PCB board-level testing for space discretes

Standards and best practices

Abstract

When electrical devices are assembled onto spacecraft and sent into space, they undergo extreme stress during the launch and throughout the duration of the mission. After the initial vibrations and shock experienced on launch, they must operate as designed for many years. Over the years, various government and industry associations created performance and test standards to ensure the devices will perform as expected in those harsh environments. This paper will review key applicable standards used to ensure the reliability and performance of International Rectifier HiRel Products, Inc. (IR HiRel) silicon discretes intended for space use.

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1 Introduction

IR HiRel is a leader in semiconductors and power management products for space with products used in over 2,000 space programs. For over 25 years, IR HiRel has been manufacturing and supplying radiation-hardened (rad hard) MOSFETs for extreme environments that meet and exceed customer requirements and expectations. IR HiRel performs part qualifications in accordance with MIL-PRF-19500 [8], which is very good for testing the products, however, it doesn't fully represent real life conditions, since the components will be mounted to a PCB when in use. Because of this, IR HiRel performs additional testing with the products attached to the PCB. The PCB mounted testing exposes the parts to more realistic conditions.

When electrical devices are assembled onto spacecraft and sent into space, they undergo extreme stress during the launch and throughout the duration of the mission. After the initial vibrations and shock experienced on launch, they must operate as designed for many years. Over the years, various government and industry associations created performance and test standards to ensure the devices will perform as expected in those harsh environments. Among the standards are:

- MIL-PRF-19500 [8]
- MIL-STD-883 [4]
- MIL-STD-750 [3][2]
- IPC-J-STD-001ES Space Addendum [7]
- IPC-TM-650 [5]
- IPC-9701A [6]
- IPC-SM-785
- ECSS-Q-ST-70-08C [1]
- ECSS-Q-ST-70-38C [2]

MIL-PRF-19500 [8], MIL-STD-883 [4], and MIL-STD-750 [3] are standards by the U.S. Defense Logistics Agency defining the performance requirements of semiconductors, test methods, and inspections to ensure they operate in the designated conditions, which is space, in our case. The IPC-J-STD-001ES Space Addendum [7], IPC-TM-650 [5], and IPC-9701A [6] are joint industry standards intended to ensure that electrical components and solder components can operate in their specified environment. The IPC-TM-650 [5] test method manual describes many of the tests from those standards. The ECSS-Q-ST-70-08C [1] is a European standard that ensures manually soldered devices will be highly reliable and withstand the vibration, shock, and environment from different environments. The ECCS-Q-ST-70-38C [2] standard ensures high reliability soldering for surface-mount and other technology. The ECSS-Q-ST-70-07 [9] is a standard that ensures the reliability of automatic soldering joints, which is what IR HiRel performs. This standard isn't referenced since the environmental tests refer to the ones listed in the ECSS-Q-ST-70-08C [1] standards.

IR HiRel performs three board-level qualification tests to simulate launch and operation in space. The first test is random vibration. This simulates the launch of the spacecraft and the root-mean-square (RMS) acceleration (also called Grms) that must be endured. The second test is the mechanical shock. This represents the shock that the components will have to withstand as a result of the various engine separations during the launch sequence. The third test is the temperature cycling. This test represents the wide temperature range the device will operate in, and ensures it won't be destroyed by the constant cycling. After performing these three tests, the solder joints are visually examined and cross-sectioned to inspect solder joint integrity.

The random vibration and thermal cycling tests are performed in accordance with ECSS-Q-ST-70-38C [2], but these tests refer to the ones listed in ECSS-Q-ST-70-08C [1]. The cross-section of solder joints is done with ECSS-Q-ST-70-38C [2]. The mechanical shock testing needs to meet the intended mission with a margin according to ECSS-Q-ST-70-38C [2]. The exact test conditions were then decided by IR HiRel based on the highest demands seen by customers.

Table 1 Standards name and description

Standard name	Description
ECSS-Q-ST-70-07	Verification and approval of automatic machine wave soldering
ECSS-Q-ST-70-08C	Manual soldering of high-reliability electrical connections
ECSS-Q-ST-38C	High-reliability soldering for surface-mount and mixed technology
MIL-PRF-19500	General specifications for semiconductor devices
MIL-STD-750	Test methods for semiconductor devices
MIL-STD-833	Test method standard microcircuits
IPC J-STD-001ES	Space applications electronic hardware addendum to IPC J-STD-001E requirements for soldered electrical and electronic assemblies
IPC-9701A	Performance test methods and qualification requirements for surface mount solder attachments
IPC-TM-650	Test methods manual

2 Random vibration

2.1 MIL-STD-883

The different standards have similar requirements for their testing. For the random vibration test, MIL-STD-883 [4], TM2026 1J requires that the device goes through 15 minutes of random vibration for each direction, X, Y, and Z. Table 1, from the MIL-STD-883 document, shows the different test conditions.

Table 2 MIL-STD-883 TM2026 random vibration test conditions

Characteristics		
Test condition letter	**Power spectral density (g^2/Hz)**	**Overall Grms**
A	0.02	5.2
B	0.04	7.3
C	0.06	9
D	0.1	11.6
E	0.2	16.4
F	0.3	20
G	0.4	23.1
H	0.6	28.4
J	1	36.6
K	1.5	44.8

2.2 ECSS-Q-ST-70-38C (and IR HiRel standards)

The random vibration testing in the ECSS-Q-ST-70-38C [2] document refers to the testing in 13.2 of ECSS-Q-ST-70-08C [1]. The ECSS-Q-ST-70-08C [1] document provides similar standards, however, they are a little less intense. Because of this, when the ECSS standards are used, IR HiRel usually increases the test conditions to be more in line with what the parts with actually go through, based on our experience. For the random vibration testing, the device is tested for five minutes per axis. The following tables from ECSS-Q-ST-70-08C [1] show the test conditions for launcher and non-launcher applications.

Table 3 ECSS-Q-ST-70-08C random vibration for launchers

Minimum severity for random vibration testing for launchers	
Frequency	PSD
20 to 60	+3dB/oct.
60 to 1000	0,27 g^2/Hz
1000 to 2000	-6dB/oct.
Global: 20 grms	
Duration: 5 minutes per axis	

Table 4 ECSS-Q-ST-70-08C random vibration for non launchers

Minimum severity for random vibration testing for all applications except launchers			
Perpendicular to PCB		Parallel to PCB	
Range (Hz)	PSD Level	Range (Hz)	PSD Level
20 to 100	+6 dB/oct.	20 to 10	+6 dB/oct.
100 to 500	1,0 g^2/Hz	100 to 800	0,5 g^2/Hz
500 to 2000	-6 dB/oct.	800 to 2000	-3 dB/oct.
Global: 28,5 grms		Global: 27,1 grms	
Duration: 5 minutes per axis			

The following table from IR HiRel's internal standards shows the increased testing level that is performed.

Table 5 IR HiRel random vibration testing

Axis	Frequency range (Hz)	Level	Grms	Duration (sec.)
X,Y,Z	20 – 100	+6dB/oct	39.9	300
	100 – 1000	1 g^2/Hz		
	1000 – 1500	-3dB/oct		
	1500 - 2000	-6dB/oct		

Testing to these conditions more than satisfies the ECSS standards.

2.3 IPC-TM-650

The following table shows the random vibration testing from IPC-TM-650 [5]. Test condition F is the closest to the ECSS and MIL-STD-883 [4] standards. This is because test conditions A-E are using units of peak acceleration with a much longer test duration. Test condition F is using root-mean-square (RMS) acceleration (also called Grms) with a shorter test duration, similar to the MIL-STD-883 [4] conditions. However, this test is a lot less intense compared to MIL-STD-883 [4] TM 2026. The test durations are the same, but the test level is 10.9 Grms compared to 36.6 Grms in MIL-STD-884.

Table 6 IPC-TM-650 random vibration testing

Test condition	Peak acceleration (Gravity Units)	Frequency Range (Hz)	Approx. traverse time (min.)	Traverses per axis	Duration per axis
A	10	5 to 55	0.5	240	2 hrs.
B	10	10 to 500	7.5	24	3 hrs.
C	15	10 to 2000	10	24	4 hrs.
D	10	55 to 2000	40	1	40 min.
E	20	10 to 2000	10	24	4 hrs.
F	10.9	10 to 2000	N/A	N/A	15 min.

The following table shows a summary of the random vibration tests listed above.

Table 7 Random vibration summary table

Test characteristics	Power spectral density	Grms	Duration
MIL-STD-883J	1.0 g^2/Hz	36.6	15 minutes/axis
ECSS-Q-ST-70-08C Table 13-3 launcher	+3 dB/oct. (20 – 60 Hz) 0.27 g^2/Hz (60 – 100 Hz) -6 dB/oct. (1000 – 2000 Hz)	20	5 minutes/axis
ECSS-Q-ST-70-08 Table 13-4 Non-launcher applications (perpendicular to PCB)	+6 dB/oct. (20 – 100 Hz) 1.0 g^2/Hz (100 – 500 Hz) -6 dB/oct. (500 – 2000 Hz)	28.5	5 minutes/axis
ECSS-Q-ST-70-08 Table 13-4 Non-launcher applications (parallel to PCB)	+6 dB/oct. (20 – 100 Hz) 0.5 g^2/Hz (100 – 800 Hz) -3 dB/oct. (800 – 2000 Hz)	27.1	5 minutes/axis
IPC-TM-650 Test condition F	0.008 g^2/Hz (0 – 10 Hz) +3 dB/oct. (10 – 75 Hz) 0.06 g^2/Hz (75 – 2000 Hz)	10.9	15 minutes/axis
IR HiRel PCB board-level test parameters	+6 dB/oct. (20 – 100 Hz) 1 g^2/Hz (100 – 1000 Hz) -3 dB/oct. (1000 – 1500 Hz) -6 dB/oct. (1000 – 2000 Hz)	39.9	5 minutes/axis

3 Mechanical shock

3.1 ECSS-Q-ST-70-38C

The ECSS-Q-ST-70-38C [2] states that the mechanical shock testing should meet the intended mission with a margin. So, the exact test conditions are determined by IR HiRel based experience and customer needs. The mechanical shock testing IR HiRel performs is shown below, in the MIL-STD-883 [4] section.

3.2 MIL-STD-883

The following table from MIL-STD-883 [4]Test Method 2002 shows the mechanical shock testing. IR HiRel uses this test as a baseline, but alters the test conditions for the PCB level mechanical shock. This is done to meet the most demanding conditions seen by our customers.

The testing we perform is closest to condition B, as there is a 1,500 G peak, 0.3 ms pulse duration, and 3 shocks per axis. The original test condition B has a 1,500 G peak, 0.5 ms pulse duration, and 5 shocks per axis, as shown by the following table from MIL-STD-883 [4] TM2002. For mechanical shock testing, a shorter pulse duration is a more severe test, since there is a higher peak acceleration per pulse duration.

Table 8 MIL-STD-883 TM2002 mechanical shock testing

Test condition	g level (peak)	Duration of pulse (ms)
A	500	1.0
B	1,500	0.5
C	3,000	0.3
D	5,000	0.3
E	10,000	0.2
F	20,000	0.2
G	30,000	0.12

3.3 IPC-TM-650

The following table from IPC-TM-650 [5] shows the IPC mechanical shock testing. Test condition E has a peak acceleration of 1,000 g with a pulse duration of 0.5 ms. There were three shocks performed in each axis (X+, X-, Y+, Y-, Z+, Z-), for a total of 18 shock pulses. This is similar, but less intense than, test condition B from MIL-STD-883 TM 2002, which has the same pulse duration with a peak acceleration of 1,500 g and less shock pulses.

Table 9 IPC-TM-650 mechanical shock testing

Test condition	Peak acceleration (Gravity Units)	Nominal duration (ms)	Waveform	Velocity change (G-ms)
A	50	11	Half-sine	350.30
B	75	6	Half-sine	286.62
C	100	6	Half-sine	382.16
D	500	1	Half-sine	318.47
E	1000	0.5	Half-sine	318.47
F	5000	0.5	Half-sine	477.70
G	50	10	Sawtooth	250.00
H	75	6	Sawtooth	225.00
I	100	6	Sawtooth	300.00

The following table shows a summary of the mechanical shock testing detailed above.

Table 10 Mechanical shock summary table

Test characteristics	**MIL-STD-883J** TM 2002.5 Condition B	**ECSS-Q-ST-70-38C**	**IPC-TM-650** Test condition E	**IR HiRel** PCB board-level test parameters
Peak acceleration (G)	1,500	Should "meet the intended mission with margin"	1,000	1,500
Pulse duration (ms)	0.5		0.5	0.3
Shocks/axis	5		3	3
Total shocks	30		18	18

4 Temperature cycling

4.1 ECSS-Q-ST-70-08C

From the ECSS-Q-ST-70-08C [1] standards, the temperature cycle test is done with a low of -55°C and a high of 100°C. The rate of change for the temperature is kept at or below 10°C/minute, with a dwell time of 15 minutes at the high and low temperatures.

4.2 MIL-STD-750

This test calls for a dwell time of at least 10 minutes with a ramp of at least 15°C/minute. The various test conditions are shown by the following table from MIL-STD-750 [2] TM1051.

Table 11 MIL-STD-750 TM1051 Temperature cycling

Step	Dwell time (minutes)	Test condition, temperature, and tolerance (°C)						
		A	B	C	D	E	F	G
1 Cold	≥ 10	-55 +0/-10	-55 +0/-10	-55 +0/-10	-65 +0/-10	-65 +0/-10	-65 +0/-10	-55 +0/-10
2 Hot	≥ 10	85 +10/-0	125 +15/-0	175 +15/-0	200 +15/-0	300 +15/-0	150 +15/-0	150 +15/-0

4.3 IPC-9701A

The following table shows the temperature cycling requirements from the IPC-9701A [6] standards. The testing that IR HiRel performs is most similar to TC5, NTC-B. These conditions mean the testing is done from -55°C to 100°C for 500 cycles. There is a dwell time of 10 minutes at the high and low temperatures, with a maximum ramp rate of 20°C/minute.

The IPC-9701A [6] also requires daisy chaining and continuous monitoring. Daisy chaining the packages/dies together means that multiple products on the PCB can be measured simultaneously. Continuous monitoring allows electrical measurements to be taken constantly during the temperature cycling process, including at the extreme temperatures. With manual monitoring, measurements would only be taken at room temperature, in between the temperature cycling. This is useful since solder joint failures can be electrically detected by measuring a brief open circuit, or a large increase in resistance. The continuous monitoring and daisy chaining provide another source of solder joint failure detection, leading to increased reliability.

Table 12 IPC-9701A temperature cycling

Test condition	Mandated condition
Cycle (TC) Condition: TC1 TC2 TC3 TC4 TC5	 0°C ↔+100°C -25°C ↔+125°C -40°C ↔+125°C -55°C ↔+125°C -55°C ↔+100°C
Number of thermal cycle requirement NTC-A NTC-B NTC-C NTC-D NTC-E	 200 cycles 500 cycles 1,000 cycles 3,000 cycles 6,000 cycles
Low temperature dwell Temperature tolerance	10 minutes +0/-10°C (+0/-5°C) [+0/-18°F (+0/-9°F)]
High temperature dwell Temperature tolerance	10 minutes +10/-0°C (+5/-0°C) [+18/-0°F (+9/-0°F)]
Temperature ramp rate	≤20°C/minute
Full production sample size	33 component samples
PCB thickness	2.35 mm
Package/die condition	Daisy-chain die/package
Test monitoring	Continuous monitoring

The following table provides a summary of the temperature cycling tests detailed above.

Table 13 Temperature Cycling Summary Table

Test characteristics	**MIL-STD-750F** TM 1051 Condition A	**ECSS-Q-ST-70-08C**	**IPC-9701A** **TC 5, NTC=B**	**IR HiRel** PCB board-level test parameters
Temperature range	-55°C – 85°C	-55°C – 100°C	-55°C – 100°C	-55°C – 100°C
Ramp rate	≤ 15°C/minute	≥ 10°C/minute	≥ 20°C/minute	≥ 10°C/minute
Minimum dwell time	10 minutes	15 minutes	10 minutes	15 minutes
Number of thermal cycles	20 minimum, or as specified	200	500	500

5 Cross section of solder joints

5.1 MIL-STD-750

MIL-STD-750 [2] TM 2071 is a visual and mechanical inspection of hermetically packaged semiconductors. It specifies which cracks are acceptable and which are rejected.

MIL-STD-883 [4] TM 2009 is similar to MIL-STD-750 [2] TM 2071, however, it is specific to ceramic packages. The inspection includes the leads, package, and lid. Possible failures include radial cracking and circumferential cracking.

5.2 ECSS-Q-ST-70-38C

The ECSS requirements for solder-joints depend on the device. For surface mount devices, such as IR HiRel's SMD-2 (similar to the SupIR-SMD), the cracks have to be less than 25% of the lap connection, with no cracks in the ceramic. This is shown by the following figure from ECSS-Q-ST-70-38C [2].

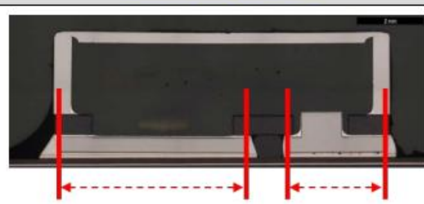
SMD type	Example device	Critical Zone definition	Acceptance criteria
Bottom terminated chip device	SMD0.5, SMD1, SMD2, SMD0.2, SMD0.22 Quad Flat Pack No lead (QFN)	 red line defines the critical zone	No crack longer than 25% of lap connection No cracks in the ceramic

Figure 1 ECSS-Q-ST-70-38 SMD crack requirements

6 PCB qualification

The following table shows the PCB level testing that was performed on the SupIR-SMD package.

Table 1 SupIR-SMD board level qualification

No.	Test	Conditions	Pass/fail	Date
1	Random vibration	ECSS-Q-ST-70-08 Test level increased to 40 Grms	Pass	7/26/2019
2	Mechanical shock	MIL-STD-883 TM2002 (1,500 G, 0.3 ms) 3 times in positive and negative direction each in X1,Y1,Z1 directions – 6 shocks per axis, 18 shocks in total	Pass	7/26/2019
3	Temperature cycle	ECSS-Q-ST-70-08 (-55°C to +100°C), 500 Cycles Ramp not to exceed 10°C/minute; dwell minimum 15 minutes	Pass	9/26/2019
4	Cross-section of solder joints	ECSS-Q-ST-70-38 Cracks in solder shall not exceed 25% of the lap connection in the critical zone	Pass	10/23/2019

The PCB level testing IR HiRel performs is chosen based on the testing procedure. In some cases, the test levels were then adjusted to more accurately reflect the conditions the devices will experience based on IR HiRel's testing and customer needs.

For the random vibration, the testing performed is based on the ECSS-Q-ST-70-08C [1] standards, but with the 30 Grms increased to 40 Grms. This also means the test level is comparable to the MIL-STD-883 [4] TM2026 1J, which calls for 36.6 Grms. However, the durations of these tests are different. The ECSS-Q-ST-70-08C [1] standards only call for five minutes per axis with the random vibration testing, where MIL-STD-883 [4] calls for 15 minutes per axis. IPC TM-650 [5] Condition F would be exceeded by MIL-STD-883 [4] TM2026 1J, as the durations are the same, but MIL-STD-883 [4] TM2026 has a test level 36.6 Grms compared to the 10.9 Grms test level of IPC TM-650 Condition F.

Since there aren't any ECSS standards for mechanical shock testing, MIL-STD-883 [4] TM2002 is used as a baseline. However, the test conditions were then modified based on the highest demands from our customers. These demands led to the 1,500 G, 0.3 ms, 18 shock total conditions that are used. This testing is exceeds the IPC-TM-650 [5] mechanical shock testing, as there is a higher peak acceleration (1,500 G compared to 1,000 G), the same number of shock pulses, and a lower test duration (0.3 ms pulses compared to 0.5 ms pulses), leading to more intense conditions.

The temperature cycling test is also done in accordance with the ECSS-Q-ST-70-08C [1] standards. This testing also exceeds the IPC-9701A temperature cycling standards. The temperature range and number of cycles are the same between the IPC and the ECSS, but the ECSS has a more intense dwell time. The MIL-STD-750 [2] TM1051 temperature cycling test doesn't compare very well with the others. The dwell time is 10 minutes for both tests, but the ramp rates are not the same. ECSS-Q-ST-70-08C [1] has a maximum ramp rate of 10°C/minute, whereas MIL-STD-750 [2] TM1051 has a minimum ramp rate of 15°C/minute. There also isn't an exact test condition with the temperature range of -55°C to 100°C, which would fall in between test conditions A and B.

The post-testing inspection is done in accordance with ECSS-Q-ST-70-38 [2]. This inspection is stricter than the MIL-STD-750 [2] alternative, since the ECSS inspection doesn't allow any cracks in ceramic for SMD devices.

7 Board thickness

The PCB itself is also an important factor. The material of the PCB determines its coefficient of thermal expansion. This means that certain PCB materials will be better suited to certain packages. The thickness of the board is also an important factor. A thinner board will generally cause the packages to have a higher amount of stress than a thicker board. There is no standard board thickness that is used, however the IPC-9701A [6] calls for a 2.35mm thick board. The SupIR-SMD PCB level testing was done on a 1.822mm thick board. It still passed all of our testing, even with the additional stress that would add.

8 Conclusion

Increased confidence with additional testing

IR HiRel tests and qualifies products in accordance with MIL-PRF-19500 [8]. Extra testing is then performed with the products mounted on a PCB, providing a more realistic experience for the products. All of IR HiRel's testing either complies with or exceeds the standards the tests were performed to or the conditions required by customers. In addition, the temperature cycling testing ends up complying with the ECSS-Q-ST-70-08C [1] and IPC-9701A [6] requirements simultaneously and the random vibration surpasses the requirements. With the qualification to MIL-PRF-19500 [8], the PCB level testing, increased test levels, compliance to multiple standards, and the 25+ year space heritage, customers can feel confident in the reliability of IR HiRel's products.

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Revision history

Document version	Date of release	Description of changes
V 1.0	2020-11-12	Initial release

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Published by

Infineon Technologies AG

81726 Munich, Germany

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Document reference