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Predicting Mission Life Performance And Reliability Of Rad-Hard Power Electronics

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In space applications, understanding equipment reliability and performance over the mission lifetime remains a critical concern for system designers. This is especially true for long duration, interplanetary and other critical missions.

To achieve confidence in space systems requires rigorous design, strict qualification and radiation testing, and controlled manufacturing and screening to eliminate manufacturing defects and infant failures. Providing performance validation over the life of the mission is addressed through extensive design analyses validated by empirical data. Doing the detailed end-of-life performance assessment requires time, resources and expertise in radiation-hardened (rad-hard) electronics that may not be available within the space equipment manufacturer's organization.

This article will explain IR HiRel's design analysis methodology for its rad-hard hermetic hybrid dc-dc converters that power spacecraft electrical subsystems. Accepted by the U.S. Defense Logistics Agency (DLA), major space equipment OEMs, and government agencies globally, this method provides end-of-life verification of the dc-dc converter specifications and performance in accordance with MIL-PRF-38534 Class K.

The data obtained from IR HiRel's design analysis shows expected performance over the life of the rad-hard hybrid dc-dc converters across the specified range of electrical loads, temperature, aging and environments. The in-depth technical reports generated using this methodology provide ample input for equipment-level analysis by system designers, reinforcing confidence in system performance and reliability over mission life.

A Layered Approach To Confidence

It is no secret that one of the major challenges in designing for 15+ year-long space missions is predicting system performance and reliability over mission life. Ideally, any subsystems, such as the dc-dc converters providing power conversion and management, should come with data analyses usable at the integration level, so that system designers can easily add the power supplies with confidence.

High product-assurance levels for the dc-dc converters are established in layers, ending with the controlled manufacturing and screening process for flight models. This last layer includes:

- Electrical test up to 100% load
- Screening over a broad operating temperature range from -55°C to 85°C
- High temperature (125°C) burn-in and life test
- Radiation environment testing to qualify the operation of the hybrid dc-dc converters at 100 kRad(Si) total ionizing dose (TID) and 82 MeV-cm^2/mg single event effects (SEE).

With this work, the results provide end-of-life verification of the hybrid dc-dc converter specification in accordance with MIL-PRF-38534 Class K.

Class K Hybrid DC-DC Converter: Design Flow To Production

Fig. 1 illustrates the design flow from specification to production release. Space missions often have detailed requirements with full documentation of compliance to the stated requirements, so IR HiRel's design flow for its Class K hybrids starts with a specification review. Once the converter specifications are reviewed and agreed upon with the customer, the next step is circuit design and simulation using commercially available tools in combination with proprietary tools and component models.

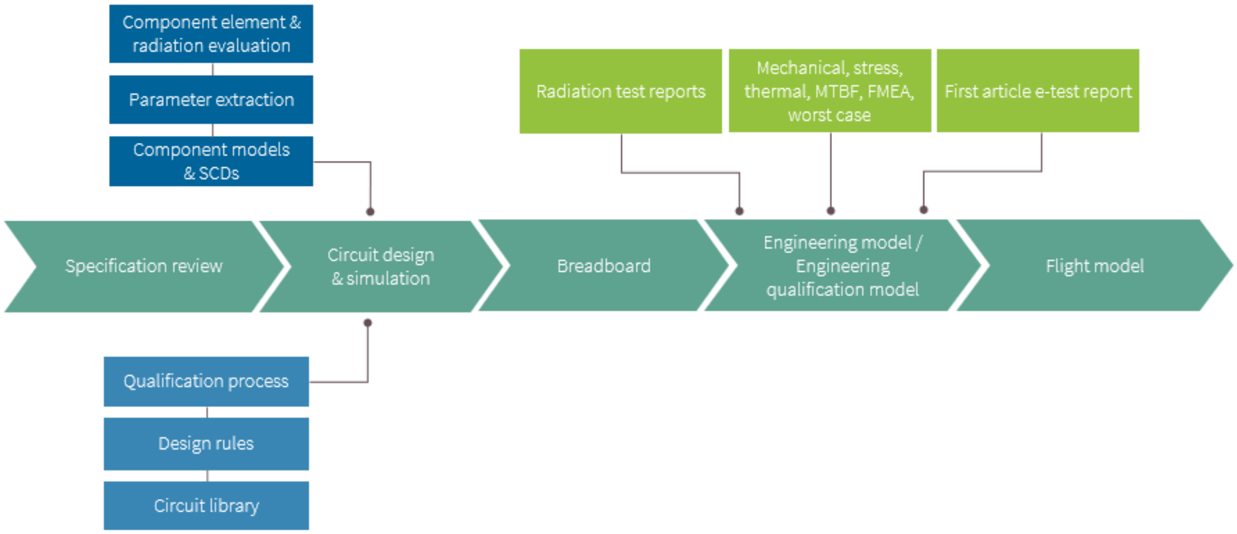


Fig. 1. Design flow to production for IR HiRel's Class K hybrid dc-dc converters.

Over time, IR HiRel has developed an extensive library of fully characterized components and associated models, including radiation performance, governed by proprietary specifications. Component characterization yields the data used for parameter extraction, which then enables examination and evaluation of radiation susceptibility of a converter's component elements. Source control drawings (SCDs) control the component specification.

Other key inputs in the circuit design and simulation process include:

- A proprietary circuit library of blocks, often proven and qualified in existing products
- Design rules for performance and manufacturability for optimal design control in manufacturing
- MIL-PRF-38534 Class K requirements
- Component and sub-circuit behavior under aging, temperature and radiation environment.

The combination of proprietary circuit designs, component selection and use in carefully designed circuits yields radiation hardness by design, which is verified by test and validated by the analyses described herein.

Next steps involve breadboarding the circuit design for electrical verification, MIL-PRF-38534 quality conformance inspection (QCI) and radiation testing and analysis. For IR HiRel's Class K hybrids, internal test procedures and analyses of the design include:

- Electrical stress and derating in accordance with MIL-STD-1547, MIL-STD-975, and EEE-INST-002
- Thermal analysis
- Reliability assessment (stress dependent) per MIL-HDBK-217 Rev F (MTBF)
- Failure mode and effects analysis (FMEA)
- Radiation testing (TID, dose rate, neutron fluence, SEE) per MIL-STD-883
- Worst-case analysis, including temperature effects, aging and radiation effects.

Available under non-disclosure agreement to our customers, these detailed analyses and radiation testing reports have been reviewed by DLA and other government bodies and accepted by customers globally for classified and government programs. This documentation is critical for system designers to quantify the behavior of the converter in their specific application and to complete equipment-level analysis and performance documentation.

First article evaluation is based on detailed procedures and accompanied by an electrical test performance evaluation and report with extensive electrical measurements and waveforms that are not available through production automated test. Such empirical data is used to validate the design analyses. This reinforces confidence in the manufacturability of a reliable product for a wide range of operating conditions and space applications.

From Component And Circuit Modeling To Simulation

Space hybrid dc-dc converters are challenging to design and manufacture for reliable performance in harsh environments. IR HiRel's Class K hybrids include up to 100 different electrical components that are individually analyzed, verified and validated through extensive testing processes.

Component selection and testing start with a parameter extraction based on the test data. This is used to build the component models and create the SCD. Proprietary component SCDs provide configuration control and support the radiation specifications and end-of-life performance. The models are then verified against measurements over various conditions and subjected to statistical analyses to establish component production test limits (per MIL-PRF-38534 Group A) documented in the component SCD. Component model integrity is crucial for design analysis at the system-level and to attain a trustworthy predictor of real-life performance.

Fig. 2 below is a good example of how IR HiRel validates integrity in the models, both for customers and ourselves. The figure has six waveforms showing different electrical characteristics of a hybrid dc-dc converter design: loop response, line rejection and stable load response. In the top row are the simulated waveforms, with the graphs from actual lab measurements on the bottom. As shown, typical simulations are very close to actual typical performance in lab tests. The shape and trend of the waveforms provide confidence in the simulation models.

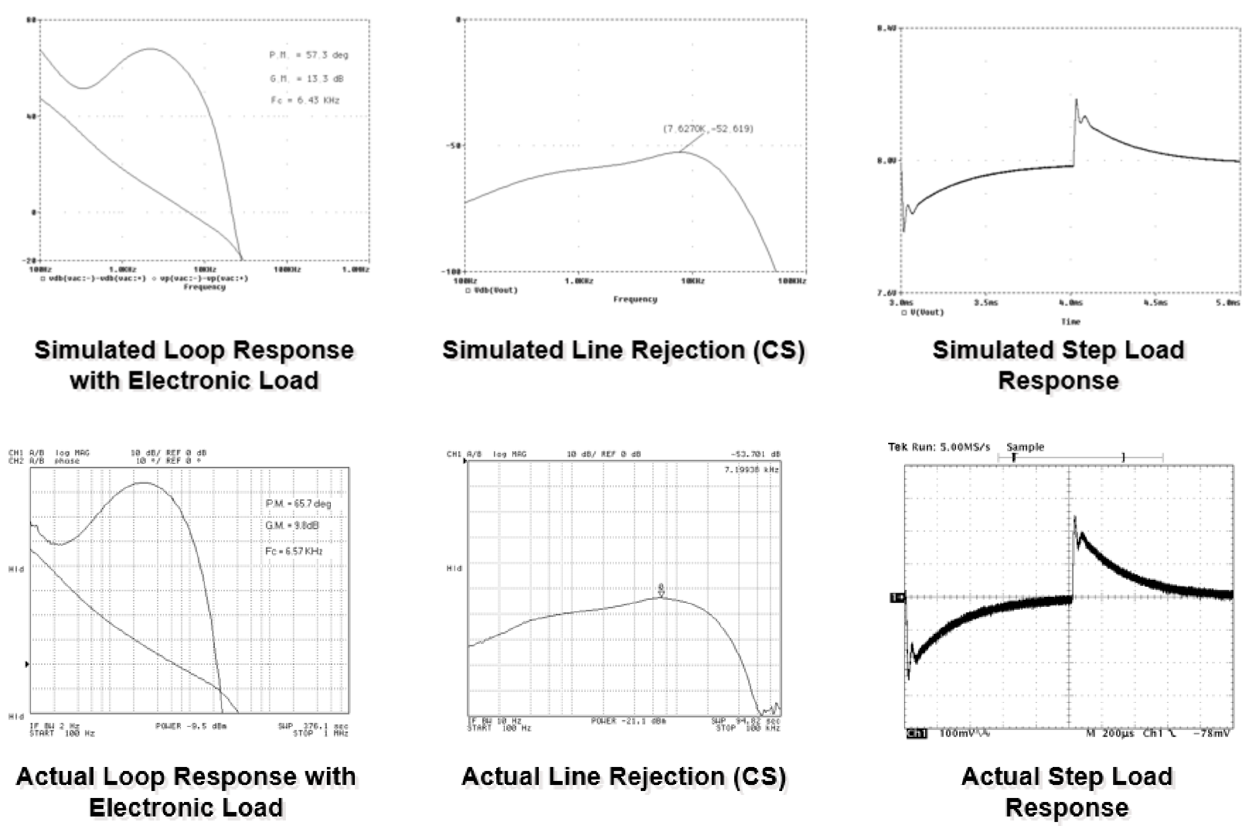


Fig. 2. Simulation example for a hybrid dc-dc converter circuit: simulated vs. actual (measured) results.

Electrical Verification And Qualification

Next step is to build engineering models for electrical verification of the converter design, and engineering qualification models for predicting compliance with the relevant standards, which include:

- Radiation testing and analysis per MIL-STD-883
- Design analysis and derating per MIL-STD-1547, MIL-STD-975 and EEE-INST-002
    - Electrical stress
    - Thermal reliability
    - Mean time between failure (MTBF)
- Failure mode and effect analysis (FMEA)
- Worst-case analysis (WCA)
- QCI per MIL-PRF-38534 Group C.

Converter-Level Radiation Testing

Radiation effects are analyzed, primarily through simulation, but it is also critical to verify by test. Equally important is having the expertise on *how* to test the products at the hybrid level and analyze those results. Working with recognized facilities (such as Texas A&M University, Naval Research Lab and Lawrence Berkeley National Lab), IR HiRel performs radiation tests on converters per MIL-STD-883 for single event effects (SEE), total ionizing dose (TID) at high dose rate (HDR) and low dose rate (LDR) where applicable, and neutron fluence (on customer request).

These test results not only show whether the converter passes or fails, but its behavior in the radiation environment. Most importantly, they prove the extent of the converter's radiation hardness.

Why this matters goes back to the notion of predicting performance over mission life. The first level of radiation hardness is survivability, where a product may stop working under a radiation event, but recovers and continues to operate. Next is functional, where a product may still operate after a radiation event, but not within specification. Finally, there is immunity, where despite the radiation environment, the product continues to operate within specification.

For hybrid converters, there is a huge difference between being functional versus immune in a radiation environment. With a functional product, after a radiation event, it may still be able to operate, but with a minor degradation of the power output by some percentage. Or the output voltage accuracy may be impacted, which could destroy the load in an overvoltage situation.

Is it worth the risk to work with parts that may only survive or partially function after radiation events? Using radiation immune parts reinforces confidence in both reliability and end-of-life performance.

Design Analysis: Stress, Thermal And Worst Case

Derating of IR HiRel's dc-dc converters under radiation provides confidence that the converter will survive and perform in radiation environment and is demonstrated by empirical measurements and extensive analysis.

Stress And Derating Analysis

The stress and derating analysis is derived from manual calculation, computer modeling and simulation. Results are then verified with empirical data and components are derated in accordance with:

- MIL-STD-1547
- MIL-STD-975
- NASA NEPP Electronics Parts & Packaging EEE-INST-002.

The table below shows a sample of IR HiRel Component derating guidelines that meet or exceed the applicable industry standard above. This analysis includes nominal and worst-case stresses for such parameters as voltage, current, and power, for all components used in the dc-dc hybrid. In some cases, individual components can number in the hundreds, making this a labor intensive, but crucial step in design validation. The outcome is a compliance statement for every component under each of the operating conditions.

Table. Example of IR HiRel component derating guidelines that meet or exceed the applicable industry standards.

		Electrical Stress		
Device Type	Parameter	Nominal	Worst Case	At Burn-in 125°C
Microcircuits, Digital	Load Current	75%	75%	100%
	Supply Voltage	110% of Nominal	110% of Nominal	110% of Nominal
	Supply Voltage, CMOS	80%	86%	100%
	Fan-out	80%	90%	100%
	Power Dissipation Junction Temperature	80% 105°C	90% 125°C	100% Mfg. rated max TJ
Microcircuits, Linear	Supply Voltage	80%	80%	100%
	Input Voltage	70% of V_{CC}	80% of V_{CC}	100% of V_{CC}
	Output Current	75%	75%	100%
	Power Dissipation	75%	85%	100%
	Junction Temperature	105°C	125°C	Mfg. rated max TJ
Bipolar Transistors	Voltage (VCE)	75%	75%	100%
	Voltage (VCB)	75%	75%	100%
	Voltage (VEB)	75%	75%	100%
	Current (IC)	75%	75%	75%
	Power Dissipation	65%	65%	100%
	Junction Temperature	105°C	125°C	Mfg. rated max TJ
MOSFETS	Voltage (VDS)	75%	75%	100%
	Voltage (VGS)	75%	75%	100%
	Current (ID)	75%	75%	75%
	Power Dissipation	65%	65%	100%
	Junction Temperature	105°C	125°C	Mfg. rated max TJ

Thermal Analysis

There are countless models and empirical data studying degradation of semiconductors, all pointing to operating junction temperature as a main cause of failure. So, the ability to minimize the junction temperature of the semiconductor die is critical for product reliability.

To examine this, we use a thermal spreading model (like that in Fig. 3) to predict the junction-to-case temperature rise for each of the semiconductor devices in the hybrid assembly. The analysis ignores heat removed by convection and radiation, since in space, heat dissipation in the hybrid happens strictly by conduction through the package. The model is based on several factors, including:

- Material thermal conductivity
- Length and width of heat flux conduction area
- Material thickness of each layer
- Full load output
- Power dissipation under worst-case operating conditions.

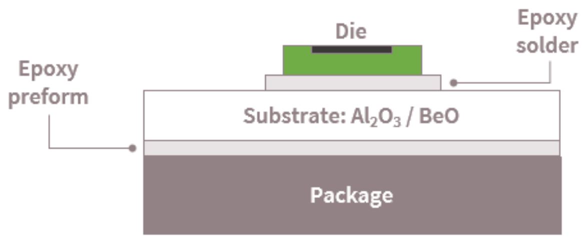


Fig. 3. A thermal spreading model is used to predict the junction-to-case temperature rise for each of the semiconductor devices in the hybrid assembly.

Reliability Analysis

The next step is reliability analysis, or mean time between failures (MTBF), per MIL-HDBK-2017F. This integrates the results of the stress and thermal analyses, and can be used for equipment-level MTBF calculations.

Failure Mode And Effects Analysis

The goals of the FMEA are twofold: first, to systematically analyze potential failure modes and effects of the individual components used in the hybrid dc-dc converter, per MIL-STD-1629A, and second, to understand how to mitigate the risk, typically either through analysis or production testing. Based on our experience, this depth of data helps designers integrate the power converter into their system with the right level of reliability.

Worst-Case Analysis

The WCA determines circuit performance under extreme conditions. Looking at component variability, temperature range, aging and radiation exposure, the analysis results ultimately provide beginning- and end-of-life performance for the converter.

Hybrid dc-dc converters are highly complex circuits, so for this analysis, intricate circuit blocks are broken down into functional ones that are analyzed individually, then combined to predict overall circuit performance. Depending on the circuit, its complexity and risk, we use different analytical methods including extreme value analysis (EVA), root sum of squares (RSS) and Monte Carlo.

The full WCA is based on a combination of manual calculation, computer modeling and simulation, and empirical data. Along with a statement of compliance, the final report includes circuit description, its theory of operation, analysis results and how it impacts the converter when integrated into the intended system. In some cases, a component specification may have to be tuned to meet the converter specification through end of life, which is done under the control of the proprietary component SCD.

IR HiRel’s worst-case analysis for its Class K hybrid dc-dc converters covers the following parameters:

- Undervoltage lockout
- Enable threshold
- Oscillator
- Output regulation
- Overcurrent protection
- Power semiconductor stresses
- Output ripple
- Efficiency and standby currents
- Magnetics
- EMI filter.

TOR-Compliance: When Class K Is Not Enough

Originally issued by The Aerospace Corporation in 2006, the Technical Operating Report established enhanced minimum technical requirements beyond MIL-PRF-38534 Class K for electronics parts, materials and processes used in the design, development and manufacture of spacecraft and launch vehicles. Contributors included major space industry manufacturers such as Boeing, General Dynamics, Harris, Honeywell, Lockheed, Northrop, and Raytheon.

Specific enhancement areas included:

- Components stress derating
- Use of established-reliability components and materials to the maximum extent possible
- Electrical and mechanical design analyses required for extreme operating conditions, including end-of-life performance
- Enhanced element evaluation.

In cases where the mission reliability requirements are above and beyond what Class K defines, IR HiRel works with our customers to produce the specific documentation needed for the program to ensure end-of-life performance of the dc-dc converters.

Rad-Hard By Design, Dependable End-Of-Life Performance

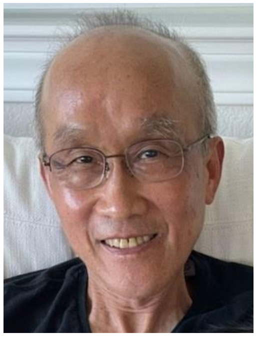
Ultimately, mission-life reliability for space-grade dc-dc converters is built in layers, starting with components that are rad hard by design or test. Hybrid design engineering experience, combined with years of expertise in how to test, qualify and manufacture these types of products, and space flight heritage all play a role.

As discussed in this article, the extensive design analyses add yet another layer of confidence in system performance and reliability over mission life. Undoubtedly a painstaking process, the outcome of which is the reduced risk and utmost confidence that the converter will perform as expected, for as long as needed, throughout the mission.

Acknowledgement

IR HiRel's design methodology is the result of over 20 years of development work in high reliability, rad hard hermetic hybrids by our San Jose Design Center. The team collectively has over 500 years of engineering experience in rad hard hybrid dc-dc converters. The work results from the contributions of several people, including Arturo Arroyo, Steve Baker, Lorentz Ou, Ho-Pu Wu and many others.

About the Author



Peter Lee is a veteran design expert in space power electronics, having spent over four decades engineering rad-hard hermetic hybrid power conversion solutions for International Rectifier HiRel Products, an Infineon Technologies company. He previously directed a research and development team creating a portfolio of space hybrid dc-dc converters that have become standards for space systems. In his current role, he is actively involved in mentoring and educating the next generation of engineers for the company. He believes that product reliability must be an engineer's first priority. Peter holds a BSEE from the University of California, Berkeley and is a member of the IEEE.

For further reading on power supply-related safety and compliance issues, see How2Power's special section on [Power Supply Safety and Compliance](#).