

Systemic Root Cause Early Failure Analysis during Accelerated Reliability Testing of Mass Produced Mobility Electronics

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ABSTRACT

Failure analysis (FA) and accelerated testing are essential tools used in mobility electronics. Yet, FA's role is underestimated and underutilized. Its administration lacks standardization and support, esp., during multi-stress accelerated reliability testing (ART). Proposed three-stage systemic early FA (SEFA) methodology provides feedback using conventional and original systematic hierarchical complementary multidisciplinary comparative tools and methods focusing on prevalent early failures (EF). Subject matter result-oriented technical root-cause FA (RCFA) is a vital part of SEFA. This paper outlines three-phase RCFA methodology along with specific methods, tools, and examples related to ART. Presented EF classifications interpret EFs' symptoms, mechanisms, and causes and propose corrective actions. Suitable RCFA-SEFA improve products and ART by precluding-resolving prevalent EF.

CITATION: Verbitsky, D., "Systemic Root Cause Early Failure Analysis during Accelerated Reliability Testing of Mass Produced Mobility Electronics," *SAE Int. J. Mater. Manf.* 9(3):2016, doi:10.4271/2016-01-0319.

INTRODUCTION

Mobility electronics are used widely in ground transportation, industrial, sea and aerospace-military (ASM) technologies, which operate in diverse and stressful environments. Modern market and global competition demand high yield; low levels of complaints, returns, and recalls; easy maintenance and speedy smooth innovations. This combination reaffirms old and creates new interrelated safety, quality, reliability, improvement-development, profitability, and testing (SQRIPT) challenges [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Mobility electronics design encompasses high speed and density analog, digital, mixed, power and special segments, diverse materials and parts; with refined software, broadband technologies, and radio frequencies. Manufacturing processes include group operations, automated and manual equipment, and also expensive tests, measurements, inspections, screenings, and qualifications (T&M). As a result, modern mass-produced mobility electronics are challenging to develop, manufacture, and maintain.

Accelerated tests utilized by mobility electronics usually follow rigorous standards and are an essential and effective part of modern electronics high SQRIPT features. Customized accelerated reliability tests (ART), however, may use multiple concurrent and/or extreme stresses (e.g., simultaneous "shakes and bakes"), tailoring and extending classical definitions and recommendations for specific needs. Both standard and customized ART are used at different phases of project and product life cycles: prediction, evaluation and verification of new designs and technologies; periodic requalification of mass-produced or modified products; manufacturing screenings and sorting, etc. Due to ART specifics, they can cause unpredictable positive and negative synergetic effects, which need feedback, calibration and adjustment to fulfill intended missions. Typically, this feedback is provided using failure analysis (FA), physics of failure

(POF) and reliability physics (RP) applied to ART, manufacturing, field samples and data (e.g., see Table 1 and [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]).

Indeed, functional nonconformities (failures) during ART are often complex events. They may be caused by unit under test (UUT) specifics (called "relevant" failures); by ART deficiencies (termed "irrelevant" failures) as well as by various miscellaneous and mixed problems. Irrelevant failures increase manufacturer risk and cost Alfa causing extra expenses. The worst-case scenario, however, involves missed or ignored failures, which allow "bad" products to slip into the field (so-called "customer risk" Beta). The field-test automodeling needs to simulate real-life failure modes, mechanisms and root causes (FMMC) nomenclature, classes and ratios with corresponding distribution of individual time to failure (TTF_{ij}) for each j-th FMMC_j and each i-th UUT_i. FA role during ART is incomparably high if field units are not available for analysis (e.g., one-time use demanding ASM products) [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35].

Electronics failures are typically explained by long-term cumulative stress-strength relation and/or gradual material degradations. On the contrary, early failures (EF) are traditionally explained by poor workmanship, escapes, misuse, weak parts, external damage, space particles, single event upset, electrostatic discharge (ESD), electromagnetic interference (EMI), etc. Yet, EF result in the highest customer's losses and frustration and are costly for the manufacturers. The most dangerous systemic recurring EF, associated with persistent significant assignable interrelated SQRIPT challenges, may be called prevalent ones. Prevalent EF include serious consistent malfunctions as well as temporary functional, but unreliable nonconformities. Basic containment, corrective and preventive actions (CAPA),

rigorous T&M, graded parts, redundancy are supposed to prevent EF. Yet, these good standard measures are inherently expensive and do not guarantee sufficient field protection unless the most important FMMC and their POF and RP are revealed, understood, contained, mitigated and/or removed [10, 11, 12, 13, 14, 15, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35]).

ART, especially its customized multi-stress variants, need FA-POFRP knowledge to correctly affect different segments of modern electronics (e.g., die-chip, assembly, package, modules, PCB, device, systems, etc.). Result-oriented subject matter FA is essential to quality and reliability assurance and ART design, performance, and interpretation. Root cause FA (RCFA) is a key part of FA. RCFA connects prevalent failures with fundamental features, functions, factors, forces, freaks, fluctuations, faults and fixes (F9 concept). A suitable closed loop ART-T&M-RCFA-MAD-CAPA process allows building combined multifaceted SQRIPT potential into the technology and organization rather than counting onto intuitive “probes and errors”-like costly and risky “solutions”. Proper RCFA recommends optimal CAPA supported by right management’s assessments, decisions and directions (MAD). [10, 11, 12, 13, 14, 15, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33].

Yet, in spite of the clear necessity of RCFA, its goals, organization, utilization and relation to FMMC, POF and RP have been frequently misunderstood and underestimated. For example, new revisions of general standards mention nonconformities, but reduce the task to statistical data analysis. Few industrial standards require general FA and those cases are limited to specific products. Thus, despite an abundance of successful specific cases, RCFA lacks guidance and execution confusing management and practitioners [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 28, 29, 30, 31, 32, 33, 34, 35].

The author’s three-stage systemic early failure analysis methodology, SEFA, is believed to adequately address the interrelated SQRIPT challenges of the modern mobility electronics (Fig. 1). Suitable FA methodology is proven to be basically universal while specific methods and tools depend on FMMC-POF-RP, product level and technology, ART, application details and resources available. Thus, SEFA approach is equally applicable to a broad range of T&M method, product’s technology and applications. The goal of this paper is to describe and exemplify prevalent EF types and classifications, practical RCFA organization and methods during various ART of modern mobility electronics.

EARLY FAILURE SPECIFICS

EFs involve malfunctions that occur during fabrication, ART, T&M, storage, handling, transportation, next level assembly, or use roughly within warranty time or equivalent testing (typically one year or ~8,000 hours). EF during the first ~100 hours of a product’s field deployment may be called super-early failure. Failures before the field deployment may be called prenatal EF, which would be consistent with traditional terms “infant mortality”, “normal/useful life”, and “product’s life time/cycle, health and diagnostics” [10, 11, 12, 13, 14, 15, 18, 19, 20, 28, 29, 30, 31, 32, 33, 34, 35].

In addition to true malfunctions, prenatal EF losses include temporary functional, but unreliable nonconformities, i.e., potential malfunctioning hazards rejected by T&M because they do not fit within specifications or manufacturing safe margins. This group in particular comprises marginal parametric shifts; visual functionally challenging nonconformities (e.g., contacts); hermetic leaks; unsuitable conformal coating and packages, etc. The temporary functional nonconformities also include intermittent, unbalanced and marginal parametric malfunctions. Temporarily functioning, prenatal and ART FA role is especially high if field samples are not available and trouble prevention completely rely on manufacturing, R&D and lab samples (e.g., single mission ASM perishables) [10, 11, 12, 13, 14, 15, 28, 29, 30, 31, 32, 33].

EF studies have revealed the following practical probabilistically deterministic specifics of the prevalent mass-produced electronics EF (cited here as EF-tailored Juran’s rules) [31, 32, 33]:

- The prevalent EF (urgent, systemic, assignable, chronic) cause most (approximately 80-90%) of SQRIPT-related troubles;
- Most of EF (roughly 80-90%) are caused by ~10-20% of vital FMMC (inherent or pertinent);
- About 80-90% of FMMC concern 10-20% of vital segments, parts, materials (mostly application-specific);
- About 80-90% of prevalent infant field EF share common FMMC with ~80-90% of prenatal and normal-life failures;
- Even marginal EF drop (~10-20%) may dramatically increase customers’ satisfaction; conversely, minor ~5-10% raise in EF could cause dramatic customers’ dissatisfaction.

Thus, suitable infant and prenatal RCFA concurrently improve field safety and reliability, reduce manufacturing losses, facilitate R&D and new project’s implementation (e.g., refer to [10, 11, 12, 13, 14, 15, 28, 29, 30, 31, 32, 33, 34, 35]).

EF TYPES AND CLASSIFICATIONS

Suitable EF classifications could significantly help to assess FMMC nature, scale and priority guiding to appropriate CAPA. Military standards and some literature distinguish relevant and irrelevant failures depending on whether they are caused by UUT or by other factors (e.g., ART deficiencies, overstress, and misuse). This classification may be complemented by another very important class, featuring missing failures. They occur due to inadequate technical documentation, inspection, test coverage or ART (“test escapes”). This class is more dangerous than irrelevant one since misleading and deceptively good results typically enable noncompliant products to pass unnoticed until field deployment. Both irrelevant and missing ART failures violate the automodeling principle, but with opposite signs: extra or lost EF quantities, or TTF_{ij} vs. field data, increasing Alfa and Beta risks, respectively [5, 6, 7, 8, 9, 10, 11, 12, 20, 28, 29, 30, 31, 32, 33].

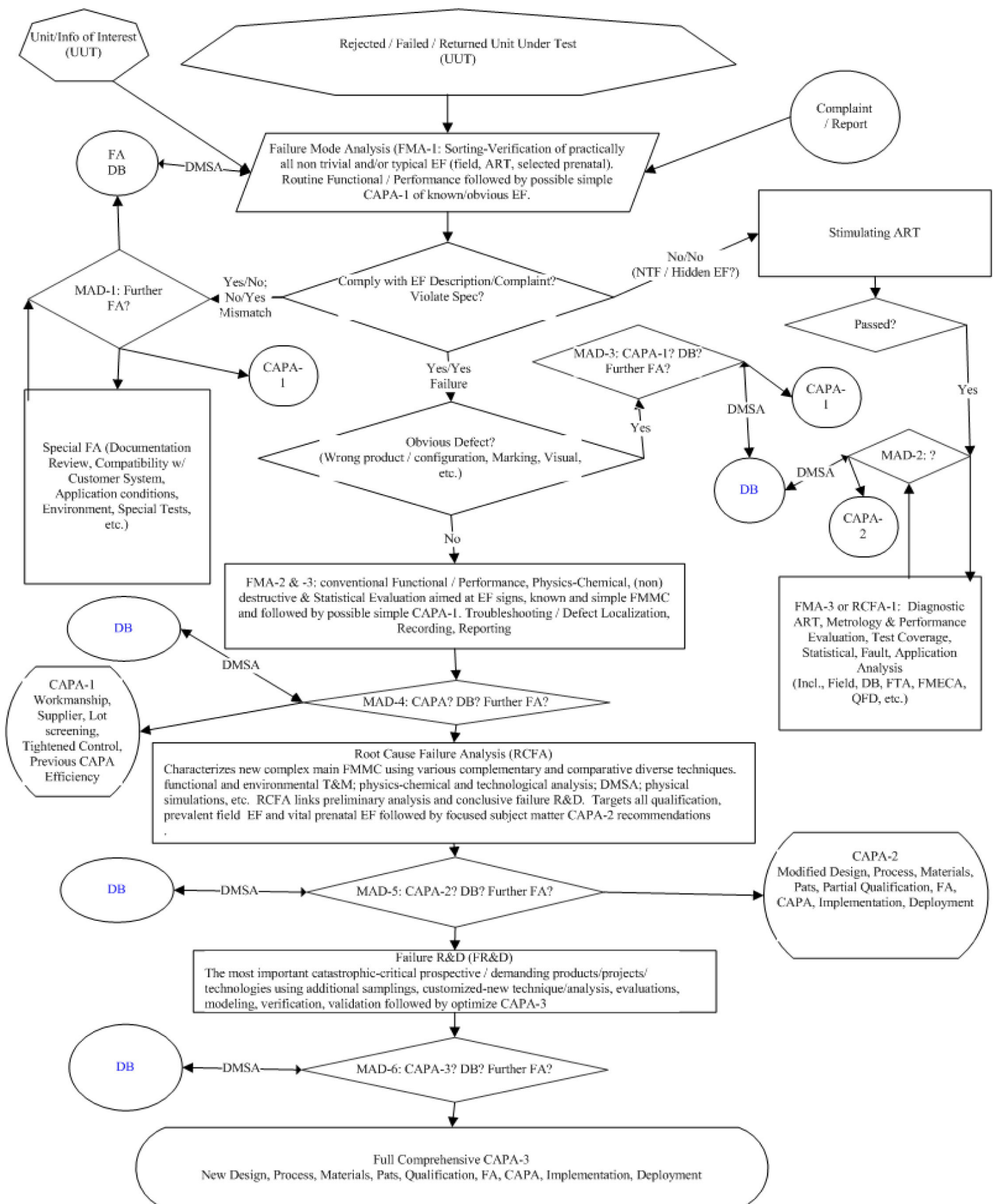


Figure 1. General SEFA Organizational Structure. MAD-Management Assessment and Decision/Direction; (F)NC-(Functional) Nonconformity (Failure); DB-Data Base; CAPA-Corrective and Preventive Action; F(M)A- Failure (Mode) Analysis; RCFA-Root Cause Failure Analysis; SDA-Statistical Data Analysis

One of the main EF-tailored Juran's rules has shown that a combination of fundamental (intrinsic-inherent-built-in) (ir)regular and (ab)normal features, factors, functions, forces, freaks along with cause ~ 80-90% of prevalent early FMMC rather than just probabilistic chances. This distinguishes true prevalent recurring built-in FMMC from mostly (mainly) sporadic, (seemingly) random, (semi) isolated process's, part's or operator's fluctuations, faults and failures, which qualify for quasi-prevalent or pseudo-prevalent EF, respectively (F9 concept). A joint F9-FTA-FMECA technique significantly improves analysis compared with usually disconnected FTA and FMECA limited by sporadic F9 [10, 11, 31, 32, 33].

The author also proposed P7 classification which is particularly helpful for SCRIPT and FMMC characterization to determine SEFACAPA "depth and breadth" based upon practical and proportional to problem's, product's, project's and peculiarity's properties and probabilities (P7). The main P7 classes include the following:

- P7-inherent-urgent:-fundamental, super-prevalent, product model-line-technology F9 scale, which cause mission-catastrophic SQRIP losses and/or risks dramatically/ significantly above a spec and necessitate emergency RCFA-CAPA, under top MAD control.
- P7-pertinent, prevalent, product model-line F9 scale, which generate critical SQRIP losses and/or risks considerably above the spec and require urgent RCFA-CAPA under MAD control.
- P7-specific/particular: quasi-prevalent major lot/batch-process scaled F9, major losses and/or risks tackled by FA-CAPA per standard operational procedures.
- P7-extraneous, peculiar: pseudo-prevalent marginal unit-process deviation-scaled F9 associated with random isolated tolerable EF usually monitored and addressed by FMA-CAPA as needed for SQRIP scale/level maintenance.
- P7-irrelevant: minor random isolated controlled F9, below the noise level, which do not require CAPA unless special SQRIP scale upgrade is desirable.

The first two classes frequently make up Juran's 20% vital failures, which cause 80% losses. They include all qualification EF, prevalent field, prenatal and R&D EF and justify RCFA. Next classes usually require monitoring FMA [10, 31, 32, 33].

Many early FMMC-POF-RP may be classified via previously proposed probabilistic-deterministic interactions; scalable degradations and deteriorations; drifts, shifts and unbalanced products accelerated by detrimental F9 and their synergetic interactions. Some normal-life and wearout failures appear to be addressed by a mixture of classical phenomenological POF-RP models, conventional Juran's "interacting dimensions" and Pecht-Dasgupta-Condra "stress-strength", "damage-endurance", "challenge-response" and "tolerance-requirement" models. This classification looks quite helpful for FMMCs-POF-RP related to classical gradual parametric drifts, occasional overstress-damages and fixed dimension-tolerance requirements [10, 11, 12, 20, 31, 32, 33].

Yet, traditional classifications do not suggest characteristic signs and root causes of failures. These include environment-functionality-induced degradations; abnormal/unexpected ("freaky") parametric parts (distributions, behavior) and/or inadequate system resilience. Besides, the conventional classifications do not address prevalent EF specifics: fast-to-avalanched degenerations and destructions; systemic recurrence; link with EF-tailored Juran's rules, P7 and F9 concepts; reversible isentropic malfunctions, etc. In order to adapt previous classifications to the specifics of mass-produced electronics prevalent EF, the following classes and their sources are proposed below (called here DIS7 concept for mnemonic purpose):

- Internal destruction (may be cumulative and gradual as suggested by conventional classification above or single catastrophic impact; caused by strains, tensions, impurity).
- Product-external (ir)relevant damages (may be cumulative, gradual per conventional classification or a vital impact e.g., overstress, inadequate equipment, fixture, T&M, storage, transportation, ESD, etc.).
- Initial strength deficiency (e.g., low coupling; narrow trace-wire; weak material/part, circuitry, mechanics, software).
- Insufficient internal robustness: part's unsteadiness, balance, debris; metastability-instability; incompatibility, corrosion, migration
- Deficient protection (e.g., porous-thin coating or passivation; electrical or hermetic leaks; EMI-ESD-EOS shieldscircuitries-software).
- Inadequate resilience vs. functional-environment loads, stresses and/or time (shifts, drifts, safe margin, software, alignment, balance, voltage spikes, polarity, etc.).
- Physically steady isentropic freaks (broadened traditional "challenge-response" and "tolerance-requirement"): "odd" materials, parts, software, system, application (isolated or massive); T&M metrology, coverage, errors; unexpected electrical/mechanical properties, etc.).
- Various miscellaneous and mixed interactive FMMC.

The above-proposed tentative DIS7 classification is based on broad interdisciplinary experience, but is a subject of further improvement and needs the following comments and examples. DIS7 classes and definitions equally apply to prevalent and unusual failures. They may be result of a single (super)dominant F9 and/or its interaction with some auxiliary F9 or synergetic result of several (quasi)equal matching and/or complementary F9. Due to complexity of F9, interactions or DIS7 class' overlaps live EF frequently belong to several DIS7 classes. An effect of rigid material's thickness and structure on brittle fraction's evolution may be assigned to (a), (d), (f) DIS7 classes. A fast corrosion/migration caused by inadequate internal purity, deficient protection and low resilience during ART match (d-f) classes (Fig.3-5). Isentropic signal's distortions/errors due to an unbalanced circuitry; "freaky" parts parametric distributions and their shifts; non-adaptable software and system tolerance fit DIS7c-g classes above (e.g., many high-speed, audio and radio reversible or "steady" EF) [10, 13, 14, 15, 18, 20, 28 35].