105 plug-in VR-105 antenna (rod) VA-105 antenna (rod) DM-105-T-1 antenna (dipole) DM-105-T-2 antenna (dipole) EMC Instrumentation Inc. Model EMA-910 electromagnetic analyzer, with the following accessories: 910-701 horn antenna 910-703 feed horn 910-705 parabolic reflector Hewlett Packard Model 141S/8553L/8552A spectrum analyzer used with the following accessories: Empire VR-105 rod antenna Empire VA-105 rod antenna Power line isolation transformer
Conducted noise	Tektronix Type 549 storage oscilloscope, with the following accessories: Type 1A1 dual trace plug-in p6028 1X voltage probes p6006 10X voltage probes p6013A 1000X voltage probe p6042 current probe Power line isolation transformer

Table 3. Radiated RF noise, BB-1M

Frequency, MHz	VO-75 limit, dBm/m^2	BB-1M level[a], dBm/m^2
350-450	-130	< -85
2100	-125	< -87.6
2200	-125	< -87.8
2300	-125	< -88.7
5500	-40	< -87.7
5600	-40	< -91.2
5700	-40	< -90.0
5800	-40	< -92.48

[a] Radiated noise from the power conditioner was below measuring instrument sensitivity, as noted.

Table 4. Telemetry lines interference levels in volts peak to peak

Circuit No.	Test point (see Fig. 12) / TM circuit	As is			High wire removed				
		BB-1M		SEP mockup	BB-1M			SEP mockup	
		1	4	4	1	2	3	1	3
1	Magnet current	0.3	13	4	0.2	-	-	-	-
2	Main vaporizer current	0.8	14	4	-[a]	-	-	-	-
3	Cathode vaporizer current	0.35	8	4	-	-	-	-	-
4	Arc voltage	7	13	5	0.25	-	-	-	-
5	Arc current	7	13	4.5	-	-	-	-	-
6	Screen voltage	3.1	9	3.5	2	4.5	-	-	-
7	Screen current	3.5	9	4	-	-	-	-	-
8	Accelerator voltage	2.6	8	4.5	-	-	-	-	-
9	Accelerator current	3	8	2.5	0.74	-	-	-	-
10	Neutralizer current	1.1	14	3.5	-	-	-	-	-
11	Neutralizer keeper voltage	3	10	3	0.4	1.2	-	-	-
12	Neutralizer keeper current	1.3	14	2.5	-	-	-	-	-
13	Cathode tip heater current	0.3	7	3.5	-	-	-	0.1	2
14	Hollow cathode keeper voltage	3	7	3.5	-	-	-	-	-
15	Hollow cathode keeper current	5	7	3	0.35	0.35	1.5	-	1.7

[a]Dash indicates that data were not taken.

Table 5. Conducted interference levels at source, reference and command

Circuit	Voltage at source, V p-p
Beam reference	1.5
Arc reference	1.5
Command ON-1	2.5
Command ON-2	2.5
Command ON-3	2.5
Command OFF-1	2.5
Command OFF-2	2.5
Command Return	3[a]

[a]Between control console return and PC signal common in SEP mockup.

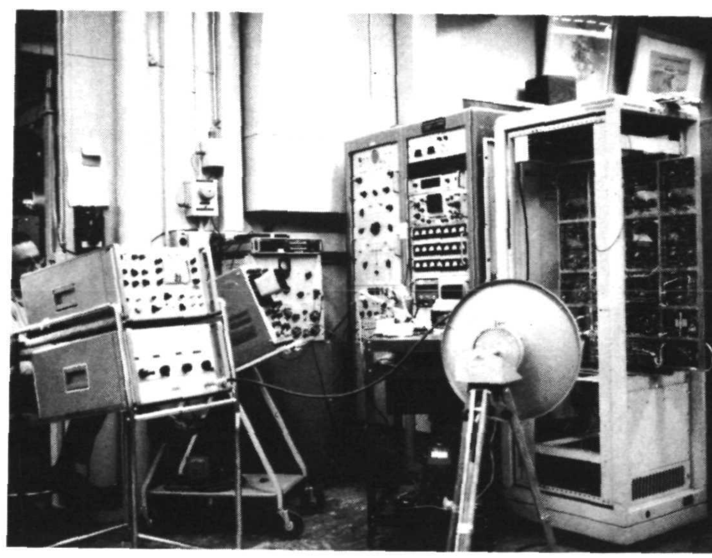

Fig. 1. Radiated test configuration, BB-1M

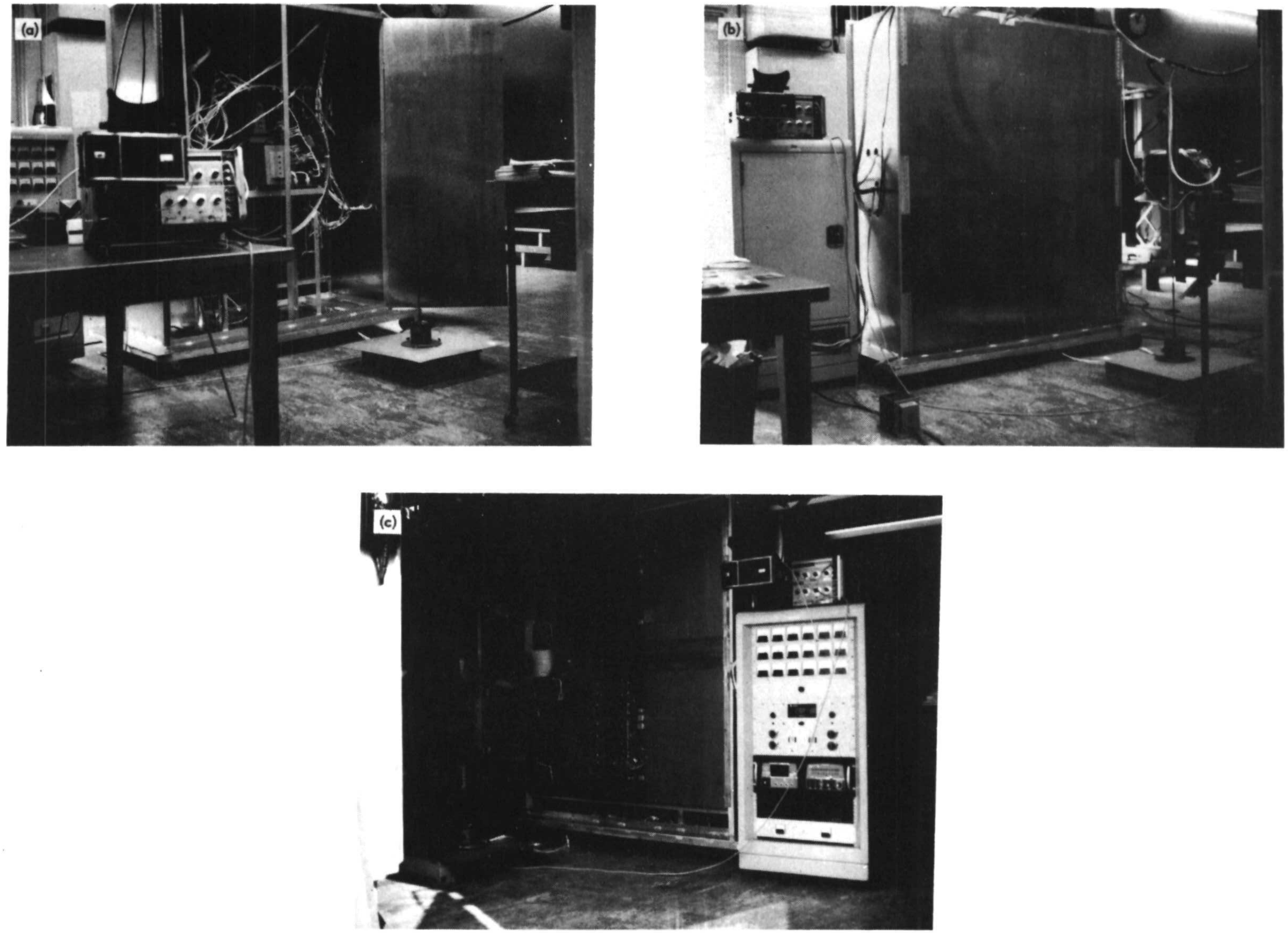

Fig. 2. Radiated interference measurement, SEP-mockup detail: (a) rear view, doors open; (b) rear view, doors closed; (c) front view

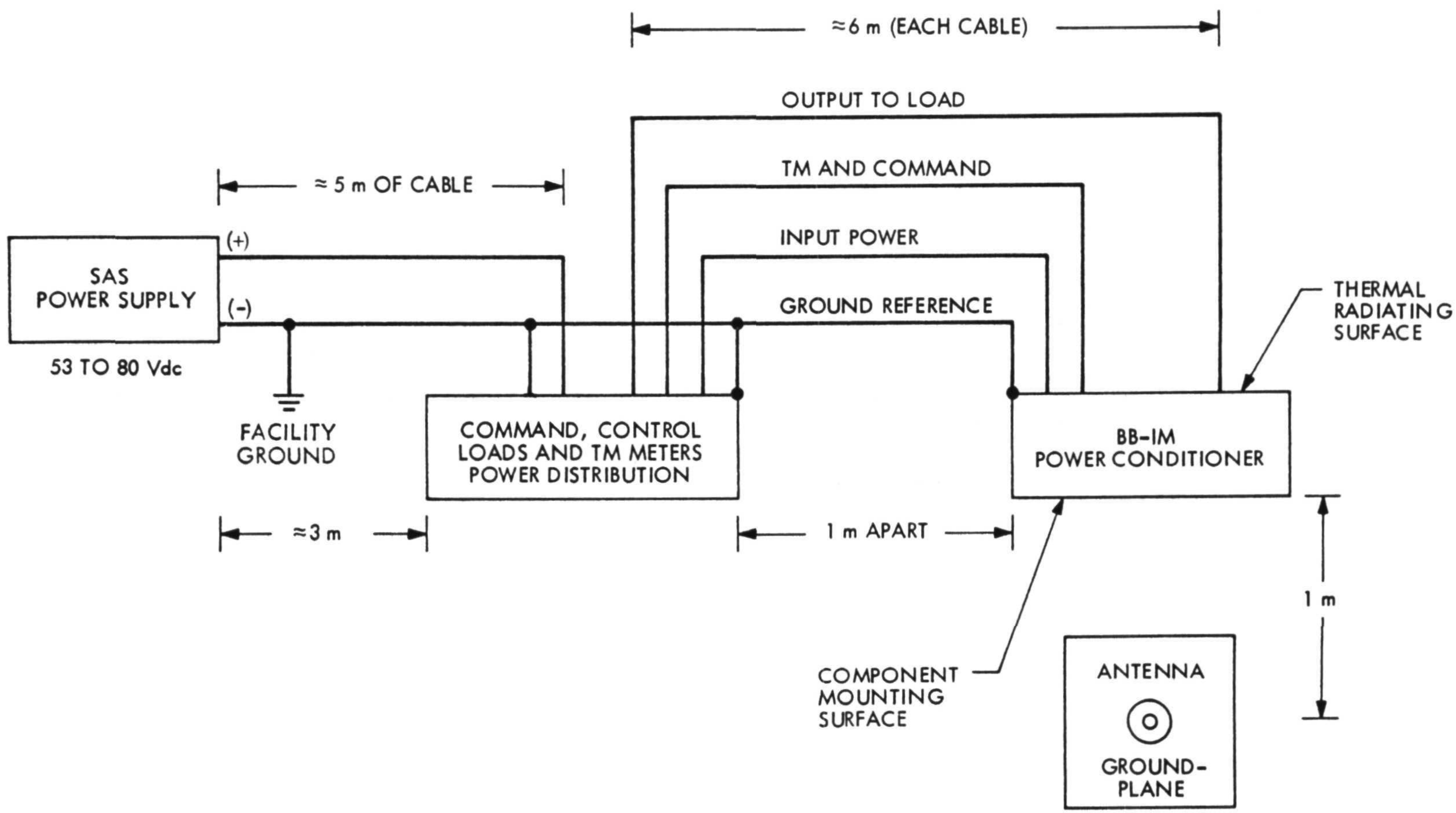

Fig. 3. Test configuration, BB-1M

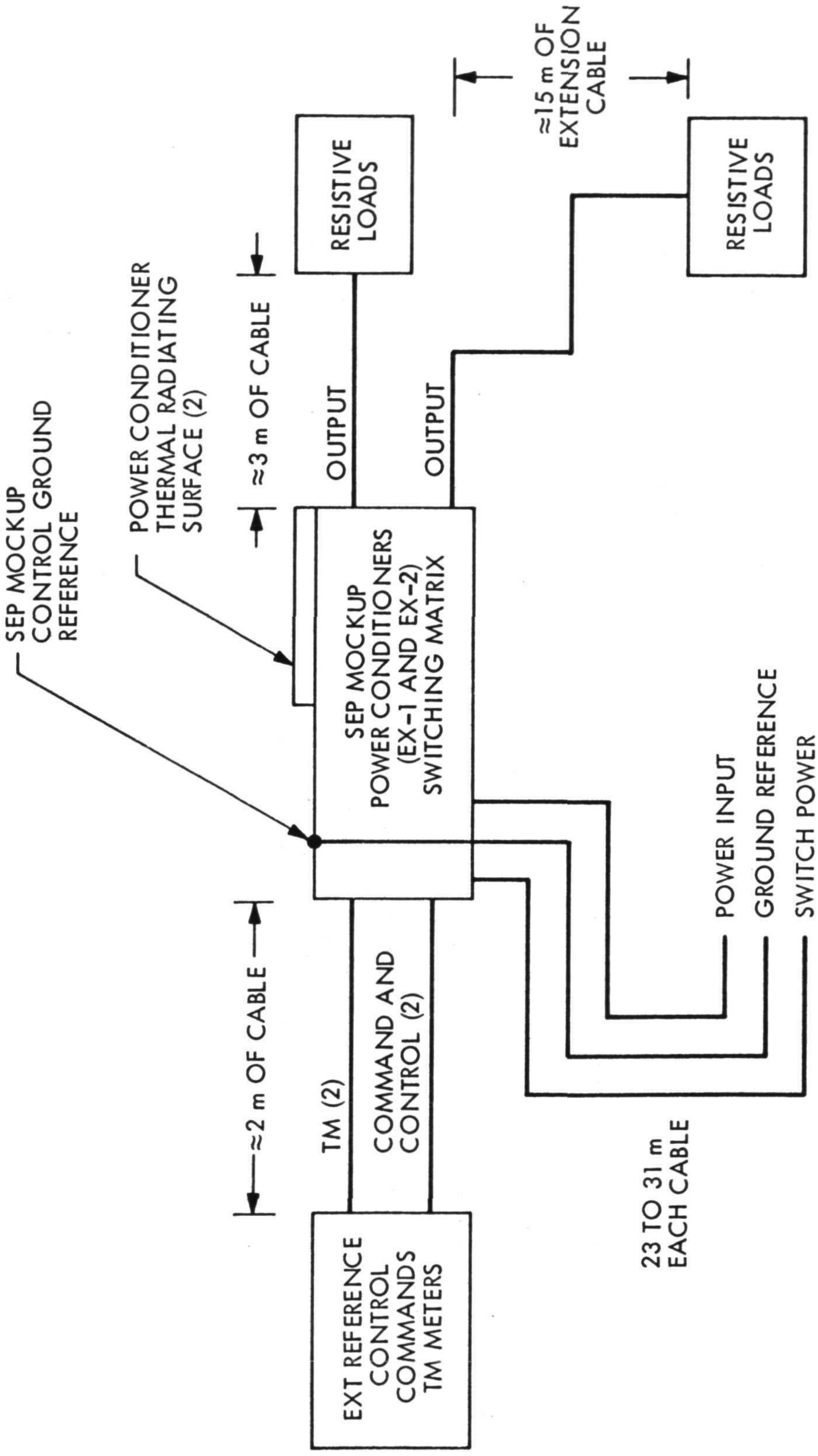

Fig. 4. Test configuration, SEP mockup

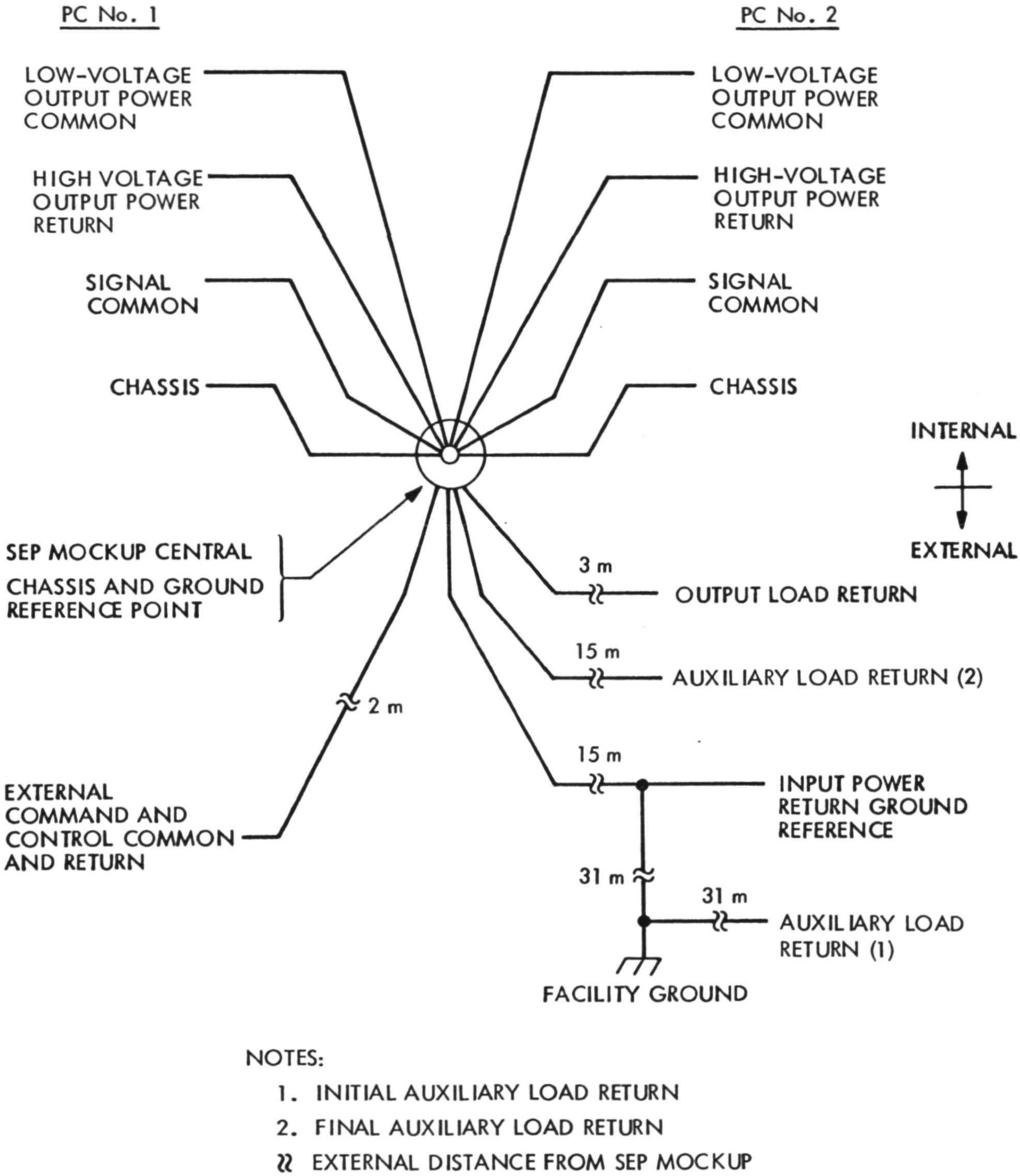

Fig. 5. Ground reference tree, SEP mockup

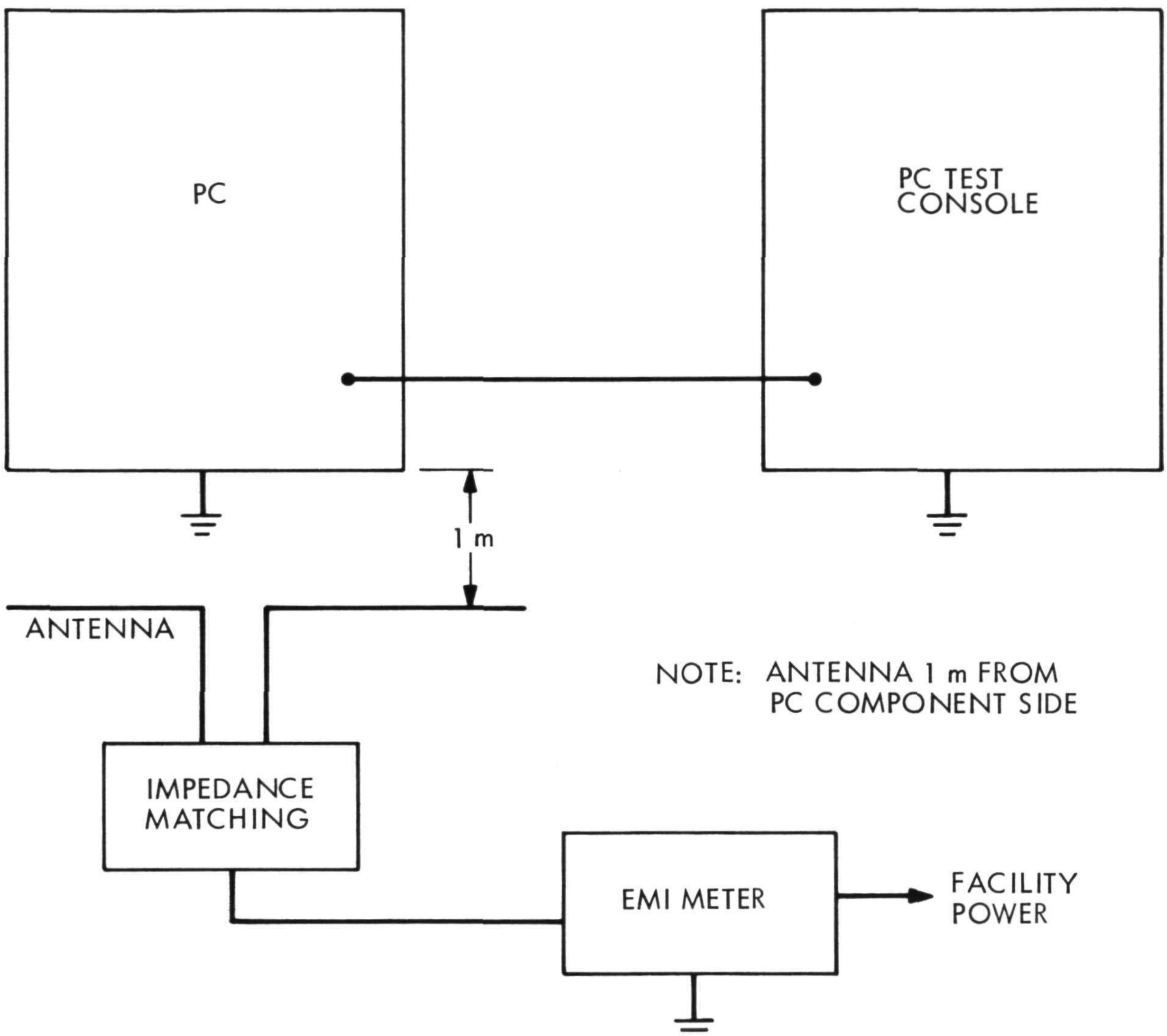

Fig. 6. Radiated interference test, BB-1M

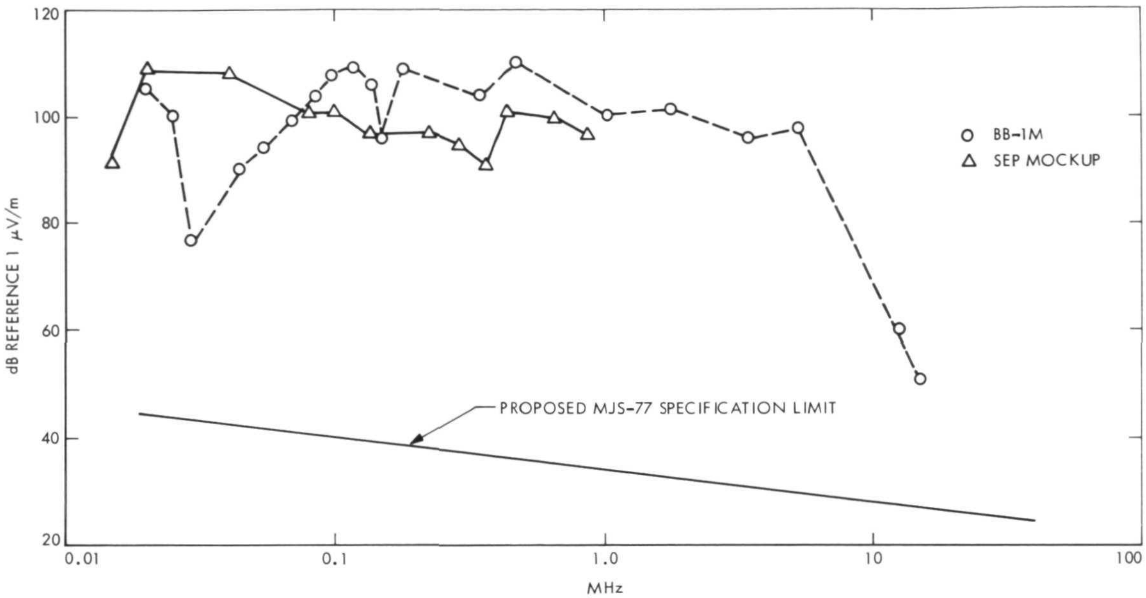

Fig. 7. Radiated narrowband interference, BB-1M and SEP mockup

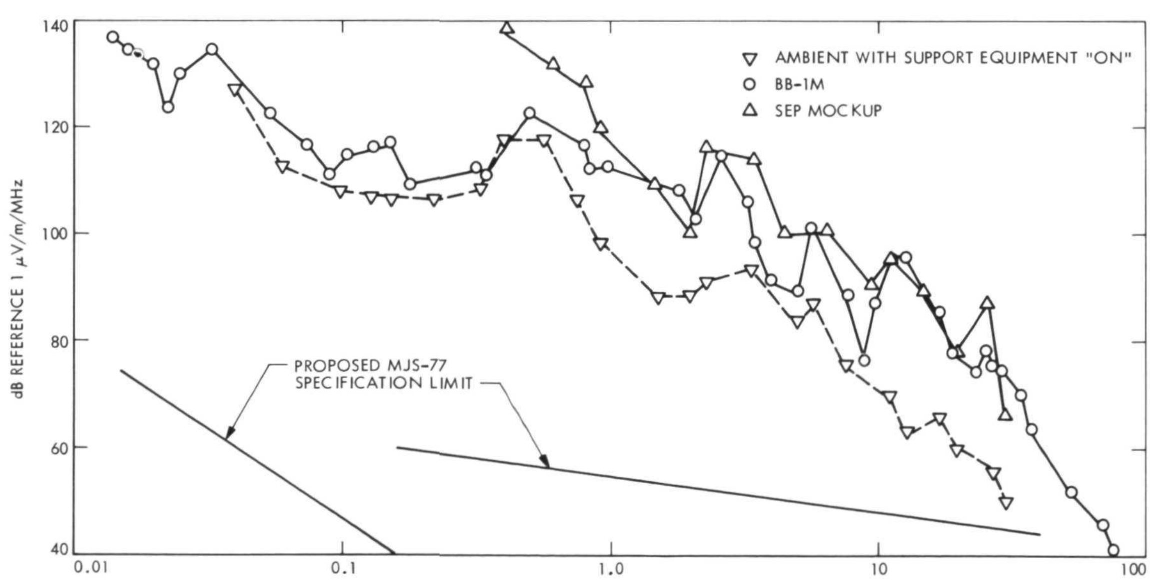

Fig. 8. Radiated broadband interference, BB-1M and SEP mockup

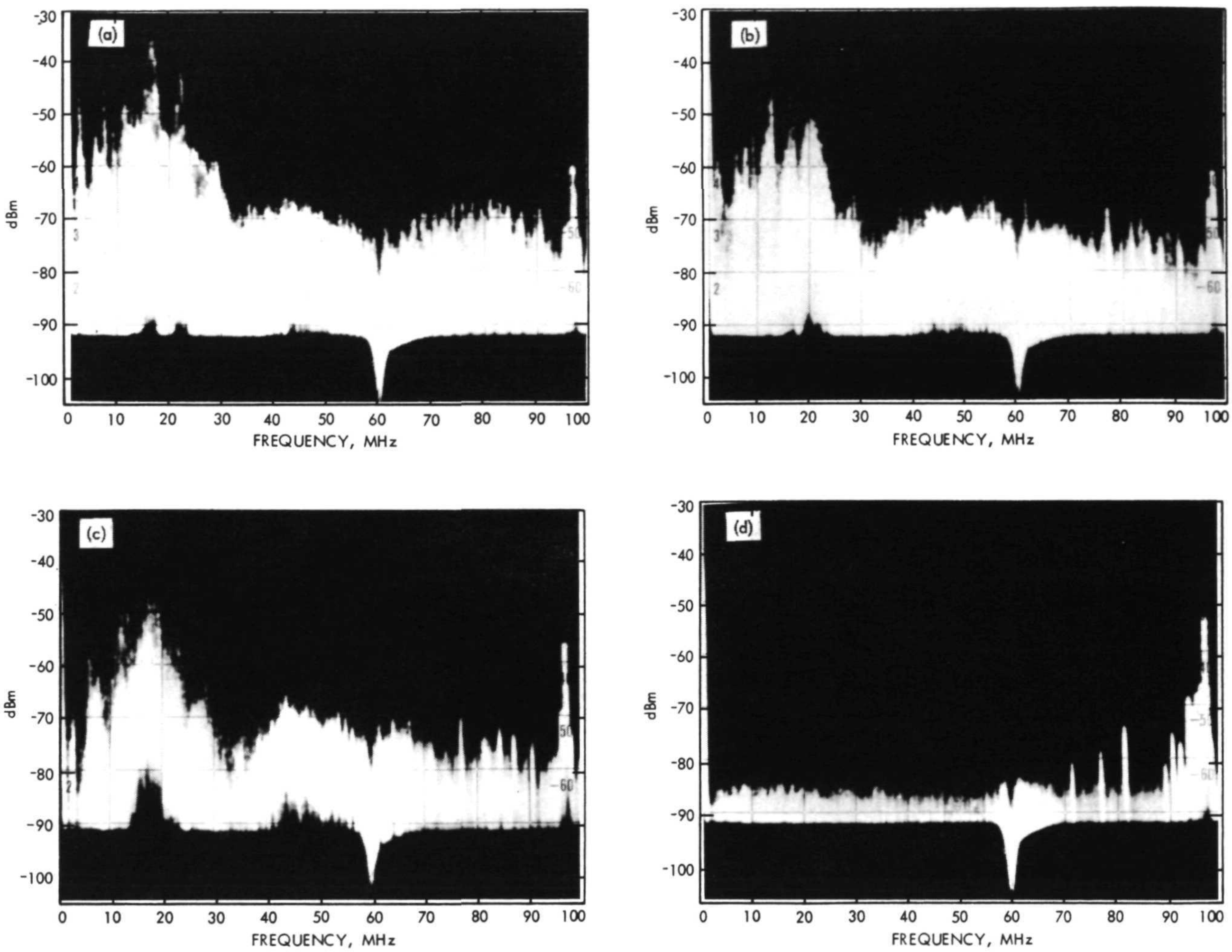

Fig. 9. Effectiveness of shielding from radiated EMI, BB-1M: (a) BB-1M, screen removed; (b) BB-1M, screen installed; (c) BB-1M, aluminum foil installed on component side; (d) laboratory ambient, power off

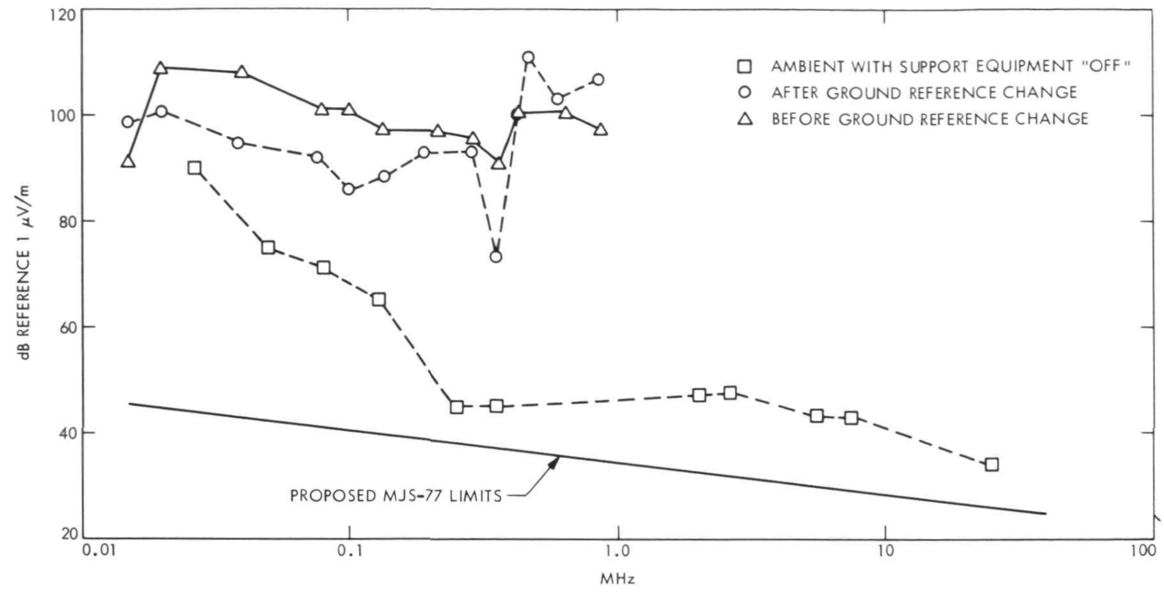

Fig. 10. Grounding influence on narrowband radiated levels

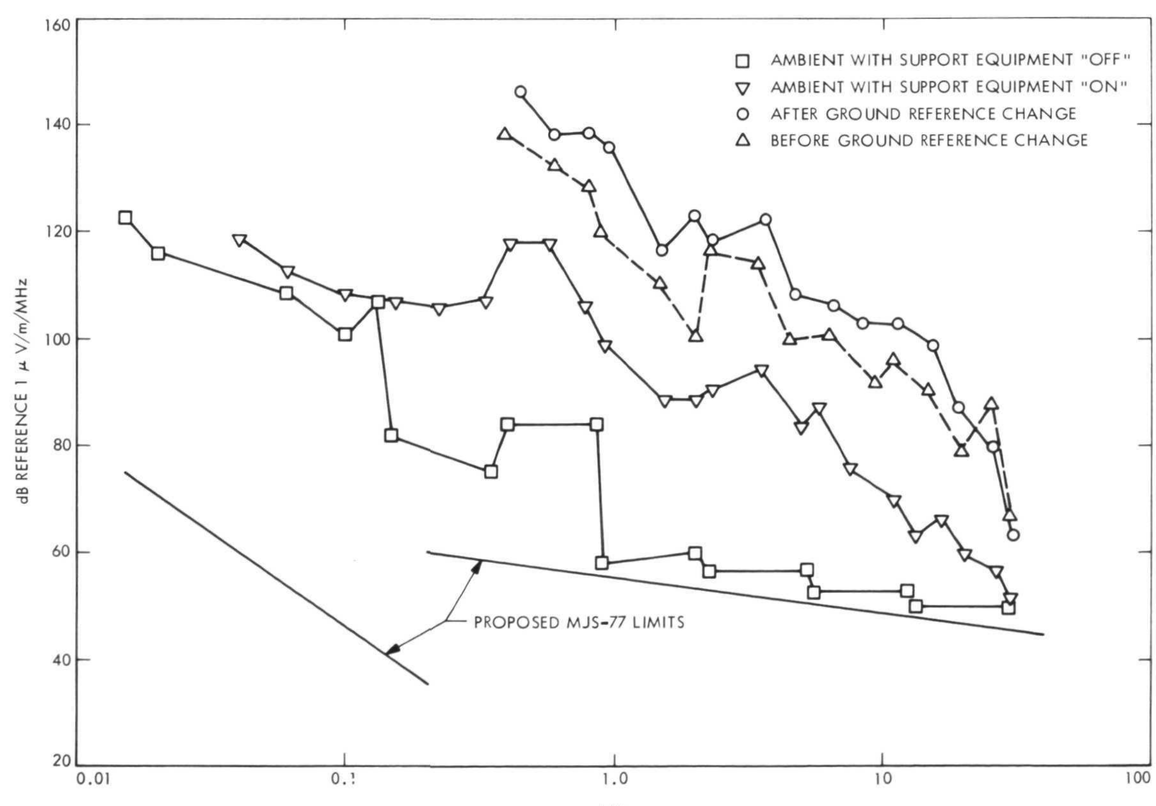

Fig. 11. Grounding influence on broadband radiated levels

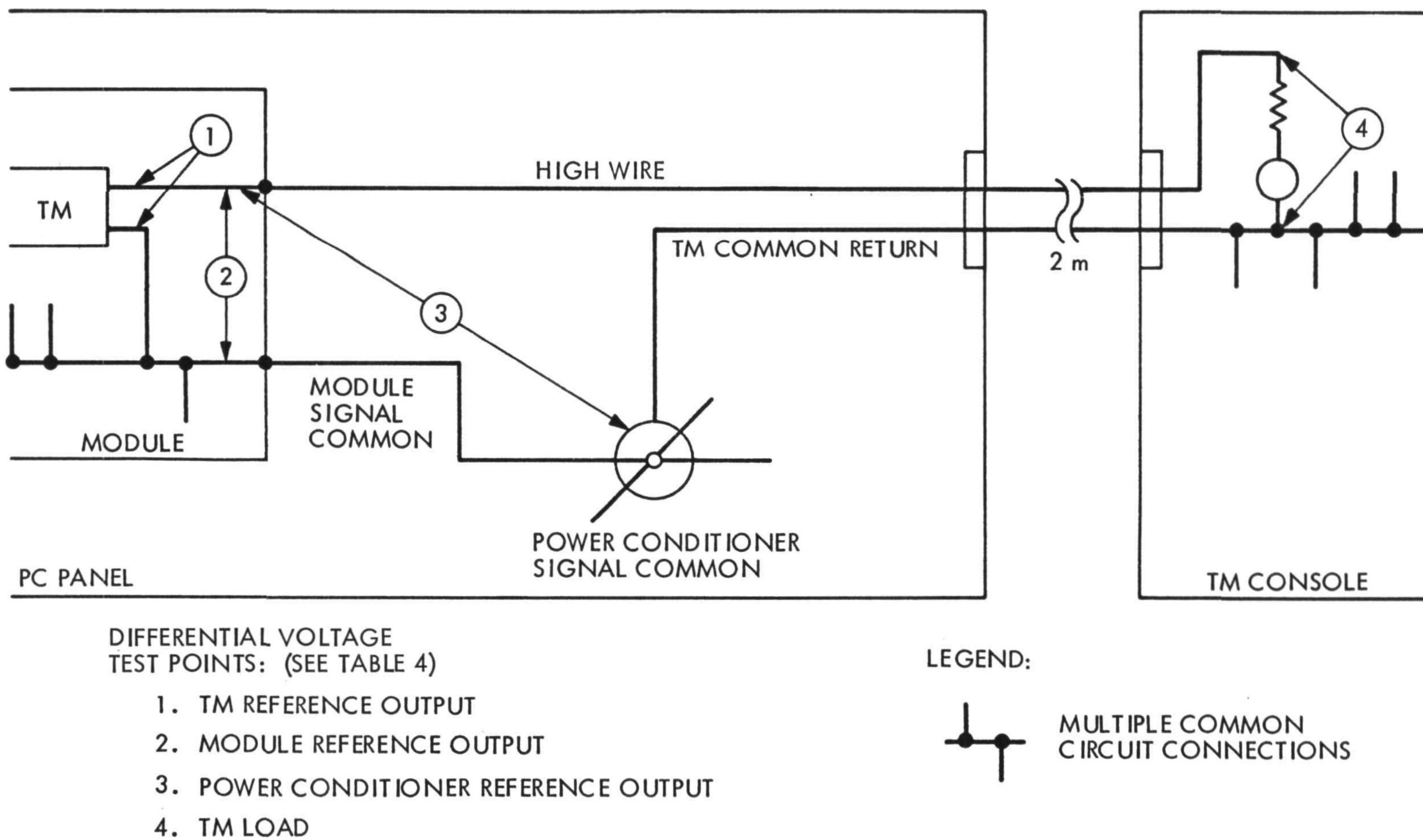

Fig. 12. Telemetry interference monitoring points

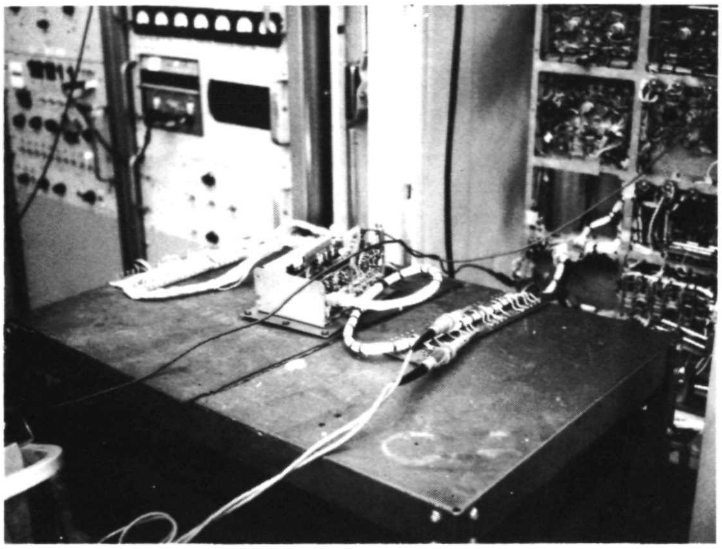

Fig. 13. Differential voltage measurement, control module of BB-1M

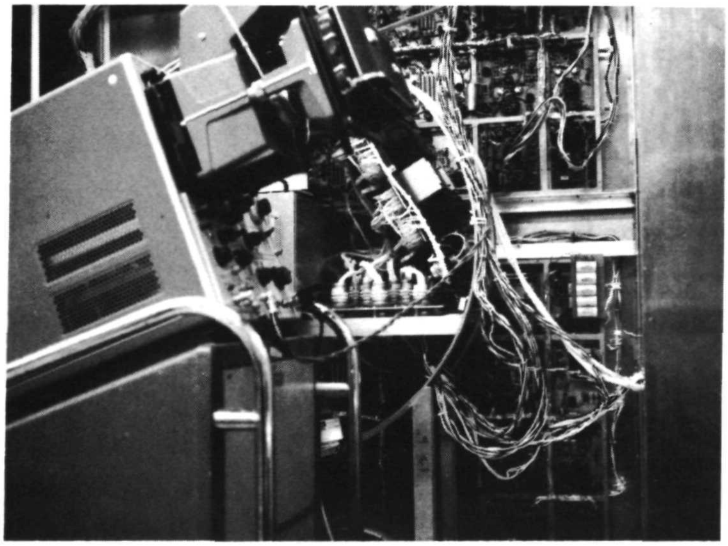

Fig. 14. Differential voltage measurement, telemetry output of SEP mockup

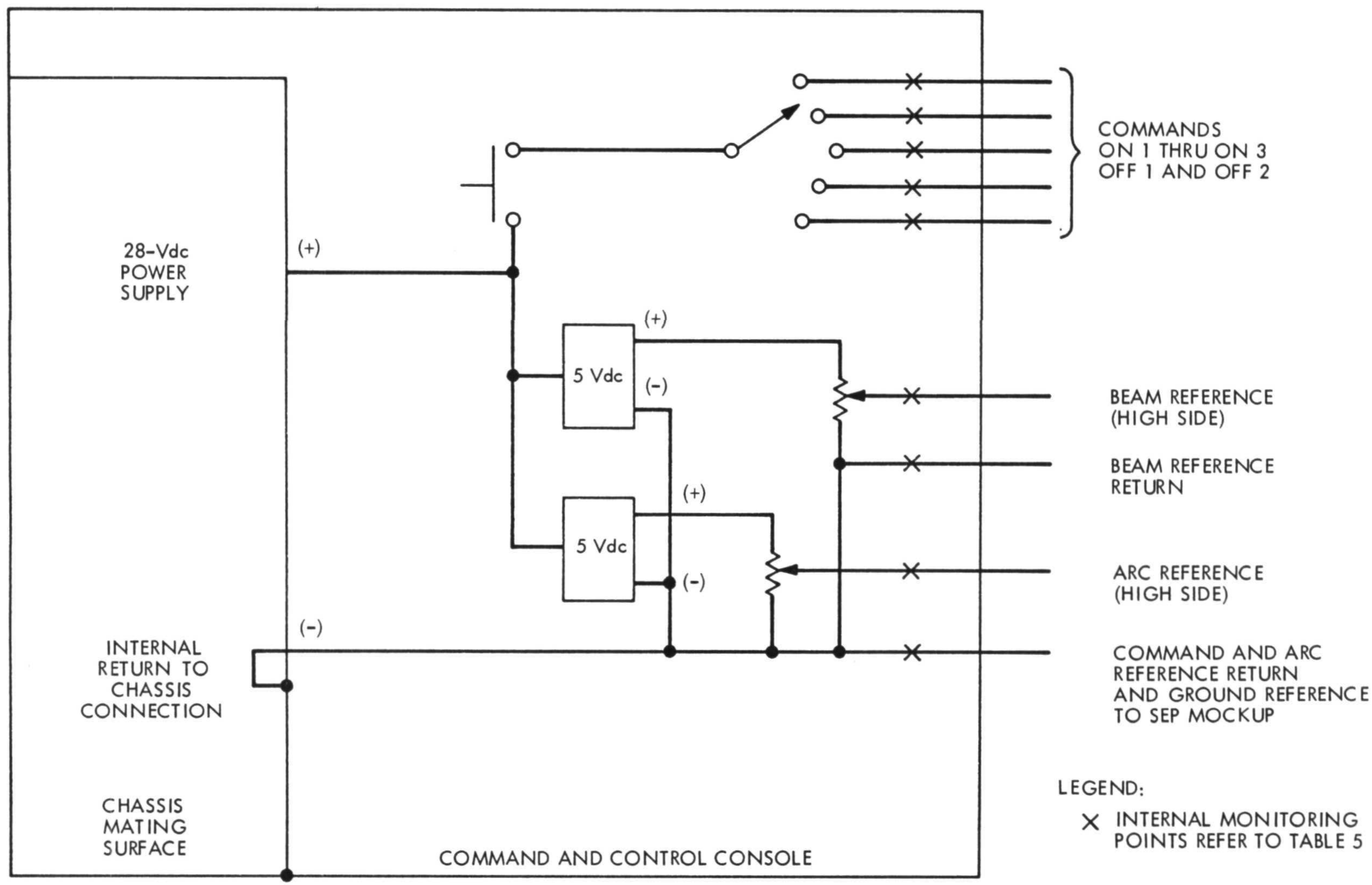

Fig. 15. Interference monitoring points, reference and command

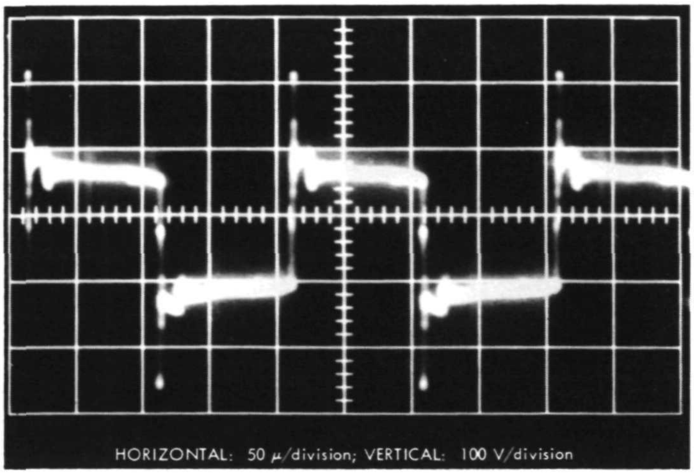

Fig. 16. Voltage waveform across primary of the output transformer, 5-kHz inverter

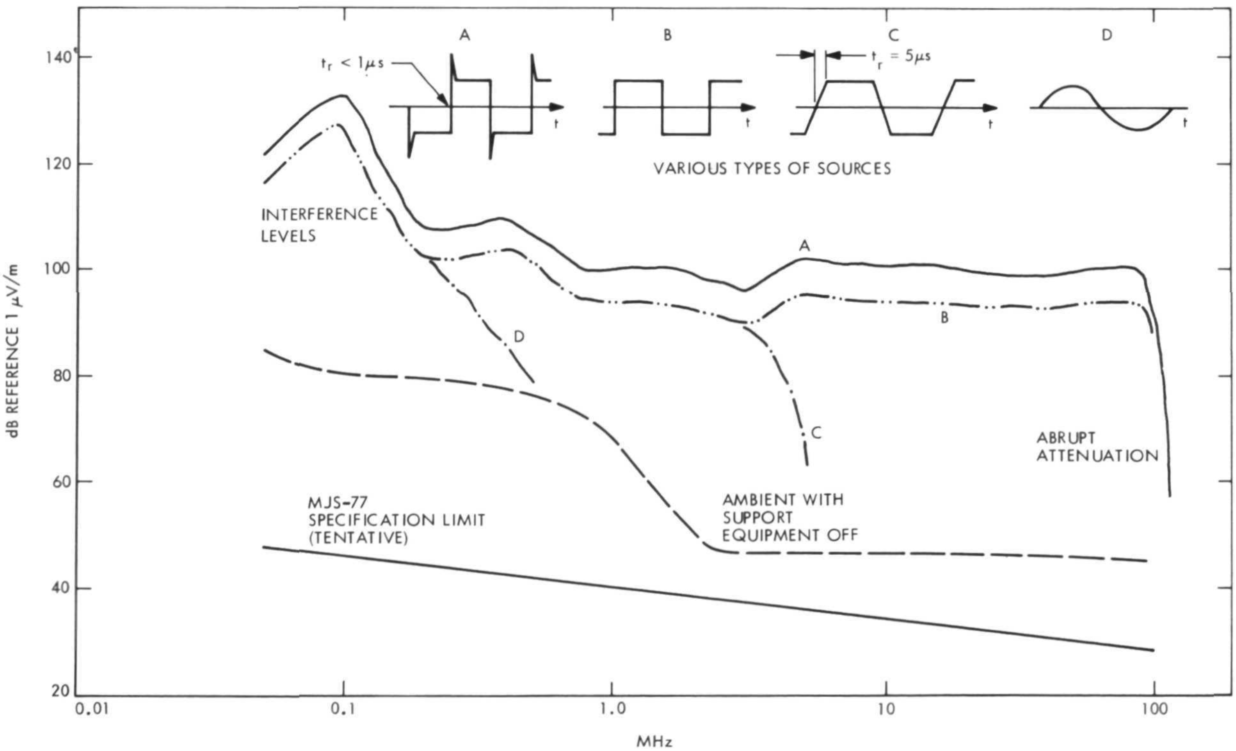

Fig. 17. Radiated narrowband interference for various source waveforms

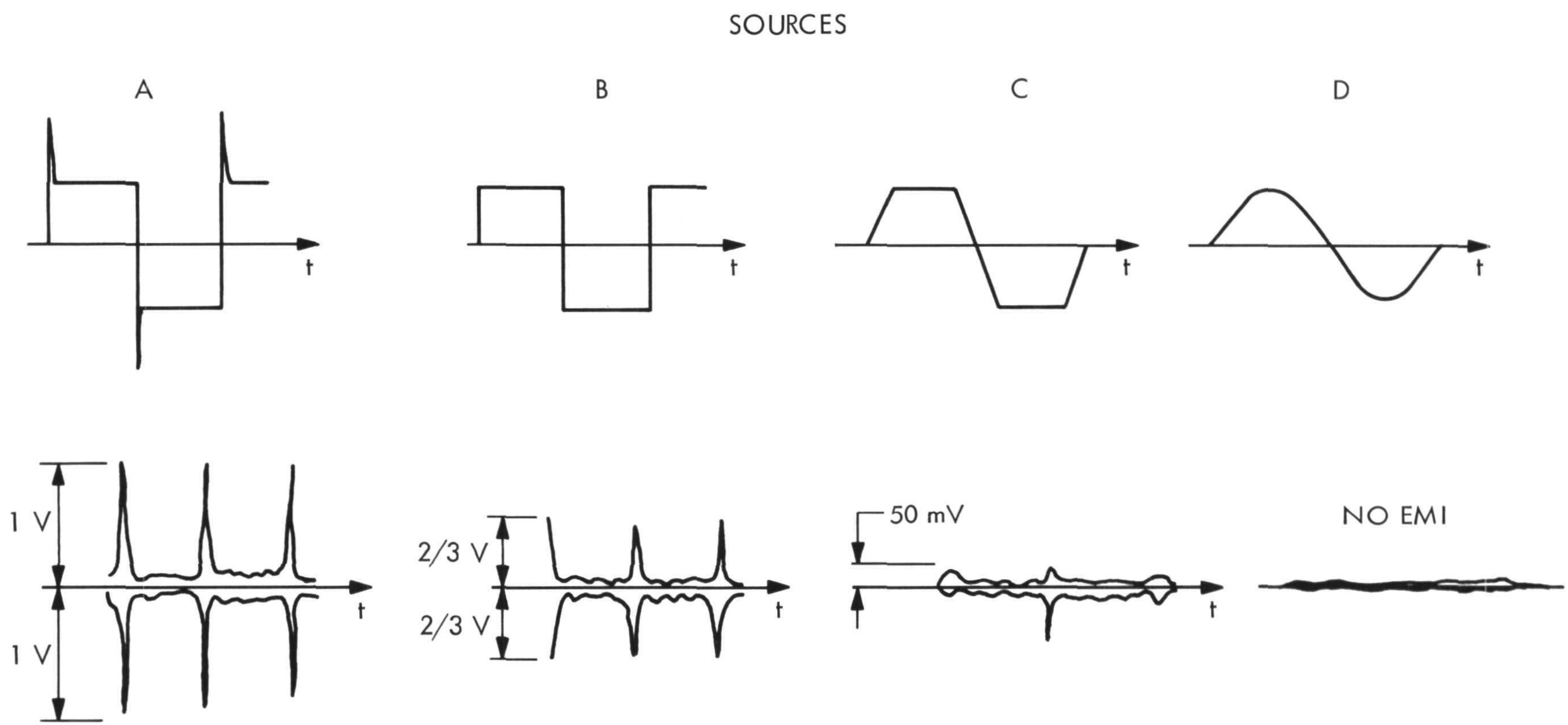

Fig. 18. Conducted time domain interference

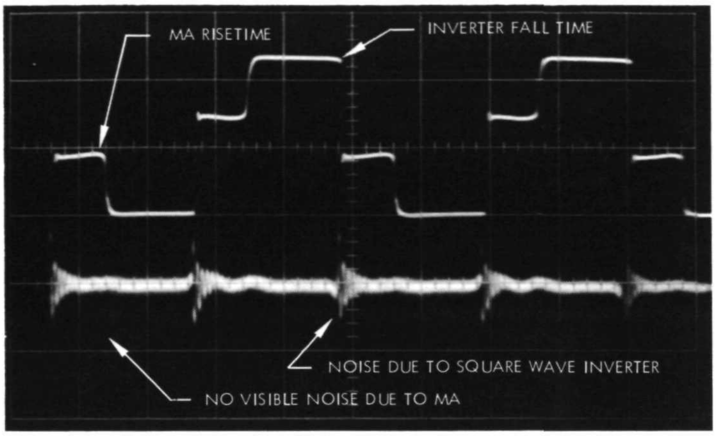

Fig. 19. Square-wave source with MA controlled output; lower trace 0.5 V/cm

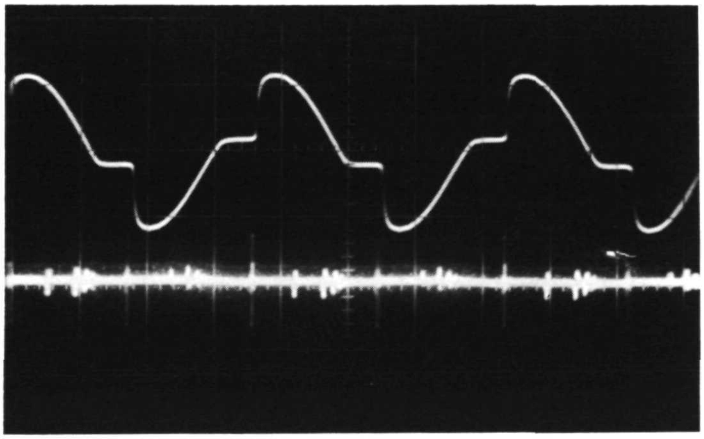

Fig. 20. Sinusoidal source with MA controlled output; lower trace 0.5 V/cm

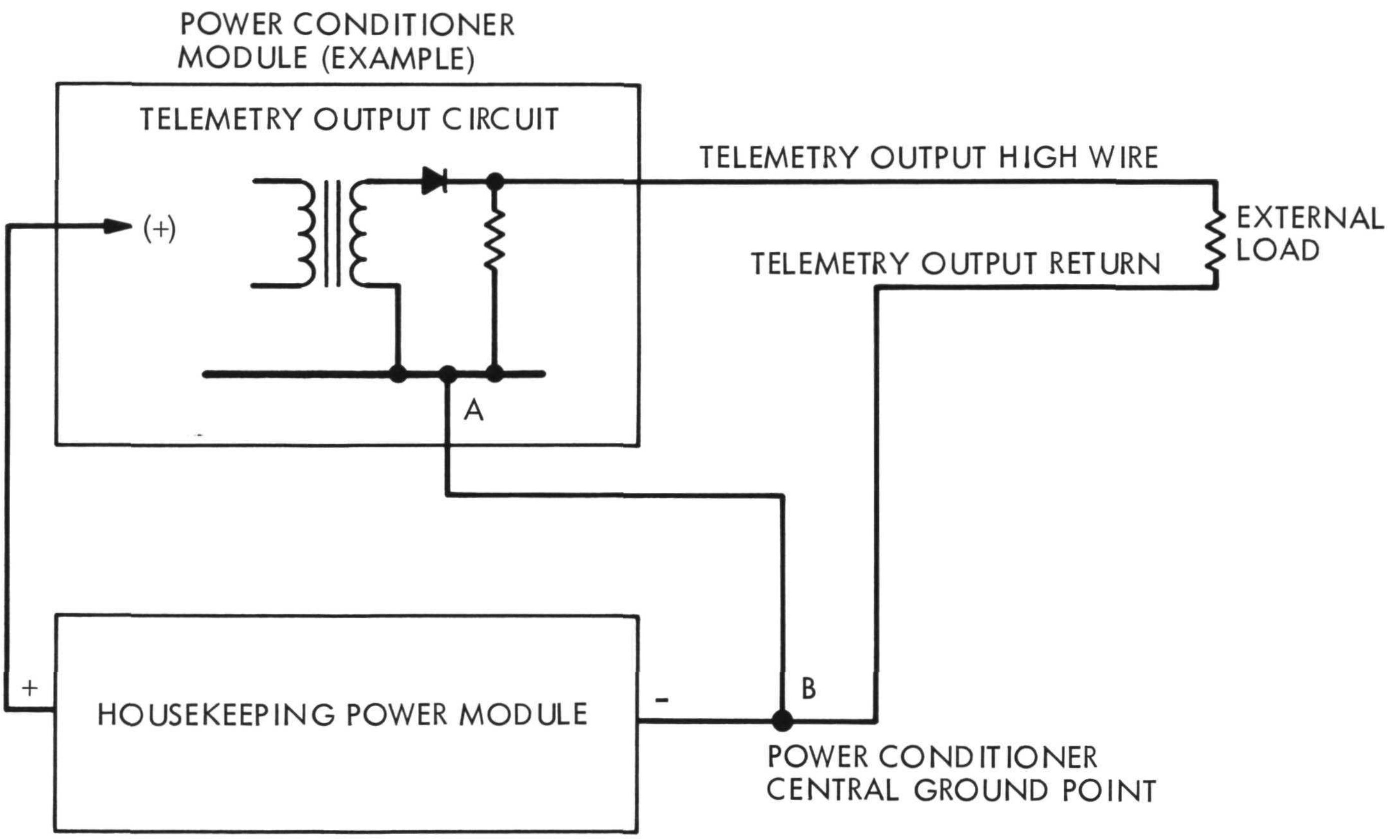

Fig. 21. Telemetry grounding, original configuration

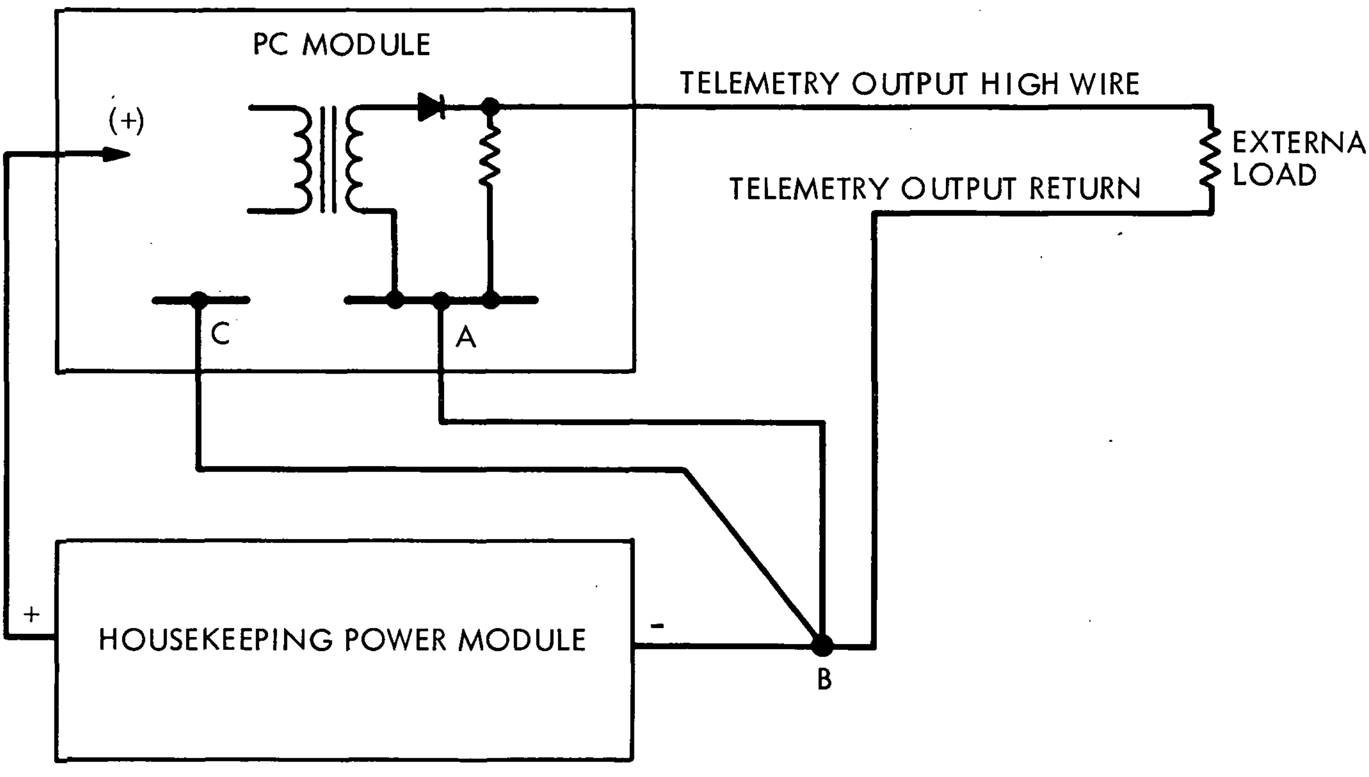

Fig. 22. Telemetry grounding, modified configuration

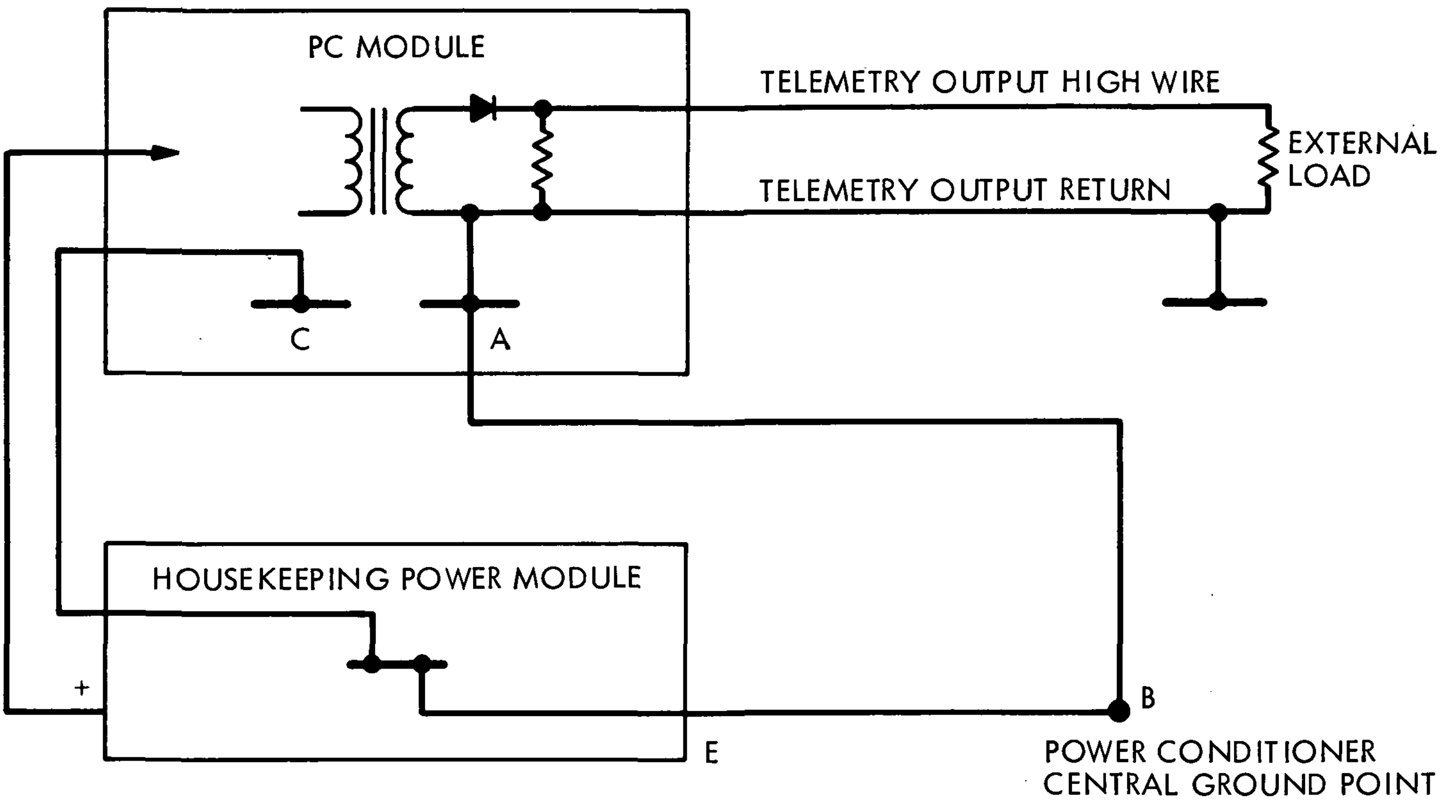

Fig. 23. Suggested telemetry grounding

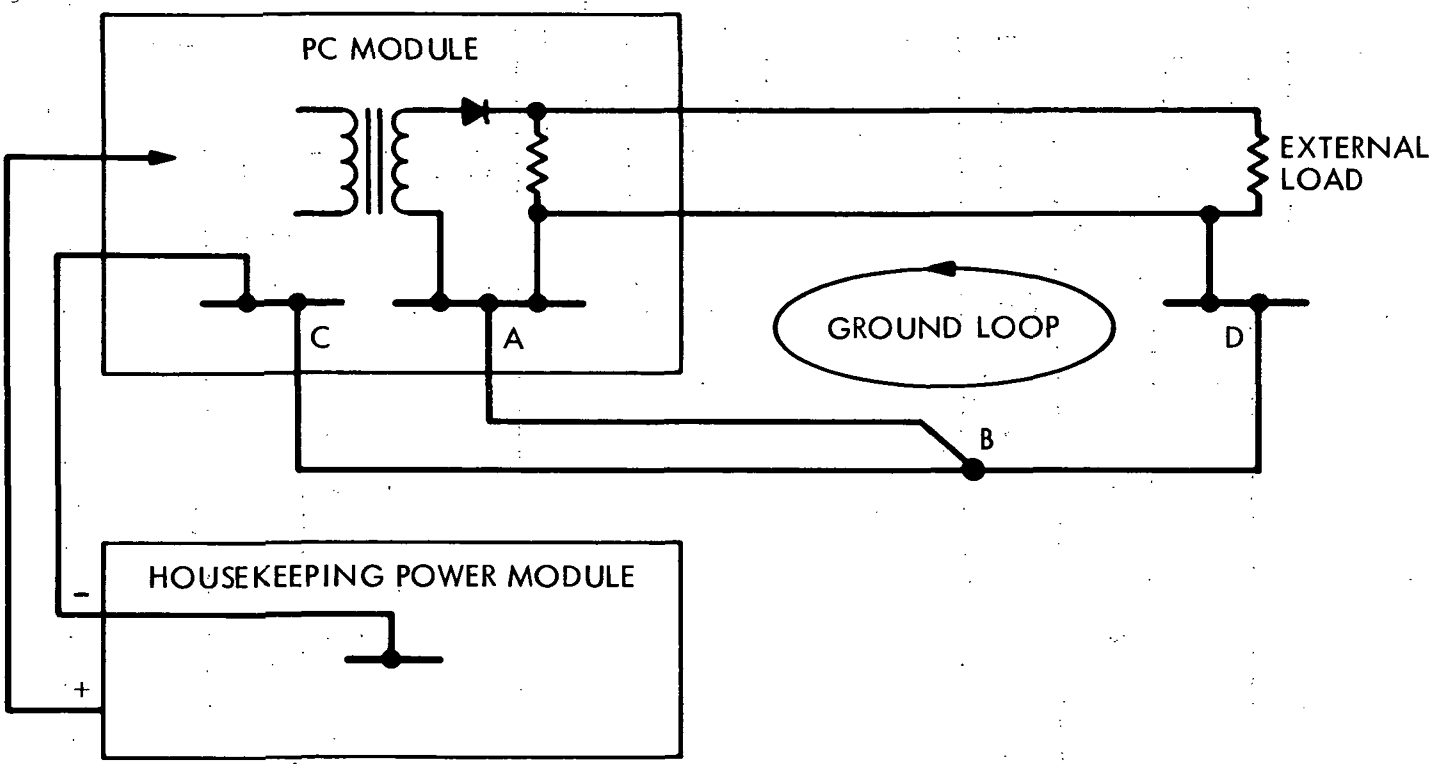

Fig. 24. Alternate telemetry grounding

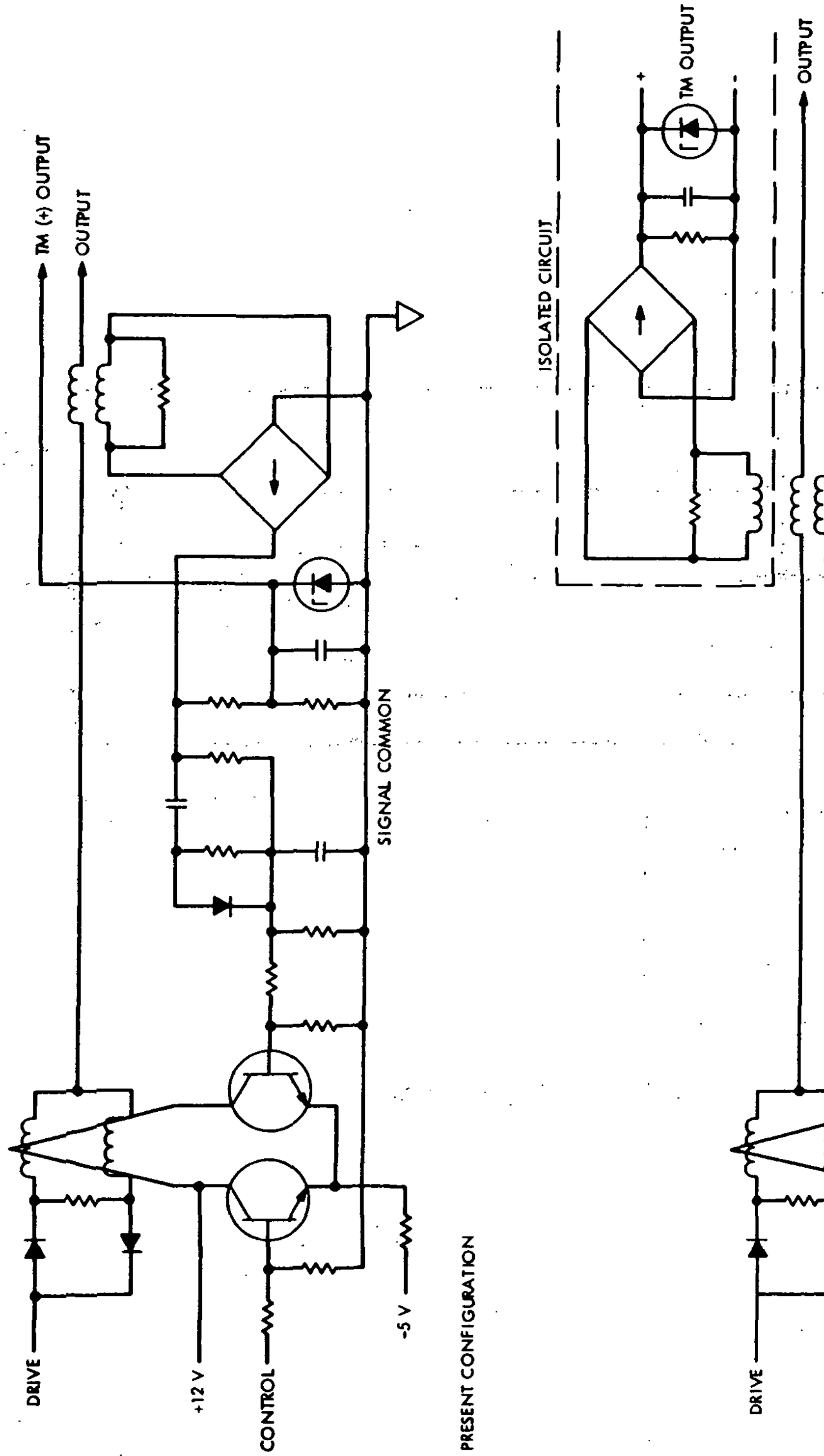

Fig. 25. Telemetry transformer source isolation, ac signals

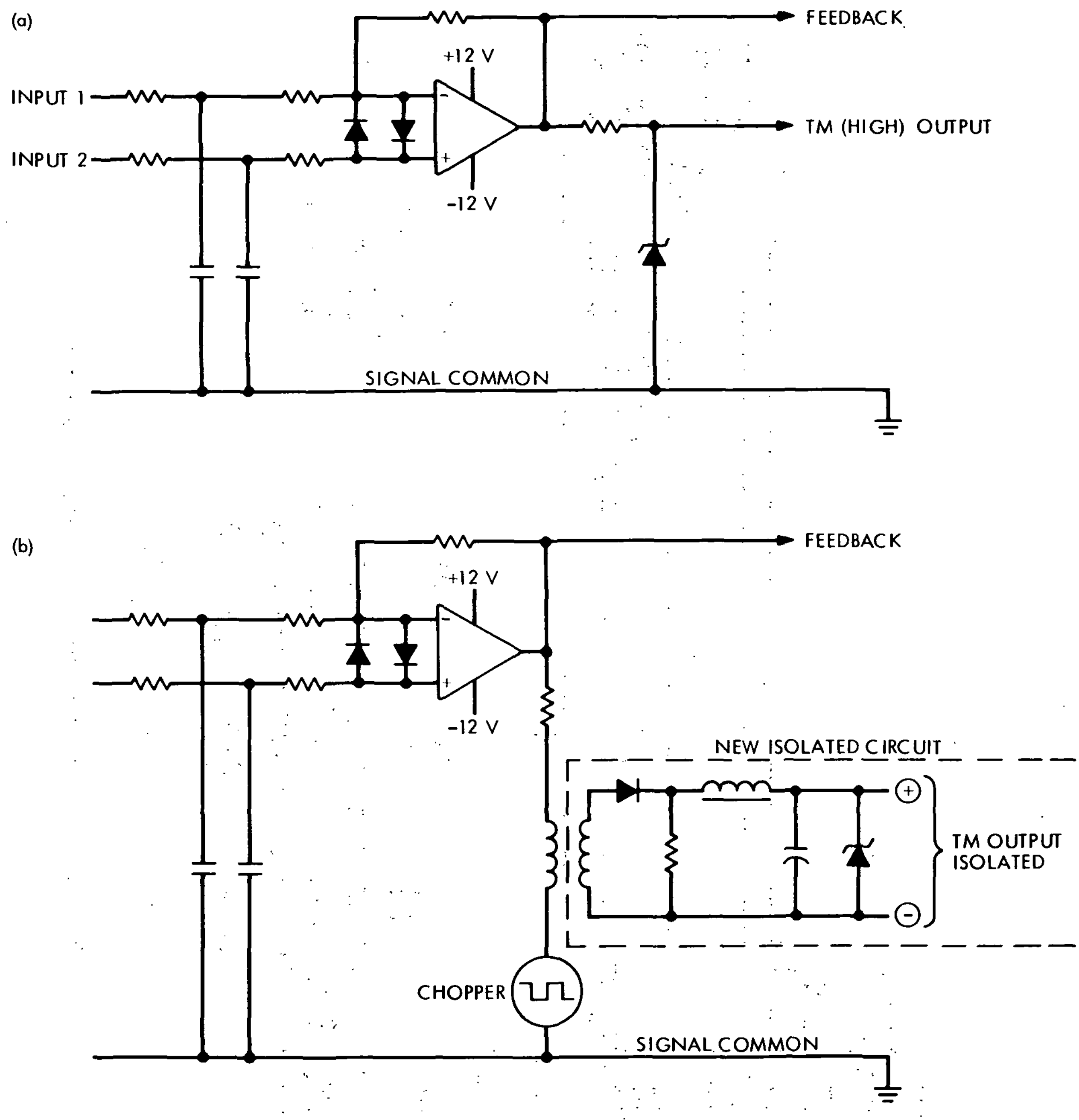

Fig. 26. Telemetry operational amplifier source isolation, dc signals

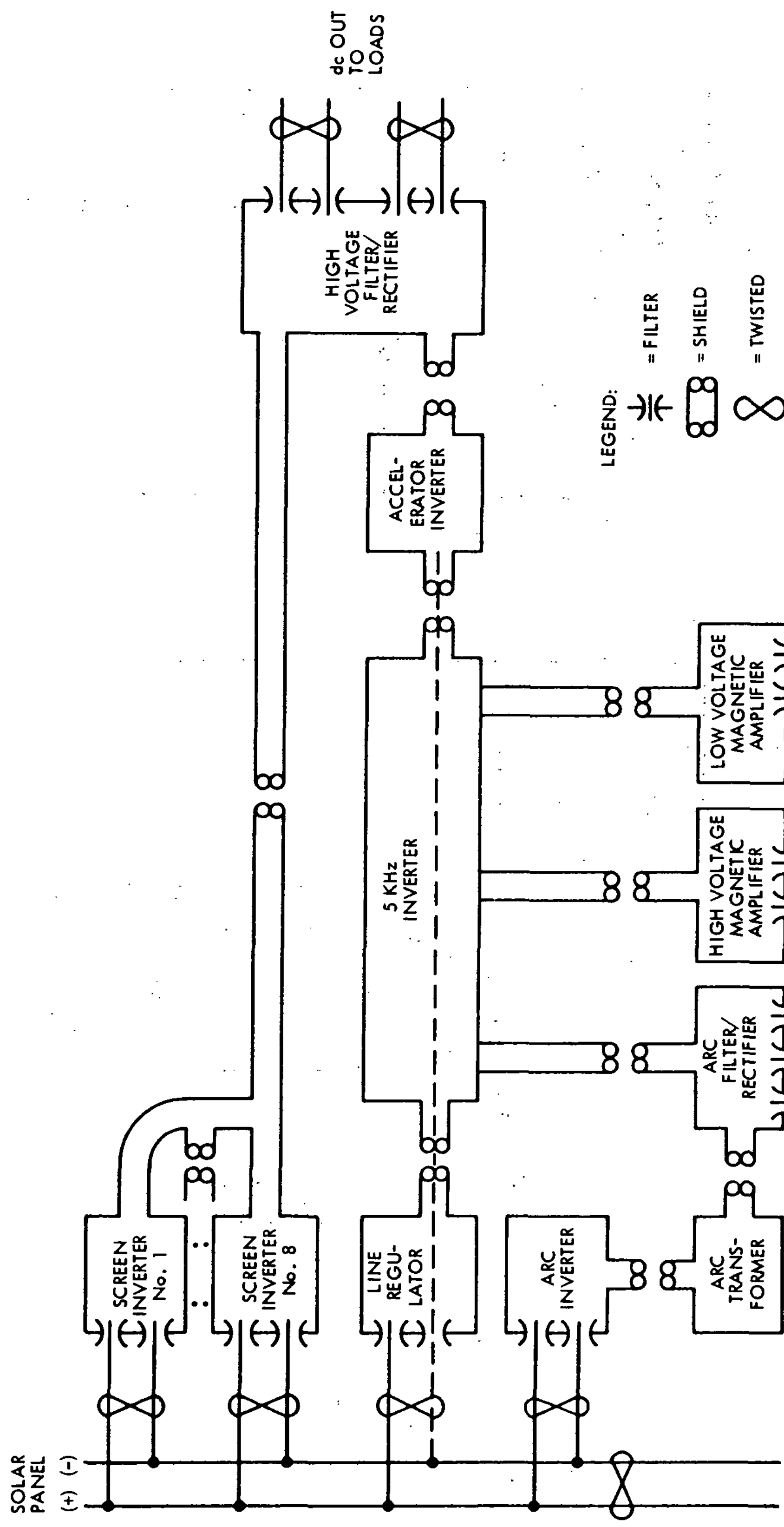

Fig. 27. Compartmentalization-type containment

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