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RHETT2/EPDM Hall Thruster Propulsion System Electromagnetic Compatibility Evaluation

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RHETT2/EPDM HALL THRUSTER PROPULSION SYSTEM ELECTROMAGNETIC COMPATIBILITY EVALUATION

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ABSTRACT

Electromagnetic compatibility measurements were obtained as part of the Electric Propulsion Demonstration Module (EPDM) flight qualification program. Tests were conducted on a Hall thruster system operating at a nominal 660W discharge power. Measurements of conducted and radiated susceptibility and emissions were obtained and referenced to MIL-STD-461C. The power processor showed some conducted susceptibility below 4kHz for the magnet current and discharge voltage. Radiated susceptibility testing yielded a null result. Conducted emissions showed slight violations of the specified limit for MIL-461C CE03. Radiated emissions exceeded the RE02 standard at low frequencies, below 300 MHz, by up to 40 dBμV/m/MHz.

INTRODUCTION

Over the past several years the Ballistic Missile Defense Organization (BMDO) through the National Aeronautics and Space Administration has sponsored the development of Hall thruster technology under the Russian Hall Electric Thruster Technology (RHETT) program. The last phase of the program (RHETT2) was to bring the technology to flight readiness. The Naval Research Laboratory (NRL) has the synergistic goal of demonstrating new space technologies with high payoff to the government. Under NRL's Electric Propulsion Demonstration Module (EPDM) program, NRL sought to demonstrate new electric propulsion systems on orbit. In 1996 the two programs were essentially combined with BMDO sponsoring the propulsion system hardware, NRL serving as the integrator, and NASA Lewis Research Center (LeRC) responsible for hardware development and qualification testing.[1]

The EPDM flight propulsion system consists of a low-power Hall thruster with cathode, a power processing unit (PPU) to operate the thruster, an analog interface unit (AIU) to operate the heaters and provide the interface between PPU and spacecraft, and a xenon propellant system. This propulsion system operates at 660 W into the discharge. The mission goal is to demonstrate multiyear operation with performance of both orbit-raising and stationkeeping functions.[1,2] The propulsion system was subjected to a battery of verification tests, including thrust measurement, vibration, magnetic dipole measurement, thruster plume/spacecraft interaction, thermal and electromagnetic compatibility (EMC).

Because of the added power electronics and presence of a plasma discharge in the majority of electric propulsion (EP) systems, electromagnetic compatibility is a significant perceived risk for potential users of this technology. Previous EMC measurements have been performed on various EP systems including arcjets, magnetoplasmadynamic thrusters, and Hall thrusters.[1,3-5] Conducted emissions and susceptibility are usually a function of the power processor design and testing typically consists simply of verifying compliance with design specifications. Radiated emissions for EP devices are usually dominated by broadband noise from the plasma discharge and often exceed common spacecraft specifications, especially in the <100 MHz frequency range. This paper summarizes the electromagnetic compatibility measurements on the EPDM flight propulsion system. Testing was conducted to insure compatibility of the propulsion system with its operational environment and self compatibility. Both conducted and radiated susceptibility measurements were obtained on the hardware along with conducted and radiated emissions measurements.

APPARATUS AND PROCEDURE

Electromagnetic compatibility testing was performed in accordance to MIL-STD-462 in order to determine compliance to MIL-STD-461C. Table I lists the conducted and radiated susceptibility and emissions tests addressed in whole or in part by this study.

Conducted susceptibility tests CS01 and CS02 were performed on the power processor by the manufacturer, Primex Aerospace Co. The EPDM system is powered by two separate lines: a primary circuit which powers the thruster functions and an auxiliary circuit for control and data handling. Both the primary power and the auxiliary power inputs were tested from 30 Hz to 100 Mhz. During testing the power supply was operated into a resistive load and the discharge voltage along with both inner and outer magnet currents were monitored. In addition, operation of the heater current at all current settings was verified.

Radiated susceptibility, RS03, was conducted at the system level at NASA LeRC. The hardware set-up inside the vacuum facility is shown in Figure 1 with all flight harnesses connected. The testing was conducted using a signal generator input to a rf power amplifier connected to a horn. The signal generator was swept from 2 GHz to 2.4 GHz while maintaining a field strength of 25 V/m at the test hardware. During these sweeps the propulsion system was operated in five different modes and monitored for any degradation. The following modes were tested: (1) through (3) cathode heater levels, no discharge; (4) Thruster operating at 660 W discharge power, and (5) Auxiliary power on, primary power off.

Conducted and radiated emission tests CE01, CE03, RE01, and RE02 were also performed at the system level at NASA LeRC. Conducted emissions were measured from 30 Hz to 50 MHz on the input power lines to the EPDM system. Radiated measurements were obtained from 14 kHz to 18 Ghz. A photograph of the test set-up is shown in Figure 1. Antennas used for the radiation emission testing were located 1 m from the hardware arranged in a semicircle behind the thruster as detailed in Figure 2. Frequency ranges for the antennas are provided in Table II. The antennas were covered with a Kapton “tent” to prevent plasma impingement. The tent and hardware were positioned in NASA LeRC Vacuum Facility 5 as shown in Figure 3. A spectrum analyzer with preselector (fronted by low noise amplifiers for 1-18 GHz) was used as the EMI test receiver. Separate broadband and narrowband sweeps were performed with the data acquisition/control software (Table II) which employed a BB/NB signal discrimination algorithm based on MIL-STD-462. This processing eliminated clearly NB signals from the BB data. Broadband levels were normalized to a 1 MHz impulse bandwidth assuming worstcase, coherent type noise; that is, with a 20log(1MHz/RBi) relation.

RESULTS

Conducted Susceptibility. The power processor showed no evidence of unacceptable susceptibility (such as shutdown or cycling) for both CS01 and CS02 on the primary and auxiliary input lines. Furthermore, no effects were observed on the monitored cathode heater currents, discharge voltage, and magnet currents for CS01 and CS02 on the auxiliary input or CS02 on the primary input. However, small effects were noted for CS01 injection on the primary input line. The results of CS01 on the primary power input are presented in Table III. Below 4kHz, a ripple corresponding to the injected frequency was present on the magnet currents and discharge voltage. For some of the CS01 testing the injection equipment could not provide full power into the PPU, so estimates of the effects at full spec levels are provided in Table III. The effect on the magnet current was a maximum of 11.2% ripple at 30 Hz decreasing to zero by 4kHz. Similarly the effect on the discharge voltage was a maximum of 4.7% at 60 Hz, decreasing to zero by 4kHz.

Radiated Susceptibility. Tests were only performed from 2 to 2.4 GHz, the frequency band of major interest to NRL for the flight application. Over this range, no effect of the radiation was observed on any of the EPDM operating parameters. Wider frequency coverage was precluded by equipment and time limitations.

Conducted Emissions. The results of CE01 from 30 Hz to 15 kHz are provided in Figure 4 for the primary power lead and in Figure 5 for the auxiliary power. Both the primary power and the auxiliary power lines were in compliance with MIL-STD-461C. Similarly, the results of CE02 from 15 kHz to 50MHz are presented in Figure 6 and Figure 7 for the primary and auxiliary power lines, respectively. The auxiliary line showed emission levels above specified limits from approximately 300 kHz to 2 MHz and from 10 to 15 MHz by up to 15 dBμA/MHz. Selected features of the spectrum were scrutinized by examination of the temporal variation of emission at the given frequency using various bandwidths. Observed pulse repetition frequencies (PRFs) of each emission feature were noted. PPU switching noise was associated with ~55 kHz PRFs (and harmonics thereof), but could also have been noted as ~27 kHz due to unequal pulse amplitudes. The primary line exceeded specification from 400 kHz to 3 Mhz by up to 25 dBμA/MHz, results similar to those obtained by the PPU manufacturer while conducting CS02 on the PPU operation into a load resistor.

Radiated Emissions. The results of the magnetic field radiated emissions, RE01, from 30 Hz to 2 MHz are provided in Figure 8. The data show little effect of the thruster on the measurement below 2 kHz. Above that range up to 2 MHz, the emission level ranges from 60 to 35 dBpT. The results of the electric field radiated emissions, RE02, from 14 Hz to 18 GHz are presented in Figure 9 for the broadband and Figure 10 for narrowband. The spectra display a high level of incoherent (random) broadband noise at low frequencies, characteristic of EP plasma devices. Indeed emissions exceeded limits below 300 MHz by up to 40 dBuV/m/MHz. This noise rolled off with increasing frequency and was replaced by coherent (impulsive) noise extending into the Ghz range. Generally, the low frequency emissions do not cause great concern as most spacecraft employ EMC measures (e.g. cable shielding) which readily inhibit interference at such frequencies. Of greater concern are the noise levels at radio/microwave communication frequencies, particularly the uplink bands. Emissions at these Ghz frequencies were typically below 40 dBμV/m/MHz.

CONCLUDING REMARKS

Flight qualification of the EPDM propulsion system included verifying system compliance to electromagnetic compatibility specifications to ensure compatibility with the spacecraft environment and self compatibility. Of major concern with electric propulsion systems is verification of proper power processor design to comply with conducted and radiated standards and radiated emissions from the plasma discharge.

MIL-STD-461C was used as the reference standard. Conducted susceptibility measurements on the power processor showed a small effect below 4kHz on the discharge voltage and magnet current. Radiated susceptibility measurements in the communication band of 2-2.4 GHz gave a null result. Conducted emissions on the primary and auxiliary power lines violated the standard by various degrees from 300 kHz 15 MHz. Radiated emissions for magnetic field were in compliance while electric field measurements were up to 40 dBuV/m/MHz above the limit below 300 MHz.

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Table I. Summary of tests conducted

CS01	Conducted susceptibility, power leads, 30 Hz to 50 kHz
CS02	Conducted susceptibility, power leads, 50 kHz to 100 MHz
RS03	Radiated susceptibility, electric field, 14 kHz to 18 GHz
CE01	Conducted emissions, power leads, 30 Hz to 15 kHz
CE03	Conducted emissions, power leads, 15 kHz to 50 MHz
RE01	Radiated emissions, magnetic field, 30 Hz to 50 kHz
RE02	Radiated emissions, electric field, 14 kHz to 18 GHz

Table II. Antenna/spectrum analyzer configurations

RADIATED MEASUREMENTS-RE02			Narrowband (NB)		Broadband (BB)	
Freq. Range (MHz)	Antenna	RL (dBµV)	RB (Hz)	VB (Hz)	RB (Hz)	VB (Hz)
0.01-0.25	PR-B1	75	300	100	3k	10k
0.25-0.5	PR-B2	75	300	100	3k	10k
0.5-1	PR-B3	75	1k	300	10k	30k
1-2	PR-B4	75	1k	300	10k	30k
2-4	PR-B5	75	1k	300	10k	30k
4-8	PR-B6	75	3k	1k	30k	100k
8-16	PR-B7	75	3k	1k	30k	100k
16-32	PR-B8	70	3k	1k	30k	100k
32-200	Biconical	70	10k	3k	100k	300k
200-350	BBD	70	30k	10k	300k	1M
350-1000	BLP	75	30k	10k	300k	1M
1000-2000	SLP with LNAs	95	100k	30k	3M	3M
2000-4000		95	100k	30k	3M	3M
4000-8000		95	100k	30k	3M	3M
8000-18000		95	100k	30k	3M	3M

RADIATED MEASUREMENTS-RE01			Narrowband (NB)		Broadband (BB)	
Freq. Range (MHz)	Antenna	RL (dBµV)	RB (Hz)	VB (Hz)	RB (Hz)	VB (Hz)
3.E-5 - 0.0005	Loop	80	10	3	N/A	N/A
0.0005-0.005		80	30	10		
0.005-0.05		80	100	30		
0.05-0.3		80	300	100		
0.3-2		80	1k	300		

CONDUCTED MEASUREMENTS-CE01			Narrowband (NB)		Broadband (BB)	
Freq. Range (MHz)	Probe	RL (dBµV)	RB (Hz)	VB (Hz)	RB (Hz)	VB (Hz)
3.E-5 - 0.0004	BCP 510	100	10	100	N/A	N/A
0.0004-0.015	BCP 510	80	30	300	N/A	N/A

CONDUCTED MEASUREMENTS-CE03			Narrowband (NB)		Broadband (BB)	
Freq. Range (MHz)	Probe	RL (dBµV)	RB (Hz)	VB (Hz)	RB (Hz)	VB (Hz)
0.015-0.15	BCP 511	75	3k	300	3k	30k
0.150-50	BCP 511	75	30k	3k	30k	300k

Abbreviations:

PR-Bx:	Passive Rod Band x	LNA:	Low Noise Amplifier
BBD:	Broadband Dipole	RL:	Spectrum Analyzer Reference Level
BCP:	Broadband Current Probe	RB:	Resolution Bandwidth
BLP:	Big Log Periodic Dipole	VB:	Video (post-detection) Bandwidth
SLP:	Small Log Periodic Dipole		

Table III. Conducted susceptibility results

Freq. Hz	Actual tested level Vrms	EST Max. spec voltage level Vrms	Voltage or PWR limited V=Voltage P=Power	EST discharge ripple V @ full Spec Inject. - Vrms (% of Nominal)	EST Magnet ripple I @ full Spec Inject. - Arms (% of Nominal)
30	2.8	2.8	V	10.6 (3.5%)	0.28 (11.2%)
40	2.8	2.8	V	10.5 (3.5%)	0.21 (8.4%)
60	4.6	2.8	V	14.1 (4.7%)	0.23 (9.2%)
80	2.8	2.8	V	12.4 (4.1%)	0.24 (9.6%)
100	2.8	2.8	V	14.1 (4.7%)	0.24 (9.6%)
200	2.8	2.8	V	12.4 (4.1%)	0.26 (10.4%)
400	1.7	2.8	V	9.3 (3.1%)	0.19 (7.6%)
500	.78	1.95	P	6.6 (2.2%)	0.13 (5.2%)
600	0.65	1.0	V	5.4 (1.8%)	0.07 (2.8%)
800	0.48	1.0	V	6.6 (2.2%)	0.06 (2.4%)
1K	1	1	V	4.6 (1.5%)	0.06 (2.6%)
2K	1	1	V	1.4 (0.5%)	0.03 (1.2%)
4K	1	1	V	0 (0%)	0 (0%)

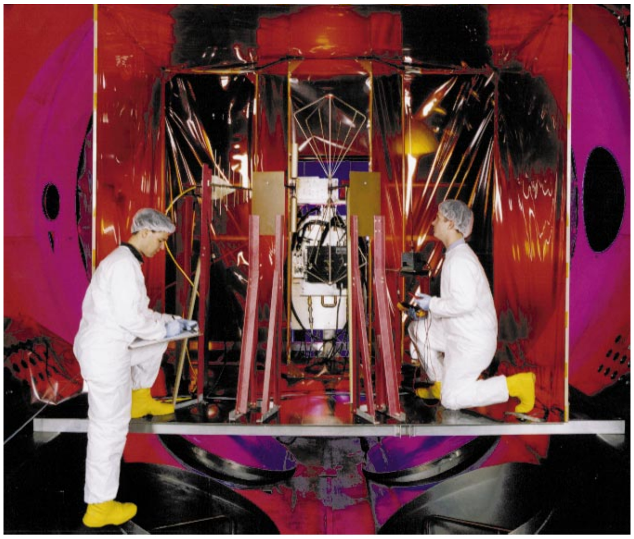

Fig. 1. EPDM flight hardware undergoing EMC testing at NASA LeRC

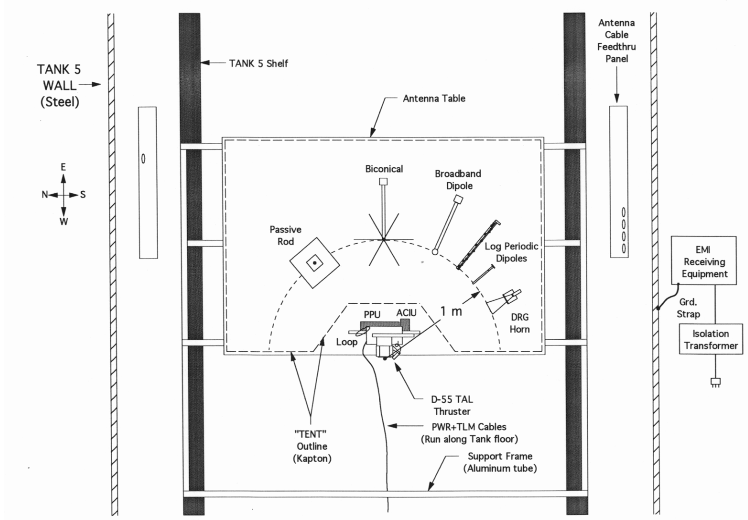

Fig. 2. Antenna placement for radiated emissions measurements

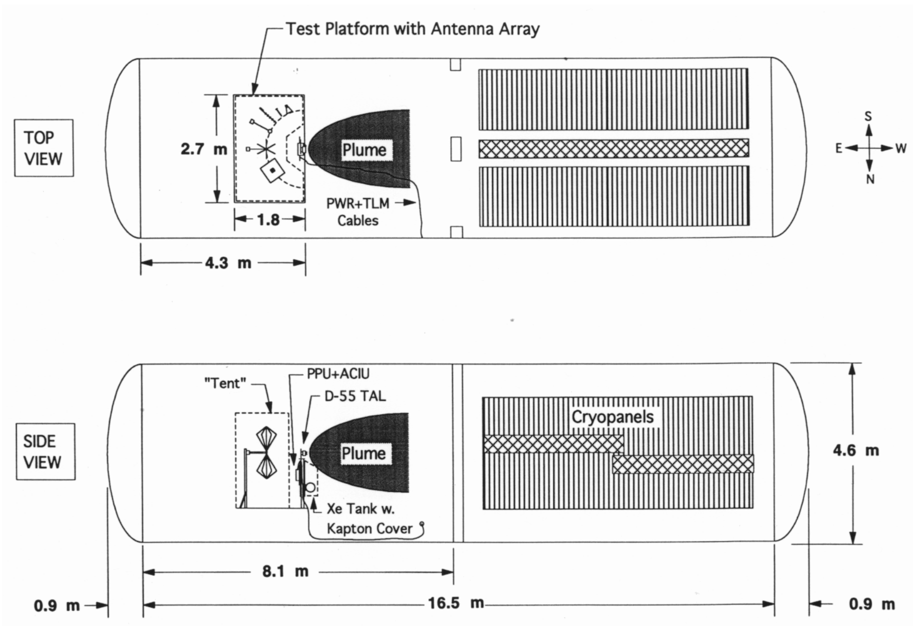

Fig. 3. EMC test pallet location in NASA LeRC Vacuum Facility 5

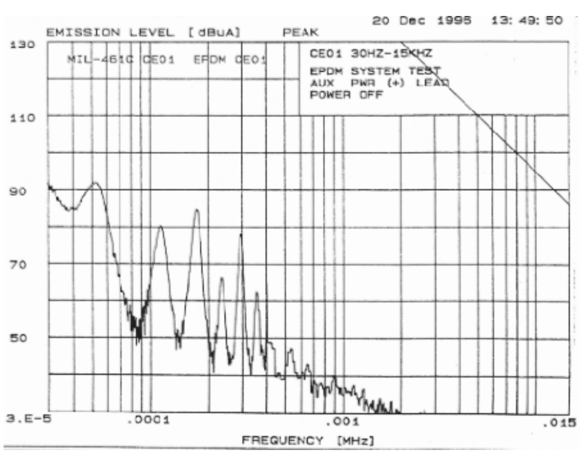

Fig. 4(a). Background

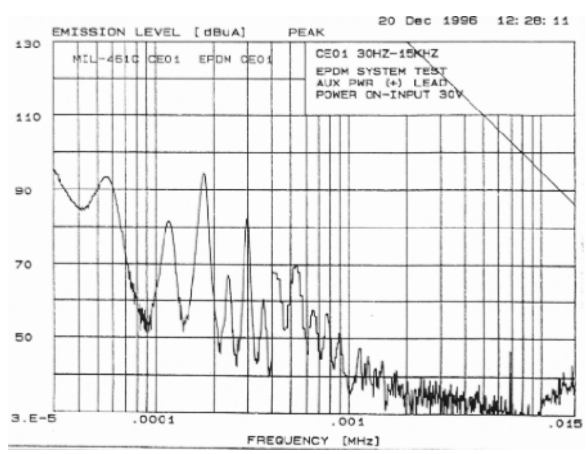

Fig. 4(b). Power on

Fig. 4. Auxiliary power line conducted emissions from 30 Hz to 15 kHz, CE01

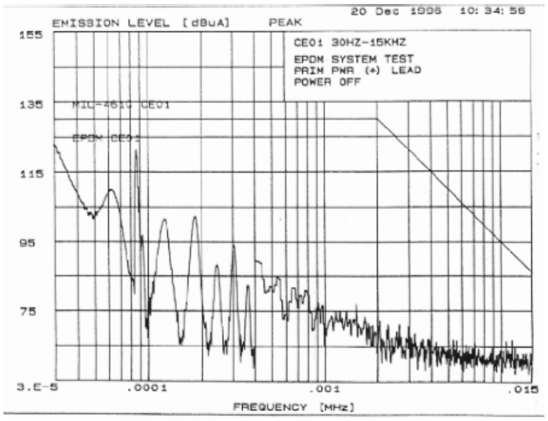

Fig. 5(a). Background

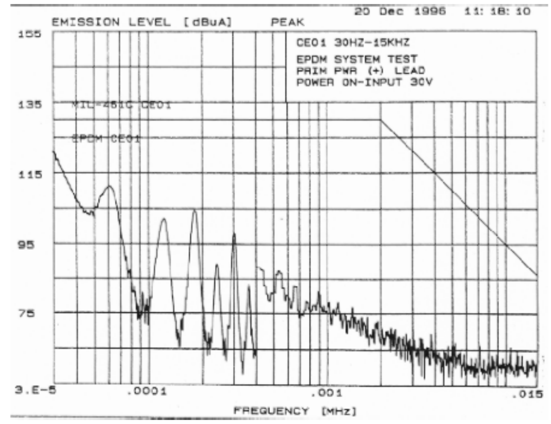

Fig. 5(b). Power on

Fig. 5. Primary power line conducted emissions from 30 Hz to 15 kHz, CE01

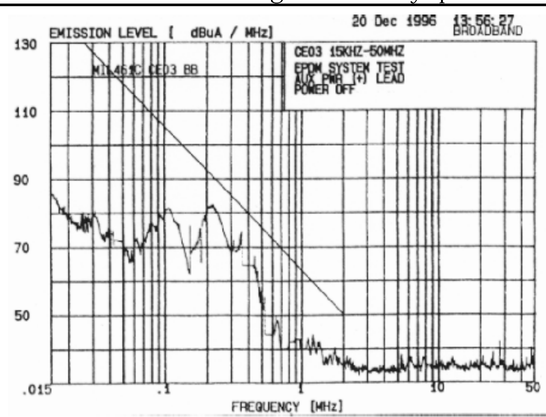

Fig. 6(a). background, broadband

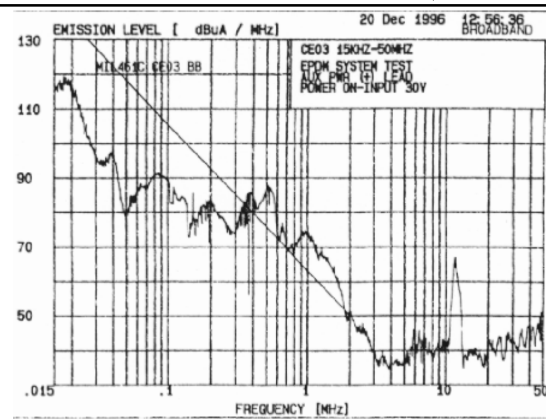

Fig. 6(b). Power on, broadband

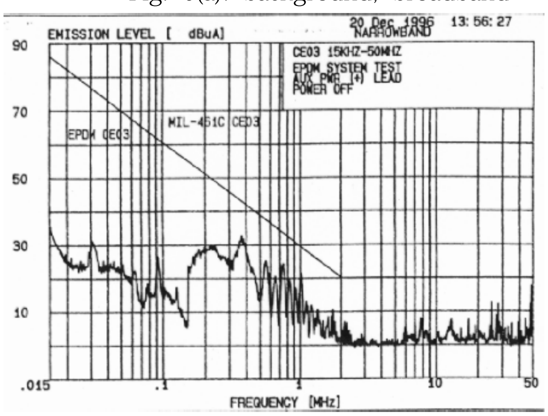

Fig. 6(c). Background, narrowband

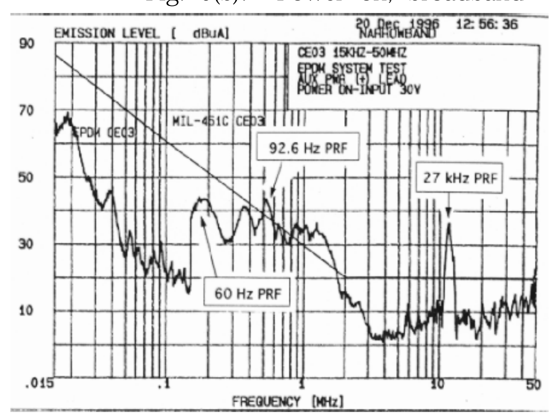

Fig. 6(d). Power on, narrowband

Fig. 6. Auxiliary power line conducted emissions from 15 kHz to 50 MHz, CE03

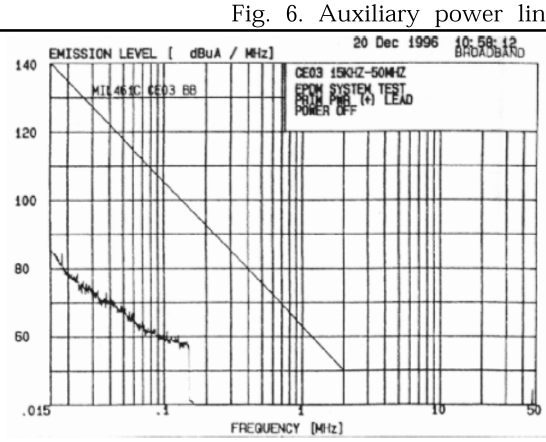

Fig. 7(a). background, broadband

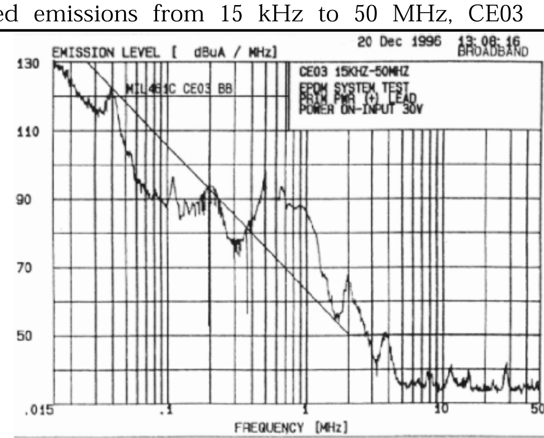

Fig. 7(b). Power on, broadband

Fig. 7. Primary power line conducted emissions from 15 kHz to 50 MHz, CE03 (cont.)

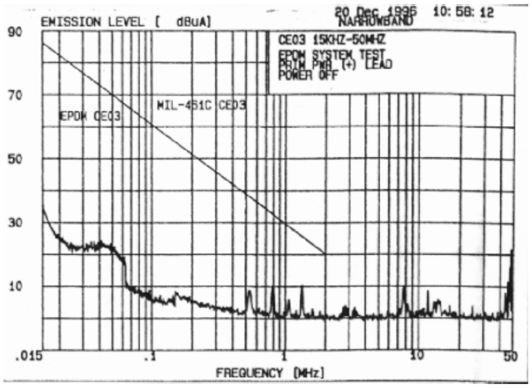

Fig. 7(c). Background, narrowband

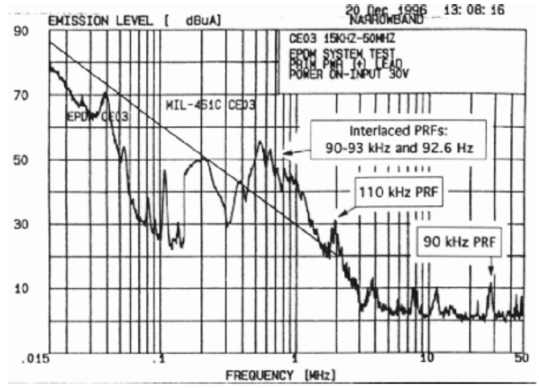

Fig. 7(d). Power on, narrowband

Fig. 7. Primary power line conducted emissions from 15 kHz to 50 MHz, CE03

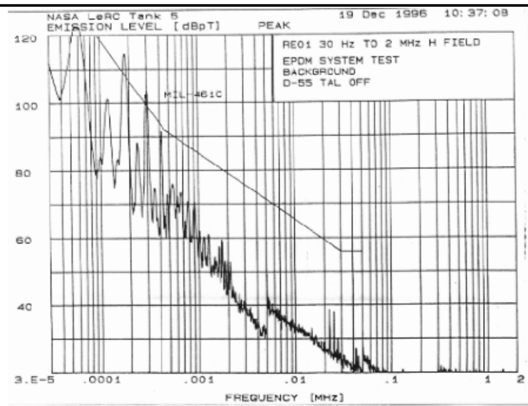

Fig. 8(a). Background

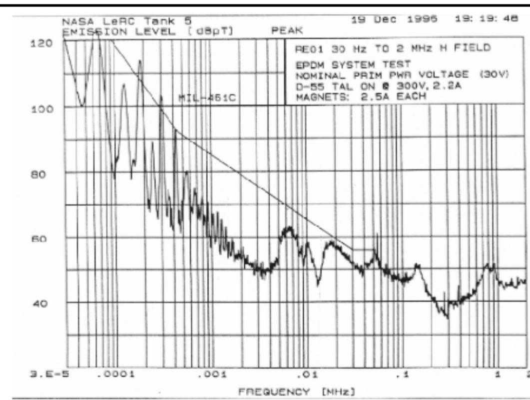

Fig. 8(b). Thruster on

Fig. 8. Radiated emissions, magnetic field, 30 Hz to 50 kHz, RE01

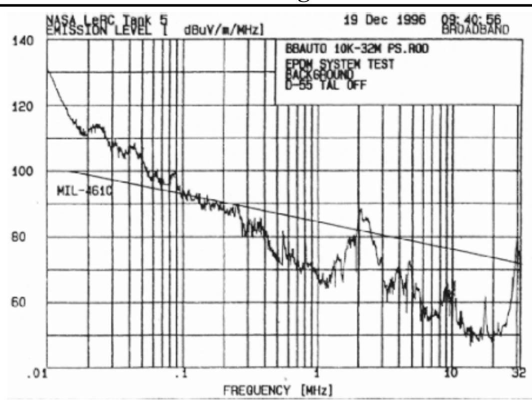

Fig. 9(a). Background, 14 KHz-32 MHz

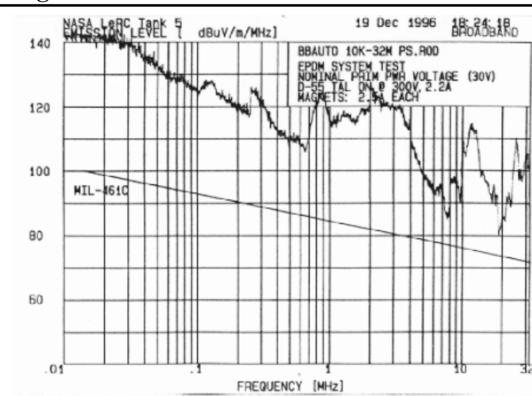

Fig. 9(b). Thruster on, 14 KHz-32 MHzz

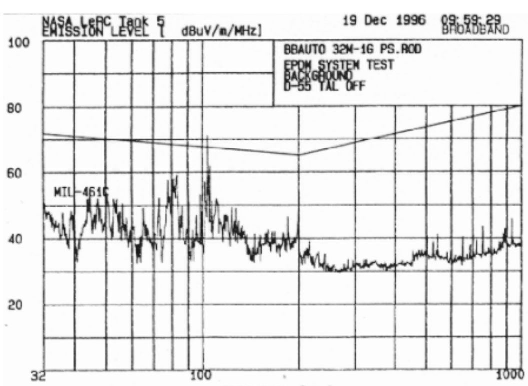

Fig. 9(c). Background, 32 MHz-1 GHz

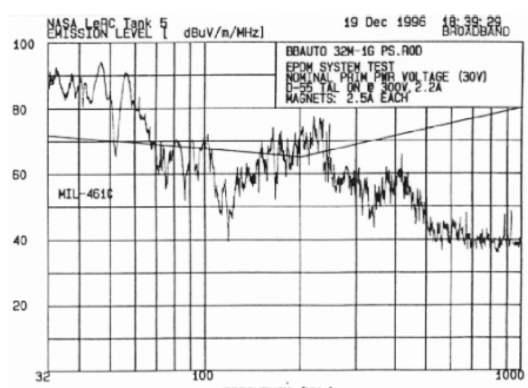

Fig. 9(d). Thruster on, 32 MHz-1 GHz

Fig. 9. Radiated emissions, electric field, broadband, RE02 (cont.)

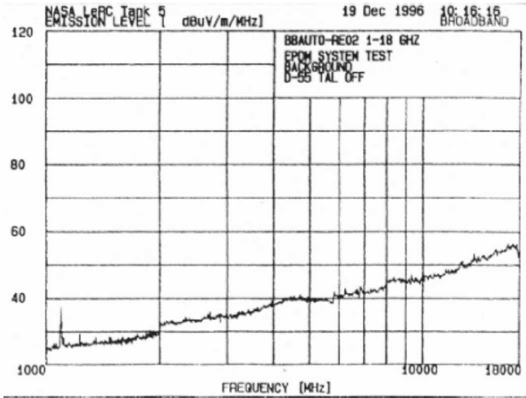

Fig. 9(e). Background, 1 GHz-18 GHz

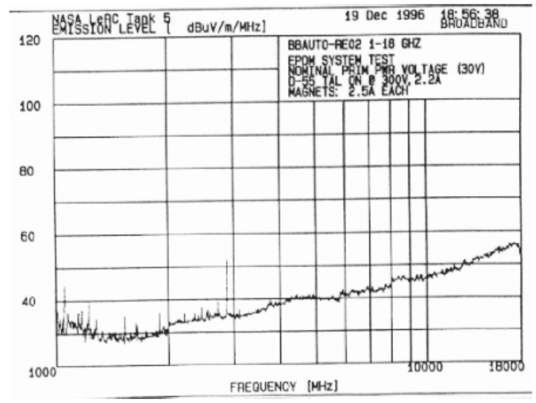

Fig. 9(f). Thruster on, 1 GHz-18 GHz

Fig. 9. Radiated emissions, electric field, broadband, RE02

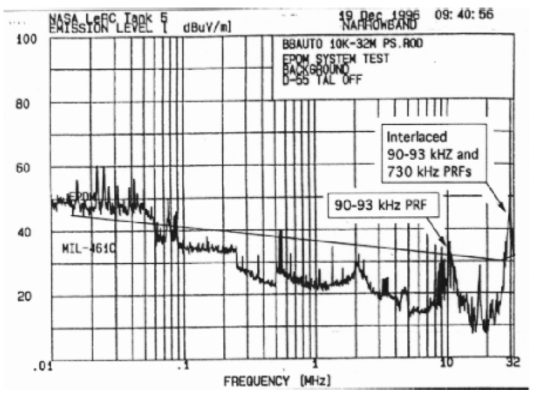

Fig. 10(a). Background, 14kHz-32 MHz

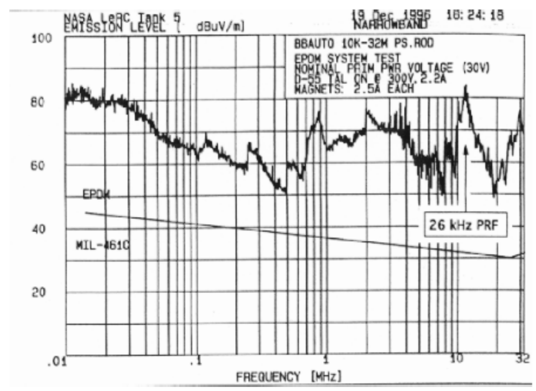

Fig. 10(b). Thruster on, 14 kHz-32 MHz

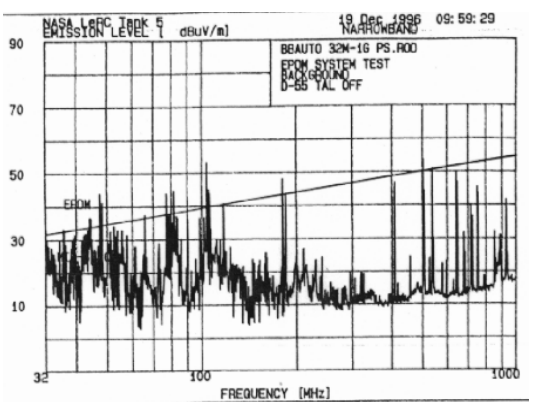

Fig. 10(c). Background, 32 MHz-1 GHz

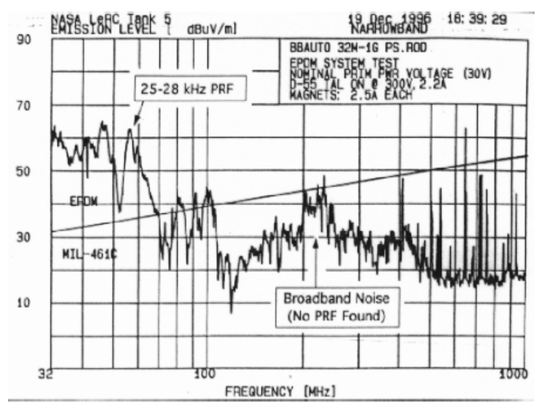

Fig. 10(d). Thruster on, 32 MHz-1 GHz

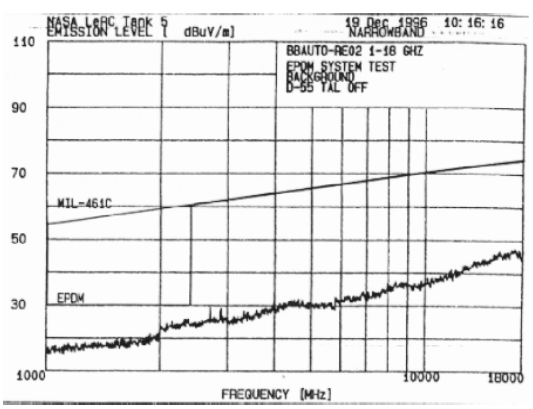

Fig. 10(e). Background, 1 GHz-18 GHz

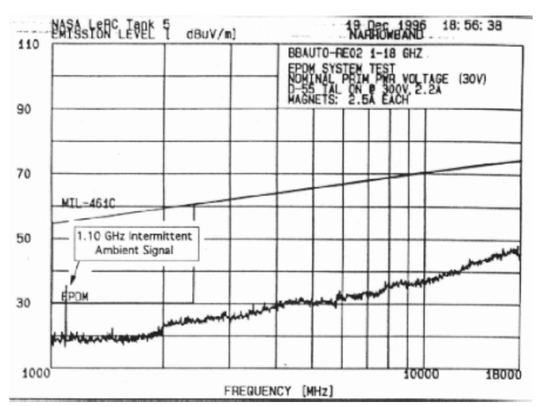

Fig. 10(f). Thruster on, 1 GHz-18 GHz

Fig. 10. Radiated emissions, electric field, narrowband, RE02.

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13. ABSTRACT ***(Maximum 200 words)***

Electromagnetic compatibility measurements were obtained as part of the Electric Propulsion Demonstration Module (EPDM) flight qualification program. Tests were conducted on a Hall thruster system operating at a nominal 660W discharge power. Measurements of conducted and radiated susceptibility and emissions were obtained and referenced to MIL-STD-461C. The power processor showed some conducted susceptibility below 4kHz for the magnet current and discharge voltage. Radiated susceptibility testing yielded a null result. Conducted emissions showed slight violations of the specified limit for MIL-461C CE03. Radiated emissions exceeded the RE02 standard at low frequencies, below 300 MHz, by up to 40 dBμV/m/MHz.

14. SUBJECT TERMS

Electromagnetic interference; EMI; Electromagnetic compatibility; EMC; Electric propulsion; Hall thrusters; Thruster with anode layer

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