Design for Reliability of Hybrid Multi-Chip Modules for Harsh Environments

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Executive Summary

Multi-chip modules (MCMs) form the backbone of high-reliability electronics. Their hybrid construction gives OEMs direct control over die selection, interconnect design, and assembly stack-up — enabling precise tailoring of both performance and lifetime. Traditional qualification methods, based on temperature acceleration, assumed environments constrained by human operators; avionics bays, crewed vehicles, and industrial cabinets where survivability had to be maintained. That assumption no longer applies.

Continued miniaturization, the digital transformation of infrastructure to the edge, and the rise of autonomous platforms — in space, undersea, or other inaccessible environments — eliminate the design constraint of human thermal limits. Today's electronics must now endure sustained junction temperatures well above 125 °C, for missions measured in decades, with no opportunity for maintenance or repair.

At Spectrum, we have developed a proven Design-for-Reliability (DfR) capability tailored to this reality. By integrating mission-profile capture, physics-of-failure modeling, and multi-stressor accelerated life testing with cumulative exposure and two-zero-failure demonstration, this framework provides statistically defensible assurance of MCM reliability where conventional single-stress testing falls short. More than an incremental improvement, it establishes a new baseline for qualifying hybrid assemblies in the extreme environments that define next-generation edge and autonomous systems.

Introduction

MCMs first emerged in the 1980s and 1990s as a way to increase density and performance before monolithic systems-on-chip (SoCs) dominated. By stacking dies or integrating multiple chips in a single package, they solved interconnect speed and footprint challenges long before "heterogeneous integration" entered the mainstream. After two decades of deployment across wireless, defense, and industrial electronics, MCMs are re-emerging as a cornerstone technology for mission-critical systems. By combining multiple materials and manufacturing processes within a single substrate, advanced heterogeneous integration merges the unique strengths of each technology. The result is higher performance, lower power consumption, improved sustainability, and continued miniaturization. By consolidating more functionality into smaller footprints, hybrid MCMs offer compact, efficient solutions ideally suited to avionics, energy, and industrial IoT applications where reliability is paramount.

The next transition is already underway. Real-time AI optimization, sensor fusion at the edge, and predictive diagnostics all depend on ruggedized microelectronics capable of deterministic performance under extreme conditions. In this role, high-reliability MCMs are more than components — they are system enablers, providing the foundation for digitization, edge processing, and long-term mission assurance. Depending on the scope of integration, an MCM may evolve into a System-in-Package (SIP) components, combining not only multiple chips but also passives, sensors, antennas, and shielding to function as a near-finished subsystem. For the purposes of this paper, the two concepts of MCMs and SIPs are interchangeable. What matters is their ability to sustain consistent performance in unforgiving environments, making them the preferred choice for platforms and applications that must operate uninterrupted for decades.

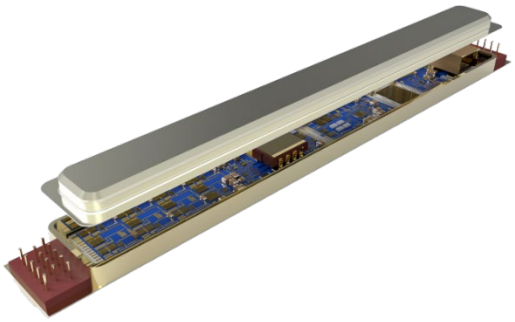

Fig. 1. 3D rendering of a hybrid MCM in a hermetic package.

These applications typically require continuous operation for over 20 years in environments where junction and ambient temperatures often above 125°C [1]. The integration of digital, analogue, and power functions within compact packaging enables high performance in constrained footprints, but it also amplifies the thermal and

mechanical stresses borne by the assembly. Ensuring dependable operation under such conditions demands qualification strategies that go beyond conventional approaches and address the unique limitations imposed by small thermal margins to maximum rated junction temperatures. Bridging this reliability gap is a necessary step toward the widespread adoption of advanced packaging in these domains.

Conventional reliability qualification is typically anchored in High-Temperature Operating Life (HTOL) testing [2], where devices are stressed at elevated temperature to accelerate intrinsic failure mechanisms. However, for advanced MCMs designed for high-temperature environments, the thermal headroom between the maximum rated junction temperature and the intended operating range is often limited to only 10–30 °C. Under such conditions, Arrhenius acceleration factor is weak, which in turn requires impractically long test durations to achieve meaningful lifetime extrapolations. For systems expected to demonstrate decades of reliable performance, this approach becomes both time- and cost-prohibitive.

This paper addresses the challenge of qualifying long-life MCMs when traditional thermal acceleration methods provide little benefit. It introduces a Design for Reliability (DfR) framework that links mission profile capture, physics-of-failure models, and cumulative stress testing into a closed-loop process. By combining constant temperature stress, thermal cycling, vibration tests, the approach provides a more realistic representation of field conditions and enables reliability estimation that extends beyond the limitations of conventional HTOL [3].

DfR Framework for Harsh Environments

The limitations of stand-alone HTOL qualification in avionics applications highlight the need for a broader methodology that embeds reliability considerations across the entire product lifecycle. Modern DfR methods shift the emphasis away from late-stage reliability demonstration and the outdated “test–analyze–fix” philosophy, toward proactively designing reliability into products and processes using physics-based, science-driven methods [1]. A Design for Reliability (DfR) framework provides this structure by linking mission profile capture, physics-of-failure modelling, and cumulative stress testing into a closed loop that spans concept, design, development, manufacturing, and deployment.

Concept Phase: Specify Reliability Goals

Reliability planning begins with the explicit definition of objectives. In avionics, this typically requires continuous operation for 20–30 years at junction temperatures exceeding 150 °C, with additional stresses from power cycling, vibration spectra in the 10–2000 Hz range, and occasional shock events (MIL-STD-810). These usage conditions are formalised in the mission profile, which becomes the reference for all subsequent modelling and test planning.

At this stage, system-level reliability allocations are established using Reliability Block Diagrams (RBDs) or Markov models, while program-level targets are set in terms of both reliability and confidence. For example, avionics modules are often required to demonstrate zero failures in test campaigns: 98.67% reliability at 20 years. The outputs of this phase are therefore a quantified mission profile and a set of programme reliability objectives that can be traced through design and test activities.

Design Phase: Identify Risks and Allocate Reliability

The design phase translates high-level reliability objectives into quantitative rules and design criteria. At this stage, potential vulnerabilities are identified, targets are allocated across assemblies, and architectural dependencies are assessed to ensure that mission requirements can be met over decades of operation.

Failure Mode and Effects Analysis (FMEA) provides the first structured evaluation, highlighting potential single-point weaknesses and guiding design teams toward mitigation actions such as redundancy, derating, or material substitution. Complementing this, baseline reliability predictions are generated using established methods such as MIL-HDBK-217F, FIDES, or manufacturer failure in time (FIT) data. While these estimates serve as an initial benchmark, they are refined through allocation exercises, which cascade system-level reliability requirements down to subsystems, modules, and individual components. This ensures that reliability growth targets are proportionally distributed and aligned with overall mission goals [1].

Architectural resilience is further captured through Fault Tree Analysis (FTA) and Reliability Block Diagram (RBD) modelling. These methods quantify the impact of interdependencies and redundancy on system reliability, helping to prioritise critical paths and guide design trade-

offs. Together, FMEA, allocation, and architectural modelling provide a holistic framework for assessing design robustness before hardware is built.

Physics-of-failure concepts are also introduced conceptually in this phase, establishing the boundary conditions that will later be quantified through accelerated testing. Known thermally activated and stress-driven mechanisms, such as dielectric wear-out, electromigration, and solder fatigue are mapped to mission stresses and materials of concern. Their role here is to inform derating rules and set the foundation for quantitative modelling in the next phase.

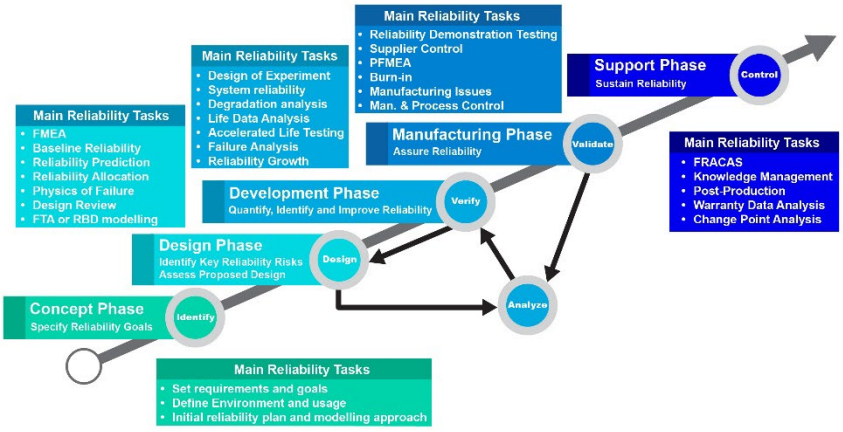

Fig. 2. A generic DfR workflow mapped across product lifecycle (concept, design, development, manufacturing).

Development Phase: Quantify & Improve Reliability

The development phase consolidates the design outputs into quantitative evaluation activities that both measure and improve reliability. Core tasks at this stage include structured design of experiments, system-level reliability assessment, degradation analysis, life data analysis, accelerated life testing, failure analysis, and reliability growth. These activities ensure that boundary conditions identified during design are confronted with empirical evidence and that emerging weaknesses are corrected before qualification.

To improve reliability, accelerated life testing (ALT) is typically employed because it allows degradation and failure mechanisms to be observed within practical test durations and can be qualitative or quantitative depending on the purpose of the test. Qualitative ALT, such as highly accelerated life testing (HALT), **is** typically applied during early development to reveal design weaknesses and dominant failure mechanisms. Quantitative ALT is used to estimate lifetime distributions under mission conditions, and its results can also be used to plan and support reliability demonstration testing (RDT) (discussed in manufacturing phase).

Estimating the life distribution under mission conditions requires testing devices at elevated stresses, recording time-to-failure data, and extrapolating the results back to the intended field profile. This extrapolation relies on acceleration models, which describe how degradation rates vary with stress variables such as temperature, vibration, or thermal cycling, etc. By fitting these models to accelerated test data, test data can be translated into credible field-life predictions. Thermally activated failure mechanisms, such as dielectric breakdown and diffusion, are typically described by the Arrhenius relation [4]:

$$AF = \frac{L_{field}}{L_{Test}} = exp\left[\left(\frac{E_a}{k}\right)\left(\frac{1}{T_{Field}} - \frac{1}{T_{Test}}\right)\right], \quad (1)$$

Solder joint fatigue, caused by repeated thermal expansion and contraction, is one of the dominant cyclic mechanisms. It is captured by the Coffin–Manson acceleration factor:

$$AF = \left(\frac{\Delta T'}{\Delta T}\right)^B, \quad (2)$$

where ΔT and $\Delta T'$ are the temperature range an and B constant characteristic of material properties. In some applications, fatigue life is also a function of the cycling frequency and high temperature where the Norris–Landzberg model is used [4]:

$$AF = \left(\frac{f_{Test}}{f_{Field}}\right)^n \left(\frac{\Delta T_{Test}}{\Delta T_{Field}}\right)^m exp\left[\frac{E_a}{k}\left(\frac{1}{T_{Field}} - \frac{1}{T_{Test}}\right)\right], \quad (3)$$

where ΔT is the temperature swing per cycle, f is the cycling frequency, and m, n are empirical exponents. Vibration-induced degradation is a critical failure mechanism in solder joints. It is often modelled using the Inverse Power Law (IPL), which describes the relationship between fatigue

life and vibration stress level. The acceleration factor (AF) for vibration stress is typically expressed using [5]:

$$AF = \left(\frac{S_{Test}}{S_{Field}}\right)^{n}, \quad (4)$$

where n is vibration exponent and S_{Test} and S_{Field} are the vibration levels under test and mission conditions respectively.

While single-stress models are adequate for typical consumer electronics, avionics missions demand more. Relying on one stress often results in weak acceleration and tests that are too long to be practical. Two complementary aspects are therefore required. First, quantitative ALT is used to estimate life distributions under combined stresses and ensure predictions extend to multi-decade operation. Second, RDT demonstrates compliance with reliability targets at the required confidence level. Together, these activities move beyond single-stressor assumptions and provide both predictive insight and statistical assurance for long-life MCMs.

To generate quantitative lifetime distributions, multi-stressor accelerated life testing (ALT) methodologies have been developed. These methods enable lifetime estimation under combined stresses and provide mechanism-specific distributions that reflect mission conditions. A widely used approach is the Generalized Eyring–Weibull (GEW) framework, which combines the Weibull life distribution with a generalized acceleration model to account for multiple stressors (e.g., temperature, humidity, vibration). Unlike single-stress models such as Arrhenius or inverse power law, GEW supports simultaneous modelling of thermal and non-thermal stresses, making it suitable for complex environments.

The 2P Weibull probability density function (PDF) is [5]:

$$f(t \mid \eta, \beta) = \frac{\beta t^{\beta-1}}{\eta^{\beta}} \, exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \quad (5)$$

where η is the characteristic life (scale parameter) and β is shape parameter. To incorporate stress dependence, the characteristic life is expressed through physics-based acceleration models. A common choice is the generalised Eyring relationship.

For example, under combined constant-temperature and vibration stress conditions, the characteristic life (η) can be written as [6]:

$$\eta(T, V) = \; c.exp\left(\frac{E_a}{kT}\right) V^{-n} \quad (6)$$

Substituting this into the Weibull PDF yields the Weibull–Arrhenius–IPL model [5]:

$$f(t|T, V) = \frac{\beta t^{\beta-1}}{\eta(T, V)^{\beta}} \, exp\left[-\left(\frac{t}{\eta(T, V)}\right)^{\beta}\right] \quad (7)$$

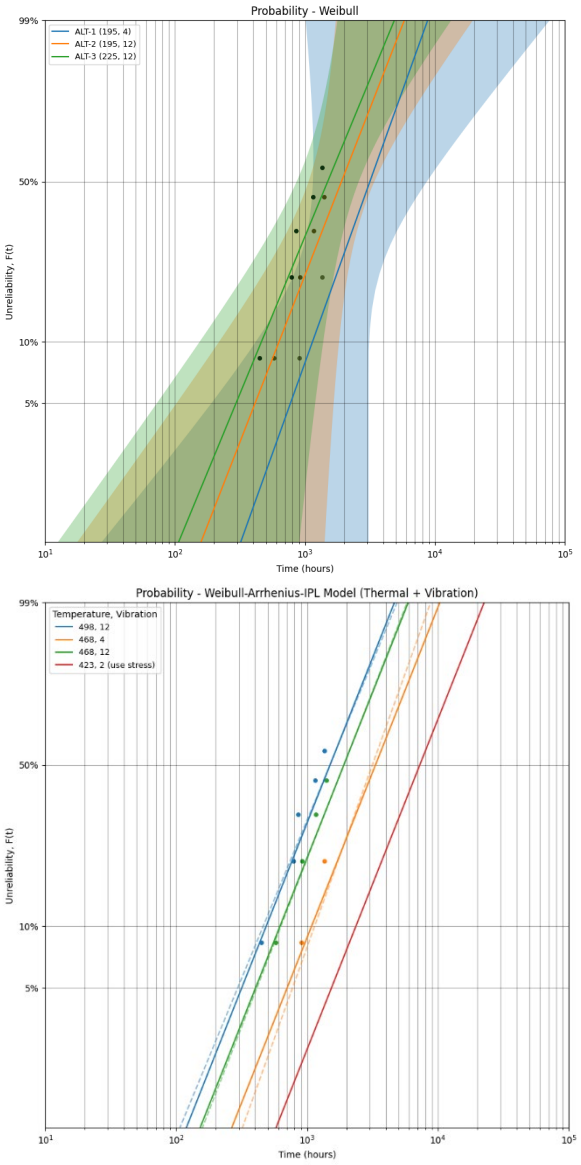

Fig. 3. ALT probability plots. Top: independent Weibull fits at each stress condition (CL = 80%). Bottom: Weibull–Arrhenius–IPL model providing a unified fit across stresses and projection to mission use (150 °C, 2 G_{rms}).

This integrated model offers a practical and physically interpretable framework for estimating lifetime distributions under mission-relevant stresses. Fig. 3 illustrates an example with two levels of analysis derived from ALT data under combined thermal and vibration stresses. The first involves independent two-parameter Weibull fits for each stress condition, providing direct stress–life distributions as observed during testing. The second applies a combined Weibull–Arrhenius–IPL model, which unifies all stress groups (ALT1–3) under a single parameterisation that captures the effects of both temperature and vibration. This model enables physics-based extrapolation to mission conditions and provides a consistent basis for long-term lifetime prediction in avionics MCMs.

Manufacturing Phase: Assure Reliability in Production

The transition from development to manufacturing shifts the emphasis from modelling to cumulative exposure testing, statistical demonstration, and process control. In avionics, qualification requires that reliability targets be both predicted and demonstrated with sufficient statistical confidence. Because sample sizes are typically limited and lifetimes must be shown at 20–30 years of continuous operation, zero-failure demonstration tests are widely employed.

Under a two-zero-failure plan, the reliability that can be claimed at a given confidence level is expressed as [6]:

$$R = 1 - (1 - CL)^{1/n}, \tag{8}$$

where R is the demonstrated reliability, CL is the confidence level, and n is the sample size with zero observed failures. For time-censored tests, where cumulative exposure is accumulated over a fixed duration, the zero-failure demonstration can also be expressed under the exponential model as [6]

$$R(t) = exp\left(-\frac{ln(1 - CL)}{T_{Test}}.t\right), \tag{9}$$

where T_{Test} is the total accumulated device hours on test and t is the mission duration.

Reliability demonstration testing (RDT) is central to manufacturing qualification because it translates reliability targets into statistically defensible evidence under mission conditions. Because long-duration tests cannot rely solely on temperature acceleration (as already discussed in the development section), RDT incorporates multiple PoF models within a cumulative exposure model [7]. For example, vibration, temperature, and thermal cycling can be combined, each linked to its governing PoF law and mapped back to mission life. This approach ensures that demonstration test duration is practicable and also reflects the multi-stresses experienced in practice.

A representative case of a multi-stressor RDT programme is the qualification of an optical transceiver MCM for avionics, targeting 98.67% reliability (80% one-sided lower confidence) over 20 years at 150 °C junction temperature shown in Table I. The programme combined Arrhenius temperature acceleration for intrinsic wear-out, Norris–Landzberg thermal cycling for interconnect fatigue, and vibration IPL models for chip-attach integrity.

RDT – Cumulative Exposure Model								
	Acceleration Model-Stress	2P Weibull β	Acceptable # of Failures	CL	AF	Test Time Field Stress	Test Time Test Stress	Cumulative Reliability
Test 1	IPL-Vibration	2.5	0	80%	3015	144720	48	73%
Test 2	Norris Landzberg Thermal Cycling 1	2	0	80%	2.1	285984	67268	93.81%
Test 3	Norris Landzberg Thermal Cycling 1	2	0	80%	6.6	427248	21403	97.53%
Test 4	Arrhenius Temperature	1.2	0	80%	26	557577	5012	98.67%

Table I. Cumulative exposure programme used for Reliability Demonstration Testing (RDT).

Together, statistical demonstration under a two-zero-failure plan and ongoing process 2Zcontrol provide the foundation for manufacturing release, translating the reliability objectives defined at concept and refined through design and development into verifiable production-level assurance suitable for avionics deployment.

Support Phase: Sustain & Update Reliability

Qualification and manufacturing release do not mark the end of reliability assurance. For avionics MCMs sustaining reliability in the field is as critical as demonstrating it at the outset. The support phase establishes the mechanisms by which reliability is monitored, updated, and controlled throughout the system's life. A core element is the implementation of Failure Reporting, Analysis, and Corrective Action Systems (FRACAS). Field anomalies, whether detected during scheduled maintenance or in service, are systematically recorded, analysed, and resolved, providing a closed-loop mechanism for detecting latent issues and preventing recurrence. Change-point

analysis and Weibull updating techniques are then applied to field failure data to identify shifts in reliability performance. These statistical tools allow emerging wear-out trends or sudden changes in failure behaviour to be detected early, supporting proactive corrective action. The support phase therefore closes the lifecycle loop.

Looking beyond current practices, advanced approaches are emerging to extend DfR with predictive and adaptive capabilities. Bayesian accelerated life testing (ALT) frameworks allow prior knowledge from design models and qualification tests to be continuously updated with new field observations, producing posterior reliability estimates that evolve with accumulated evidence [8]. Digital twin methodologies extend this further by embedding physics-of-failure models into virtual replicas of deployed systems, enabling predictive analytics that combine stress histories, environmental monitoring, and usage patterns [9]. In avionics applications, these approaches provide not only improved fidelity in reliability estimation but also actionable insights for maintenance scheduling and mission planning.

Conclusion

Ensuring decades-long reliability of multi-chip modules (MCMs) in harsh environments requires moving beyond traditional temperature-based qualification. This paper demonstrated a Design for Reliability (DfR) framework that embeds reliability across concept, design, development, manufacturing, and support. By combining mission profile capture, physics-of-failure modelling, and multi-stressor accelerated life testing with cumulative exposure and two-zero-failure demonstration, the framework delivers both predictive insight and statistical assurance. It provides a scalable path for qualifying MCMs to meet the stringent demands of avionics and industrial applications, while emerging tools such as Bayesian updating and digital twins promise further improvements in sustaining reliability over system lifetimes.

For more information on hybrid MCMs and other solutions from Spectrum Control visit spectrumcontrol.com

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