Techniccal Paper
International Journal of Aerospace System Engineering
Vol.9, No.1, pp.1-15 (2022)

ISSN 2383-4986
EISSN 2508-7169
http://dx.doi.org/10.20910/IJASE.2022.9.1.1

EMC Safety Margin Verification for GEO-KOMPSAT Pyrotechnic Systems

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Abstract

Pyrotechnic initiators provide a source of pyrotechnic energy used to initiate a variety of space mechanisms. Pyrotechnic systems build in electromagnetic environment that may lead to critical or catastrophic hazards. Special precautions are need to prevent a pulse large enough to trigger the initiator from appearing in the pyrotechnic firing circuits at any but the desired time. The EMC verification shall be shown by analysis or test that the pyrotechnic systems meets the requirements of inadvertent activation. The MIL-STD-1576 and two range safeties, AFSPC and CSG, require the safety margin for electromagnetic potential hazards to pyrotechnic systems to a level at least 20 dB below the maximum no-fire power of the EED. The PC23 is equivalent to NASA standard initiator and the 1EPWH100 squib is ESA standard initiator. This paper verifies the two safety margins for electromagnetic potential hazards. The first is verified by analyzing against a RF power. The second is verified by testing against a DC current. The EMC safety margin requirement against RF power has been demonstrated through the electric field coupling analysis in differential mode with 21 dB both PC23 and 1EPWH100, and in common mode with 58 dB for PC23 and 48 dB for 1EPWH100 against the maximum no-fire power of the EED. Also, the EMC safety margin requirement against DC current has been demonstrated through the electrical isolation test for the pyrotechnic firing circuits with greater than 20 dB below the maximum no-fire current of the EED.

Key Words : Pyrotechnic, Electro Explosive Device, Electro Explosive Subsystem, Electro Magnetic Compatibility, Safety Margin

1. Introduction

The first use of the term “pyrotechnics” for explosive and propellant-actuated devices in the aerospace field was by Harry Lutz of McDonnell Aircraft Company during the Mercury program[1]. In response to a concern voiced by program management about using explosive devices in close proximity to the astronaut, Harry said, “Don’t call them explosives, call them pyrotechnics[1].” This was quickly shortened to “pyros,” which sounded even less threatening[1].

Pyrotechnics initiators are used in various ways in space, including rocket ignition, safety and recovery, launcher stages and fairing separations, launcher-payload separations, releases of solar arrays, antennas, booms, covers, inflation of systems for shielding, protection and landing, propulsion system valve operations, and mechanism off-load releases[2]. Pyrotechnics are extensively applied because of their high efficiency and despite a number of disadvantages,

Received: Jan. 06, 2022 Revised: Jun. 13, 2022 Accepted: Jun. 22, 2022
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limited engineering approaches, and some unexplained failures[1,3]. The only external energy required is an initiation input[1]. High efficiencies are high energy delivered per unit weight, small volume, compact, long term storable energy, controllable initiation and output energies, and little initiation external energy required[1,3]. Disadvantages are single shot, cannot be functionally checked before flight, impulsive loads (pyro shocks), safety issues due to contain explosive materials and inadvertent functioning[1,3]. Inadvertent functioning are only small forces sometimes required to initiate, static electricity, lightning, electromagnetically induced energy, and stray energy in firing circuits[1].

The EES(Electroexplosive Subsystem) buildup in electromagnetic environments that may lead to critical or catastrophic hazards[4]. The EMC(Electro-magnetic Compatibility) verification shall be shown by analysis or test that the EES meets the requirements of inadvertent activation[4]. The purpose of worst case electromagnetic hazard analysis is to provide an analytical method for evaluating potential RF(Radio Frequency) hazards to EED(Electroexplosive Device)s[4]. All critical and catastrophic hazard configurations must be analyzed[4]. All computations shall be formalized using an aperture parameter so that evaluation of power delivered to the EED results from a simple multiplication of the assumed electromagnetic environment and the aperture as a function of frequency[4]. The results of this calculation, the worst case power to the EED, as a function of frequency shall be compared with the RF NF(no-fire) level[4]. The results of this comparison shall be presented as a dB of safety parameter[4]. This dB of safety parameter is a function of frequency and is defined as $dB_S = 10 \log_{10} (P_{NF}/P_{EED})$ where P_{NF} is the NF level, and P_{EED} is the calculated worst case power delivered to the EED[4].

The MIL-STD-1576[4] and two range safeties, AFSPC(Air Force Space Command)[5] and CSG(Guiana Space Centre)[6], require the safety margin for electromagnetic potential hazards to spacecraft pyrotechnic systems to a level at least 20 dB below the NF power level of the EED.

This paper verifies the two safety margins for electromagnetic potential hazards to the GK(GEO-KOMPSAT) pyrotechnic systems. The first is verified by analyzing in the section 5.1 against a RF power. The second is verified by testing in the section 5.2 against a DC(Direct current) current.

2. Pyrotechnic EMC Safety Requirements

2.1. MIL-STD-1576 Requirements

Inadvertent activation: The EES shall be designed to limit the power produced at each EED by the electromagnetic environment acting on the subsystem to a level at least 20 dB below the maximum PP(pin-to-pin) DC NF power of the EED[4]. Electrical isolation: Firing circuits that do not share a common fire command shall electrically isolated from one another such that current in one firing circuit does not induce a current greater than 20 dB below the NF current level in any firing output circuit[4]. NF sensitivity: Unless otherwise specified EEDs shall be designed to withstand a constant DC firing pulse of up to 1 A and 1 W power (minimum) for a period of 5 minutes (minimum) duration without initiation or deterioration of performance (dudding)[4]. EMC verification: It shall be shown by analysis or test that the EES meets the requirements of inadvertent activation[4]. The radiated and conducted electromagnetic environment will produce a peak AC(Alternating Current) power level at the EED and this level must be compared to the maximum DC NF power level of the EED, which is determined from the square of the DC NF current times the nominal bridgewire resistance[4]. Electromagnetic environment: In lieu of knowledge of the actual environment to be experienced by a particular EES, an electromagnetic environment of 2 W/m^2, from 1 MHz to 50 MHz, and 100 W/m^2 from 50 MHz to 32 GHz, shall be assumed[4].

2.2. AFSPC Range Safety Requirements

The system circuitry shall be designed and/or located to limit RF power at each EED (produced by range and/or vehicle transmitter) to a level at least 20 dB below the PP DC NF power of the EED[5]. EEDs shall be designed to withstand a constant DC firing pulse of 1 A and 1 W power for a period of 5 minutes without initiation or deterioration of performance[5]. RF survivability shall meet the testing criteria described in MIL-STD-1576[5].

2.3. CSG Range Safety Requirements

Electroexplosive initiators shall provide a level of safety at least equivalent to initiators of the type 1 A, 1 W, 5 minutes NF[6]. Sensitivity to radiated electromagnetic fields: The electrical circuits of pyrotechnic systems shall be designed so as to limit the current induced on the ignition circuit to at least 20 dB below the maximum NF current, when they are exposed to an electromagnetic field of a power density equal to 2 W/m^2 from 50 kHz to 50 MHz, and 100 W/m^2 from 50 MHz to 18 GHz[6]. Electrical equipment (control, measurement, firing) connected to the electric pyrotechnic devices shall be designed so as to limit the current induced on the ignition circuit to at least 20 dB below the maximum NF current[6].

2.4. EMC Safety Requirements Summary

Pyrotechnic EMC requirements and safety margin verification are summarized to cover MIL-STD-1576[4], and two range safeties of AFSPC[5] and CSG[6]:

- NF sensitivity: DC current of 1 A and RF power of 1 W for a period of 5 minutes duration.
- Electromagnetic environment: 2 W/m^2, which corresponds to an E(electric)-field amplitude of $\sqrt{377 \times 2}$ = 27.5 V/m, from 50 kHz to 50 MHz, and 100 W/m^2, which corresponds to an E-field amplitude of $\sqrt{377 \times 100}$ = 195 V/m, from 50 MHz to 32 GHz.
- Safety margin verification: >20 dB below the maximum NF current by analysis or test.

2.5. System Level Verification

ECSS-E-HB-20-07A[7] describes at system level verification for pyrotechnic subsystem:

- Compatibility of pyro circuits with launcher and launch pad RF environment by analysis: ECSS-E-ST-33-11C[8] requires that, when exposed to RF conditions, the induced power does not exceed 20 dB below the no-fire power and 20 dB below the RF sensitivity threshold[7,8]. The compatibility of the initiator to the environment is specified to be demonstrated by a system analysis[7]. The initiators control harness features a STP(twisted shielded pair)[7]. The coupling of the E-field to the bridgewire occurs through the harness shielding, by the transfer impedance phenomenon[7]. The E-field induces DM(Differential Mode) current in the bridgewire, and CM(Common Mode) voltage between the bridgewire and the structure of the initiator[7].
- Safety margins demonstration by test: It is important to note that demonstrating by test that the current induced in the pyrotechnic initiators is always 20 dB below the NF current[7]. For initiators having a NF current of 1 A, 20 dB below means 100 mA or 100 dBμA, which can be demonstrated by design to be impossible (because of all the safety barriers)[7]. An EGSE(Electrical Ground Support Equipment) is detecting any occurrence of a current reaching the NF current minus 20 dB[7].

3. EED Characteristics and Application to Pyro Valve

3.1. EED Characteristics

The Hi-Shear's (new name of Chemring Energetic Devices) PC23[9] initiator and cross sectional view[10] is depicted in Fig. 1. The PC23 is the commercial equivalent to NSI(NASA Standard Initiator) for non-NASA customers (cf. NSI is only available through NASA)[11]. The initiator is a two pins electrically activated, hot-wire, EED which provides a source of pyrotechnic energy used to initiate a variety of space mechanisms for use on both satellite and launch vehicle applications[10]. Mechanisms include pyrotechnic valves, separation nuts/bolts, cable/bolt cutters, pin pullers and many others[10]. The initiator consists of a glass to metal sealed header (with receptacle), a bridgewire welded across the header pins, energetic ignition mix (ZPP; zirconium potassium perchlorate typical) consolidated onto the bridgewire, and a welded closure output[10]. When an electrical stimulus is applied to the header pins the current heats the thin bridgewire which in turn heats the consolidated ignition mix[10]. Once the ignition mix reaches its auto-ignition temperature the energetics undergo a self-sustaining reaction which produces heat, gas, and hot particles[10]. These thermal outputs are used to ignite secondary energetics in an energetic train/cartridge or can be used perform work in a device without any additional booster[10].

Squib upon its ignition provides a quantity of gas[12]. Squibs are often utilized for a source of gases for uses such as the actuation of mechanical devices[12]. The passage of an electric current through the bridge wire igniting the first charge, which in turn ignites the second charge, which in turn ruptures the closure plate and thereby supplies gas at the second opening[12]. The first charge, wherein the initiator is more sensitive to current, and provides a hot flame for igniting the sustainer portion, a first charge is provided which is quite certain to be ignited by a current through the bridge wire[12].

The Dassault's ESI(ESA Standard Initiator) 1EPWH100[13,14] squib and cross sectional view[15] is depicted in Fig. 2. Dassault's initiator family consist of ignitors, squibs and detonators[14]. They all use MIRA(RApide Inflammation Mix) powder as initiating powder. Squibs use GBSe(Nitroglycerin crushed Nitrocellulose Spherical) as booster charge[14]. Two powders, MIRA and GBSe, are parts of 1EPWH100[13]. Two main customers are satellites for squibs and launchers for igniters and detonators[14]. The common core and composition are identical in the Dassault's initiator family and an additional charge is for the corresponding applications[15]. The 1EPWH100 is longer than the NSI but presents the same screwed interface[16]. A MIRA ignition composition to initiate powder is placed in contact with the filament[17]. The pyrotechnic composition is charged in an antistatic case to protect against ESD(Electrostatic Discharge)[17]. During the passage of the current, the filament heats by the joule effect and ignites the ignition composition, thereby achieving the combustion[17]. A squib consists of an igniter with a propellant composition of GBSe powder which is an additional charge using to be the energy of pyro mechanism[17]. During the initiation of the igniter, the propellant composition performs a combustion-deflagration transition in contact with the flame, leading to the production of gas, and therefore pressure[17].

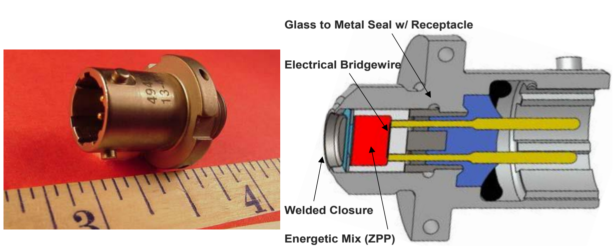

Fig. 1 PC23[9] and cross sectional view[10]

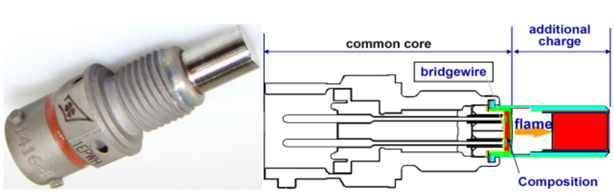

Fig. 2 1EPWH100[13,14] and cross sectional view[15]

The principle pyrotechnic load is 114 mg ZPP powder for PC23[9] and 40 mg MIRA plus 100 mg GBSe powders for 1EPWH100[13,14,16,18]. Total mass of active material, ignition composition plus additional charge, depends on the type of squib[18]. The characteristics of the PC23 and 1EPWH100 are shown in Table 1. Reliability and almost characteristics both PC23 and 1EPWH100 are equivalent. For both PC23 and 1EPWH100, the NF current is 1 A/1 W for a period of 5 minutes and the bridgewire resistance is 1.05 Ω[9,16,19,20]. The insulation resistance is minimum 1 GΩ[9] for PC23 and 100 MΩ[16,19,20] for 1EPWH100.

3.2. PC23 RF Sensitivity

The PC23 uses ZPP as its propellant[21]. This propellant is extremely sensitive to energy input; only milliwatts are required to ignite the mix[21]. The energy can come from any number of sources[21].

ESD and stray currents from external E-fields are two of main concerns[21]. To contend with this, the designer and user must pay close attention to basis electric practices: minimize antennae effects (voltage differences between conductors) by the use of STP; and maintain good RF shielding throughout the circuit (e.g., multiple shield grounding, no opening in shields and RF type shield termination)[21]. Shields should be grounded to vehicle structure through the initiator connector and body[21]. The firing circuit EMC margins are as follows[21]:

a. The circuitry that carries the firing current from the firing sources to the PC23 shall limit the power produced at each PC23 by the electromagnetic environment acting on the circuit to a level at least 20 dB below the maximum PP DC NF power of the PC23[21].
b. The circuitry shall be designed to limit the power produced at least device in the firing circuit that can complete any portion of the firing circuit to a level at least 6 dB below the minimum activation power for each of the safety devices[21]. Bonding of the pyrotechnic circuit elements should be in accordance with 2.5 mΩ requirements of AIAA S-113-2005 paragraph 5.1.15.a[21]. For reference a summary of all RFI(Radio Frequency Interference) tests conducted on the PC23 to date are tabulated in Table 2[21]. The values listed are the "conservative" values from all the tests run[21]. They represent the most sensitive initiator because the power was directly injected into the initiator without any attenuation losses[21].

The results of all RFI tests conducted to date, both PP and PC(pin-to-case) show the PC23 to be most sensitive at 9 GHz pulsed power[21]. A Bruceton test conducted at this frequency, in Table 3, determined the energy needed to fire the PC23[21]. Both the 1967 data and the 1983 data (NASA Reports: F-B2303-9 and F-C5867-2) for 9 GHz firings of PC23's, show long functioning times, often a minute or more[21]. This indicates that the 9 GHz firing mechanism is by "cookoff" or small circulating electric current resonating through the bridge wire[21].

Table 1 PC23[9] and 1EPWH100[16,19,20] characteristics

Characteristics	PC23	1EPWH100
All-fire current	3.5 A at +77 °F	3.5 A/40 ms at 20 °C, 5.0 A/10 ms (-90; +100 °C)
Reliability, confidence level	<0.999, 95%	<0.999, 95% for satellite
Nominal firing current	>5 A/4 ms	>5 A/10 ms or >4.1 A/15 ms
No-fire current	**1 A/1 W – 5 min** (-165; +165 °F)	**1 A/1 W – 5 min** (-90; +100 °C)
Safe no-fire current for testing	<10 mA	<10 mA
Functioning time	<2 ms (I=5 A)	<5 ms
Hermeticity	$<10^{-6}$ atm.cm^3/s	$<10^{-6}$ atm.cm^3/s
Nominal peak pressure, 10 cc	650±125 psi	No available data
Bridgewire resistance	**1.05±0.1 Ω**	**1.05±0.15 Ω**
Insulation resistance	**>1000 MΩ**/250 V_{DC}	**>100 MΩ**/500 V_{DC}
Static sensitivity (all leads shorted to case, between leads)	25 kV/500 pF/ 5000 Ω	25 kV/500 pF/5000 Ω

Table 2 PC23 RF test summary[21]

Frequency	Power Mode*	Device Mode**	Mean Energy to Fire
10 MHz	CW	PP	Between 0.45 and 0.50 W
243 MHz	CW	PP	Between 9 and 10 W
950 MHz	CW	PP	Between 6 and 7 W
2.7 GHz	Pulsed	PP	Between 0.2 and 0.3 W
9.0 GHz	**Pulsed**	**PP**	**Approximately 0.12 W**
9.9 GHz	Pulsed	PP	Approximately 0.45 W
13.835 GHz	CW	PP	Greater than 20 W
15.003 GHz	CW	PP	Greater than 10 W
16.0 GHz	Pulsed	PP	Between 0.35 and 0.75 W
33.2 GHz	Pulsed	PP	Greater than 5 W
1.5 MHz	CW	PC	Greater than 5.0 W
10 MHz	CW	PC	Approx. 0.75 to 1.0 W
243 MHz	CW	PC	Approx. 0.50 W
950 MHz	CW	PC	Between 2 and 2.25 W
2.7 GHz	Pulsed	PC	Approximately 0.20 W
9.0 GHz	**Pulsed**	**PC**	**Between 0.085 and 0.09 W**
9.9 GHz	Pulsed	PC	Between 0.2 and 1 W
13.835 GHz	CW	PC	Greater than 20 W
15.003 GHz	CW	PC	Greater than 15 W
16.0 GHz	Pulsed	PC	Between 0.35 and 2.5 W
33.2 GHz	Pulsed	PC	Greater than 5 W

*CW: Continuous Wave, **PP: Pin-to-Pin, PC: Pin-to-Case.

Table 3 Bruceton test summary @ 9 GHz[21]

	GHz Pulsed	9.0	9.0
	Mode	PP	PC
	Std Dev	0.094	0.160
	No. Fired	21	21
	No. Non-Fired	21	21
PC23 Firing Probability (milliwatts)	0.1% *	35.3	11.0
	50%	107.4	86.9
	99.9%	326.7	686.4
Functioning Times (seconds)	Low	0.07	8.71
	Avg	65.8	96.8
	High	266	281

*Predicted no-fire level with 95% confidence.

3.3. 1EPWH100 Squib Application to Pyro Valve

The GK used PV(Pyrovalve)s on spacecraft propulsion systems. The function of PV is to definitely shut down or open a fluid circuit[16,22,23]. Reliability is a primary performance for satellite PVs as it is considered as a single point failure for the satellite mission[19]. The PVs in exploded view[22] for NO(Normally Opened) and NC(Normally Closed) is depicted in Fig. 3. A NO and a NC PVs before and after actuation are depicted respectively in Fig. 4 and Fig. 5[23]. Actually one squib is sufficient for actuating PV[16]. Each valve consists of two 1EPWH100 squibs located in the upper body, connected in parallel, providing firing redundancy[22]. The energy needed for actuation is supplied by a redundant pyrotechnic system and transmitted by the deformation of a patented titanium thin flexible membrane[16,23]. In the PV case, the actuator is the flexible membrane[16] and the energy supplied to the punch (mobile part) by the membrane[16]. In both PV types, a punch shears weakened sections to open or close the fluid circuit[23].

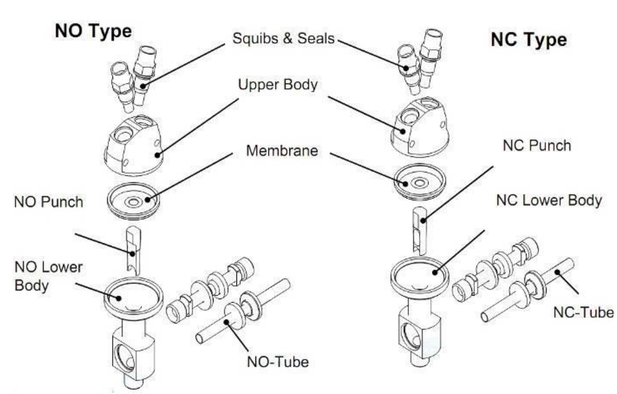

Fig. 3 Pyrovalves in exploded view for normally opened (left) and normally closed (right)[22]

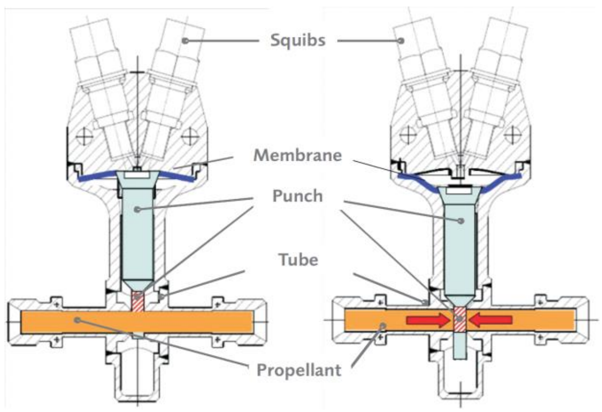

Fig. 4 A normally opened pyrovalve before (left) and after (right) actuation[23]

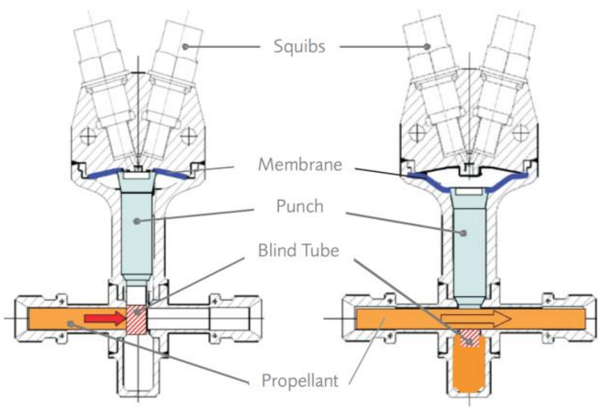

Fig. 5 A normally closed pyrovalve before (left) and after (right) actuation[23]

4. GEO-KOMPSAT EES Description

4.1. Pyrotechnic Firing Circuits

The fundamental requirement of the pyrotechnically energized function is that it must occur reliably when correct commanded at correct time and must not occur under any other circumstances[24]. To supply the initial energy step, a chain of items is needed to condition and command the electrical pulse for application to the initiator bridgewire[24]. The catastrophic train of events that could result from accidental firing of the pyrotechnic means that much more severe safety requirements apply for this than for any other branch of the power distribution subsystem[24]. Special precautions are needed to prevent a pulse large enough to trigger the initiator from appearing in the circuit at any but the desired time[24]. Switches are required to isolate the initiator until firing is imminent, and afterwards to prevent a drain on the power supply system due to a short circuit to ground potential, which frequently occurs in initiators[24]. This usually means three inhibiting stages in series, which require three failures before any unsafe condition is produced[24].

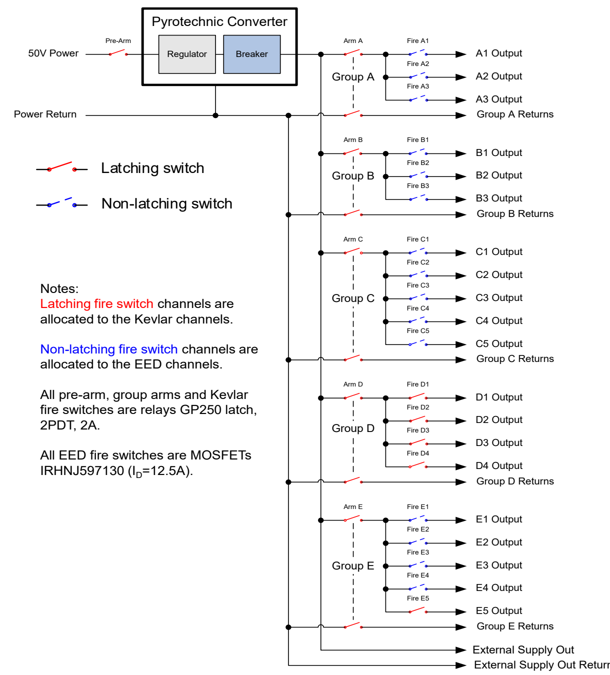

Fig. 6 Command chains of pyrotechnic firing circuits

Figure 6 is the command chains of the GK pyrotechnic firing circuits shown only primary side. The redundant circuits are implemented to separated board. Each pyrotechnic board includes a reliable pyrotechnic converter and a switch network. The pyrotechnic firing circuit includes the functions of command and management. The architecture of switch network is based on group allocation and four serial safety barriers (a pre-arm, group arm and fire switches, and a pyrotechnic converter). Each group arm switching relay isolates entirely the pyrotechnic output from other group channels and system ground. The EED channels are dedicated to standard pyrotechnic devices. The Kevlar channels are dedicated to Kevlar cutters or more generally to heating devices for release mechanism. The GK pyrotechnic firing circuits provide redundant control power for firing actuators (the solar array release devices, the PVs and the battery bypass devices) and solar array motors to control deployment speed and prevent from unwanted switching of actuators. The PVs and the battery bypass devices are actuated by the EED mode channels. The solar array release devices and motors are actuated by the Kevlar mode channels. The battery bypass devices are extended through the external supply output.

A reliable pyrotechnic converter consists of a regulator and a breaker as shown in Fig. 7. The current limit amplifier and the voltage sensing error amplifier in regulator are tied at the PWM(Pulse Width Modulation) comparator input with a priority for current detection. On fire command, the pyrotechnic converter provides a window output pulse by the "synchronization & window" circuit in Fig. 7. The circuit insures the pyrotechnic output current that fire switches will only carry the current but never switch it. It means that upon fire command to EED channels, the pyrotechnic converter supplies power to the initiator only after a delay and stops the power before the end of the command. The pyrotechnic converter controls the voltage and current levels seen by switches whatever failures. The breaker operates by the "synchronization & window" output and protects output overcurrent and overvoltage.

Pyrotechnic converter operates two modes, EED and Kevlar, implemented in hardware and can't be changed between two modes. The pyrotechnic firing waveforms in EED and Kevlar modes are shown in Fig. 8. In EED mode, the converter operates during a fixed duration with regard to the fire switch ON time. Fire command activates the corresponding fire MOSFET and the synchronization circuit which activates pyrotechnic converter with a window output pulse of typical 35 ms. In Kevlar mode, the converter operates continuously since the synchronizing circuit output is permanently forced at high level. The right sequence of commands and switching is determined by the flight software. The pre-arm, group arm and fire relays are ON before pyrotechnic converter ON (Kevlar MODE ON command in Fig. 8) and pyrotechnic converter is OFF (Kevlar MODE OFF command in Fig. 8) before the pre-arm, group arm and fire relays OFF.

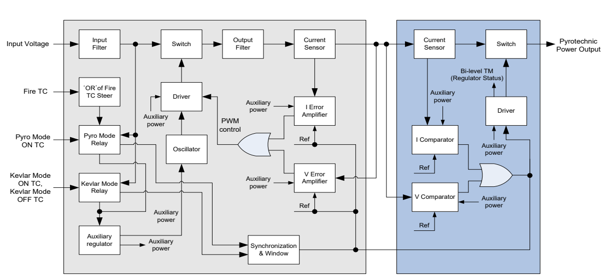

Fig. 7 Block diagram of pyrotechnic converter consists of a regulator and a breaker

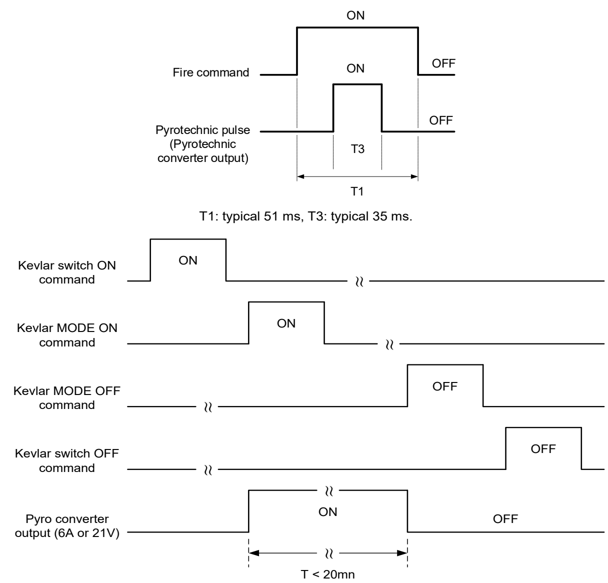

Fig. 8 Pyrotechnic firing waveforms in EED mode (top) and Kevlar mode (bottom)

Table 4 Output characteristics of pyrotechnic converter

Current limit	6 A ±1 A
Voltage regulation	21 V ±1 V
Pulse duration	EED channel: fixed to 35 ms ±3 ms. Kevlar channel: adjustable through 100 ms steps.
Priority (current limit vs. voltage regulation)	Current limit
Creation of pyrotechnic pulses	With an internal and external On/Off synchronization
Overcurrent protection	Set to 7.5 A nominal
Overvoltage protection	Set to 27.5 V nominal

Table 4 shows output characteristics of pyrotechnic converter. The pyrotechnic converter automatically operates a current limit of 6 A or a voltage regulation of 21 V with priority of current limit. Output pulse duration is fixed to 35 ms by hardware for the EED channel, and can be adjustable through 100 ms steps from external commands for the Kevlar channel. The pyrotechnic converter protects nominal output overcurrent of 7.5 A and overvoltage of 27.5 V.

4.2. EES Harness and Shield Termination

Electrical screening of the pyrotechnic electronics and of the wiring, which must be in STP, has to be provided to prevent electromagnetic radiation from generating currents in the circuit[24]. The firing circuit including the EED is completely shielded from the EED back to a point in the firing circuit to eliminate RF entry into the shielded portion of the system. The wiring uses the shielded jacketed twisted pairs with 22 AWG(American Wire Gauge) (Axon reference ESCC 3901 002 48[25]). The wires have been routed very close from spacecraft structure to minimize radiated coupling. The cable shielding in the ESCC-3901/002 specification provide a minimum of 92% of optical coverage[26]. The shields will bring an efficient screening effect. With the exception of cable shielding, there are no gaps or discontinuities in the shielding, including the termination at the back faces of the connectors, nor apertures in any container which houses elements of the firing circuit. Shields are terminated to each connector body using the potting with conductive material and provide 360° continuous shield continuity without gaps. This shield termination provides greater than 20 dB attenuation at all frequencies of the expected electromagnetic environment. Shields are not be used as intentional current-carrying conductors. Shields are grounded to structure at multiple-point. Pyrotechnic harnesses are separated other bundles such as power, command and telemetry and RF cables.

5. Pyrotechnic EMC Safety Margin Verification

5.1. EMC Safety Margin Analysis against a RF Power

The NEA(non-explosive actuator)s are not effected by EMI(Electro Magnetic Interference) and ESD [27]. They are safe because explosives are not present, do not require the special handling needed with pyrotechnic devices, and actuation causes no debris or pollutants[27]. Initiation of these NEAs is not susceptible to ESD and EMI effects and does not require special shielding[27]. They are not EMC sensitive without any phlegmatization risk and may be excluded from the hazard class “Explosives”. Therefore, this paper is only focused on the explosive actuators such as the NSI equivalent PC23 and the ESI 1EPWH100 squib. Two pins of explosive initiator connector may act as antenna to RF energy[28]. The initiator can be initiated either of static electricity and RF radiation forms of energy if a high enough level exists[28].

The objective of radiated mode coupling analysis is to assess the safety margin in DM and CM considering the E-field coupling. In CM, the assessment considers the coupling at surface, created by the harness and the structure plane, and the coupling at connector level. In DM, the assessment considers the coupling created by the harness loop and the coupling at connector level. Fig. 9 shows block diagram of pyrotechnic EMC safety margin analysis for RF power. A 20 dB safety margin must be then demonstrated between NF power, in DM and CM currents, and the sum of all these contributions by E-field coupling. The radiated mode coupling analysis assumes a conservative approach by not considering in a first step the influence of the shield and by assessing with above the structure plane at a different height and length.

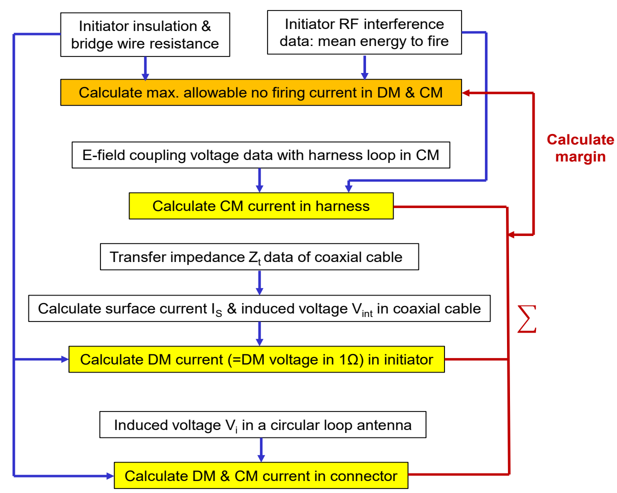

Fig. 9 Block diagram of pyrotechnic EMC safety margin analysis of RF power

For PC23, the RFI test results in Table 2 presents the sensitive level (mean energy to fire): 0.12 W[21], which corresponds to $\sqrt{0.12}$ = 350 mA in 1 Ω, at 9 GHz for the PP and 0.085 W[21], which corresponds to $\sqrt{0.085/10^9}$ = 9.2 μA in 1 GΩ and $\sqrt{0.085/10^8}$ = 29 μA in 100 MΩ, at 9 GHz for the PC. Unfortunately, the RFI sensitivity for 1EPWH100 squib is not available. Therefore, we take the same hypothesis as PC23.

5.1.1. E-field to Cable Coupling on Pyrotechnic Harness

E-field Coupling in CM:

The objective of E-field coupling in CM is to assess the CM current between PC created by the E-field coupling. Fig. 10 shows E-field coupling model with harness in CM. The CM coupling converts an ambient electric or magnetic field to a CM voltage into the loop area, A = length x height = l x h. A CM voltage, V_{CM}, is generated by coupling created by the harness and the structure plane. This voltage, V_{CM}, acts as a potential EMI source to push CM current around the loop area. The insulation resistance is 1 GΩ for PC23 and 100 MΩ for 1EPWH100. The E-field coupling voltage with harness loop in CM(i.e. field-to-cable CM coupling into box-cable-box ground loop area)[29] is shown in Fig. 11. For frequencies lower than λ/2, where λ = wavelength in meters, field-to-cable CM coupling increase with frequency at a rate of 20 dB/decade[29]. This increase continues until the half-wave length resonance l = λ/2 is reached[29]. Above this, the length l exhibits multiple resonances[29]. Adjacent half-wave length sections tend to cancel each other and leave only one λ/2 segment to become the effective pickup antenna[29]. Therefore, l is replaced by λ/2[29]. The cable is acting like an unintentional pickup antenna[29]. Field CM coupling converts an E-field strength into an open-circuit voltage, V_{CM}, as Eq. 1[29]:

$$CM\ coupling = 20\log\left(V_{CM}/_E\right)$$
$$V_{CM} = 10^{\left(CM\ coupling/_{20}\right)} \times E \tag{1}$$

where V_{CM} = induced loop voltage (V), E = incident field (V/m).

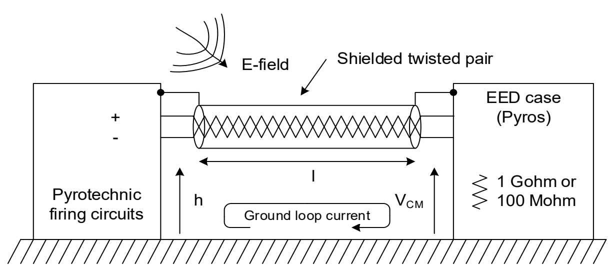

Fig. 10 E-field coupling model with harness in CM

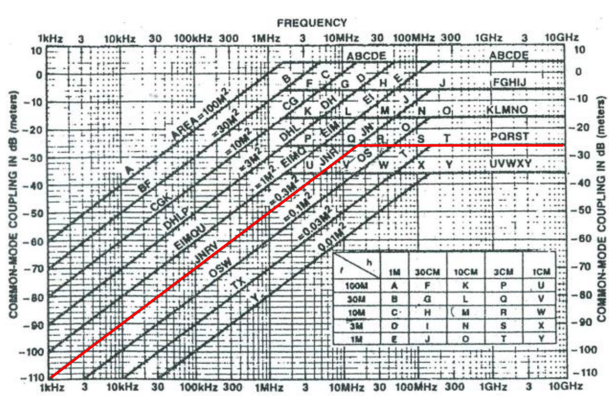

Fig. 11 E-field coupling voltage with harness loop in CM[29]

Table 5 shows CM current and voltage exposed on an E-field between PC for a height h = 3 cm and length l = 10 m, a h = 1 cm and l = 10 m, a h = 3 cm and l = 3 m, and a h = 1 cm and l = 3 m. For a h = 3 cm and l = 10 m (area 0.3 m^2, see red R curve in Fig. 11), this coupling mode is liable to generate CM current levels shown in Fig. 12. The EMC safety margin requirement has been demonstrated in CM with 58 dB for PC23 initiator and 48 dB for 1EPWH100 squib against the NF current.

Table 5 CM current exposed on an E-field

Freq.	E-field	Loop area(h x l), curves in Fig. 11	I_{CM} (A) in 1 GΩ	I_{CM} (A) in 100 MΩ
50 kHz (L <λ/2)	27.5 V/m (=2 W/m^2)	3 cmx10 m, 0.3 m^2, R	4.6E-12	4.6E-11
		1 cmx10 m, 0.1 m^2, W	1.4E-12	1.4E-11
		3 cmx3 m, 0.09 m^2, S	1.4E-12	1.4E-11
		1 cmx3 m, 0.03 m^2, X	3.3E-13	3.3E-12
50 MHz (L >λ/2)	27.5 V/m (=2 W/m^2)	3 cmx10 m, 0.3 m^2, R	1.5E-09	1.5E-08
		1 cmx10 m, 0.1 m^2, W	4.9E-10	4.9E-09
		3 cmx3 m, 0.09 m^2, S	1.5E-09	1.5E-08
		1 cmx3 m, 0.03 m^2, X	4.9E-10	4.9E-09
	195 V/m (=100 W/m^2)	3 cmx10 m, 0.3 m^2, R	1.1E-08	1.1E-07
		1 cmx10 m, 0.1 m^2, W	3.5E-09	3.5E-08
		3 cmx3 m, 0.09 m^2, S	1.1E-08	1.1E-07
		1 cmx3 m, 0.03 m^2, X	3.5E-09	3.5E-08
32 GHz (L >λ/2)	195 V/m (=100 W/m^2)	3 cmx10 m, 0.3 m^2, R	1.1E-08	1.1E-07
		1 cmx10 m, 0.1 m^2, W	3.5E-09	3.5E-08
		3 cmx3 m, 0.09 m^2, S	1.1E-08	1.1E-07
		1 cmx3 m, 0.03 m^2, X	3.5E-09	3.5E-08

E-field Coupling in DM:

The objective is to assess the DM current between PP through 1 Ω load created by the E-field coupling. Fig. 13 shows E-field coupling model with harness in DM. Both E-field and magnetic flux density are coupled directly into box-to-box interconnecting cables[29]. An ambient electric and magnetic fields converts into a DM voltage, V_{DM}, into the bridgewire resistance, 1 Ω, both PC23 and 1EPWH100. The concept of transfer impedance for a coaxial cable, used for radiated susceptibility or emission modeling, is transposable to STP[30]. The whole STP behaves as a pseudo-coaxial link[30]. Fig. 14 shows coaxial cable and E-field coupling model[30]. In an unbalanced shielded cable (e.g., coaxial), a current, I_S, forced on the shield in the cable-to-ground loop[30]. Because of shield imperfections a small voltage, V_{int}, appears in the inner space between the center conductor and the shield[30]. This voltage is normalized to a 1 meter long sample, such as Eq. 2[30]:

$$V_{int} = Z_t\left(\Omega/_m\right) \times I_s \times l \tag{2}$$

where Z_t = shield transfer impedance, V_{int} = longitudinal voltage induced inside the shield over length “l”, causing a noise current to circulate in the center conductor, I_s = external current injected into the shield by the EMI source.

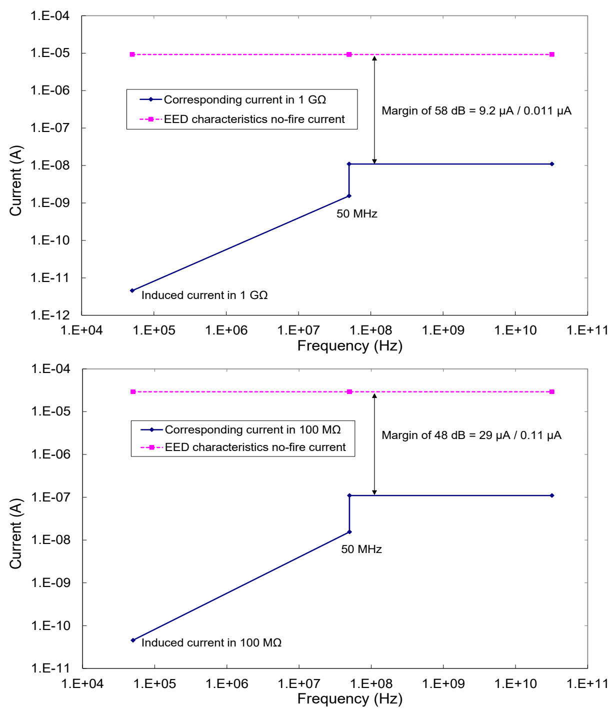

Fig. 12 Corresponding CM current for h=3 cm and l=10 m in PC23 of 1 GΩ (top) and in 1EPWH100 of 100 MΩ (bottom)

Unbalanced lines include the coaxial cable family[29]. For unbalanced lines the DM coupling physics is divided into two parts[29]: (1) field-to-cable coupling in the form of coupled cable surface currents, and (2) transfer impedance of the cable. The latter converts surface currents into DM voltages at the input terminal of the victim[29].

The current for l <λ/2, I_s, flowing on the surface of the coaxial cable as a result of the open circuit induced voltage, V_{int}, impressed on the cable external impedance, Z_t, is as Eq. 3[29]:

$$I_s = \frac{V_{int}}{Z_t} = \frac{\pi f l^2 \varepsilon E}{\sqrt{2}} = 1.96 \times 10^{-5} \times l^2 \times f_{MHz} \times E \quad (3)$$

where E = incident field (V/m), l = length of cable (m), ε = permittivity of free space (capacitance of air) = 1/(36π) = 8.84 (pF/m), f = frequency (Hz), f_{MHz} = frequency (MHz).

The current on the shield for l <λ/2, is uniform along the cable length[31]. Total transfer impedance is Z_t x l[31]. When the coaxial cable length exceeds l >λ/2, it is no longer correct to multiply Z_t by the physical length l of the cable since the current is no longer uniform over the braid but is distributed over a sinusoid[30,31]. Therefore, l is replaced by λ/2. To summarize this rule[31]: use Z_t(cable) = Z_t(Ω/m) x l for l <λ/2, and use Z_t(cable) = Z_t(Ω/m) x (λ/2) for l >λ/2. The surface current for l >λ/2, I_s, is as Eq. 4[31]:

$$I_s = \frac{\pi f \left(\lambda/2\right)^2 \varepsilon E}{\sqrt{2}} = \frac{\pi 300^2 \varepsilon E}{10^6 \times 4\sqrt{2} \times f_{MHz}} = 0.44 \times \frac{E}{f_{MHz}} \quad (4)$$

The induced voltage, V_{int}, can be directly related through the cable total transfer impedance[31]: V_{int} = I_s x Z_t = I_s x Z_t(Ω/m) x l for l <λ/2, and V_{int} = I_s x Z_t = I_s x Z_t(Ω/m) x (λ/2) for l >λ/2.

The induced voltage, V_{int}, appearing in the shield due to the loop current is not directly seen as a differential voltage across the wire pair[30]. For STP with single braid, each wire 1 and 2 is exposed to the same voltage V_{int}, such as if the symmetry was perfect, the difference $V_{int}(1)$ – $V_{int}(2)$ would be null[30]. Since there is a certain percentage of unbalance in the wire resistances, capacitance to shield and leakage inductance through the braid's holes vs. the shield, the differential voltage will be as Eq. 5[30]:

$$V_{DM} = V_{int} \times X\% \times \frac{R_L}{R_S + R_L} \quad (5)$$

where X% is the unbalance percentage of the pair. Depending on the quality of the balanced link, X may range anywhere from 1 to 10%[30], with typical value being 5%[30], for high speed data links. We assumed conservative 10% for the (X% x R_L / (R_S+ R_L)): V_{DM} = V_{int} x 10%.

Figure 15 shows transfer impedance for typical coaxial cable[31]. The Z_t is expressed in ohms and normalized to a 1 m shield length[31]. Below about 100 kHz (this is called the Ohm's Law region), Z_t is practically equal to the shield DC resistance[31]. Above about 10 MHz, Z_t increases with frequency due to proportional to the leakage inductance between the shield and the inner conductor[31]. Above several MHz for loose braids, a capacitive coupling between the shield and the inner conductor becomes significant[31].

A coaxial cable at high frequencies acts as a triaxial cable because of skin effect[32]. A STP has characteristics similar to a double-shielded, or triaxial, cable[32]. The signal current flows in the two inner conductors, and any induced noise current flows in the shield[32]. The RG-550 double braid is used for the transfer impedance in E-field coupling analysis in DM.

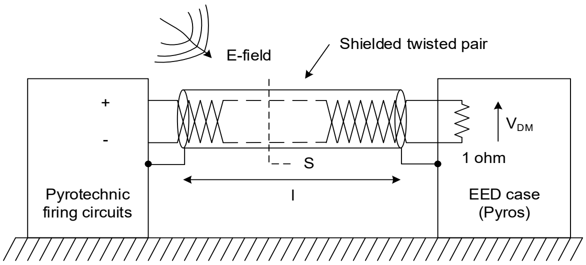

Fig. 13 E-field coupling model with harness in DM

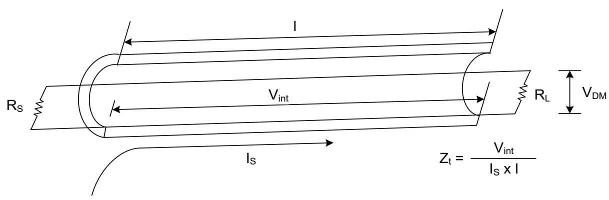

Fig. 14 Coaxial cable and E-field coupling model[30]

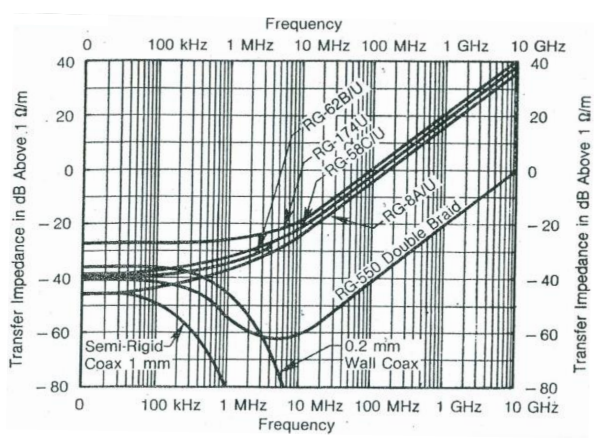

Fig. 15 Transfer impedance of typical coaxial cable[31]

Table 6 DM current and voltage exposed on an E-field

Frequency	E-field	L = 10 m*	L = 3m*
50 kHz (L <λ/2)	27.5 V/m (=2 W/m²)	Is = 2.70 mA Vc = 109 μV Vd = 10.9 μV Ir = 10.9 μA	Is = 243 μA Vc = 2.93 μV Vd = 0.293 μV Ir = 0.293 μA
50 MHz (L >λ/2)	27.5 V/m (=2 W/m²)	Is = 243 mA Vc = 6 mV Vd = 0.6 mV Ir = 0.6 mA	Is = 243 mA Vc = 6 mV Vd = 0.6 mV Ir = 0.6 mA
	195 V/m (=100 W/m²)	Is = 1.73 A Vc = 42.7 mV Vd = 4.27 mV **Ir = 4.27 mA**	Is = 1.73 A Vc = 42.7 mV Vd = 4.27 mV **Ir = 4.27 mA**
32 GHz (L >λ/2)	195 V/m (=100 W/m²)	Is = 2.70 mA Vc = 319 μV Vd = 31.9 μV Ir = 31.9 μA	Is = 2.70 mA Vc = 319 μV Vd = 31.9 μV Ir = 31.9 μA

*Is: Induced current, Vc: CM voltage, Vd: DM voltage, Ir: Corresponding current in 1 Ω.

Table 6 shows DM current and voltage exposed on an E-field between PP for a length l = 10 m and 3m. This coupling mode is liable to generate DM current levels shown in Fig. 16. The EMC safety margin requirement has been demonstrated in DM with 38 dB margin both PC23 initiator and 1EPWH100 squib against the NF current.

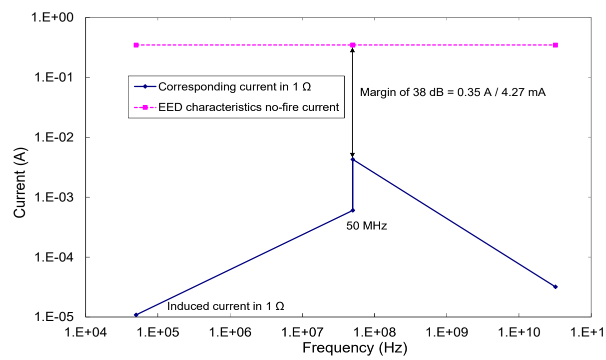

Fig. 16 Corresponding DM current in 1 Ω for L=10 m

5.1.2 E-field Coupling at Connector

The objective is to assess the DM and CM voltages at connector level due to E-field coupling. Fig. 17 shows E-field coupling model at connector level. For these of analysis, a simplified loop antenna model is appropriate for evaluating the impact on the E-field generated due to various interfering noise source bandwidths as well as the distance relationship of the STP to the ground plane. The voltage induced by an incident E-field across a loop is assessed with the formula as Eq. 6[32]:

$$V_i = \frac{2\pi AE}{\lambda}\cos(\theta) = \frac{2\pi AE}{\lambda}\frac{1}{\sqrt{1+\left(\frac{4l}{\lambda}\right)^2}} = \frac{2\pi lhE}{\lambda\sqrt{1+\left(\frac{4l}{\lambda}\right)^2}} \qquad (6)$$

where λ = wavelength of the interfering noise source, A = area of the loop by the l and h, l = length of the cabling conductor, h = average height of cabling conductor above the ground plane, E = E-field intensity of the interfering source, θ = angle measured between the E-field and the plane of the loop.

For a circular single-loop antenna, the effective height is (2πA)/λ[32]. We consider a loop in DM equal to 0.7 cm (l) x 0.3 cm (h) and in CM equal to 1 cm (l) x 1 cm (h). Considering a 30 dB shielding effectiveness brought by the conductive potting at rear of firing circuit's connector and by backshell at rear of EED connector, the voltage induced by the E-field is equal to Table 7 & Fig. 18 for DM current and

Table 8 & Fig. 19 for CM current. The EMC safety margin requirement has been demonstrated in DM with 22 dB both PC23 initiator and 1EPWH100 squib, and in CM with 100 dB for PC23 initiator and 90 dB for 1EPWH100 squib against the NF current.

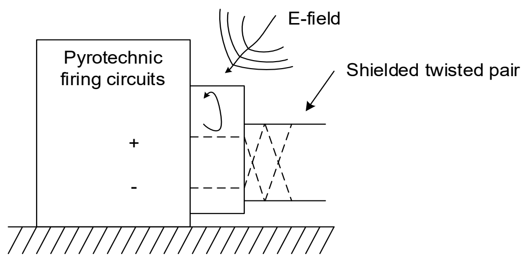

Fig. 17 E-field coupling model at connector level

Table 7 Corresponding DM current by E-field coupling with connector

Freq. (Hz)	E-field (V/m)	Induce DM voltage (V)	Induce DM voltage with 30 dB shielding (V)	Corresponding current in 1 Ω (A)
5.0E+04	27.5	6.05E-07	1.91E-08	1.91E-08
5.0E+07	27.5	6.05E-04	1.91E-05	1.91E-05
5.0E+07	195	4.29E-03	1.36E-04	1.36E-04
3.2E+10	195	8.71E-01	2.76E-02	2.76E-02

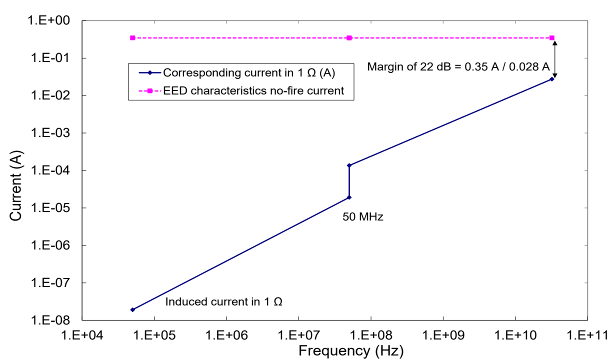

Fig. 18 Corresponding DM current in 1 Ω

Table 8 Corresponding CM current by E-field coupling with connector

Freq. (Hz)	E-field (V/m)	Induce CM voltage (V)	Induce CM voltage with 30 dB shielding (V)	Corresponding current in 1 GΩ (A)
5.0E+04	27.5	2.88E-06	9.11E-08	9.11E-17
5.0E+07	27.5	2.88E-03	9.11E-05	9.11E-14
5.0E+07	195	2.04E-02	6.46E-04	6.46E-13
3.2E+10	195	2.98E+00	9.43E-02	9.43E-11
Freq. (Hz)	**E-field (V/m)**	**Induce CM voltage (V)**	**Induce CM voltage with 30 dB shielding (V)**	**Corresponding current in 100 MΩ (A)**
5.0E+04	27.5	2.88E-06	9.11E-08	9.11E-16
5.0E+07	27.5	2.88E-03	9.11E-05	9.11E-13
5.0E+07	195	2.04E-02	6.46E-04	6.46E-12
3.2E+10	195	2.98E+00	9.43E-02	9.43E-10

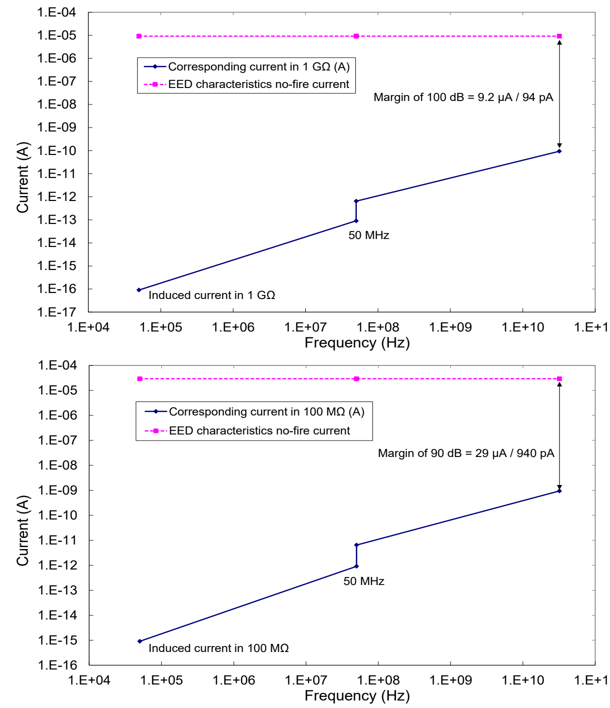

Fig. 19 Corresponding CM current in 1 GΩ (top) and 100 MΩ (bottom)

5.1.3. E-field Coupling Analysis Results

The different analysis results of E-field coupling between the incident E-field and the pyrotechnic subsystem are shown in Table 9. The DM result is applicable to both PC23 initiator and 1EPWH100 squib. The CM result in 1 GΩ is applicable to PC23 initiator and in 100 MΩ is applicable to 1EPWH100 squib. The EMC safety margin requirement has been demonstrated in DM with total 21 dB and in CM with total 58 dB for PC23 initiator and 48 dB for 1EPWH100 squib against the NF current.

Table 9 Result of E-field coupling analysis

E-field coupling mode, Initiator	DM in 1 Ω	CM in 1 GΩ	CM in 100 MΩ
Coupling result at harness level (1)	4 mA	0.011 μA	0.11 μA
Coupling result at connector level (2)	28 mA	9E-11 A	9E-10 A
Total coupling (1) + (2)	32 mA	0.011 μA	0.11 μA
NF current sensitivity	350 mA	9.2 μA	29 μA
Margin	21 dB	58 dB	48 dB

5.2. EMC Safety Margin Test against a DC Current

A fundamental characteristic of the pyrotechnic element is that it can function only once[24]. Unlike all other hardware onboard, the pyrotechnic to be used for flight can never be fully tested before it is required to operate in earnest[24]. The PVs cannot be actuated at system level on a flight satellite, as it would be necessary to replace the PVs which are welded to the tubing[22]. The verifications at system level cover all aspects of propulsion functioning with the exclusion of the firing of the PVs[22]. The PV correct behavior is however electrical check out: squib bridgewire and insulation resistances[22].

The pyrotechnic firing circuit behaviors in the integrated system test are measured on satellite skin connectors to separate pyrotechnic firing circuits and its EEDs. The pyrotechnic orders for the functional and DC electrical isolation test are as follows:

- One pyrotechnic load is simulated in EGSE by a 1 Ω and a 50 mΩ connected in series during about 8 ms. The 50 mΩ monitors the FIRING_CURRENT. A gain of 20 applied to convert from measured voltage on a 50 mΩ to ampere.
- The rest of the pyrotechnics are grouped on another 1 Ω load in EGSE. The 1 Ω monitors the SUM_ALL_UNFIRING_CURRENT.
- Fired pyrotechnic pulse voltage and current are digitized (any one pyrotechnic plus rest of the pyrotechnics).
- Pyrotechnic spurious pulse acquired through the rest of the pyrotechnics. The spurious pulse demonstrates the 20 dB safety margin to DC NF current.

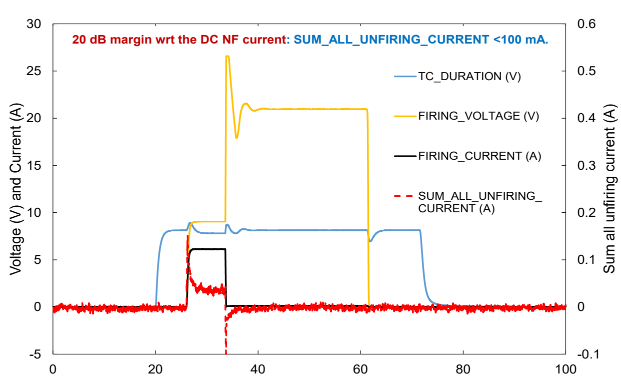

Fig. 20 Functional and electrical isolation test results for the pyrotechnic firing circuits

Figure 20 shows the functional and electrical isolation test results measured on a skin connector for the pyrotechnic firing circuits in the integrated system test. The functional test results demonstrate pyrotechnic firing circuit behaviors. The auxiliary power of pyrotechnic converter in Fig. 7 operates by the fire command from external. The TC_DURATION waveform of 51 ms measured at auxiliary power output. The breaker of pyrotechnic converter operates by the “synchronization & window” circuit. The FIRING_VOLTAGE and FIRING_CURRENT waveforms are output characteristics of EED mode channel. The pyrotechnic converter automatically operates a current limit of 6 A during a pyrotechnic load of 1 Ω simulated about 8 ms and then a voltage regulation of 21 V after a pyrotechnic load removed. Output pulse duration of the FIRING_VOLTAGE is fixed to 35 ms. The electrical isolation test results demonstrate >20 dB below the DC NF current level. The SUM_ALL_UNFIRING_CURRENT waveform was less than 100 mA, during a pyrotechnic load of 1 Ω simulated about 8 ms, which means no spurious activation of all un-firing channels (i.e. no coupled current to all un-firing channels from a firing channel). A maximum limit of 100 mA (i.e. no spurious detection) comes from DC NF current of 1 A in 1 Ω with 20 dB margin. The EMC safety margin requirement has been demonstrated for pyrotechnic firing circuits with >20 dB below the DC NF current level of 1 A. The firing circuits do not share a common fire command and be electrically isolated from one another such that current in one firing circuit does not induce a current greater than 20 dB below the DC NF current level (i.e. SUM_ALL_UNFIRING_CURRENT <100 mA) in any firing output circuit. Also the control circuits are electrically isolated so that a stimulus in one circuit does not induce a stimulus greater than the actuation level in any firing circuit.

6. Conclusions

Pyrotechnic initiators provide a source of pyrotechnic energy used to initiate a variety of space mechanisms[10]. The fundamental requirement of the pyrotechnically energized function is that it must occur reliably when correct commanded at correct time and must not occur under any other circumstances[24]. Pyrotechnic systems build in electromagnetic environment that may lead to critical or catastrophic hazards[4]. Special precautions are need to prevent a pulse large enough to trigger the initiator from appearing in the pyrotechnic firing circuits at any but the desired time[2]. The EMC verification shall be shown by analysis or test that the pyrotechnic systems meet the requirements of inadvertent activation[4]. The MIL-STD-1576[4] and two range safeties, AFSPC[5] and CSG[6], require the safety margin for electromagnetic potential hazards to pyrotechnic systems to a level at least 20 dB below the NF power level of the EED.

This paper verifies the two safety margins for electromagnetic potential hazards. The first is verified by analyzing against a RF power to cover MIL-STD-1576[4], and two range safeties of AFSPC[5] and CSG[6] electromagnetic environment: 2 W/m^2 from 50 kHz to 50 MHz, and 100 W/m^2 from 50 MHz to 32 GHz. The second is verified by testing against a DC current of 1 A. The radiated mode coupling analysis assumes a conservative approach by not considering in a first step the influence of the shield and by assessing with above the structure plane at a different height and length. The radiated mode coupling analysis used the sensitive values from the PC23 RFI test results. For PC23, the RFI test results presents the sensitive level (mean energy to fire): 0.12 W[21] at 9 GHz for the PP and 0.085 W[21] at 9 GHz for the PC. For 1EPWH100 squib, we do not have any information for RFI sensitivity. Therefore, we take the same hypothesis as PC23. The EMC safety margin requirement against RF power has been demonstrated through the E-field coupling analysis in DM with 21 dB both PC23 and 1EPWH100, and in CM with 58 dB for PC23 and 48 dB for 1EPWH100 against the NF power level of the EED. Also, the EMC safety margin requirement against DC current has been demonstrated through the electrical isolation test for the pyrotechnic firing circuits with greater than 20 dB below the NF DC current level of the EED. The firing circuits are electrically isolated from one another such that current in one firing circuit does not induce a current greater than 20 dB below the NF current level in any firing output circuit.

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