Electronic Materials Aging

Contact: Gordon Long — glong@mitre.org

JSR-20-2B

November 2020

JASON
The MITRE Corporation
7515 Colshire Drive
McLean, Virginia 22102-7508
(703) 983-6997

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
November 2020

2. REPORT TYPE

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Electronic Materials Aging

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
1319JAPM

5e. TASK NUMBER
PS

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The MITRE Corporation
JASON Program Office
7515 Colshire Drive
McLean, Virginia 22102

8. PERFORMING ORGANIZATION REPORT NUMBER
JSR-20-2B

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Nuclear Security Administration
NA-115, Office of Engineering and Technology Maturation
1000 Independence Ave SW, Washington, DC 20585

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION D. Distribution authorized to National Nuclear Security Administration and their contractors only. Reason: report addresses official use only information and activities. Other requests for this document shall be referred to NA-115, Office of Engineering and Technology Maturation.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

JASON was tasked to recommend rapid discovery processes to more effectively uncover electronic material and device aging and failure modes. In addition, JASON was asked to suggest methods to determine, verify, and validate device reliability in an accelerated way. Also, JASON was asked to suggest ways to improve the scientific understanding of the aging of electronic materials to expedite testing and screening, i.e., qualification procedures, while increasing the evidence for improved reliability. Finally, JASON was asked to suggest ways to use modeling and simulation as predictive tools to meet the above challenges. This report summarizes JASON's efforts to provide guidance on science-based discovery processes to uncover aging and failure modes in electronic materials and devices, so that the responsible NNSA teams can effectively determine, verify, and validate device reliability in an accelerated way.

15. SUBJECT TERMS
COTS electricity, bathtub curve, airborne electronics, materials and accelerated aging, square root biased

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
OUO	OUO	OUO	UL		Ross Agee
					19b. TELEPHONE NUMBER *(include area code)* 202-586-2772

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Contents

1 EXECUTIVE SUMMARY

Nuclear weapon performance requirements include lifetimes in the 20 or 30 year range, though it is not unusual for weapons systems stored in the US Stockpile to experience lifetimes beyond their requirements. Commercial off-the-shelf (COTS) electronic parts and systems, familiar from their many uses in commercial applications, are used with increasing frequency in modernization and life extension programs for nuclear weapons. The impetus for using COTS electronics in military applications, including nuclear weapons systems, arises from the opportunity to benefit from the sophistication and rapid pace of development for commercial electronics, which drive towards smaller size, weight, and power consumption, with improved performance, while eliminating the high costs and long development times that traditionally plague the defense industry.

During storage, most of the electronic materials and components within a nuclear weapons system are unpowered and electrically inactive over a majority of the system lifetime; when activated they need to function only for a short time. NNSA, sponsor of this report, described how determining the reliability of successfully executing a demanding, short duration, operational sequence over extended lifetimes, after a long dormancy, challenges NNSA's ability to model, predict, and meet system performance requirements under Stockpile to Target Sequence environments. This JASON Study addresses the challenge of assuring reliability of Stockpile weapons given the increased use of COTS electronics for maintenance and mitigations, especially as new generations of COTS technology are being introduced rapidly in the commercial sector. The Study focuses on the intersection of the scientific understanding of materials aging and the failure modes and mechanisms of electrical components and devices, with approaches used to test, screen, and monitor aging components and systems, to maintain the reliability of nuclear weapons.

JASON was tasked to recommend rapid discovery processes to more effectively uncover electronic material and device aging and failure modes. In addition, JASON was asked to suggest methods to determine, verify, and validate device reliability in an accelerated way. Also, JASON was asked to suggest ways to improve the scientific understanding of the aging of electronic materials to expedite testing and screening, i.e., qualification procedures, while increasing the evidence for improved reliability. Finally, JASON was asked to suggest ways to use modeling and simulation as predictive tools to meet the above challenges. This report summarizes JASON's efforts to provide guidance on science-based discovery processes to uncover aging and failure modes in electronic materials and devices, so that the responsible NNSA teams can effectively determine, verify, and validate device reliability in an accelerated way.

JASON gathered information for this report from two days of briefings organized by the Sponsor and a separate virtual tour of Integra, which is the company responsible for testing of electrical components, and the electronic subsystems and systems, acquired and assembled by the Kansas City National Security Campus and Sandia National Laboratories. In addition, JASON organized seven presentations or discussions with experts from industries and academia on topics central to this Study. The Sponsor also answered JASON requests for additional information during the seven-week period that the Study was performed.

Research and assessments by JASON highlighted the materials science challenges associated with understanding aging phenomena and failure modes of COTS materials and systems that are largely dormant over decades. The failure modes affecting electronic *components* (with their continual evolution to smaller feature sizes), such as electromigration and diffusion, are different from, although related to, the failure modes of *circuits and subsystems* (with their interfaces, connectors, wire bonds, solder joints, etc.), where substrate warping, whisker formation, crack growth, and the like dominate. The aeronautics, aerospace, automotive, and medical device industries face similar design and assembly challenges – to ensure reliable performance and extremely low failure rates in electronics built with commercial components, often for high-consequence applications.

To achieve a robust, up-to-date, and science-informed process to understand and mitigate failure modes of aging electronics, JASON emphasizes the need for an effective organizational and leadership structure, so that NNSA can verify, validate, and monitor device reliability. A forward-looking program of focused materials research and development, as well as assessment, is essential for NNSA to stay ahead of issues that will arise in selecting and qualifying future COTS electronic components. This will remain important as long as consumer electronics continue to change rapidly; there is no one-and-done solution that will solve the challenges associated with materials aging and reliability of COTS electronic systems with long dormancy. The science and engineering approaches to be developed must include a means to share new knowledge learned, including the expected failure modes for electrical components and devices and the impact of aging, and to promulgate strategies to mitigate possible problems. In this way, future life extension programs can benefit from the accumulated wisdom of prior studies and experience.

In order to achieve the goals of more reliable weapons systems, JASON recommends the Physics of Failure approach, which is based on understanding possible modes of failure, and combines experimental and simulation tools to narrow the design space to achieve more reliable systems. NNSA can learn from industry, NASA, and the Department of Defense's experience with Design for Reliability, which is a framework to conceptually incorporate the goal of reliability into the full life cycle of a system from design through obsolescence. Design for Reliability combines a bottom-up approach, assembling parts into a full system (analogous to NNSA's existing program to integrate COTS electronics into nuclear weapons systems), along with a top-down assessment of system reliability.

To address the Statement of Work, JASON identified Findings and made Recommendations that ran through the themes of COTS electronics, science topics central to aging of materials, electronic components, and systems, Physics of Failure as a design strategy informed by better understanding of possible modes of failure, and Design for Reliability as a process for accountability and reliability growth. The Findings and Recommendations are given below.

1.1 Findings

1. The rapid design cycle for commercial off-the-shelf (COTS) electronics is aligned with the demands of commercial markets, but does not align with design cycles or lifetime requirements for weapons systems, nor does it enable a well-controlled supply chain for components (e.g., resistors, capacitors, printed wire boards, etc.) needed for weapons applications.

   (a) Traditionally, variability in the quality and reliability of parts, as well as concern about future availability of parts due to obsolescence, is partially mitigated by life-of-program buys for weapon systems, thus missing future upgrades in performance and capabilities possible with short design time cycles.

   (b) There can be corresponding challenges in assuring reliability in new electronic technologies using legacy military standard tests.

2. The challenges associated with ensuring high reliability of COTS electronics over long times, under demanding environmental conditions, and for high-consequence applications, are also found in the aeronautics, aerospace, automotive, and medical device industries. These in-

dustries have developed, and continue to develop, approaches to manage the challenges of aging and reliability assurance, including investigating the materials level processes that cause electronics to fail when stresses are applied. While each industry faces different environmental stresses (e.g., temperature, humidity, and atmosphere), there can be significant commonality in the underlying mechanisms of aging and failure. Information sharing can accelerate each sector's work to assess aging under their specific stressors.

3. A goal of reliable performance after 40-60 years of un-monitored storage poses difficult, and perhaps unrealistic, challenges for electronic components to electrical subsystems and systems, whether or not COTS materials are utilized. Reliability in the presence of material aging can be improved by careful assessment of defects and their mechanisms of evolution, integrating self-tests into the system, monitoring characteristics at regular time intervals, and life-cycle replacements.

4. Understanding the aging of materials, components, and subsystems involves:

    (a) mechanisms that span from atomic to the micron (and larger) scales;

    (b) designs and material processing steps that introduce structural heterogeneity (including interfaces and defects);

    (c) manufacturing steps in assembling subsystems and systems from components that may be imperfectly compatible; and

    (d) the environmental conditions and history that introduce chemical and mechanical stresses that can drive changes.

    All of these factors should be assessed before new electronic devices or systems are introduced into a weapon system.

5. It is well known that most physical processes in electronic materials have rates whose temperature dependence is more complex than simple Arrhenius behavior, arising from multiple activated processes and their interactions. However, parametric testing design often relies on such simplified assumptions, which may lead to incorrect lifetime estimates.

6. The risk of failures due to aging requires increased attention because of rapid advances in miniaturization of electronic components and increased parts density in electronic systems. Components with smaller feature sizes can be more susceptible to degradation than larger ones, if these issues have not been addressed in their design, because:

   (a) In powered systems, voltages are applied over shorter device distances, leading to larger electric fields. This may lead to high field-induced materials changes, including local stresses.

   (b) Diffusion lengths over the decades of storage may be commensurate with critical materials or device sizes (e.g., a grain size or a metal thickness).

   (c) Larger components, containing multiple crystal grains or multiple ferroelectric domains (in capacitors as well as transducers), have parallel and redundant transport pathways, making their properties and performance more robust.

   Assessing electronic materials, devices, and systems requires increasing power characterization techniques to locate and assess possible pathways to failure.

7. (b) (5)

(b) (5) [redacted]

8. Traditional over-voltage testing, which can reveal manufacturing variability, may not yield useful information about aging-related effects in dormant parts.

9. There is a trade-off in highly accelerated stress screening (HASS) between finding defects and not damaging the items that pass the test, i.e., creating "walking wounded." In other cases, legacy tests may no longer be appropriate for modern electronics, so reconsideration of screening protocols for COTS components is warranted.

10. In qualification testing, a subset (or lot) of items is tested to identify poorly performing items, poor manufacturing processes, etc. A natural way to allocate resources is to assign the number of tests for a given failure mode in proportion to the corresponding a priori estimated probability of failure, which is "strong profiling." However, a mathematically optimal strategy for screening, given a fixed resource, is "square-root biased sampling", where the distribution of tests is based on the square root of the a priori probabilities.

11. Concepts such as *Physics of Failure* and *Design for Reliability* overcome some of the shortcomings of the standards-based reliability tests recommended in MIL handbooks. Industry continues to utilize and develop robust reliability programs that combine Physics of Failure and Reliability Growth processes seeking to ensure that qualified COTS components can perform over long periods and survive dormant phases. Simulation capabilities have shown promise in assisting the reliability

analysis of electronics in industry, but it is not clear how well this approach has been adopted or is being developed within NNSA as part of their reliability activities.

12. A variety of physical processes, including electromechanical and acoustic resonance technology, can provide sensitive indicators of changes in electronic materials and circuits. The development of Power Spectrum Analysis techniques for exploiting such signatures should provide nondestructive means to identify internal defects, such as cracks, delamination, and voids, and other early signatures of aging-related failures, and may provide a route for periodic monitoring of stored components and systems.

13. Reliability Growth, as conceived by DOD and industry, aims to improve reliability over time; it is a practice and not a mathematical model. Reliability Growth has been proven to be an effective way to maintain a system from acquisition through to retirement.

14. The next generation of reliability management processes includes Design for Reliability and Design for "X," where X can be function, manufacturability, testing, reliability, or sustainment. DOD and industry have already adopted Design for Reliability. NNSA and SNL are interested in these processes and are considering their use, but JASON lacked documentation to understand whether the COTS Transformation Initiative would achieve the goals of Design for Reliability with respect to integrating COTS electronic materials into nuclear weapons systems.

15. Monitoring and surveillance of Stockpile weapons is used to identify signs of aging and to initiate mitigations for defects that are found. This approach compensates for the risk of incomplete understanding of the aging of materials and systems.

16. NNSA has multiple parallel paths addressing COTS certification and reliability with complex rules, unclear decision-making and reporting requirements. This perceived complexity can result in protracted timelines for solving problems that other industries solve effectively in months.

1.2 Recommendations

JASON provides 15 recommendations. The first recommendation provides an overall structure to a materials-science informed, Physics of Failure and Design for Reliability plan that is then amplified by the recommendations that follow.

1. NNSA should create an Electronic Materials Reliability Coordination Plan (EMRCP) under which the research efforts on electronic materials aging work cooperatively, and have well-defined responsibilities to support the use of COTS electronics in the Stockpile. Such a plan should include coordination among:

    (a) systematic research on the changing materials and designs of COTS electronics that will be available for future use in the Stockpile;

    (b) linked experimental and modeling research on defects and aging processes and development of predictive tests for various components and assemblies

    (c) materials evaluation and selection of reliable components;

    (d) component, subsystem, and system testing focused on the most likely failure modes and linked iteratively to modeling at relevant scales;

    (e) surveillance of both components and actual systems, and additional "witness" components and systems;

    (f) assessing life-cycle replacement for different electronics subsystems

(g) with (a-f) linked via a Physics of Failure and Design for Reliability process.

To accomplish these steps, NNSA's EMRCP should include a focused materials sciences research program that anticipates and addresses the evolving COTS technology landscape, which will likely be driven by non-defense market pressures. The program should have responsibility to characterize the relevant material properties, including failure modes, so that science-based understanding of new materials and component choices will already be in place when the need arises to use new COTS components. A framework should be established to share this knowledge with the responsible program teams.

2. NNSA should partner with the Department of Defense and NASA to support the formation of a COTS Reliability Consortium with aeronautics, aerospace, automotive, and biomedical device companies to share common knowledge and practices, and possibly to leverage COTS manufacturers to produce designs with long lifetimes that enhance long-term reliability and minimize aging of both dormant and powered components and systems. Cooperation in the materials research relevant to the use of COTS electronics in reliability-critical applications should reduce unnecessary duplication, saving resources, and producing better results.

    (a) NNSA should form a "storage-aging advisory panel" with experts in materials science, electronics, and reliability, from government agencies and laboratories, universities, and industry, to evaluate the impact of the evolution in COTS electronics on systems reliability for high-consequence applications.

    (b) NNSA should invest in basic materials science research aimed at characterizing the reliability-impacting aging processes that occur at the ever-smaller feature sizes found in COTS electronic components. Experiments, theory and simulation must all play an essential role in such a program, with machine learning potentially offering new insights from data-rich experiments.

3. NNSA's EMRCP should accelerate the process by which new COTS electronics materials and devices can be assessed and qualified for use in the Stockpile by systematically evaluating the changing materials, manufacturing, and designs against a baseline of trusted materials and devices. This work will require a well-designed plan of research with an integrated, iterative process of experimental characterization, modeling, and evaluation of outcomes of stress testing.

4. NNSA's EMRCP should include development of component and subsystem designs that enable regular monitoring through subsystem testing done in the field, in order to ensure reliable functioning of the electronics components. There should be a suitable plan for this surveillance activity, which allows only limited access to the interior of the system, with no further disassembly required.

5. NNSA's EMRCP should consider implementing continuous, automated recording of the environments to which all components and systems are exposed, including temperature, humidity, power, and vibration (accelerations) so that there are clear records that can inform characterization of any faults that are discovered.

6. NNSA should view with skepticism expectations of long-term stability and reliability when adopting COTS electronic components whose design and manufacture were predicated on applications in commerical products with limited service lifetimes. This is especially true for technologies like BME MLCCs, where commercial pressures for maximum energy density force the adoption of exceptionally small feature sizes, and where the reactivity of the materials requires processes and dopants whose impact on component lifetimes is not fully understood.

7. (b) (5) [redacted]

8. The effectiveness of over-voltage testing of electronic components, e.g., as used in COTS Qualification, to determine suitability for long-term dormant reliability needs to be re-examined.

9. Stress screening in different tests should be targeted at the most likely modes of failure for a given component or system. Reconsideration should be given to tests that overstress parts, since these may introduce "walking wounded" in the Stockpile.

10. For qualification testing, NNSA should consider the mathematically optimal strategy of "square-root biased sampling", where the distribution of tests is based on the square root of the a priori probabilities.

11. During or before the design phase, SNL should develop a scientific understanding of the most probable failure modes of COTS components and the circuits assembled from them. An accurate model of the device and system must be created, i.e., coupled electrical, mechanical, and thermal responses, which should be used to improve designs and model behavior of stored systems. Experiments are needed to verify and validate the simulations.

12. NNSA's EMRCP should develop rapid, non-destructive testing methods, including electrical, electromechanical, and acoustic resonance, designed to identify defects (micro-cracks, delamination, or voids) that are likely to result in component or system failures during storage aging.

Establishing a database of such device "fingerprints" will allow changes of individual units to be monitored over the life of a system.

13. NNSA should formalize their adoption and use of Design for X processes, including Design for Surveillance and, most particularly, Design for Reliability, in the design and management of their weapons systems. This step requires broad collaboration from fundamental materials scientists to surveillance engineers. To succeed, the process needs to be intentional, documented, and tracked.

14. NNSA's EMRCP should consider complementing or extending the existing surveillence program by using "witness systems," whereby a large number of each of the electronic components, subsystems, and systems are assembled, placed in a representative test environment, left mostly unpowered as the actual systems of interest, and monitored periodically for the lifetime of the weapon system. The low cost of the electronic components and subsystems may enable a larger-scale supplement to the traditional surveillance program than is possible for fully operational systems.

    (a) NNSA's EMRCP should complement or extend the existing surveillence program by locating aged examples of components in storage, such as never-powered-up "old stock" and logistics stockpiles (not necessarily weapons stockpiles) that may contain components purchased 20-30 years ago, and test appropriately to establish failure rates and failure mechanisms. These contemporary aged components may not have been stored in as benign environments as the systems of concern, but helpful inputs to reliability assessments can come from these "witness components."

15. NNSA's EMRCP should evaluate the feasibility and advisability of a life-cycle replacement approach for each of the major electronic subsystems to reduce the risk associated with aging of COTS components.

This Page Intentionally Left Blank

2 INTRODUCTION

2.1 Study Objectives

Reliability of the performance of US nuclear weapons is critical to deterrence. The lifetimes of the weapons span decades, modernization programs take years to decades, and the design requirements are discussed in terms of a 20-30 year time frame, though it is not unusual for actual lifetimes to be longer. Commercial off-the-shelf (COTS) electronic parts are used frequently within the modernization programs. The systematic use of COTS electronics within military programs began already in 1994 with a memo from Defense Secretary William Perry, "Specifications & Standards - A New Way of Doing Business." The evolution of the commercial market for electrical, electronic, and electromechanical parts has only accelerated the use of COTS components in military systems.

Most of the electronic materials and components within a weapon system are electrically inactive for a majority of the system lifetime. Determining the reliability of successfully executing a highly demanding, short-duration, operational sequence for systems that have been dormant over extended time periods challenges our ability to model, predict, and meet system performance requirements under Stockpile to Target Sequence (STS) environments. Traditional methods for probing failure rates and evaluating probabilities related to successful performance, so as to assess the reliability of the weapons systems, are focused on systems with a normal duty cycle and so may not be appropriate for the long dormancy of electrical components of relevance here.

Thus, the Sponsor seeks new approaches to rapidly discover failure mechanisms and aging phenomena needed to ensure that high reliability electronics are fielded to the Stockpile. This increased materials science understanding is particularly important for COTS electronic materials. Increased understanding of electronic materials at the individual component, device, and next level of assembly should reduce occurrences of yet undiscovered failure mechanisms or unique aging behavior that limits service lifetime.

2.2 Statement of Work

The Statement of Work is given in Appendix 1, Chapter 12. JASON was tasked with recommending rapid discovery processes to more effectively uncover material and electronic device aging and failure modes. Further JASON was asked to suggest methods to determine, verify and validate device reliability in an accelerated way. New approaches to improve electronic aging understanding are also desired to reduce reliability and qualification testing while increasing the evidence for reliability. Input on the use of modeling and simulation as predictive tools is also a desired outcome. JASON was posed six questions:

1. For COTS electronic materials and components, how can we use materials science knowledge to improve accelerated aging testing methods to better understand the impact of aging on reliability and confidently qualify components for deployments of 20 years or more?
2. Considering the long dormant periods of most system components, does NNSA's approach to accelerated aging in COTS electronic materials and components appropriately probe aging phenomena and uncover potential aging and failure mechanisms?
3. Are current techniques to determine and validate electronic material and device reliability estimates appropriate for long dormancy, short duration high-demand operations over extended lifetimes?
4. Considering Reliability Growth Models, as used in DoD reliability methods, are there improvements to the current NNSA/DOE reliability methods to

   (a) accelerate qualification;
   (b) increase confidence in reliability estimates by leveraging systems and sub-system testing during development and qualification;
   (c) reduce qualification and/or production acceptance testing protocols.

5. What changes could be made to the NNSA COTS testing methods that would reduce the overall time to qualify, while preserving high reliability operation of electronic assemblies?

6. What are the critical science areas that need further consideration and review (if any)?

We provide answers to these questions in Chapter 10.

2.3 Study Process

The background for the Study was obtained from two sets of briefings, both virtual given the COVID-19 pandemic. On 22 June 2020, we received a two-hour virtual tour of Integra, the company responsible for testing of electrical components, and the electronic subsystems and systems, acquired and assembled by the Kansas City National Security Campus (KCNSC) and Sandia National Laboratories (SNL). There was both a presentation and a walking video tour of the facility.[1] We also received two briefings from speakers[2] with extensive industrial knowledge of COTS electronic components, including issues of materials science and reliability. On 29-30 June 2020 we received two days of briefings from government and academia[3] organized by the Sponsor,

[1] We thank John Baima (Integra) and Terry Davis (KCNSC).

[2] Kerry Bernstein, formerly an engineer with IBM as well as a DARPA program manager, and Gordon Charles, formerly a General Manager with Analog Devices.

[3] The briefers were Ed Cole (SNL), Terry Davis (KCNSC), Jesse Leitner (NASA Goddard Space Flight Center), Rudy Mijares (AFMC), Scott Nicolaysen (SNL), Heather Quinn (LANL), John Schwartz (SNL), Dawn Skala (SNL), Susan Trolier-McKinstry (Penn State), Paul Vianco (SNL) and Rena Zurn (SNL).

covering materials science, reliability, and aging topics central to the study, testing methodologies, the SNL approach to reliability, the DoD approach to reliability, the DOE-Space and NASA approaches to COTS electronics, and SNL surveillance activities. We thank Rachel Barnhill (NNSA) and Matthew Johnson (NNSA) for organizing these two days of briefings and for providing additional information during the discussions and as follow-ups to the briefings.

In addition, the Study team engaged a number of experts from industry and academia for additional presentations and discussions around the themes of materials aging, reliability, dormant storage, and simulation tools, including (i) 7 July 2020: Alan Devoe, the CEO of Presidio Components, which is a US manufacturer of high reliability ceramic capacitors; (ii) 13 July 2020: Ann Swift, an expert in reliability engineering from IBM; (iii) 14 July 2020: Clive Randall, a Professor of Materials Science at Penn State, who is an expert on base metal electrode multilayer ceramic capacitors; (iv) 15 and 20 July 2020: Daniel Weidman, MIT Lincoln Laboratory, who is an expert on reliability and dormant electronics; and (v) 21 July 2020: Ed Dodd and Gil Sharon from Ansys Sherlock, a company that provides automated electronics design analysis software using methodologies based on the procedures known as Physics of Failure. A list of the titles of the presentations is provided in Appendix 2, §13. We thank all of these individuals for sharing their time and expertise, which gave us a much enhanced view of capabilities outside the NNSA and the National Laboratories relevant to the themes of this report.

2.4 Aging of Electronics in the Stockpile

For the purposes of this report, aging refers to physical and chemical changes to a material that alter the function of the component, circuit, device, or assembly. The effects can be gradual, e.g., a change in a material property such as an increase in resistivity, or abrupt, such as fracture of a solder joint or failure of the component to function at all. Typical electrical equipment is powered, which continually drives some level of electromigration and places the material under some elevated stress. In contrast, the materials under consideration in this report will likely be unpowered during most of their lifetime. In addition, various thermally and stress-driven transport processes are active and can drive physical and chemical changes, which, even if slow on the scale of a few years, can become significant on the time scale of decades. These stresses are generally associated with chemical and mechanical changes driven by environmental conditions, whether it is mean temperature, temperature cycling, humidity, or mechanical stress such as warpage of the materials as a consequence of handling or the effects of different environmental conditions, etc. The rates of chemical and physical changes, even for materials in a dormant state, are important since the technological evolution of COTS electronics produces functional features in devices with ever smaller scales so that reduced times are needed for a change in function-relevant structural characteristics. These topics will be discussed more at several places in this report.

2.5 Structure of the Report

This report has individual Chapters discussing themes central to the questions posed to JASON. In particular, we provided discussion of

CHAPTER 3: COMMERCIAL OFF-THE-SHELF ELECTRONICS Provides background on COTS electronic materials, including their use in industry and prior studies of the aging of electronic materials.

CHAPTER 4: MATERIALS AND ACCELERATED AGING Provides a discussion of a number of important materials science themes relevant to the issues surrounding how materials evolve in time. Brief discussions are given of molecular level Arrhenius models, the possible influence of diffusion on time scales of many decades for devices with small (nanometer scale) features, and stress-driven macroscopic scale changes such as voids and whiskers.

CHAPTER 5: A CASE STUDY: CAPACITORS Provides a brief discussion of the trade-off between the use of precious metal electrode multilayer ceramic capacitors (MLCCs) versus base metal electrode (BME) MLCCs. (b) (5) [redacted] Some remarks about appropriate use of accelerated life testing are also given.

CHAPTER 6: PHYSICS OF FAILURE CHARACTERIZATION OF MATERIALS, DEVICES AND CIRCUITS Provides a brief discussion of the use of physical responses of materials and devices to various stresses, including Power Spectrum Analysis and electromechanical and mechanical (acoustic) stresses, to characterize COTS components and assemblies. The idea of 'fingerprinting" using such responses may provide a means for tracking changes over years and decades.

CHAPTER 7: TESTING AND PHYSICS OF FAILURE Provides a brief discussion of accelerated life testing for qualifying materials for weapons systems and the Stockpile. The approach known as Physics of Failure, which is used for assessing possible failure modes and so gives feedback to improve the designs, is discussed.

CHAPTER 8: RELIABILITY GROWTH The management process used to improve the reliability of a system, from the design to the end of life, is described. This approach is used successfully by the Department of Defense and in industry.

CHAPTER 9: CONTEXT FOR THE RECOMMENDATIONS Provides discussion on structural issues associated with the NNSA efforts to do qualification testing and surveillance of COTS electronic components, including working with materials science groups for scientific and engineering input. This context informs the Recommendations.

CHAPTER 10: ANSWERS TO THE SPONSOR'S QUESTIONS JASON provides brief answers to the Sponsor's questions, which were listed in the Statement of Work.

CHAPTER 11: FINDINGS AND RECOMMENDATIONS The various Findings and Recommendations that are provided in each of the Chapters are listed.

This Page Intentionally Left Blank

3 COMMERCIAL OFF-THE-SHELF ELECTRONICS

3.1 Background

Commercial off-the-shelf (COTS) electronics refer to electronic components that are passive (inductors, resistors, capacitors) or active (filters, diodes, switches, integrated circuits,) and whose designs are driven by commerical applications. More generally, the Society of Automotive Engineers (SAE) defines COTS electronics as "An electronic component developed by a supplier for multiple customers, whose design and configuration are controlled by the supplier's or an industry specification." In addition to the individual electrical components, COTS can refer to electronic assemblies and electromechanical assemblies. COTS can also include software enabled technologies, e.g., transitioning from application-specific integrated circuits (ASICs) to field programmable gate arrays (FPGAs) moves from fixed, application-specific circuits to software-enabled logic circuits that can be applied to future generations of hardware. As a general feature, the development of architectural design standards for COTS electronic components means that typically they can be integrated together. The electronics and electromechanical systems can then be adopted for use in government applications, including the military, without changes.

On top of this picture of the electronics market we can superpose Moore's law and other similar scaling theories, which effectively describe the increase in functionality and density as well as the decrease in critical dimensions for electronic components over time. The technological changes have been driven by new materials, new and smaller fabrication methods, and advances in integration tools. Two illustrations of this shrinking of electronics technology are shown in Figure 1, including (a) the decrease in dimensions, from about 100 nm to close to 10 nm, of CMOS devices starting in 2003 and (b) a field-

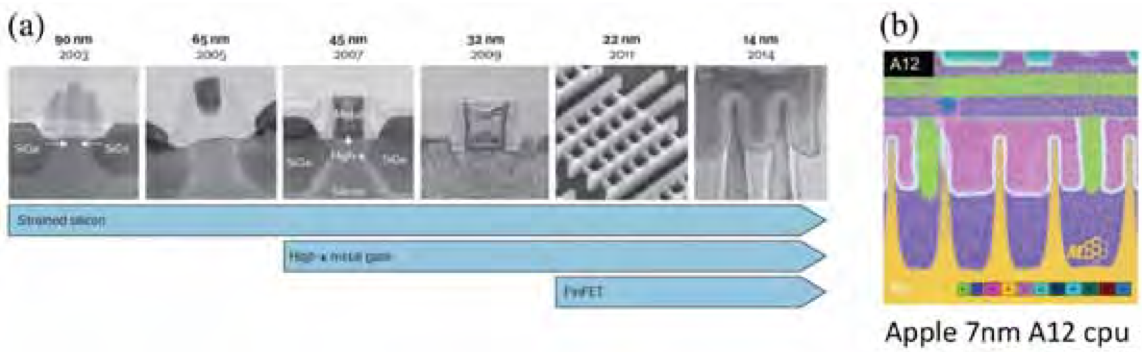


Figure 1: The decreasing feature size of electronic components. (a) The shrinking of CMOS technology from 2003 – 2014 [1]. (b) A field-effect transistor used in the Apple A12 CPU, where different colors indicate different atomic elements used in the 7 nm fabrication process.

effect transistor used in the Apple A12 CPU, where different colors indicate different atomic elements used in the 7 nm fabrication process. In many related technological advances, layers of different materials are commonly used. In addition, a well known example of advances in COTS electronics through reductions in device size can be illustrated by comparing two microprocessors - the Intel 4004 (1971) and the Intel®10th-generation Core™i7 (2019). The smallest feature size decreased a thousand times from 10 microns to 10 nanometers, and the clock rate increased by a comparable factor from 740 kHz to 1.3 GHz. The number of transistors increased a million times, and the computing power (the product of the number of transistors and the clock rate) increased a billion times.

Thus, the desire to use COTS electronics in non-commerical applications arises from the opportunity to leverage the rapid pace of development and sophistication of commercial electronics. By using COTS parts, Defense Agencies can leverage large commercial investments in manufacturing, the drive towards smaller size, weight, and power consumption, and increased performance, while eliminating high costs and long development times that traditionally plague the defense industry. At this time, COTS electronic components and materials have at least partially replaced the custom designed and fabricated parts that were used previously for weapons systems.

In this Study there is a focus on material behavior of COTS electronic components as it impacts performance and aging of dormant (stored, largely unpowered) systems. As will be discussed more below, decreasing length scales representative of the continued technological innovations introduce challenges for materials over long time scales due to the natural evolution of materials. For example, the radical reduction in feature size ℓ_f in COTS components and devices can change the nature of failure modes and has implications for the time scale over which some failure modes may appear. For atoms and vacancies, with diffusion constant D, the diffusion length in time t is $\ell \approx (Dt)^{1/2}$, so failure through diffusive processes becomes more important at longer time scales, possibly those comparable to storage times. Likewise, for structural defects such as dislocations and grain boundaries, the relative size a/ℓ of an atom (scale a) becomes a larger fraction of the local geometry, and so the ratio of the surface energy to the bulk energy varies as $1/\ell$. These considerations become important as the device size continues to shrink, and additional materials and interfaces are packed into a smaller structure. We will discuss these topics in more depth in Chapter 4.

3.2 Technical Challenges to COTS Reliability for Military Applications

Several decades ago, the military was a significant consumer and driver of electronic applications. Traditionally, in weapons systems, custom parts were used and strong control was exerted over the part manufacturers; reliability still had to be assessed. From the 1970s to the mid-1990s this fraction dropped from 20 % of commercial sales to about 1 %, where it remains today. Sales data of integrated circuits from recent years make clear that the military remains only a small fraction of the electronics market and so cannot alone be expected to drive new products, enforce quality, or improve reliability (Figure 2).

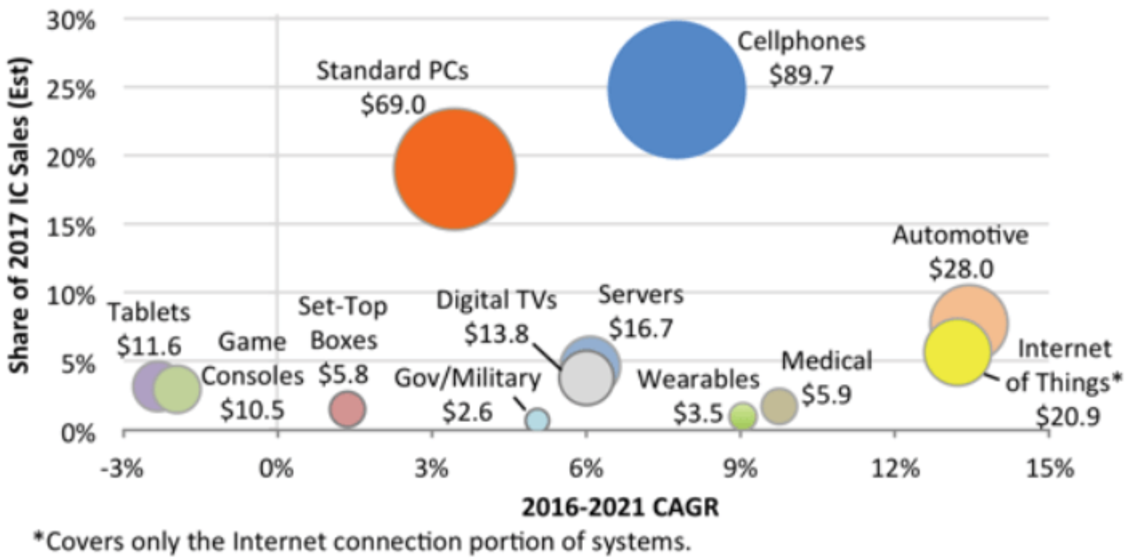


Figure 2: IC Sales versus compound annual growth rate (CAGR). (b) (5) [redacted]

There are challenges with utilizing COTS electronics for weapons applications. The reliability of COTS parts is in some cases unproven, because they have been in existence for a only short time, and can be difficult to assess, because they are typically aimed at a short-term commercial market. Furthermore, the use of COTS parts brings with it an inherent risk due to the lack confidence in the traceability of the materials used in manufacturing, differences in the targeted lifetimes and use environments in defense applications, counterfeiting, lack of influence on the electronic designs, and the perception of a lack of quality. Because the timescale for the turnover of the COTS technologies has shortened, obsolescence of components is a continuing issue, though this can be compensated by making life-of-program buys, which brings its own risks when the system may be expected to be operational for many decades. All of the above features mean that the transformation to COTS electronics poses challenges to life extension programs and other weapons programs. Nevertheless, (b) (5) [redacted]

The Sponsor's questions for this Study are driven by these long-term trends as well as recent experience in component production, (b) (5) [redacted] Longer term, however, there is the concern that COTS parts are increasingly driving what is available for microelectronics, so NNSA is considering approaches to integrate the kinds of electronic components they expect to be able to obtain in the future. An additional stress with this evolution of technology is that the cycle time for modernization of COTS has grown increasingly shorter, so a new component or circuit may be generations out of date in a decade or two.

If successfully implemented, COTS electronics can be expected to produce substantial cost savings and reduced time to produce a first operational unit, (b) (5) [redacted] The approach to use COTS parts in a war reserve system was not without risk, and represented a new paradigm that spanned all stages of development, production, and surveillance." Thus, the War Reserve COTS Insertion Process (WRCIP) began in FY2001. (b) (5) [redacted]

(b) [redacted] the approach and development, including developing a detailed database for electronic components, was rated a success [4]. (b) (5) [redacted]

3.3 Industrial Approaches to COTS Reliability

The consumer electronics industry generates enormous numbers of devices with limited lifetimes, which precludes this industrial sector from worrying much about long-time reliability. In contrast, military applications require high reliability over long times, and typically involve challenging environmental conditions. Some of these requirements and conditions are also found in the aeronautics, aerospace, automotive, and medical device industries. The challenges of incorporating COTS electronics into designs has been recognized in these industries, which are thus impacted by consumer electronic trends, methodologies for testing, and reliability in the face of increasing miniaturization, etc.

For their longer-life systems, these technology-rich industries face challenges associated with aging. For example, the automotive industry appears to be facing similar reliability and aging issues and seeks reliability (e.g., robustness during use, safety, security) over time frames of at least 10-15 years. For subcomponents, the automotive industry targets a failure standard of 0 ppm over 15 years for sub-components generally [5] and specifically for Electronic Control Units "a target of <10 ppm/year and 1 ppm/year concerning each subcomponent" [6]. These needs are accentuated as electric cars become more common. Also, aging of materials and electronic packages impacts aerospace systems: it is not uncommon for development of satellites to take on the order of four to seven years, so they face challenges with dormant electronic systems put in place early in the project, with the added feature that after launch it is generally not possible to service the equipment.

While JASON recognizes differences between the challenges faced in weapons-related, deterrence-critical technologies, here we indicate some common themes regarding COTS electronics, aging, and reliability expressed for automotive technologies. For example, [5] note:

"Using state-of-the-art semiconductor process technologies for devices in a car is necessary to fulfill today's performance requirements and even more future requirements with respect to the e-car. But it leads to a mission which seems to be a paradox: combining more robustness of the complete system and quality of its subcomponents with less mature technologies. A way out of this dilemma can only be found by reviewing carefully today's qualification and validation processes and understand their strengths, weaknesses and capabilities. This must be the starting point for an evolution to a qualification strategy which is suitable for this fundamentally changed situation. Therefore the limits of today's qualification methods will be discussed as well as some suggestions for future strategies will be made to bring complexity, quality and robustness in an early phase of product lifetime together. The roles of the parties in the supply chain shall be highlighted in these strategies as well."

As a further example of the thinking that is present in the automotive design space, we note that [6] highlight: "Key [problems] that emerge from a general analysis of requirement[s] for robustness in automotive components are:"

1. "Identification of safety critical behaviors not protected by redundancy, thus introducing the need [for] additional efforts to be guaranteed safe;
2. Selection and evaluation of proper test to quickly identify and possibly correct random faults appearing along useful lifetime;

3. Integration of the test procedures into the mission operating system, taking care of security issues that may eventually originate."

Specifically, from a briefer (Gordon Charles), JASON heard that analog integrated circuit suppliers must work hard to meet automotive reliability specifications, and perhaps that it is much harder to meet automotive reliability specifications than to meet MIL-SPEC. For example, lifetime failure specifications from a circuit company perspective were said to be approximately 500 – 1000 parts per million (ppm) for the consumer sector, 50 – 100 ppm for the industrial sector, and 1 ppm (on a 15-20 year lifetime) for the automotive sector. One plausible conclusion from these failure rates is that if you want to design a reliable product, buy your parts from an automotive supplier since they have both the high-reliability mandate and the volume necessary to identify all of the defects down to ppm levels, and they will have the data to back up their claims.

One operational feature suggested in the literature on reliability in the automotive industry is a triangular interaction between the semiconductor manufacturers, the COTS manufacturers, and the original equipment manufacturers (OEM) [5]. In the weapons system of interest to the Study, the latter would be the team of SNL and KCNSC. This "triangular information exchange" contrasts with the more linear structure apparent in the SNL approach to managing reliability.

Continuous process and design improvements on COTS electronics for the weapons application may be more difficult since the military is a relatively small buyer compared to other commercial consumers. One approach to leverage the suppliers so as to influence process improvement in the commercial sector would be to join with companies in the aeronautics, aerospace, automotive, and medical devices industries, which share at least some of the technical, safety and aging challenges. As will be discussed more below, a possible alternative approach to seeking reliability for function following many dormant decades is to have shorter design cycles with more frequent system updates; the lifetime is then limited to the next iteration of the design cycle. Of course, this approach will bring with it other, possibly more serious, reliability issues.

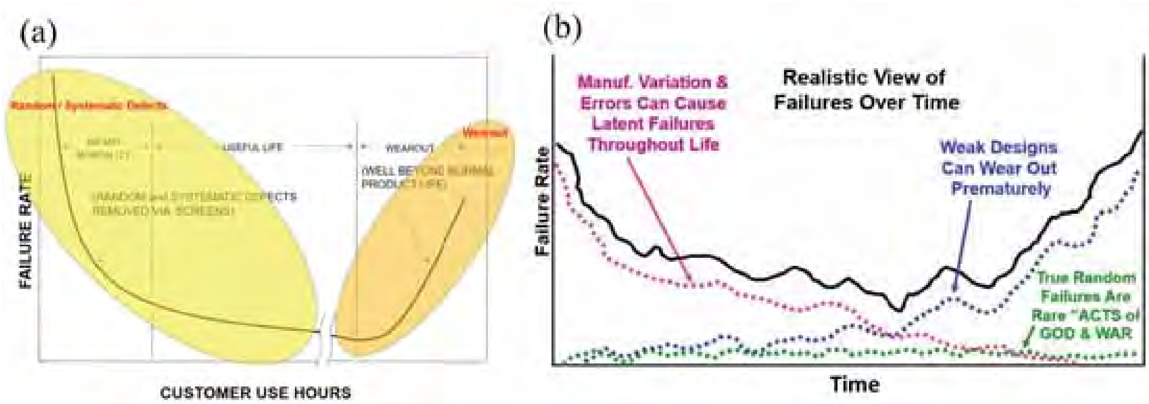


Figure 3: The bathtub curve. (a) A traditional interpretation based on roughly independent time periods of material and/or system responses [7]. (b) A modern interpretation in terms of the sum of three independent failure rates [8].

3.4 The Bathtub Curve

In reliability studies, a standard characterization of the failure rate of a system versus operational time is presented in terms of the bathtub curve, which is shown by the black curve in Figure 3(a) [7]; the elliptical regions of different colors were used by one industrial briefer (A. Swift from IBM) to emphasize the variability to be expected with this general trend. There is a traditional interpretation of the time variation in failures, which was offered in nearly every briefing where reliability was a theme, which is based on roughly independent time periods of material and/or system responses: A sharp decrease in the early time failure rate ("infant mortalities") is followed by a period where the failure rate is constant, which is typically described as random failures; finally, wear-out sets in and the failure rate increases more rapidly.

While a conceptually simple depiction of reliability over the lifetime of a system, the bathtub curve is not necessarily useful for quantifying the actual system lifetime. The modern literature, apparently better informed by data on the failure rate of materials and systems, offers a more nuanced interpretation of the shape of the bathtub curve (Figure 3(b)). Instead, the response is understood as the sum of three independent failure rates active during the operational life of a system: a decreasing failure rate tied to the quality of the part and its manufacturing, an increasing failure rate due to wear-out, and a small number of random occurrences [8]. Understanding the multiple contributors to the failure rate during the lifetime of a system, which for the nuclear deterrent applications of interest here is mostly unpowered, is one of the challenges faced when integrating COTS electronics in the Stockpile.

3.5 Earlier Studies of Materials Aging

Industrial and governmental studies focused on equipment aging are not new. Indeed, many of the challenges faced today have much in common with the technical considerations and approaches to reliability that were part of earlier studies. For example, a 1980 study of safety-related equipment for nuclear power plants, which at the time were to be designed for 40 year lifetimes for which no data on equipment functionality at such long times was available, concluded that “The dominant picture that results from the study is that there is no comprehensive, scientifically rigorous solution to the problem of accelerating the aging of equipment. Aging that can be accelerated in ways that yield verifiable correlation between real and simulated aging is an exception rather than the rule. Since degradation due to aging is generally a very complex process, this is not a surprising conclusion ...” [9]. The authors noted in Chapter 3 of [9], which was focused on the concepts important to accelerated aging, that such tests were important for equipment qualification for nuclear safety applications. As an approach to handling this problem, the suggestion was made that “Surveillance keyed to the known degradation/failure mechanisms of equipment is a potential complement to, if not a substitute for, accelerated aging." These issues will also appear in this report. We will also highlight that advances in numerical simulation tools, and Physics of Failure approaches, offer more insights for assessing reliability of dormant systems than was available just a couple of decades ago.

3.6 Prior Studies of Reliability of Electronics Dormant for Long Periods

Even prior to the ready availability and ubiquity of integration of electrical circuits, and COTS electronics in particular, it was common for electronic components to sit idle for long periods of times, e.g., safety systems present in automotive or aerospace vehicles, missile defense systems, fire alarms, etc. Closer to the applications at hand, there are sea mines and artillery shells (utilizing proximity fuzes and more complicated, such as laser-homing systems), sonobuoys, and the like that must operate without testing over many decades. During storage or periods of non-use the electrical systems are still exposed to environmental insults, e.g., temperature, humidity, radiation, cycles of such variables, vibrations, etc. In at least some cases, systematic studies, indicated below, were conducted to assess reliability taking into account possible failure modes and using models to predict behavior, much as they are discussed today.

We also note that there is a body of literature on estimating rare events. This topic may be a little peripheral from the main topic of materials aging central to this Study, but for the interested reader we provide some remarks in Appendix 3 (§ 14).

3.6.1 Reliability study from the 1990s

One summary from the mid-1990s seems particularly valuable: *Long-Term Non-Operating Reliability of Electronic Products* [10].[4] The objective of this study was to develop a procedure to predict the quantitative effects of non-operating periods on electronic equipment reliability. The different chapters discuss topics that still seem relevant [11], e.g., failure mechanisms, long-term reliability of non-operating electronics (including plastic-encapsulated microcircuits), testing, and a framework for assessing reliability of non-operating systems, with the caveat that many technological innovations in materials and scaling down of electrical components have occurred over the past twenty years. The basic framework to failure analysis, obtained by multiplying probabilities of independent failure rates, is used (as it is often still used today), with caveats given for uncertainties associated with the finite shelf-life of various components (similar to a bathtub curve for individual elements). The overall structure is similar to the kinds of discussions given for today's applications and projects. The Physics of Failure and Reliability Growth paradigms, discussed in Chapters 6-8, are a major improvement over these earlier approaches.

3.6.2 A study of aging of plastic encapsulated microcircuits

As an example of early work on long-term reliability, McCluskey et al. [12] addressed the design of long-life, high reliability systems that used COTS plastic encapsulated microcircuits (PEMs). There were concerns about whether PEMs could survive in harsh environments over long periods of continuous or intermittent operation. The authors note that studies in the commercial sec-

[4] For other historical insights see the Air Force report *RADC-TR-85-91, Final Technical Report: Impact of Non-Operating Periods on Equipment Reliability* by D.W. Colt and M.G. Priore, May 1985. Note that the MIL-HDBK-217 module used for prediction of electronic reliability is based upon the RADC-TR-85-91 standard. The MIL-HDBK-217 standards and approach were criticized in the 2015 NRC report *Reliability Growth: Enhancing Defense System Reliability* [13].

tor had demonstrated that PEMs made using the best commercial materials, processes, and quality control approaches do perform reliably in harsh environments. However, leading up to the work, it was unknown whether PEMs were reliable in applications requiring operation after long periods (10-20 years) of unpowered (dormant) storage. The authors presented the results of five studies of reliability following long-term storage, including PEMs, hermetic microcircuits, and assemblies stored for up to 28 years in various storage locations around the world. The authors concluded that "Regardless of the storage conditions, commercial grade PEMs, without screening or incoming inspection, survived assembly and extended storage, even though, in some cases, degradation was observed on the boards." Although only peripherially related to the present study, this work does highlight that evaluation of the reliability of stored components is possible, and has been done in the past for some COTS electronic materials.

3.7 A Study of Assurance of COTS Parts in Airborne Electronics

More recently, and more similar to the specific questions addressed in the present report, the U.S. Department of Transportation and the Federal Aviation Administration sponsored a report [14], which was published in 2017, to assess and formulate an assurance framework for COTS parts in airborne electronic hardware (AEH).[5] In the report, several topics are discussed that overlap the challenges faced by NNSA for assessing reliability of COTS electronics, e.g., the report includes discussion of

1) "the use of existing standards and guidance documents as a structure for future evolution of COTS standards,

[5]Contributors to the report were from Airbus, Boeing, FAA, GE Aviation Systems, Hi-Tec Systems, Honeywell Aerospace, Rockwell Collins, Rolls Royce, Saab, Texas A&M University and UTC Aerospace Systems.

2) possible future COTS standards to implement this structure,

3) the need for combined industry/regulatory/manufacturing research to develop COTS AEH issues mitigations, including the development of COTS standards and guidance,

4) mechanisms to shorten the slow evolution of standards,

5) a candidate structure for relevant and emerging COTS standards linked to evolving development assurance standards, and

6) the identification of standard bodies responsible for the implementation of the ongoing COTS solution(s)."

SNL and KCNSC can benefit from developing working relationships with the above industrial groups both in learning, but possibly also in standards, to better leverage the designers and manufacturers of COTS electronic components.

3.8 Assuring Reliability in COTS Parts for Use in Aerospace Applications

NASA and other entities operating in space as well as the automotive sector face similar problems to NNSA in making use of COTS electrical, electronic, and electromechanical (EEE) parts in applications where reliability over an extended lifetime (dormant or active) is required [2, 15, 16, 17]. This section highlights features of the NASA/aerospace approach that may be useful in pursuing the use of COTS electronics parts in reliability-critical NNSA missions. The topics covered are NASA's view of COTS reliability, failure experience in space systems, screening incoming parts, obtaining reliable data for COTS parts, testing of COTS parts, and the importance of materials knowledge in assessing COTS parts. Also, NNSA may wish to learn how SpaceX and other commercial space-oriented companies are approaching the COTS reliability problem, though we recognize that these companies likely operate on a very different model of reliability, risk and renewable technologies.

3.8.1 NASA's view of reliability in the use of COTS electronics

NASA and other aerospace enterprises recognize that the use of COTS EEE parts is a potent trend in the design and modification of future high reliability systems – as does NNSA. This trend is driven by the worldwide commercial electronics boom, e.g., long-life durable goods in the automotive, manufacturing, safety, and aerospace sectors, among others. To take advantage of the low cost and sometimes superior performance of COTS electronics it is necessary to develop methods to quantify their reliability. In general, this means development of new methods of modeling and experiment, as well as manufacturers' information, to discover the reliability of COTS electronics before and as they are procured [16, 17], i.e., a quantitative risk reduction approach where COTS parts present a significant design advantage, aside from reliability. The traditional MIL-SPEC system of parts procurement is now dwarfed by orders of magnitude by other users of EEE parts. It will cost more and more money to maintain the traditional approach, but there may be no choice but to at least maintain aspects of the MIL-SPEC system, selectively.

3.8.2 Experience in failure rates for spacecraft

NASA, as well as other aerospace entities, have long experience with failure rates for systems that demand high reliability. An important point in this experience is that the failure rates in spacecraft are 5 to 150 times larger during launch than in flight. This implies that stress testing of COTS electronics should emphasize vibration tests and combine vibration with other stresses. For example, COTS electronics can be examined with acoustic resonance (Chapter 7) by using a low frequency to mimic aspects of launch and a high frequency to look for changes in resonances as well as coupling between subsystems.

The large experience base in the aerospace industry offers a rich field for learning more about relevant failure rates. The very large numbers of rocket launches to orbit the existing and future mega-constellations of communications satellites means that failure experience will accumulate quickly in the near future. A challenge will be getting access to the data from commercial ventures, such as Starlink and Kepler, etc. We note that SpaceX has shown significant interest in cooperation with other aerospace entities on other topics, such as their visor-sat and dark-sat to reduce the interference of Starlink satellites with astronomy (`https://www.spacex.com/updates/starlink-update-04-28-2020/`).

3.8.3 Screening of electrical, electronic, and electromechanical parts

In the aerospace industry there are typically two, somewhat overlapping, choices in obtaining reliable parts: environmental test screening and better control of the manufacturing process. When COTS electronics are incorporated in a design the process control aspect is largely put aside (unless there is a special relationship with the vendor) and one must rely on screening. "Screening is to some extent a crutch that allows one to use parts that do not, as delivered, meet all the requirement of a given application" (Ch. 19, [18]). The difference between production control and screening in securing high reliability parts is illustrated qualitatively in Figure 4, where the production controlled parts and COTS parts are characterized as parameter probability density distributions with the same mean and different variances. Clearly production control is the preferred option.

However, for COTS electronics, knowledge of production control is typically fragmented or unknown. Hence, screening may be the only available

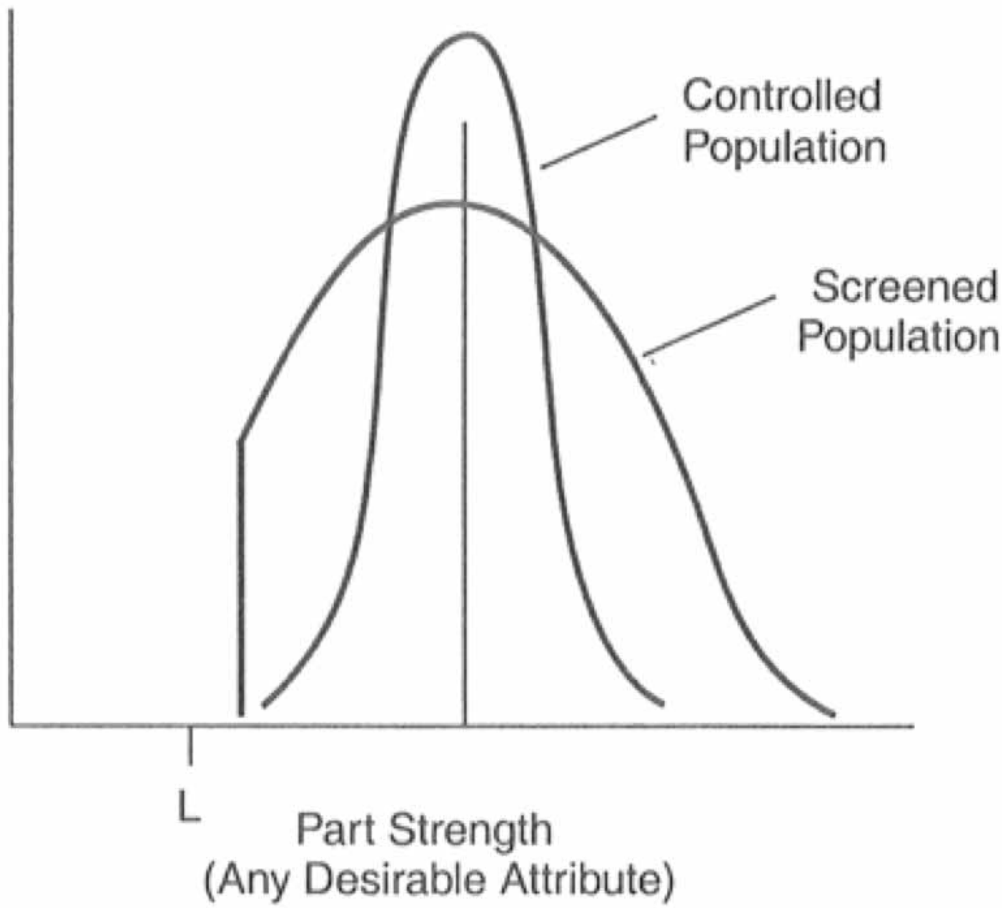


Figure 4: Variability in quality of COTS electronics. The vertical axis is the probability density and the horizontal axis is some desired attribute of COTS electronics. Note that for the screened population there are fewer parts near the acceptible limit (L). Reference: [18]

option. Below we discuss briefly methods of getting information about the reliability of COTS electronics from information sources and testing.

Testing of COTS parts: The objectives of testing for long-term reliability focus on quantifying very small changes in degradation processes that evolve on long time scales. With insight into these phenomena lifetime reliability can be better understood and predicted for COTS components. Leitner [17]) gives a good summary of the NASA approach and lists some innovations in existing methods that are summarized below. These approaches move beyond the typical highly accelerated stress screening (HASS) testing with vibration, over voltage and humidity. NNSA, with SNL and KCNSC, is pursuing many of these approaches (as well as others indicated below), and working with NASA and others, with frequent communication, can optimize government efforts.

Non-destructive Methods: Testing is typically divided into non-destructive and destructive testing. Leitner [17] lists some methods not typically pursued in non-destructive testing of parts:

ND1 X-ray imaging (two- and three-dimensional modes)

ND2 Nuclear magnetic resonance imaging

ND3 Acoustic microscopy, especially for voids, cracks, and material boundaries

ND4 Time Domain Reflectometry (TDR) – quickly localizes packaging, bonding, and substrate problems

ND5 Electromagnetic emissions detection – changes in known emissions as well as emissions that arise over time

In Chapter 7 we discuss novel ways of using acoustic stimulus and response to probe very small structures in COTS electronics and devices. Unwanted electromagnetic emissions are a serious concern in printed circuit boards, microcontrollers, and processors. Existing experimental and modeling tools, e.g., signal integrity measurements and modeling tools (such as from Altium Inc. and Mentor Inc.) may be useful in quantitative measurements of the time evolution of degradation phenomena revealed by electromagnetic emissions and their impact on signals within microprocessors [19].

Fault isolation techniques can be used on electronic components and subsystems that are known to have failed to pinpoint the faulty components. NASA approaches to this topic include:

FI1 Thermal imaging – useful for short circuits or over-current conditions

FI2 Infrared emission spectroscopy (IREM) – useful to isolate transistor gate leakage

FI3 Optical beam induced resistance change (OBIRCH) to locate on-die metal shorts and oxide defects

There are also standard methods that can be used in novel ways. For example, power spectrum analysis combined with a variety of stimuli is also discussed in Chapter 7.

Destructive Testing: Highly accelerated life-time testing (HALT) is already in use for reliability-critical NNSA applications. Leitner [17] illustrates NASA approaches that move beyond the typical HALT variables of vibration, temperature, voltage, and humidity. Further NASA testing makes use of microscopy tools as well as elemental composition techniques. These tools typically require destruction (de-layering) of the part to reveal the components to investigate.

Microscopy tools are used in research to characterize materials and can be useful to track down specific defects and anomalies that cause an observed failure. These tools include SEM (Scanning Electron Microscopy) for imaging, FIB (Focused Ion Beam) for imaging, ion milling and sample preparation, STEM (Scanning Transmission Electron Microscopy) for very high-resolution imaging to characterize thin film defects and small particle contaminants, TEM (Transmission Electron Microscopy) for extremely high resolution imaging to characterize defects in transistor gate oxides, and

AFM (Atomic Force Microscopy) for atomic level surface analysis and electrical characterization. We note that these tools are for materials research to understand faults at the materials level and their evolution with stresses and time.

Materials composition techniques can also be useful. Techniques mentioned by Leitner [17] in the NASA approach include: EDS/EDAX (Energy Dispersive X-Ray Spectroscopy) for elemental composition, revealing desired and contaminant materials, ELLS (Electron Energy Loss Spectroscopy) for small area elemental composition, spectroscopy by X-ray photo electrons (XPS) for molecular composition, spectroscopy by auger electrons (AES) for elemental analysis, Raman spectroscopy for molecular composition, and time-of-flight secondary ion mass spectroscopy ((TOF-SIMS) for characterization of impurity concentrations (dopants and contaminants). We note that, as for the tools in the preceding paragraph, these are materials research laboratory techniques that require significant investments in equipment and personnel support. SNL is aware of all of these approaches for materials characterization.

3.8.4 NASA's recognition of the importance of materials science knowledge in assessing reliability of COTS electronics

As early as 2017 NASA recognized the need, and made recommendations, for "screening methods and physics-based modeling that are related to packaging, electrical performance, and unique requirements for specific applications, such as extreme temperature, or extended thermal cycling." This quote is from JPL's "Commercial Off-The-Shelf (COTS) Parts Risk & Reliability User & Application Guide" [16]. Leitner [17] notes that "validated modeling at the material level provides a common thread across the breadth of component types being considered." Investigation at the materials level can thus reveal common threads in failure modes where intrinsic materials defects are driven to failure by physical stresses, such as high current density, high electric fields, oxidation/reduction reactions, and/or by the passage of time. The NASA approach seeks to use materials level knowledge to develop a generalized modeling framework applicable to a broad spectrum of both active and passive components.

The NASA strategy at the high level is to put emphasis in modeling on materials knowledge of groups of devices to validate physics models of failure mechanisms [17]. This approach would retain empirical measurements as needed and minimize reliance on descriptive statistical methods with a limited physical basis. Some examples of using validated physical models of degradation and failure are finite-element techniques to simulate behavior/defect activation due to changes in applied and external stresses [20] and abstracting peripheral elements in multi-scale simulations.

3.9 Findings

1. The rapid design cycle for commercial off-the-shelf (COTS) electronics is aligned with the demands of commercial markets, but does not align with design cycles or lifetime requirements for weapons systems, nor does it enable a well-controlled supply chain for components (e.g., resistors, capacitors, printed wire boards, etc.) needed for weapons applications.

    (a) Traditionally, variability in the quality and reliability of parts, as well as concern about future availability of parts due to obsolescence, is partially mitigated by life-of-program buys for weapon systems, thus missing future upgrades in performance and capabilities possible with short design time cycles.

    (b) There can be corresponding challenges in assuring reliability in new electronic technologies using legacy military standard tests.

2. The challenges associated with ensuring high reliability of COTS electronics over long times,under demanding environmental conditions and for high-consequence applications, are also found in the aeronautics, aerospace, automotive, and medical device industries. Some applications in these industries require reliability of components that may be dormant, or nearly so, over years or decades. These industries have developed, and continue to develop, approaches to manage the challenges of aging and reliability assurance. While each industry faces different environmental stresses (e.g., temperature, humidity, and atmosphere), there can be significant commonality in the underlying mechanisms of aging and failure. Information sharing can accelerate each sector's work to assess aging under their specific stressors.

3. A goal of reliable performance after 40-60 years of un-monitored storage poses difficult, and perhaps unrealistic, challenges for electronic components to electrical subsystems and systems, whether or not COTS materials are utilized. Reliability in the presence of material aging can be improved by careful assessment of defects and their mechanisms of evolution, integrating self-tests into the system, monitoring characteristics at regular time intervals, and life-cycle replacements.

3.10 Recommendations

1. NNSA should create an Electronic Materials Reliability Coordination Plan (EMRCP) under which the research efforts on electronic materials aging work cooperatively, and have well-defined responsibilities to support the use of COTS electronics in the Stockpile. Such a plan should include coordination among:

    (a) systematic research on the changing materials and designs of COTS electronics that will be available for future use in the Stockpile;

(b) linked experimental and modeling research on defects and aging processes and development of predictive tests for various components and assemblies

(c) materials evaluation and selection of reliable components;

(d) component, subsystem, and system testing focused on the most likely failure modes and linked iteratively to modeling at relevant scales;

(e) surveillance of both components and actual systems, and additional "witness" components and systems;

(f) assessing life-cycle replacement for different electronics subsystems

(g) with (a-f) linked via a Physics of Failure and Design for Reliability process.

To accomplish these steps, NNSA's EMRCP should include a focused materials sciences research program that anticipates and addresses the evolving COTS technology landscape, which will likely be driven by non-defense market pressures. The program should have responsibility to characterize the relevant material properties, including failure modes, so that science-based understanding of new materials and component choices will already be in place when the need arises to use COTS components. A framework should be established to share this knowledge with the responsible program teams.

2. NNSA should partner with the Department of Defense and NASA to support the formation of a COTS Reliability Consortium with aeronautics, aerospace, automotive, and biomedical device companies to share common knowledge and practices, and possibly create leverage with COTS manufacturers to produce designs with long lifetimes that enhance long-term reliability and minimize aging of both dormant and powered components and systems. Cooperation in the materials research relevant to the use of COTS electronics in reliability-critical

applications should reduce unnecessary duplication, saving resources, and producing better results.

(a) NNSA should form a "storage-aging advisory panel" with experts in materials science, electronics, and reliability, from government agencies and laboratories, universities, and industry, to evaluate the impact of the evolution in COTS electronics on systems reliability for high-consequence applications.

(b) NNSA should invest in basic materials science research aimed at characterizing the aging processes that occur at the ever-smaller feature sizes found in COTS electronic components. Experiments, theory and simulation must all play an essential role in such a program, with machine learning potentially offering new insights from data-rich experiments.

4 MATERIALS AND ACCELERATED AGING

Understanding the aging of electronic components, devices, and subsystems introduced into Stockpile weapons is an important goal. During years of storage, their behavior evolves through a complex interplay of mechanical, chemical, and electrical processes. The material's microstructural evolution involves grain boundaries, changes in the interfacial region between dissimilar materials, and cracking due to stresses that arise from thermal or electrostrictive expansion and contraction, vibration, corrosion, and other sources. For assembled circuits, aging also refers to changes caused by the failure of solder joints or wire bonds, the formation of cracks, and the penetration of water and other substances through device cases. Predicting how materials and assemblies age is thus a problem that combines the *materials science* of nanoscale structures, including interfaces and defects (or their equivalent for more complex composites), *materials processing* to shape materials into devices, *manufacturing* to build systems from electronic components and subsystems, and *environmental* conditions that impact mechanical and chemical stresses that could drive changes. Predicting how the devices within a system will age over decades of storage requires a multi-disciplinary examination of the evolution of materials and devices to develop realistic models of behavior that can be projected into the future. Such predictions are constrained by the considerable uncertainties that more generally challenge such extrapolations.

4.1 Material Evolution During Aging

A strong imperative and direction for electronic components has been an almost relentless miniaturization of device dimensions to achieve higher circuit functionality and density at lower cost. Such components dominate the COTS market. Fabrication methods for these miniaturized devices must meet extremely tight tolerances, because they can be highly sensitive to small imperfections in the component materials, such as a dielectric or metallic alloy, or dopant concentrations. There are thinner internal connections, and fewer and smaller crystalline grains, so a greater volume fraction is composed of disordered grain boundaries and interfaces, compared with older-generation components. Chemical impurities and physical defects thus play an increasingly important role in the evolution of the device, especially since these chemical constituents and defects can move over distances comparable to feature sizes in the electronic components during aging. Quantum mechanical effects also begin to appear at the nanoscale. All of these considerations lead to a reduced stability and an increased fragility for COTS electronics components at the present time, a situation expected to accelerate in future generations of devices. Even at present, larger, more stable components are retained when greater system reliability is required, e.g., for certain aerospace and automotive applications [21].

To quantify the implications of these trends for an ideal single-phase material, Figure 5 shows how the classical fluctuation $\Delta X/\bar{X}$ in a thermodynamic property X, compared with its average $\bar{X}$, varies with the number of atoms N in the system. For instance, fluctuations in energy, stress, and strain in three dimensions all scale as $\frac{\Delta N}{N} \propto 1/N^{1/2} \propto 1/\ell^{3/2}$, where ℓ is the typical linear dimension of the system. As feature sizes reach 10 nm, fluctuations in thermodynamic quantities will reach percent levels [22]. Similarly, as the radius of a wire r decreases by a factor of 100, its properties become 100-fold less well determined, because they scale as $\frac{\Delta X}{X} \propto 1/r$. Not surprisingly, the accuracy and precision of continuum models begin to fail as nanometer scales are approached.

Another aspect of device miniaturization is that typically there is a concomitant reduction in grain size, which leads to a dramatic increase in volume fraction of grain boundaries within the polycrystalline materials used (Figure 6). This is important, because grain boundaries are poorly under-

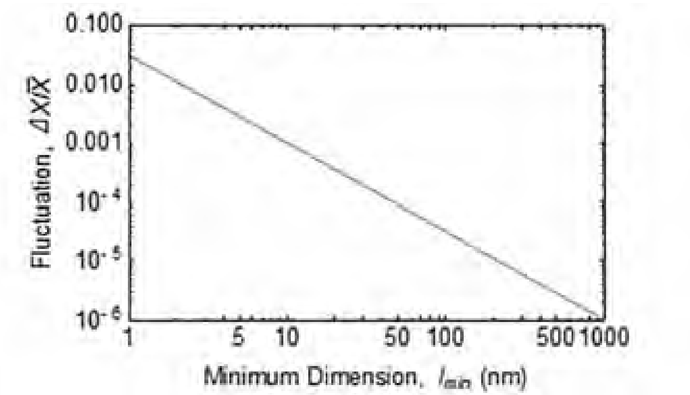


Figure 5: Classical scaling for a three dimensional system between the relative fluctuations $\Delta X/\bar{X}$ of a thermodynamic property and the physical size ℓ of a system, where the atomic size is taken to be 0.1 nm. The magnitude of the fluctuations increase from 0.1 % to 3 % as ℓ decreases from 10 to 1 nm.

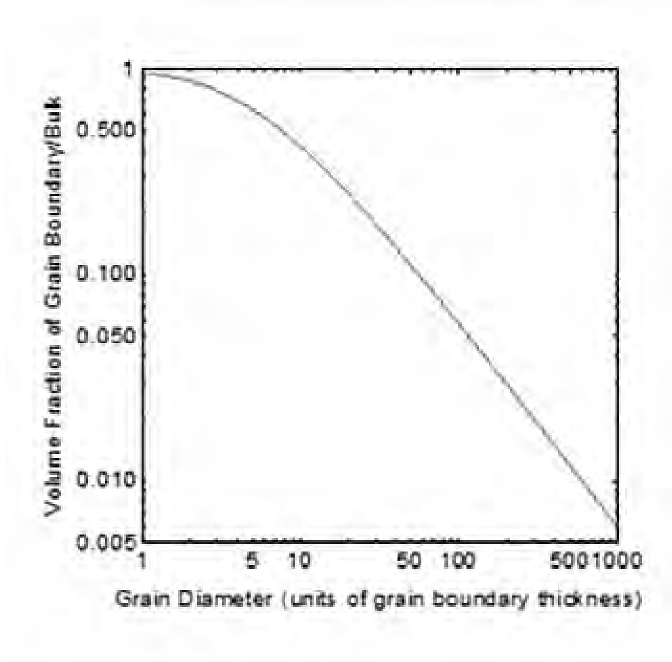


Figure 6: Volume fraction of grain boundaries relative to the bulk (grain interior plus boundary) for spherical grains, shown as a function of grain diameter, given in units of grain boundary thickness. For example, for a grain boundary thickness of 1 nm, the volume fraction of grain boundaries approaches 6 % as grain diameters reach 100 nm, and 42 % for grain sizes of 10 nm.

stood. Often they are high-angle (incoherent) grain boundaries, which are typically approximated as an amorphous region for lack of a better description. The composition of grain boundaries is also variable, as they act as a sink where defects and impurities are concentrated, even in nominally pure materials. When chemical compounds or interfaces between different chemical constituents are present, the boundaries become regions similar to those of a chemical solution.

Hence, the thermodynamic states of polycrystalline and ceramic materials, let alone their transport properties, are ill-defined. This is illustrated by a diffusivity that is often, but not always, expected to be significantly larger within grain boundaries than for bulk crystals. The overall diffusion through the bulk polycrystalline material is then determined by the combination of diffusivities and volume fractions of grain boundaries and the crystal. In short, the materials science of such boundaries is an important but complex problem.

Although there is an established quantum mechanical theory of chemical kinetics, validated by experiments [23, 24], the same cannot be said of diffusion and phase growth in condensed matter. Simple models assume that Arrhenius behavior with a single activation energy may be used, but the actual behavior is more complex. Empirical evidence of more than one activation energy is commonly observed in experiments conducted over a broad temperature range, including conditions approaching room temperature. The traditional use of temperature to "accelerate" kinetically-based aging processes therefore becomes increasingly suspect as one extrapolates to room temperature, all the more so for components having small, submicron internal structures for the reasons summarized above.

The relatively cautious assessment we offer regarding materials science at submicron scales implies that there is considerable opportunity for fundamental research to be done in this domain. We expect materials science at the nanoscale to be increasingly important, as electronic, fluidic, and mechanical components all tend toward smaller spatial dimensions. Hence, understanding and characterizing material properties at these scales will have enormous impact in government and industrial applications. We recommend investing in this area of scientific and engineering research, and since much of the work is at the basic level, we expect that there can be fruitful collaborations between national laboratories, academia, and industry.

4.2 Arrhenius Kinetics

In general, simple changes in materials composition (atomic species) or structure (e.g., vacancies or substitutional impurities) are modeled using a rate equation based on an underlying picture of independent collisions or hopping between sites at a rate or frequency

$$k = Ae^{-\frac{E_a}{k_B T}}, \tag{4-1}$$

where E_a is the activation energy for a molecule, k_B is Boltzmann's constant, and T is the absolute temperature. The prefactor A is often referred to as the frequency factor. In elementary chemical models of collisions $A \propto T^{1/2}$.

The Arrhenius formalism is also used to describe *diffusion kinetics* where $k = D$ is the diffusion constant and $A = D_0$ is a prefactor that reflects the atomic environment that influences the diffusion of a particular defect (vacancy, impurity) or atomic component. The *diffusion length*, the distance that a defect or impurity will move during a time t, is given by $L_D = (Dt)^{1/2}$. There is a long and richly detailed history of studies of diffusion processes for silicon integrated circuits, for example the diffusion of oxygen within silicon to form an oxide layer SiO_2, or the diffusion of ion-implanted impurities such as P or B, to form n- or p-type Si. Although much of that characterization took place decades ago, there remain important open questions about processes of diffusion and materials and device evolution, over the very long times, and for the nano-scale dimensions under consideration here:

1. Diffusion constants are strongly dependent on the concentration, electronic charge, local fields and other details of the local environment in the material. Simulations of diffusion and materials evolution are therefore not straightforward, even for these well-characterized materials systems.

2. As previously noted, there is empirical evidence that more than one activation energy is observed as evaluations are conducted over a broad temperature range, and under different conditions of electric field, stress, and other parameters (see the next section, § 4.3).

3. The diffusion lengths L_D at room temperature may be a significant fraction of a feature size in nanostructured devices and materials developed over the past 40 years. If such diffusivity is coupled with a driving mechanism that causes defects to nucleate and grow, then detrimental structural changes can occur during aging. Defect recombination, and accumulation of defects or impurities at interfaces and grain boundaries, may substantially change device properties.

4. We should anticipate and try to model the evolution of materials and devices during aging that *might not* appear under accelerated life tests, nor over shorter device lifetimes, by using appropriate experimental data.

These observations are particularly germane since the dependence on temperature, and the underlying concept of independent elementary processes, forms the basis for the Arrhenius approach to accelerated aging.

4.3 Arrhenius Characterization of Electronic Materials

High temperatures are used in accelerated testing of electronic materials and devices to identify thermally activated failure mechanisms based on structural defects. The analysis is usually based on an Arrhenius law with a single activation energy E_a,

$$F \propto e^{-\frac{E_a}{k_B T}}, \tag{4-2}$$

where F is the measured quantity. This approach assumes that the failure mechanism at the high temperatures used for accelerating testing also dominates failure at the operating temperature, typically near 300 K.

Many failure mechanisms are based on the diffusion of atoms or vacancies through a material. The diffusion constant is $D = D_0 e^{-\frac{E_a}{k_B T}}$ [25]. The atomic diffusion constant follows an Arrhenius law, with an activation energy E_a determined by the structural defects near the diffusing atom. Typically, E_a is a fraction of the bond strength, so ≈ 1 eV.

The effect of atomic diffusion in an electronic material is proportional to the number N of diffusing atoms. Solids possess many kinds of structural defects and in a volume V the concentration N/V of diffusing atoms or vacancies ranges from the atomic density $N/V \approx 10^{23}$ cm^{-3} to concentrations that are orders of magnitude lower. For example, an amorphous material has structural defects throughout its volume, while a silicon crystal has few structural defects, but possesses atomic impurities and dopants. An interesting case is a polycrystalline material. For a crystal grain, the number of atoms N_s on the grain boundary compared with the number N_v in the volume is

$$\frac{N_s}{N_v} \approx \frac{L^2/a^2}{L^3/a^3} \approx \frac{a}{L}, \tag{4-3}$$

where $a \approx 0.1$ nm is the atomic spacing. Depending on their characteristics, crystalline materials can have grains with a wide range of sizes ranging from $L \approx 10$ nm to the size of the sample, resulting in a wide range in the concentration of diffusing atoms. For a multilayer ceramic capacitor (MLCC), the grain size is $L \approx 100$ nm, and the fraction of atoms on the grain boundaries, $N_s/N_v \approx 10^{-3}$, so corresponds to orders of magnitude lower number densities than the typical bulk concentration. On the other hand, the activation energy for diffusion along a grain boundary is reduced by the empty volume associated with the locally high fraction of defects.

Another case to consider is diffusion of atoms along the core of a dislocation. Here, the number of atoms N_c along the core of a dislocation of length L, compared with the number in the volume, is

$$\frac{N_c}{N_v} \approx \frac{L/a}{L^3/a^3} \approx \frac{a^2}{L^2}, \tag{4-4}$$

where L can vary from a short distance to the size of the sample. The concentration of dislocations varies greatly between materials and their condition, from zero for a single crystal, to large values in a heavily distorted metal, with a corresponding change in the concentration of atoms that diffuse along their cores.

A relatively small concentration N/V of atoms located on grain boundaries, dislocation cores, or other structural defects, which have a correspondingly low activation energy E_a, can dominate atomic diffusion at room temperature, even if high temperature accelerated testing identifies another alternate mechanism. To illustrate this effect, the Arrhenius rate, which is proportional to the concentration of diffusing atoms, is plotted in Figure 7 for two cases: (orange) a high concentration N_o/V_o with a high activation energy $E_a = 1$ eV, and (blue) a much lower concentration $10^{-3}N_o/V_o$ with a lower activation energy $E_a = 0.1$ eV. These cases might illustrate the diffusion of an atomic vacancy through the bulk crystal compared with the diffusion of atoms along a grain boundary, as discussed above. Accelerating testing at 1000 K would predict that the failure rate at room temperature would be dominated by the high activation energy mechanism and predict a relatively long lifetime. In fact, a crossover to the low activation energy process occurs below 500 K, which predicts a much shorter lifetime. The real situation is clearly more complex. But multiple activation energies could be relevant, leading to Arrhenius plots with upward curvature and a shorter lifetime than that predicted by the simple model.

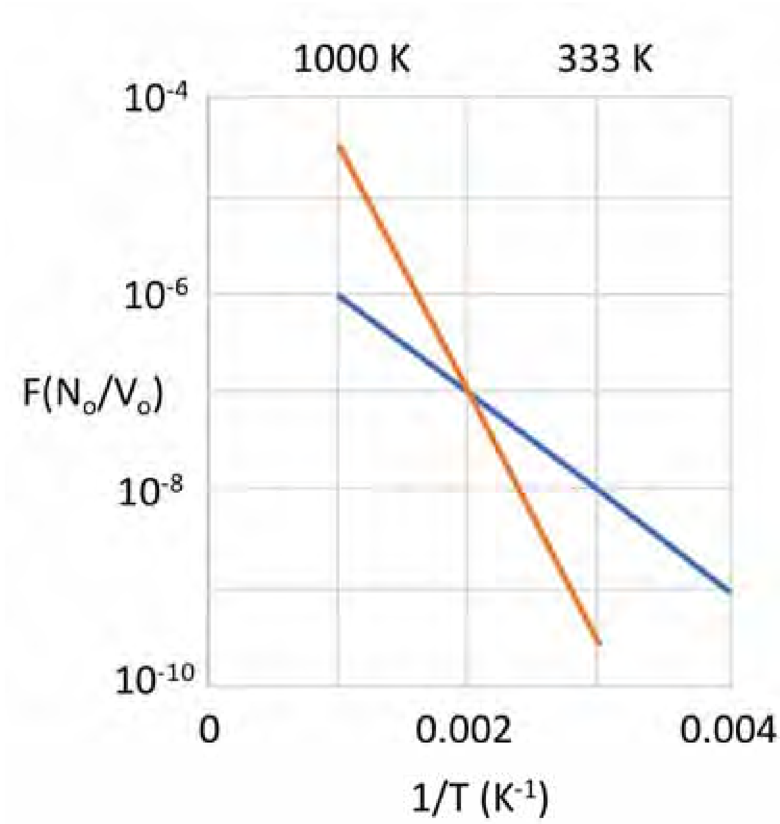


Figure 7: Illustration of the diffusion of an atomic vacancy through the bulk crystal compared with the diffusion of atoms along a grain boundary, as discussed above (orange) a high concentration N_o/V_o with a high activation energy $E_a = 1$ eV, and (blue) a much lower concentration $10^{-3}N_o/V_o$ with a lower activation energy $E_a = 0.1$ eV. A crossover to the low activation energy process occurs below 500 K.

4.4 Accelerating Aging

The goal of accelerated aging is to predict the outcome of physical and chemical changes occuring in a material over some long time by performing tests over a much shorter time. Usually, the accelerated testing is done by increasing environmental insults: elevating the temperature (which accelerates the rates of most chemical and physical processes, although when there are competing processes, some of which may be protective, it does not necessarily accelerate failure), elevating voltages, increasing the concentration of harmful or corrosive substances (often water vapor) in the environment, cycling the temperature, which then couples in the mechanical stesses associated when thermal expansion and contraction, bending, etc. Obtaining meaningful results from such tests requires significant understanding of the underlying physical phenomena that couple structural evolution to defects and driving forces (e.g., 'the physics of failure'). Such understanding is essential to confidence that the accelerated environment provides operational understanding of the actual effects over time under operational conditions. For instance, a briefer (J. Leitner of NASA-GSFC [17]) said: "Thermal acceleration to quantify flash non-volatile memory data retention at ambient temperature makes little sense."

It is well understood that most processes of interest are not governed by a simple Arrhenius equation with a single activation energy and prefactor. Instead, degradation results from cooperative interaction of several processes, each with its own kinetic barrier. Many physical processes are known to have induction times, e.g., void swelling in irradiated metals, and others to be auto-catalytic, e.g., corrosion that may begin with a pinhole penetration of a protective layer. Such behavior is far from Arrhenius.

4.4.1 An application to multi-layer capacitors

An illustrative model is given in experiments undertaken by C.A.Randall et al. [26], who used highly accelerated lifetime testing (HALT) to predict the mean time to failure (MTTF) of multilayer ceramic capacitors (MLCCs). Randall's work re-examined an equation that has underpinned the industry in predicting the MTTF [27]:

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n exp\left(\frac{E_A}{k_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right), \tag{4-5}$$

where t_1 is the MTTF under a voltage, V_1 and temperature T_1; t_2 is the MTTF under different voltage, V_2 and temperature T_2, and n is a *voltage* *acceleration exponent*. The relatively small dimensions (thicknesses less than 1 micron) of the dielectric layers in these MLCCs produced a non-linear change in n, which in turn gave rise to results such as those shown in Figure 8.

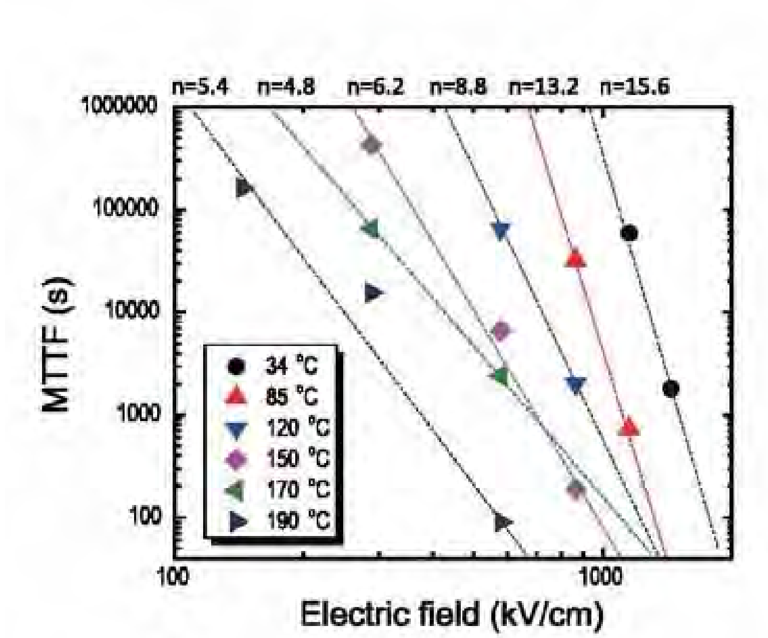


Figure 8: Mean time to failure data for MLCCs tested at various temperature and dc electric field bias conditions. The data are plotted using the standard log-log approach, with the HALT equation (4-5) presented in the text [26].

There are a number of important insights gained from [26]: (1) standard and well-established means of HALT testing of components cannot assume to hold true as the feature sizes of those components (e.g., dielectric or metal thicknesses) are substantially reduced, (2) the parameters that are used in the testing, and the use of extreme conditions, may lead to failure mechanisms and corresponding MTTFs that are particular to those testing conditions, and (3) the data do not fit simple Arrhenius models since the physical mechanisms responsible for materials and device evolution are more complex. Importantly, the research in [26] offers improvements over the traditional analysis used, as it provides a more fundamental understanding of the critical defects and microstructure governing the degradation of the MLCCs.

Despite its well-known limitation, analysis of thermally accelerated aging using a simple Arrhenius model with a single activation energy remains a standard approach in accelerated testing. Because it is straightforward in concept and application, it can be a useful 'rule-of-thumb' approach, if used with care. The topic of Arrhenius and non-Arrhenius responses remains an active area of research for understanding and lifetime predictions, e.g., in the aerospace [28] and automotive industries [21].

4.5 Interactions

Real world failures can arise from interactions among several processes in a material. The most familiar example is probably stress corrosion, which results from a combination of a chemically hostile environment, the presence of tensile or shear stress, and stress concentration at the tips of Griffith cracks that are present in almost all materials and objects, when the reduction in potential energy due to crack growth is greater than the increase in surface energy. Stress reduces the kinetic barrier to reaction, increasing the rate of corrosion in a crack, especially at its tip where the stress is greatest. As the crack grows, the stress concentration at its tip increases, further accelerating corrosion.

Such synergetic out-of-equilibrium processes may occur in other, often unanticipated, circumstances. The free energy required to drive the reactions and material restructuring is available whenever materials are out of equilibrium. For example, any two substances can be out of equilibrium where they are in contact, including interfaces, solder bonds to metals (for which there is an extensive literature, because of their technological importance and the catastrophic consequences of fracture or debonding), and spatially varying concentrations of solutes or dopants in semiconductors (the entire electronics industry is built on such junctions), or other solids. Even shear stress itself represents a departure from equilibrium and the availability of free energy that may manifest as creep or as catastrophic static fatigue failure.

Most interactions in materials, even if anticipated, cannot be reduced to simple analytical descriptions. Even direct modeling and simulations may be challenged to identify all possible features of materials evolution owing to the large parameter space. In response, it is important, where possible, to design with these limitations in mind. Systems designed to avoid failure may be managed with a combination of redundancy, surveillance (noting that failure may occur roughly simultaneously across a broad class of exemplars), timely replacement after intervals they are known to survive, and actual aging studies conducted on prototypes under operational conditions. These latter studies are possible when the operational system has a long development time: a few prototypes may begin aging long before the last operational systems are built, and even long before the initial operational capability (IOC). In addition, a large number of the electronic components and subsystems can be assembled so that they are identical to those in the Stockpile, put in storage and/or a representative test environment, and tested periodically during the lifetime of the weapon, i.e., "witness systems."

4.6 Two Case Studies

4.6.1 Tin Whiskers

An informative example of the evolution of a material is the case of tin whiskers [29], which refers to the growth of thin metal filaments from a tin surface. Their evolution provides an example of available free energy leading to the formation of new structural features that make lead-free tin solders unreliable or unusable. The whiskers have diameters from 1 to 5 microns and millimeter lengths. Their presence can cause electrical short circuits. The tin whiskers were first identified in the 1940s and many theoretical reasons were given for their formation and growth. It took at least three decades to obtain evidence that whisker growth is initiated when compressive stresses exceed some minimum level. It is now generally understood that tin whiskers are driven by mechanical stress: shear stresses imply nonequilibrium conditions that can relax by any number of processes, ranging from creep to formation of crystallographically preferred geometries like whiskers (except in the ideal case of hydrostatic pressure, compression as well as tension produce shear stress).

Relatively soon after the problem was identified, it was shown that co-deposition of lead could reduce or eliminate the growth of the tin whiskers, which is now believed to be because lead relaxes internal stresses. In the 1960s scientists showed that whisker growth could also be mitigated by a nickel underlay. An important take away is that the growth rate of whiskers can vary from seconds to years, because it relates to the effects of macroscopic stresses on the sample. Thus, several effects acting together can generate whisker growth, as described by Galyon [29].

4.6.2 Kirkendall Voids

The Kirkendall effect is another case in point, with voids formed at interfaces between constituents having different diffusion rates (Figure 9); the phenomenon was first identified by Kirkendall in 1942 for the interdiffusion between copper and zinc in a copper/brass system. This manner of void formation has been documented in many materials systems, and for planar (layers), cylindrical (wires), and spherical (e.g., solder joints) configurations, where it has also been imaged at the scale of tens of nanometers. It is well enough understood that it is now utilized to design voids into nanocrystalline materials [30].

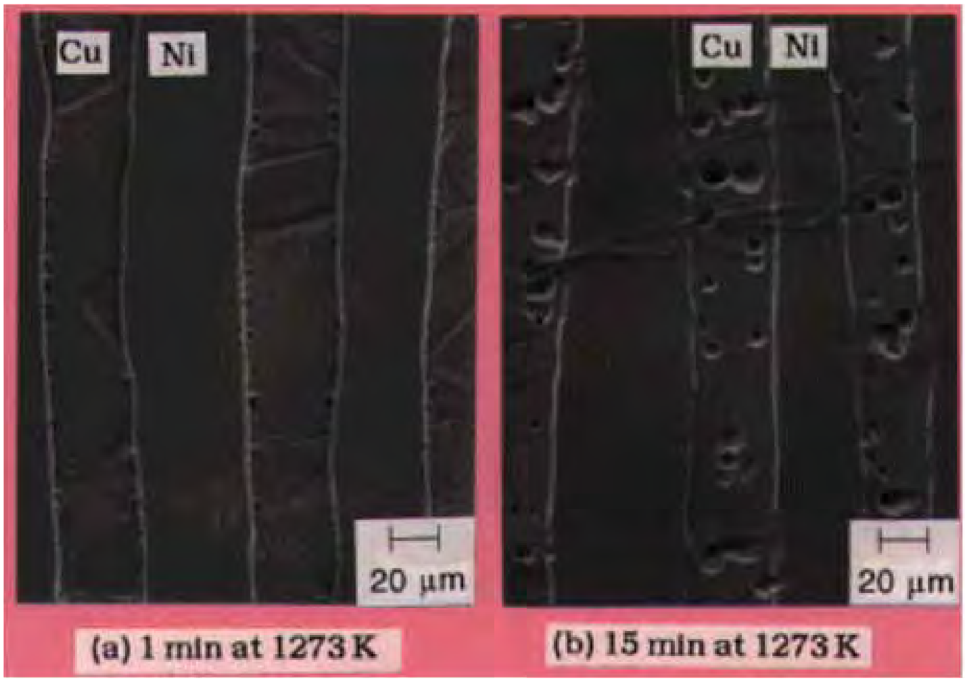


Figure 9: Micrographs of a laminate of copper and nickel, before (left) and after (right) heat treatment. Voids occur in the copper because copper diffuses faster in the nickel than vice versa. Reference: `http://www.phase-trans.msm.cam.ac.uk/kirkendall.html` where credit for the image was given to Professor David Matlock of the Colorado School of Mines.

4.7 Mechanical Stresses and Cracking

The two most important points to reiterate about cracking are that (1) it is still not possible to predict exactly where, when, and how a component will fail under long-term imposed stresses, and (2) fracture is not just a mechanical process, but is also sensitive to chemical interactions. That is, the presence of impurities or the appearance of external chemical constituents at any incipient fracture tip can have a large effect on the formation and propagation of a crack.

Hydrogen, even in trace quantities, is notorious for its ability to affect failure, e.g., embrittlement, and so affects a wide variety of materials. Also, hydrogen can be (or become) present for many reasons, such as the accumulation of moisture, or the build-up of long-term chemical reaction products.

Even under controlled conditions, fracture is therefore the rare event – initiation of a crack at a transient stress concentration, accelerated fracture propagation due to chemical weakening, or (perhaps temporary) blockage of fracture tip growth by impurities – that can determine the rate-limiting factors controlling failure of a component.

4.8 Findings

4. Understanding the aging of materials, components, and subsystems involves:

   (a) mechanisms that span from atomic to the micron (and larger) scales;

   (b) designs and material processing steps that introduce structural heterogeneity (including interfaces and defects);

   (c) manufacturing steps in assembling subsystems and systems from components that may be imperfectly compatible; and

   (d) the environmental conditions and history that introduce chemical and mechanical stresses that can drive changes.

   All of these factors should be assessed before new electronic devices or systems are introduced into a weapon system.

5. It is well known that most physical processes in electronic materials have rates whose temperature dependence is more complex than simple Arrhenius behavior, arising from multiple activated processes and their interactions. However, parametric testing design often relies on such simplified assumptions, which may lead to incorrect lifetime estimates.

6. The risk of failures due to aging requires increased attention because of rapid advances in miniaturization of electronic components and in-

creased parts density in electronic systems. Components with smaller feature sizes can be more susceptible to degradation than larger ones, if these issues have not been addressed in their design, because:

(a) In powered systems, voltages are applied over shorter device distances, leading to larger electric fields. This may lead to high field-induced materials changes, including local stresses.

(b) Diffusion lengths over the decades of storage may be commensurate with critical materials or device sizes (e.g., a grain size or a metal thickness).

(c) Larger components, containing multiple crystal grains or multiple ferroelectric domains (in capacitors as well as transducers), have parallel and redundant transport pathways, making their properties and performance more robust.

Assessing electronic materials, devices, and systems requires increasing power characterization techniques to locate and assess possible pathways to failure.

4.9 Recommendations

3. NNSA's EMRCP should accelerate the process by which new COTS electronics materials and devices can be assessed and qualified for use in the Stockpile by systematically evaluating the changing materials, manufacturing, and designs against a baseline of trusted materials and devices. This work will require a well-designed plan of research with an integrated, iterative process of experimental characterization, modeling, and evaluation of outcomes of stress testing.

4. NNSA's EMRCP should include development of component and subsystem designs that enable regular monitoring through subsystem testing done in the field, in order to ensure reliable functioning of the elec-

tronics components. There should be a suitable plan for this surveillance activity, which allows only limited access to the interior of the system, with no further disassembly required.

5. NNSA's EMRCP should consider implementing continuous, automated recording of the environments to which all components and systems are exposed, including temperature, humidity, power, and vibration (accelerations) so that there are clear records that can inform characterization of any faults that are discovered.

5 A CASE STUDY: CAPACITORS

5.1 Background

Here we make a few remarks about precious metal electrode (PME) multilayer ceramic capacitors (MLCCs), and their far less expensive cousins – the base metal electrode (BME) MLCCs. The latter were introduced originally in the mid-1980s, with Ni and Cu as common electrode materials, and $BaTiO_3$ as a common dielectric. The market is currently dominated by Japanese and Korean manufacturers, who manufacture these literally in trillion-piece quantities. (b) (5) [redacted]

Advances in processing have enabled commercial BME MLCCs to be manufactured with continual reductions in layer thickness (see Fig. 10), thus increasing their energy density ($\frac{1}{2}CV^2$ per unit volume). In normal commercial applications they have attained very high reliability. In 2013/14, when the 445306-series capacitor was chosen, it offered a dramatic reduction in physical volume (compared with a traditional MIL-SPEC PME part) for the same capacitance and voltage rating: for example, a 1 μF 25 V X7R-dielectric BME capacitor in that series, in the smallest available package ("0805"[6]), occupied a PCB footprint area approximately five times smaller than a high-reliability PME capacitor with the same ratings (which came in a 1712-size package).

[6] For a given capacitance and voltage rating, an X7R MLCC capacitor is available in multiple sizes. Kemet's 1 μF 25 V X7R high-reliability capacitor, for example, comes in sizes from their smallest choice ("0805" – meaning 0.080″ by 0.05″) all the way through larger packages, specifically 1206, 1210, 1812, and 2220.

(b) (5) [redacted]

[redacted]

Maximum volumetric density requires more and thinner layers, with greater vulnerability to process variations. Research results suggest that the number of grains per dielectric layer is more critical than the thickness itself for determining the rated voltage and life expectancy of a BME capacitor [34]. Furthermore, a common design suggestion is that layers should be at least five grains thick (C. Randall, presentation to JASON, 14 July 2020), as is also evident in Figure 10. As seen in the figure, contemporary high-density BME capacitors are manufactured with layer thicknesses of 1 μm or less, and with shrinking dielectric grain sizes.

(b) (5) [redacted]

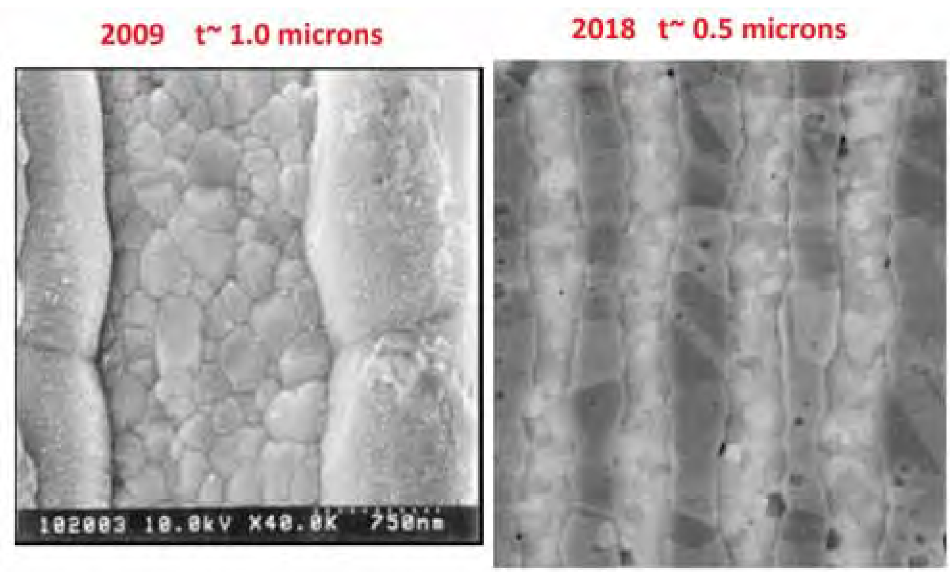


Figure 10: Typical BME MLCCs, with layer thickness (t) decreasing with subsequent generations. Adapted from a presentation to JASON by C. Randall, 14 July 2020.

A 2012 NASA study of failure mechanisms in $BaTiO_3$-based MLCCs found that there was greater early-time failure rate for thinner dielectric layers, though these were not typical "infant mortalities" [33]; see also [34]. Rather the authors suggested that heterogeneities in processing to prepare the MLCCs were the likely cause of failures. Indeed, in Qualification failures first seen in 2018, some samples exhibited voids extending more than halfway through the dielectric.

5.2 Return to PME in Weapons Applications?

[redacted] (b) (5) [redacted]

[redacted]

(b) (5) [redacted] In addition, we note that the vast majority of state-of-the-art BME MLCCs are manufactured by companies of foreign (Japanese and Korean) ownership (this year the domestic manufacturer Kemet was acquired by Yageo, and AVX was acquired by Kyocera).

Compared with the situation in 2013, the current state-of-the-art is such that, *when comparing MIL-PRF-32535 qualified MLCCs* (as opposed to those of commercial or automotive grade[11]) the available PME parts are competitive in terms of density (capacitance and voltage rating for a given package size) with the corresponding MIL-qualified BME parts of the highest density. The attached document "Supplemental Information Sheet for Electronic QPL-32535" (dated 4/16/2020; see Appendix 5, § 16), for example, shows that the popular highest-density MIL-PRF-32535 BME MLCCs (100 nF/10 V in 0402; 180 nF/25 V in 0603, and 1 μF/25 V in 0805) are also available in PME (in 0805 the PME parts reach 0.47 μF at the higher 50 V rating; in the document the PME parts are listed as "Presidio Components").[12]

(b) (5) [redacted]

[11] We confined our comparison to BME parts that are specified for "high-reliability" applications. A quick look at parts that are available in "automotive" grade, and in "general purpose" grade, reveals capacitors of considerably higher energy density: (b) (5) [redacted] (the highest density Kemet offers in that grade) could be compared with 10 μF X7R parts (from TDK, Murata, or Taiyo Yuden) of the same size and voltage rating, but in automotive grade. If one were to accept "general purpose" parts, there are 15 μF parts from TDK in that grade.

[12] Additional relevant MIL-spec documents are "MIL-PRF-32535/4 w/AMENDMENT 4" (2/14/2020), for 0805 size, and corresponding documents for other sizes (MIL-PRF-32535/3 for 0603, MIL-PRF-32535/2 for 0402, MIL-PRF-32535/1 for 0201, etc.)

Interestingly, in the smallest size (0201), the only available MIL-32535 qualified MLCC is of PME construction (10nF/10V), see MIL-PRF-32535/1 and "Supplemental Information Sheet for Electronic QPL-32535." It is worth noting, also, that the only manufacturers listed on this document for MIL-spec BME capacitors are Kemet and AVX, now owned by Taiwanese and Japanese corporations, respectively.

(b) (5) [redacted]

5.3 Reliability and Testing

PME technology, which has been used for decades for high-reliability satellite and military applications, has a proven record of long-term reliability. By contrast, capacitors using base metal electrodes (BME), which are subject to oxidation, require initial firing in a reducing atmosphere, with attendant creation of oxygen vacancies in the dielectric. This may be considered a warning flag for long-term materials and device reliability, given that oxygen vacancies will migrate over time, accumulating at grain boundaries. COTS manufacturers have sought to mitigate these effects with proprietary dopants and subsequent annealing in reducing atmospheres with somewhat higher oxygen content. They are not forthcoming about their trade secrets, and they are free to vary their processes as they see fit, leaving customers with critical requirements (such as NNSA) out of the loop. In conversations with Presidio, we were told of examples where, under extreme thermal stress (e.g., at 200°C) BME capacitors fail quickly, whereas their air-fired PME parts last 1000 times longer under the same punishment.

(b) (5) [redacted]

5.4 Reconsidering the Choice of MLCC

(b) (5) [redacted] the reduced COTS density of MIL-PRF-32535 parts (compared with commercial or automotive grade parts), alongside improved PME manufacturing technology that yields density comparable to those parts, it would seem advisable for NNSA to select MLCCs manufactured with proven PME technology. The significantly higher per-part cost of PME MLCCs is offset by far by greater proven qualification and reliability (from installed use in satellite, aerospace, military, and legacy nuclear electronics) not to mention the costs of system-level rework when BME parts are found to be inadequate. (b) (5) [redacted]

Viewing the density issue from a higher level, we are concerned that the drive to the highest density capacitors may arise from a lack of appreciation of the potential reliability tradeoffs at the point where module *requirements* are specified. To meet those requirements, circuit designers are forced to capacitor choices with the highest energy density, i.e., COTS BME.

We understand the need to adopt COTS *active* components (e.g., plastic encapsulated microcircuits), because components of comparable performance cannot be found with hermetic ceramic construction. But for MLCCs there is no analogous driver, since PME MLCCs of comparable energy density to MIL-SPEC BME MLCCs are available in the smaller package sizes and are manufactured in the US; and, in situations where larger capacitances are required, PMEs should be the preferred choice, accepting the tradeoff of a larger overall footprint.

5.5 Remarks about Qualification Testing of Electronics

JASON was presented with the steps in Qualification testing used for capacitors by KCNSC, as specified by SNL. Capacitors of many sizes and ratings, made from the same standard process, are obtained from a given manufacturer. (b) (5) [redacted]

It is apparently common practice to qualify some parts by subjecting them to voltages that are multiples of the rated operating voltage of the part. The justification is that the over-voltage will cause failure in marginal or poorly manufactured parts, and is thus identifies poor manufacturing consistency –(b) (5) [redacted] However, it is not clear that such over-rating testing yields useful information about aging-related effects in dormant parts.

Taking the example of ceramic capacitors, some contemporary parts (of commercial grade, not MIL-spec) are made with very thin dielectric films – down to 0.5 μm – and normally operate at very high electric fields, as much as 30 MV/m or more. With these thin dielectrics, operating at a multiple of rated voltage creates very high fields that can cause dielectric breakdown. The part fails, but the failure mode does not reflect accelerated wear out. While high electric fields do accelerate migration of oxygen vacancies, it is not clear that this is relevant to the lifetime of a dormant part.

Note that such high-voltage tests are not advisable for many other kinds of contemporary electronic components. For example, CMOS logic chips will fail catastrophically at voltages as low as $1.3V_{\mathrm{DDmax}}$. This failure occurs not because of an accelerated wearout mechanism, but rather because this voltage pushes the low-voltage MOSFETs into "second breakdown", causing high currents and catastrophic electromigration. The part is destroyed and the failure says nothing about the lifetime of the component if operated within the specified voltage envelope.

JASON recommends reconsideration of testing protocols for COTS.

5.6 Findings

7. (b) (5) [redacted]

(b) (5) [redacted]

8. Traditional over-voltage testing, which can reveal manufacturing variability, may not yield useful information about aging-related effects in dormant parts.

5.7 Recommendations

6. NNSA should view with skepticism expectations of long-term stability and reliability when adopting COTS electronic components whose design and manufacture were predicated on applications in commerical products with limited service lifetimes. This is especially true for technologies like BME MLCCs, where commercial pressures for maximum energy density force the adoption of exceptionally small feature sizes, and where the reactivity of the materials requires processes and dopants whose impact on component lifetimes is not fully understood.

7. (b) (5) [redacted]

8. The effectiveness of over-voltage testing of electronic components, e.g., as used in COTS Qualification, to determine suitability for long-term dormant reliability needs to be re-examined.

This Page Left Blank Intentionally

6 TESTING AND PHYSICS OF FAILURE

6.1 Traditional Approaches to Electronics Reliability

The reliability of an electronic device is related to its ability to perform a desired function for an expected lifetime. The traditional approach to determining the reliability dates back at least to the 1960s where statistical methods were used to describe the probability of failure and expected lifetimes. This has led to a number of standards related to reliability, such as the Military Handbook 217, 338, and others. MIL-HDBK-217 uses a model for failure rate of an electronic system (λ_e) given by:

$$\lambda_e = \lambda_b \, a_T \, a_S \, a_q \, a_e \, a_R \tag{6-6}$$

where λ_b is the base failure rate provided by the handbook, a_T is the factor accounting for the effect of temperature on failure, a_R is the power rating factor, a_S is the factor accounting for voltage levels, a_q is the factor accounting for the quality of the device, and a_e is the factor accounting for environmental stressors. Thus, the overall failure rate is determined by extending the baseline failure rate by multiplication factors that are typically taken as constants. We note that the approach to reliability described in MIL-HDBK-217 has been criticized in a 2015 NRC report [13].

This approach allows for an estimate of the mean time between failures (MTBF), which is often a basis for evaluating the reliability of components. The multiplication factors are developed to be device specific and tailored from experimental testing or field data with Arrhenius functions having activation energies accounting for the failure driven by temperature, stress, etc. In essence, all of the physics and mechanisms of the failure modes and kinetics of degradation are lost in the phenomenological descriptors of reliability evident in equation (6-6). In addition, this approach assumes that the effect of temperature is independent of power and environment on the failure of a component, which is in contrast to the impact of coupled fields

(b) (5)

[redacted]

on device degradation and failure rates often found in practice. Nonetheless, these methods for estimating failure rate have formed the basis for numerous handbooks and standard approaches to reliability. In addition, these references are only updated periodically to account for the evolution in electronics technology. The effort to upgrade these handbooks take significant time and are often reactionary to the technologies that have been fielded since the last revision. The process to update the standards may have very little ability to account for the rapid pace of change of technologies found in COTS electronics and is not well suited to address the changes and failures possible in dormant electronics.

The use of standards has provided guidelines to develop reliable electronics, mainly through a statistical approach that is coupled with a testing program. In such programs, samples are exposed to stressors such as heat, humidity, vibrational loads, solar illumination, and powered conditions. While a number of experiments can be performed with these typical stressors, they generally fall into the class of highly accelerated life testing (HALT) and highly accelerated stress screening (HASS). HALT testing is typically used on a smaller number of parts and is used in the initial design phase. HALT testing is intended to fail the systems by determining the limits of operation and helps to identify weaknesses in the design or manufacturing of the component. Once design decisions are completed through the HALT testing process, production can begin. HASS testing is then used where production parts are tested at levels higher than their intended use, but not to stress levels as high as those found in HALT testing. HASS testing can uncover defective parts and problems with manufacturing and, along with additional environmental (E-Test) and destructive (D-Test) testing, makes up the electronic assembly production testing of parts, subsystems and systems that are in the Stockpile, see Figure 11.

Together, HALT and HASS play an important role in the reliability process, but themselves do not provide an understanding of degradation physics and kinetics that are linked to the underlying processes. Thus, while HALT and HASS can help to ensure initially reliable designs and manufacturing, they are not suitable for determining material, component, subsystem or system degradation, or aging during dormant, unpowered storage. In response, approaches based on understanding the failure modes and their underlying physical mechanisms and using them to help drive the reliability process will enable the development of reliable electronics for both dormant and active use cases.

6.2 Physics of Failure for Electronics

Another approach that is widely used is to guide the notion of reliability analysis based on the expected failure modes by starting with a root cause analysis. This approach is referred to as the Physics of Failure. In this process, failure modes are related to the underlying physical mechanism that prevent the electronic component or system from being able to perform its expected function. The failures may occur in the form of corrosion of contacts, voids, fracture and delamination of contacts and interconnects, chemical reactions, diffusion, and defect formation in materials. These failure modes are often driven by environmental stressors and use conditions. These conditions form the basis of reliability testing in order to better understand if the device or system designs are sufficiently robust against the anticipated failure modes. A key aspect of this assessment process is to determine which failure modes are most detrimental to the operation of the device or system and then design either the operational limits or the device/system structure to guard against the stressors that would induce these failure modes. The ranking of the most critical failure modes for device or system reliability is called the Failure Mode, Effects, and Critical Analysis process (FMECA).

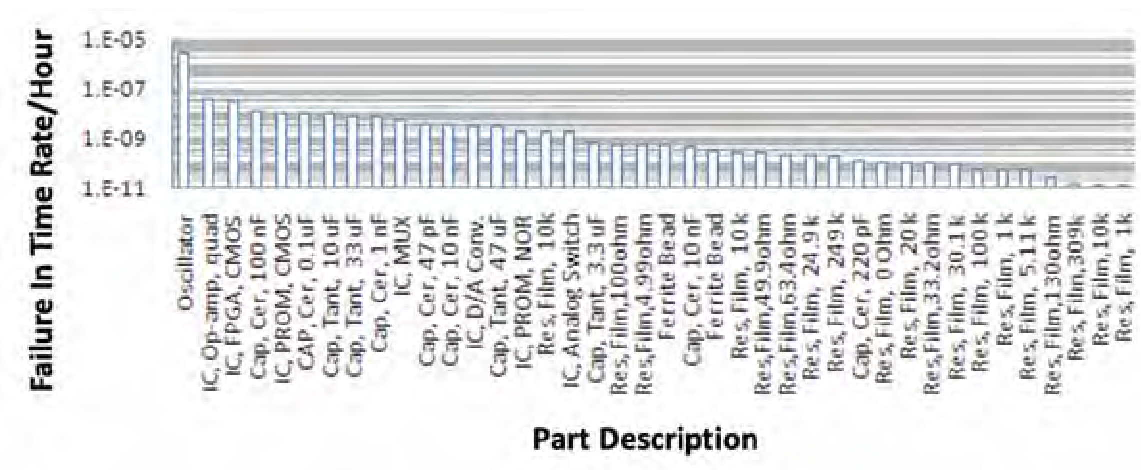


Figure 12: Example of FMECA performed on an RF radio system. Analysis shows that the oscillator dominates the FIT rate/hour (failures in time, i.e., number of failures in 10^9 hours of use. Example taken from briefing by D. Weidman [36].

From an empirical point of view, FMECA is performed by subject matter experts who have knowledge of the behavior and architecture of devices and subsystems and the likely failure modes based on its designed usage. The effect of the known failure modes on system reliability are then ranked and most of the design and testing is focused on eliminating the failure modes judged most critical. An example is given in Figure 12. In a discussion with Dan Weidman from MIT Lincoln Laboratory, JASON learned that this process can take hundreds of hours to implement properly, but is a necessary method for improving the reliability process. After performing FMECA, the HALT and HASS testing parameters can be set to verify that the most critical defects are properly eliminated, thus focusing the reliability tests toward a root cause failure approach as shown in Figure 13.

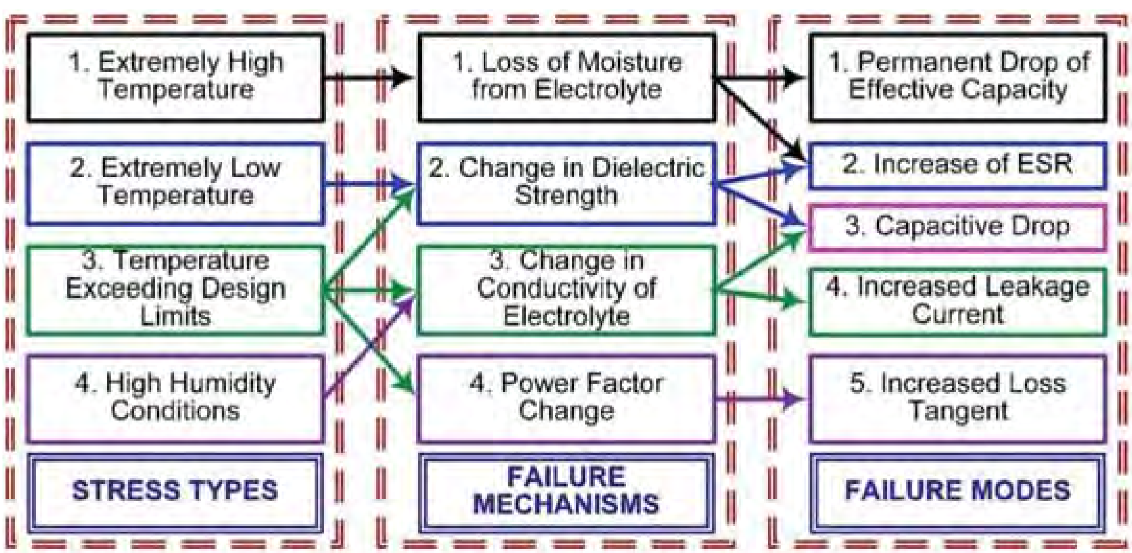


Figure 13: Example of FMECA and its link to testing parameters and critical effects for an electrolytic capacitor [37].

The use of subject matter experts (SMEs) in determining the FMECA is an indirect way of bringing materials science and physics into the reliability process due to the focus on underlying mechanisms. The knowledge of SMEs comes from an understanding of device design, testing history, and field failures. However, due to the dearth of comparable information on dormant electronics with one shot operation, this method still leads to more uncertainty in the process than desired.

Often the failure rates for dormant electronics are simply determined by modifying the failure rates of active devices by a constant factor (between 0–3%) and thus is itself a guess. The leap between the physics and understanding of failure during dormant operation versus active operation needs additional attention from the scientific research community. However, the commercial drive to obtain this knowledge is relatively small since the majority of COTS electronics are not intended to be kept in dormant stages for a long period of time. Thus, there is a clear need for the research community to advance the materials science of failure and device aging to help to address the reliability of COTS electronics.

6.3 Square-Root Biased Sampling

In the standard approach to qualification testing, a subset (or lot) of items is tested to identify poorly performing items, poor manufacturing processes, etc. Generally a fixed resource, e.g., a set number of tests, is to be expended to perform the qualification testing.

To develop qualification testing, subject matter experts may estimate possible failure modes, suggest corresponding tests, and estimate a priori probabilities for each failure mode. Straightforward assignment of the number of a certain test in proportion to the corresponding probabilities is referred to as strong profiling [38]. It turns out that strong profiling is not more efficient at identifying a failed item than uniform random testing. However, Press [38] shows that a mathematically optimal strategy is “square-root biased sampling”, where the distribution of tests is based on the square root of the a priori probabilities. NNSA should consider this approach to make more efficient their qualification testing.

6.4 Modeling and Simulation-Based Approaches

One method that can be used to increase the understanding of failure modes and the response of devices to external stressors is the use of physics-based modeling of components and subsystems. It is not expected that model-based approaches will ever replace testing, but they can be used to augment testing and provide an understanding of the effect of stressors on devices and systems. In a case where sufficient fidelity is contained in a model, some predictions may be possible by capturing the formation of damage and its subsequent impact on device characteristics. It is the growth and creation of models that capture the salient underlying multiphysics, multiscale responses of a device that will enable more and improved model-based predictions. In some cases, industry is pushing towards an "electronics digital twin" to help with the design and reliability of electronic systems. While these approaches are in their infancy, it is known that the Department of Defense is planning to develop the digital twin (simulation) approach in efforts to create future systems. The promise of this approach is that simulations can be used to optimize designs and predict system performance before investing in physical prototypes and manufacturing. As long as the models capture the physics and materials science of devices, it will increasingly be possible to understand aging. This provides an opportunity to extend modeling and simulation approaches to improve design of both testing and systems for both active and dormant environments.

There are a few attempts to create software codes for digital twins and reliability predictions of electronics. Siemens uses electronic computer-aided design (ECAD) and mechanical computer-aided design (MCAD) software tools as part of the product lifecycle management to enable improved designs for reliability and manufacturing. In the National Research Council's 2015 *Reliability Growth Report: Enhancing Defense System Reliabilities* [13], it was pointed out that Ford Motor Company uses computer-aided simulations to find mistakes in electronic designs before proceeding to FMECA and prototypes.

While there are many proprietary software tools and approaches used in industry, an example of a commercially available tool set is provided by Ansys. Their reliability software Ansys Sherlock, utilizes simulation tools for thermal (Fluent and IcePak), mechanical (Ansys Mechanical), and electrical environments (Ansys Siware) that devices may experience, as sketched in Figure 14). Ansys Sherlock takes into account degradation parameters and other failure effects from a database of experiments performed on commercially available components. Thus, in principle, they are able to approximately simulate the effect of mechanical failures (voids, fracture, delamination), hotspot and thermal environments, and applied voltage and power on device degradation and performance through these simulation tools. This software has been applied to numerous commercial electronics and is currently being extended for use in radiation environments. While it is not clear if this software captures all of the proper kinetics of degradation, it does provide an example of the kind of software tools available for simulating the reliability of electronics and creating a digital twin. With appropriate validation, similar tools could help to reduce the number of experiments needed to be performed to ensure reliability. In addition, the digital twin features could help investigate field failures and determine the root cause analysis.

To improve the simulation capabilities, it may be possible to integrate high fidelity physics-based simulations that accurately capture effects needed in reliability simulations (e.g., improve constitutive models for plasticity and failure in metallic joints, diffusion of elements, fracture, defect formation, and coupled electrothermal induced failures). Such high-fidelity physics-based models could be developed by organizations found in the Engineering Sciences Research Foundation or the Material Science organizations at Sandia National Laboratories.

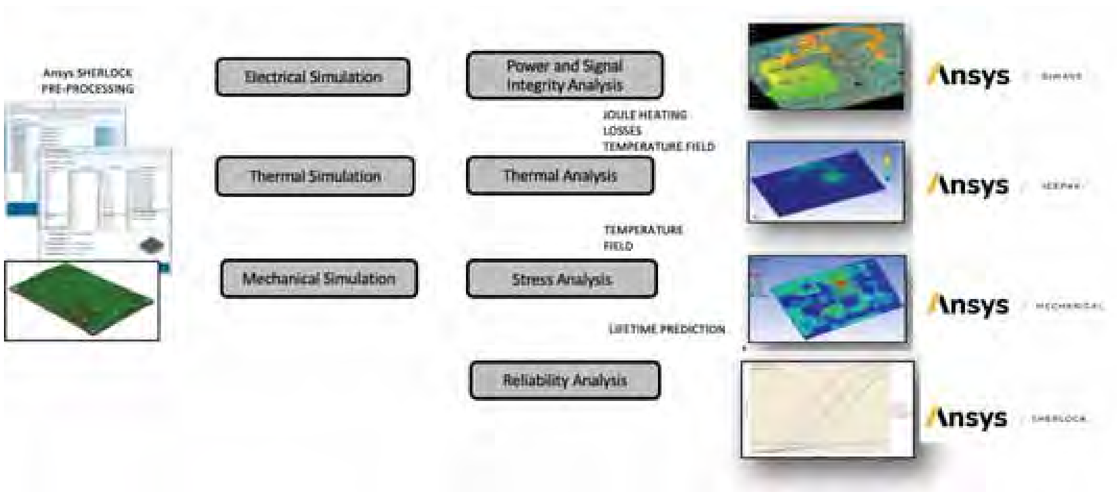


Figure 14: Diagram showing the flow for the commercial item Ansys Sherlock and other software simulation tools used to predict device reliability [39].

6.5 Findings

9. There is a trade-off in highly accelerated stress screening (HASS) between finding defects and not damaging the items that pass the test, i.e., creating "walking wounded." In other cases, legacy tests may no longer be appropriate for modern electronics, so reconsideration of screening protocols for COTS components is warranted.

10. In qualification testing, a subset (or lot) of items is tested to identify poorly performing items, poor manufacturing processes, etc. A natural way to allocate resources is to assign the number of tests for a given failure mode in proportion to the corresponding a priori estimated probability of failure, which is "strong profiling." However, a mathematically optimal strategy for screening, given a fixed resource, is

"square-root biased sampling", where the distribution of tests is based on the square root of the a priori probabilities.

11. Concepts such as *Physics of Failure* and *Design for Reliability* overcome some of the shortcomings of the standards-based reliability tests recommended in MIL handbooks. Industry continues to utilize and develop robust reliability programs that combine Physics of Failure and Reliability Growth processes seeking to ensure that qualified COTS components can perform over long periods and survive dormant phases. Simulation capabilities have shown promise in assisting the reliability analysis of electronics in industry, but it is not clear how well this approach has been adopted or is being developed within NNSA as part of their reliability activities.

6.6 Recommendations

9. Stress screening in different tests should be targeted at the most likely modes of failure for a given component or system. Reconsideration should be given to tests that overstress parts, since these may introduce "walking wounded" in the Stockpile.

10. For qualification testing, NNSA should consider the mathematically optimal strategy of "square-root biased sampling", where the distribution of tests is based on the square root of the a priori probabilities.

11. During or before the design phase, SNL should develop a scientific understanding of the most probable failure modes of COTS components and the circuits assembled from them. An accurate model of the device and system must be created, i.e., coupled electrical, mechanical, and thermal responses, which should be used to improve designs and model behavior of stored systems. Experiments are needed to verify and validate the simulations.

7 PHYSICS OF FAILURE CHARACTERIZATION OF MATERIALS, DEVICES AND CIRCUITS

In this JASON study, the Sponsor requested a focus on electronic materials at the device and next level of assembly. This is of particular importance in evolving COTS systems, where new materials and designs may fall outside the existing basis of known behavior. Characterization of the materials processes involved in failure modes at this level, coupled with modeling and simulation, are a key part of the Physics of Failure approach to reliability assurance for electronic systems. Identifying the mechanisms of failure makes it possible to design interpretable tests, and provide quantitative inputs to models that can be used to screen the impacts of many different combinations of designs and materials combinations that fall within the boundaries of characterized systems.

Many of the tools required for the characterization of defects and their behavior require destructive analysis with painstaking, time-intensive characterization. We saw outstanding examples of this in the Sponsor's briefings related to bonding and packaging in assembly of electronic systems and defects in semiconductor microelectronics. We see no way to bypass this critical aspect in building system reliability. However, it is possible to improve the focus of in-house efforts and ensure that they are structured to provide needed information for device and system qualification when it is needed. This focus requires systematically building on the knowledge for legacy electronic devices and circuits, and focusing R&D efforts on developing new information about emerging COTS electronics technologies well before they may become a design element for the Stockpile. Working with other defense agencies or industrial sectors (see Chapter 3.3) that have similar long-life requirements will also allow NNSA programs to focus internal efforts on assessments essential for truly unique Stockpile requirements.

7.1 Approaches for Detecting Early Signs of Aging

In addition to pre-design qualification, the Physics of Failure approach should also inform interpretation of empirically-designed stress tests, characterization of fully assembled systems, and long-term monitoring of the electrical systems in the Stockpile. Developing tests that can detect early stages of degraded performance due to aging, or materials aging that is a precursor to failure, is particularly challenging. A powerful approach is detecting changes with respect to an initial baseline of performance using physically-based indicators, as discussed in at least two briefings to JASON (J. Leitner, NASA GSFC [17], (b) (5) [redacted] Detection based on physical responses of elements within a circuit, such as thermal responses, power fluctuations, and electronic emissions can be useful indicators.

7.1.1 Power spectrum analysis

One promising approach is fingerprinting of either device-level or circuit-level performance characteristics using Power Spectrum Analysis (PSA) [41]. In general, PSA is based on measuring the frequency spectrum of responses of an electrical system to applied electronic stimuli. In the examples presented to JASON, the stimuli were dynamic voltages applied in configurations not related to the normal use mode. This approach allows a generic test protocol that does not need to be tailored to the specifics of the test circuit. As such, it may provide a useful basis for *Design for Test* approaches discussed in Chapter 8.2. Also, JASON recognizes that failure analysis to support PSA techniques will provide long-term value to the program.

The assessment of thermal aging on Zener diodes was presented as an example of the use of PSA, as shown in Figure 15 [41]. There was a significant difference in the power spectrum of the devices after a long thermal stress test (500 hours at 140°C), and continuing smaller changes with longer thermal

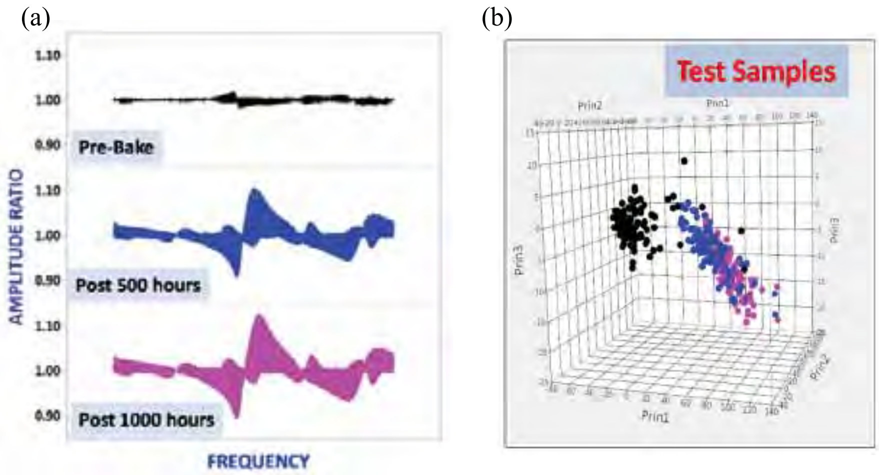


Figure 15: Power spectrum analysis of a Zener diode [41]. (a) Normalized PSA spectra before thermal stress, and after 500 and 1000 hours of heating at 140°C. (b) Principal component analysis of the spectra for multiple tested diodes under the same conditions; before bake (filled black circles), after a 500-hour bake (filled blue circles), and after a 1000-hour bakes (filled pink circles).

annealing (Figure 15(a)). A principal component analysis of the results, displayed in Figure 15(b), emphasizes the changes following thermal aging. In contrast, the standard test parameters for Zener diodes showed no significant changes with annealing time (data not shown here). SEM images of the Cu-Al interface are shown in Figure 16 before and after the thermal stress [41]. Growth of a Cu-Al intermetallic region is evident in the area of the bond pad (Figure 16(b)).

This PSA approach was also used to demonstrate different signatures from different lots of microelectronic circuits, and for differences among nominally identical electronics from different manufacturers. This approach could be used in monitoring as an empirical indicator of changes in electronic systems, which could be used to trigger more in-depth analysis. Ideally, a catalog of changes under various stressing scenarios leading up to failure would be developed in advance and correlated with underpinning physical characteristics in a true Physics of Failure approach.

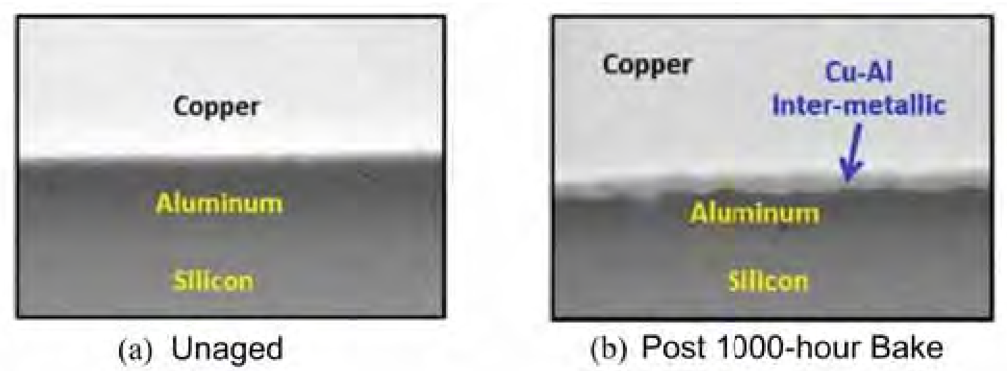


Figure 16: SEM images of a cross section of the bond-pad for the diodes (a) before and (b) after thermal stress at 140°C. (Length and frequency scales are absent in the original publication) [41].

7.1.2 Strain-induced resonances in electronic components

Many components of the electrical circuits of interest have piezoelectric properties that may serve as a physical indicator of aging effects, especially those related to mechanical stress. Silicon and Germanium have long been known to have piezoresistive properties [42, 43], and barium titanate ($BaTiO_3$), which forms the dielectric for base metal electrode capacitors, is piezoelectric (a discussion of piezoelectric materials is provided in Appendix 4, Chapter 15). Mechanical responses in the structure can be excited by sweeping the frequency of an applied ac voltage, with especially strong responses near any resonant frequencies in the structure. Piezoelectricity is reciprocal, so the resulting deformation generates a voltage. Resonances in electronic components could also be excited mechanically by using piezoelectric actuators positioned near the component on the circuit board or mounted directly on critical components.

The pattern of mechanical resonances for an electronic circuit could be detected by a modified PSA approach. The resulting spectrum and phase plot would provide a fingerprint of the circuit, recorded when it is built. The fingerprint could be compared with spectra recorded later, after it has aged in storage. This approach could also be used to probe a single critical com-

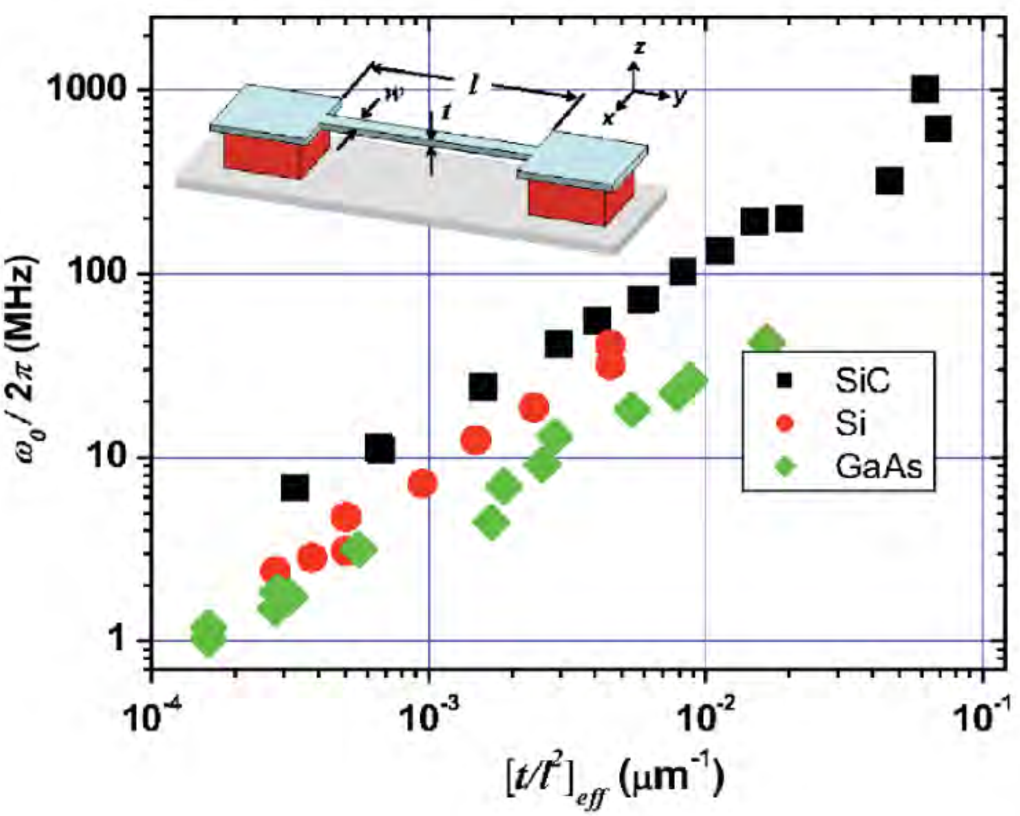


Figure 17: Frequency versus geometric parameters for SiC, Si, and GaAs beams (thickness t and length L). [44]

ponent or device, by exciting it electrically or with a piezoelectric actuator. Developing this technique would require detailed assessment at the *device* level (similar to that demonstrated for the Zener diode described above) and at the *circuit* level. It could prove a useful complement to another strain-detection option presented to us, Fourier Transform IR Spectroscopy applied to package stress. For example, changes in mechanical resonance frequencies are sensitive indicators of cracks.

Nano-electromechanical systems (NEMS) provide examples of electronic resonators at the micron size scale, as shown in Fig. 17 [44]. Semiconductor cantilevers that are excited by applying an ac current in an applied magnetic field have deflections with characteristic sizes $\frac{l^2}{t}$, where t is the thickness and

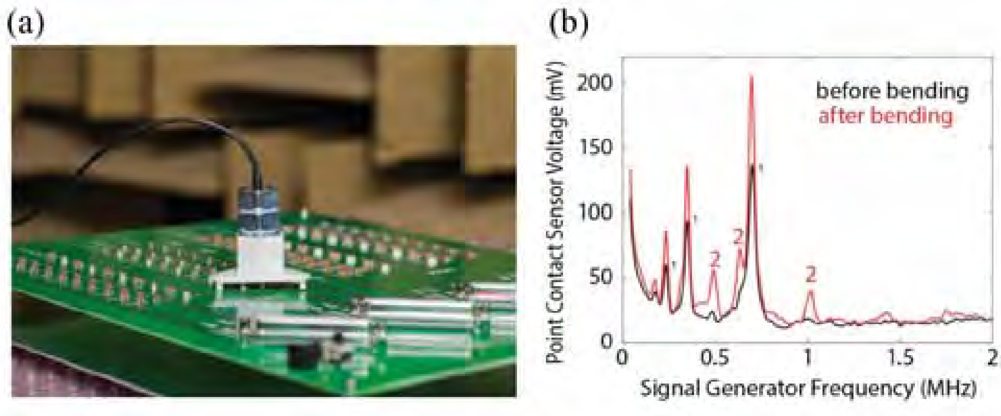


Figure 18: Acoustic signature of damage in a BME capacitor. (a) Test arrangement. (b) Resonant peaks in the sensor voltage that show changes after stress by bending. After Fig. 3 from [45].

l is the length of the cantilever. The predicted frequency:

$$f_0 = 1.05 \left(\frac{E}{\rho}\right)^{\frac{1}{2}} \left(\frac{t}{l^2}\right) \tag{7-7}$$

is in good agreement with the data. The resonant frequencies range from $f_0 = 1$ MHz to 1 GHz.

The use of acoustic signatures to detect damage in a BME capacitor made from barium titanate is shown in Fig. 18. Stress is applied by physically bending the capacitor (Fig. 18(a)) while the spectrum of mechanical resonances is electrically probed by a point contact sensor on the circuit board; peaks in the range $f_0 = 0$ to 1 MHz are observed (Fig. 18(b)). After bending, some of the original peaks drop in amplitude and additional peaks occur at $f_0 = 0.5$ MHz, 0.7 MHz and 1 MHz, as shown in Fig. 18(b), presumably due to cracks formed in the material. These experiments demonstrate the ability to characterize piezoelectronic components by electrically observing their mechanical resonances, i.e., this sort of response could potentially be used for fingerprinting.

7.1.3 Additional imaging opportunities

There are new insights being gained by variations of X-ray imaging. For example, X-ray ptychography is a technique that combines scanning X-ray microscopy and coherent diffractive imaging. The method has been used to provide high-resolution 3D images of a CMOS integrated circuit at a resolution of tens of nanometers. In a recent paper, the approach was used to give non-destructive, three-dimensional views of integrated circuits; the authors showed images of an entire chip volume and high-resolution images of arbitrarily chosen subregions [46]. It will be valuable to consider benefits that might come from utilizing new imaging modalities, especially if these can be operated in ways that allow faster throughput.

7.2 Findings

12. A variety of physical processes, including electromechanical and acoustic resonance technology, can provide sensitive indicators of changes in electronic materials and circuits. The development of Power Spectrum Analysis techniques for exploiting such signatures should provide non-destructive means to identify internal defects, such as cracks, delamination, and voids, and other early signatures of aging-related failures, and may provide a route for periodic monitoring of stored components and systems.

7.3 Recommendations

12. NNSA's EMRCP should develop rapid, non-destructive testing methods, including electrical, electromechanical, and acoustic resonance, designed to identify defects (micro-cracks, delamination, or voids) that are likely to result in component or system failures during storage aging.

Establishing a database of such device "fingerprints" will allow changes of individual units to be monitored over the life of a system.

8 RELIABILITY GROWTH

8.1 Background: DoD Approaches

Reliability growth is a practice DoD established in the mid-1980s and was codified in a DoD handbook first published in 1981, a document that has been updated over the decades and is still widely cited today [47]. Definitions from this document are useful:

"Reliability growth is the positive improvement in a reliability parameter over a period of time due to implementation of corrective actions to system design, operation or maintenance procedures, or the associated manufacturing process."

"Reliability growth management is the management process associated with planning for reliability achievement as a function of time and other resources, and controlling the ongoing rate of achievement by reallocation of resources based on comparisons between planned and assessed reliability values."

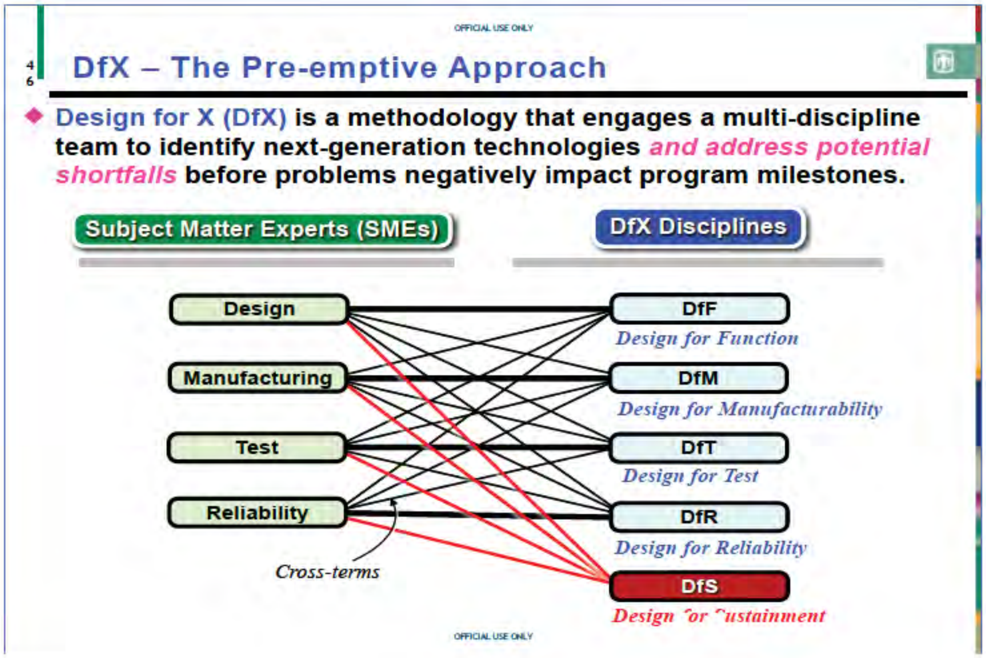
The National Research Council (2015 Appendix C [13]) documents some of DoD's history in reliability practices. DoD practiced reliability growth management throughout the mid-1980s to the mid-1990s. In 1998 a key U.S. Military Standard for reliability programs was cancelled (Reliability Program for Systems and Equipment Development and Production, MIL-STD-785B [48]), moving DoD away from the use of reliability growth as a management practice. A 1998 NRC report [49] began to caution DoD that changes to the treatment of reliability to support test and evaluation were needed. By 2008 a Defense Sciences Board taskforce was assembled to review DoD's approach to developmental testing and evaluation and found that a substantial number of DoD systems entering Initial Operational Testing and Evaluation (IOT&E) were operationally ineffective and unsuitable [50].

Thereafter, starting about 2008 DoD began to return to reliability growth practices (see DoD5000.02 starting in 2008 and subsequent releases [51]). By 2016 the Director of Operational Test and Evaluation (OT & E) remarks: "The most successful programs are incorporating reliability growth into their contracts and have reliability thresholds as KPPs [Key Performance Parameters]." [52] Reliability growth approaches are common in industry so NNSA can learn from both DoD and industry about implementation and practice of these ideas.

8.2 Design for Reliability

Reliability growth management aims to design high reliability into the system design. However over the years, reliability growth practices have taken on the form of test-analyze-and-fix, employing reliability techniques such as failure modes and effects analysis, robust parameter design, block diagrams and fault tree analyses, physics-of-failure methods, simulation methods, and root-cause analysis [13]. These different kinds of approaches, with common goals, have now been synthesized into a coherent framework. Today, DoD (b) and industry [39] are moving into Design for Reliability (DfR) processes. DfR conceptually builds reliability into the full lifecycle of a system from design through obsolescence. Rather than simply making system development decisions meant to guarantee reliability growth, reliability itself becomes one of the design parameters [54].

Design for Reliability, like reliability growth, is a process or practice and not a singular mathematical model. Modeling and simulation to support the identification of design challenges and aging mechanisms can be part of a DfR process. Reliability growth, as practiced with DfR, is a pre-emptive path forward, in contrast to being reactionary and surprised by problems. Design



(b) (5) [redacted]

for Reliability requires expertise from material sciences to systems engineering and naturally lends itself to taking both bottom up (piece-parts to full system) and top down assessment of system reliability. The former shares elements with current NNSA-SNL-KCNSC practices for integrating COTS electronics into nuclear deterrence systems, as described in the briefings JASON heard, while the latter reflects ideas present in the DoD approach.

NNSA shared a broader "Design for X" (DfX) concept they are using in the Global Burst Detection program, as shown in Fig. 19 (b) (5) [redacted] Here X can be function, manufacturability, testing, reliability, or sustainment.

(b) (5) [redacted]

(b) (5)

[redacted]

8.3 Design for Reliability and Reliability Growth in the Aerospace Industry

Due to the critical need for reliability in spacecraft (see § 3.8), Design for Reliability and reliability programs have long been recommended practice for even small spacecraft projects [58, 59]. Requirements for Reliability Growth in DoD programs have waxed and waned with time, but are making a resurgence as discussed in the previous sections. Typical program management specifies DfR objectives, assigns responsibility for accomplishing the objectives, and sets out milestones for evaluating progress in achieving the objectives. The program also includes design, evaluation and testing. The interfaces with other aspects of a spacecraft program require firm coordination, e.g., with quality assurance, test, and spacecraft configuration. Reliability programs are described in more detail by Hecht, e.g., Ch. 8 [59].

8.3.1 The Design for Reliability process

The management process for incorporating reliability into spacecraft design can be accomplished in a variety of ways that assign responsibility. Running from least to most extensive and costly are: (A) designers responsible for reliability; (B) designers responsible, but with guidance from management; (C) designers responsible, but with guidance from reliability organization; and (D) responsibility resident in a separate reliability organization [58]. Typically, the choice is governed by the cost and size of the spacecraft and risk.

One is likely to spend more on reliability depending on the cost and criticality of the mission, e.g., Earth orbit versus deep space missions.

8.3.2 Figures of merit for reliability

A key factor in Design for Reliability is a figure of merit for assessing the overall success of a design in terms of reliability. If one takes a measure of overall reliability R as the probability of no failures in a time t, where $R \propto e^{-\lambda t}$, a figure of merit is MTBF (Mean-Time-Between-Failures), which is equal to λ^{-1}. Typically, a failure is taken as a mission critical failure, not just any failure at all. Another figure of merit, where reliability varies with time, i.e., $R(t)$, is the MMD (Mean Mission Duration), where $\mathrm{MMD} = \int t \, \mathrm{d}R$, where again t is time and R reliability. Both of these figures of merit are used in reliability growth programs for spacecraft [58]. The reliability parameter $R(t)$ could be measured if a large number of mission results are available or, more likely, calculated using an overall system reliability model.

8.3.3 Failure mode analysis and failure reporting

Failure mode and effects analysis is practiced in evaluating components for spacecraft. FMECA (Failure Modes, Effects and Criticality Analysis) procedures are recommended for spacecraft designers and MIL-STD-1629 is a useful guide for implementing this procedure. Failure mode reporting and corrective action (FRACAS) are a key element in any reliability program. COTS parts failure reporting would be a valuable area for cooperation among entities that have reliability-critical missions, e.g., NASA, DoE, spacecraft, and automotive industries.

8.4 Periodic Testing and Surveillance

Monitoring and surveillance of electronic systems in the Stockpile can potentially increase reliability by detecting small changes in components as early signs of aging, catching failed parts, and by determining whether subassemblies might be out of specifications due to small changes in many parts. But the value of designs that allow self-testing and monitoring at regular time intervals must be balanced against the system-level complexity of such designs, which might itself reduce system-level reliability or introduce new vulnerabilites. Limited-life components have similar trade-offs between risks and possible benefits. Several approaches are possible:

Self-testing: Design and build the electronic assembly in refurbished or remanufactured systems so that it can test itself, either under external command, or by pre-assigned schedule. Potential benefits of such a design include:

ST1 Timeliness: Provide frequent monitoring and timely reporting of electronic changes, defects, and failures.

ST2 Coverage: For newly introduced designs, this approach could cover all weapons in the Stockpile.

ST3 Health check: Allow for categorizing an individual weapon as needing maintenance if failing, or as out-of-service if failed.

ST4 History: Record large quantities of data to determine trends and rare events over the Stockpile.

Potential challenges and limitations of such a design for monitoring include:

ST5 Complexity: Complication of design may itself reduce reliability.

ST6 Power: Many systems are unpowered during deployment; an additional internal power source would be needed, which itself would have a limited lifetime, perhaps less than the average lifetime of the components under test.

ST7 Communication: The results of the test must be reported, and external commands may be needed. Any required channel could introduce a security threat.

ST8 Comprehensiveness: Test conditions should not include any significant stresses , or most insults (though current HASS testing may overstress with temperature, and perhaps overvoltage).

Periodic external testing: Because other limited-life components require maintenance, weapons are periodically serviced, providing an opportunity for non-destructive testing of the electronic assembly at the same time. This approach to the design of refurbished or remanufactured systems is more feasible than self-testing, with some of the potential benefits:

ET1 Timeliness: Not nearly as frequent as self-testing, but superior to current practice.

ET2 Coverage: For newly introduced designs, this approach could cover all systems in the Stockpile at some cadence.

ET3 Health check: Allow for categorizing an individual weapon as out-of-service, if failed, but only when known.

ET4 History: Record quantities of data to determine trends and rare events over the Stockpile.

Nevertheless, the remaining challenges in such a strategy are:

ET5 Complexity: Complication of design may itself reduce reliability.

ET6 Delay: Problems would not be noticed until the next scheduled service, perhaps years after the problem originated.

ET7 The system itself would need to be designed to allow access to the electronics during servicing, which may itself complicate system design.

ET8 Comprehensiveness: Test conditions cannot include any stressing conditions (except temperature, and perhaps overvoltage), or most insults.

Sampled surveillance: This is in fact the current approach; selected weapons are removed from the Stockpile and subjected to various nondestructive or destructive tests. The benefits and challenges of this approach are well understood and the main issues are which and how many such tests to carry out, taking into account the coverage and expense.

8.5 Findings

13. Reliability Growth, as conceived by DoD and industry, aims to improve reliability over time; it is a practice and not a mathematical model. Reliability Growth has been proven to be an effective way to maintain a system from acquisition to retirement.

14. The next generation of reliability management processes includes Design for Reliability and Design for "X," where X can be function, manufacturability, testing, reliability, or sustainment. DoD and industry have already adopted Design for Reliability. (b) (5) [redacted]

15. Monitoring and surveillance of Stockpile weapons is used to identify signs of aging and to initiate mitigations for defects that are found. This approach compensates for the risk of incomplete understanding of the aging of materials and systems.

8.6 Recommendations

13. NNSA should formalize their adoption and use of Design for X processes, including Design for Surveillance and, most particularly, Design for Reliability, in their design and management of their weapons systems. This step requires broad collaboration from fundamental materials scientists to surveillance engineers. To succeed, the process needs to be intentional, documented, and tracked.

14. NNSA's Electronic Materials Reliability Coordination Plan (EMRCP) should consider complementing or extending the existing surveillence program by using "witness systems," whereby a large number of each of the electronic components, subsystems, and systems are assembled, placed in a representative test environment, left mostly unpowered as the actual systems of interest, and monitored periodically for the lifetime of the weapon system. The low cost of the electronic components and subsystems may enable a larger-scale supplement to the traditional surveillance program than is possible for fully operational systems.

    (a) (b) (5) [redacted]

(b) (5) [redacted]

15. NNSA's EMRCP should evaluate the feasibility and advisability of a life-cycle replacement approach for each of the major electronic subsystems to reduce the risk associated with aging of COTS components.

9 CONTEXT FOR THE RECOMMENDATIONS

In developing the focused recommendations for this report, the overall qualification process for War Reserve COTS components has provided an essential context. (b) (5) [redacted]

[redacted]

This simplified history provides the context for one of our key recommendations, that NNSA partner with DoD and NASA to form a COTS Reliability Consortium with aeronautics, aerospace, automotive, and biomedical device companies. This recommendation parallels, but likely goes beyond the recommendation (b) (5) [redacted] that NNSA actively participate in the NWC Working Group on commercial electronic parts. In the course of this Study, we have heard from several representatives of different industries that require significant electronic parts reliability. There is significant commonality between their needs and those of the weapons program. A culture emphasizing the uniqueness of the needs of the Nuclear Weapons Program may have contributed to NNSA scientists and engineers largely failing to engage with industry or the MIL-SPEC process. This must be changed.

(b) (5) [redacted]

Finally, we note that the entire process of selection and testing of the proposed BME capacitor part did not seem to be informed by a body of internal knowledge that we would have expected, given that BME capacitors had been a growing COTS component for some time. This provides insight into our recommendation that NNSA establish a systematic assessment of the impact of the changing materials and designs of COTS electronics that will be available for future use. One of the Actions noted (b) (5) [redacted] is establishment of a COTS catalog of approved qualified parts. Such a catalog is likely to be reactive and possibly overly conservative. A forward-looking program of R&D and assessment is essential for NNSA to stay ahead of issues that will arise in selecting and qualifying future COTS components. This will remain an issue as long as consumer electronics continue to change rapidly – there is no 'one and done' solution that will 'solve' this issue. NNSA must have an active program to stay ahead of the curve.

The lack of coordination revealed (b) (5) [redacted] also informed our evaluation of the briefings that NNSA provided for this Study. Many of these briefings provided strong technical information, and they covered many different aspects of materials aging and assurance of Weapons Systems. However, there was no overarching briefing or other information that linked these different briefings into a coherent whole. (b) (5) [redacted] It appears that different aging-related R&D activities are 'stove-piped' in different organizational lines without a single point of coordination.

Our recommendations address the goal of verifying and validating device reliability in an accelerated way. However, our recommended program can only succeed if there is top-level commitment to a coordinated structure with a single high-level point of responsibility and clearly defined goals for supporting future modernization programs through forward-looking R&D on the evolving landscape of COTS electronics.

9.1 Findings

16. NNSA has multiple parallel paths addressing COTS certification and reliability with complex rules, unclear decision-making and reporting requirements. This perceived complexity can result in protracted timelines for solving problems that other industries solve effectively in months.

(b) (5)

[redacted]

10 ANSWERS TO THE SPONSOR'S QUESTIONS

In this section, we give answers to the six questions in the Statement of Work. Where appropriate we make reference to appropriate sections in the report.

1. For COTS electronic materials and components, how can we use materials science knowledge to improve accelerated aging testing methods to better understand the impact of aging on reliability and confidently qualify components for deployments of 20 years or more?

   Answer: NNSA should focus materials science efforts on emerging COTS electronics materials and designs to inform systematic failure mode analysis tied to Physics of Failure experiments and simulations (components and systems); see the discussion in Chapter 6. For a specific system of components and connectivities, a subject matter expert (or small team of such experts) will generally be able to identify the major failure modes, and estimate which are more likely. A materials research program should be aimed at reducing the occurrences of each failure mode in configurations and systems common to NNSA assemblies. Moreover, the materials-science informed accelerated aging will provide increased confidence in coordinated development and use of modeling. The use of additional characterization methods that yield "fingerprints" of electronic components, subsystems, and systems can help provide signatures of changes that occur internally to materials over time, some of which may be linked to possible failure modes; see the discussion in Chapter 7. The understanding from the various material science efforts, tied to potential failure modes, can inform the plethora of possible testing that can be done. Sharing insights, knowledge, and experience with other government and industry organizations, e.g., NASA and the automotive, aeronuatics, and aerospace industries, who share similar needs for building reliability via accelerated aging tests, will build an improved database from which to understand component and system aging.

2. Considering the long dormant periods of most system components, does NNSA's approach to accelerated aging in COTS electronic materials and components appropriately probe aging phenomena and uncover potential aging and failure mechanisms?

   Answer: Not consistently. There are examples where this is done well, e.g., the "Development of the Package Life Test"[14] protocol is a positive example. In general, however, there does not appear to be a planned, consistent Physics of Failure approach (integrated experiments and simulations) that links identification of manufacturing defects with interactions or stresses driving long-time evolution or natural processes leading to change at the component and systems levels. The testing approach is not linked to possible failure modes, e.g., as discussed in Chapter 6, which is a necessary step to tie testing to aging phenomena that result in failure. The present testing approach, e.g., MIL Handbook standards for HALT and HASS, probes some manufacturing defects, but does not systematically identify interactions or stresses driving long-time materials evolution or natural processes leading to change that can affect function at the component and systems levels. Given the rapidity of change of structure and manufacturing strategies of COTS components, it should be anticipated that methods of assessing aging phenomena and potential failure modes must similarly evolve. Few of the aging mechanisms summarized in the materials discussion in Chapter 4 are tied to the kinds of testing done in HALT or HASS.

3. Are current techniques to determine and validate electronic material

(b)(5) [redacted]

and device reliability estimates appropriate for long dormancy, short duration, high-demand operations over extended lifetimes?

Answer: No. There are examples where this is done well, e.g., the work presented on "Electronic Defect Detection and Localization"[15] in semiconductor electronics is a positive starting point in one area of materials research. However, in general there does not appear to be a planned, systematic Physics of Failure approach (integrated experiments and simulations) that codifies evolving COTS materials, designs and failure modes, and links those through characterization, testing, and modeling to aging processes over extended lifetimes. The current NNSA screening techniques for COTS electronic components identify some manufacturing defects, but do not systematically identify interactions and stresses driving long-time evolution or natural processes leading to change at the component and systems levels. The fundamental materials science knowledge needed to understand aging of unpowered, long dormant, materials is currently lacking. Whatever approach is taken here will likely be challenged to itself change as COTS electronics evolve with smaller feature sizes, e.g. see the discussion in Chapter 4.

4. Considering Reliability Growth Models, as used in DoD reliability methods, are there improvements to the current NNSA/DOE reliability methods to

   (a) Accelerate qualification.

   (b) Increase confidence in reliability estimates by leveraging systems and sub-system testing during development and qualification.

   (c) Reduce qualification and/or production acceptance testing protocols.

(b)(5) [redacted]

Answer: Yes. See Recommendations 1-15. In particular, NNSA should formalize their adoption and use of Design for Reliability, as well as "Design for X," where X represents other topics relevant to weapons development, such as function, manufacturability, testing, and surveillance, in their development and management (including life extension programs) of their systems. This will require collaboration between materials scientists, electrical engineers, and surveillance engineers. To succeed, the process needs to be intentional, documented, and tracked. To accelerate qualification, and reduce qualification and production acceptance testing, knowledge of the most likely failure modes for a component or system is needed to design appropriate tests, which can be combined with Physics of Failure insights (integrated experiments and simulations). The aerospace industry and NASA have reliability programs that face similar challenges, e.g., § 3.8 and § 8.3, and so there is potentially opportunity for learning and collaboration to improve reliability assessments and growth models.

5. What changes could be made to the NNSA COTS testing methods that would reduce the overall time to qualify, while preserving high reliability operation of electronic assemblies?

   Answer: NNSA should focus electronic testing methods on the most likely failure modes for a given component or system. The failure modes should be identified through carefully conducted experiments and modeling with recognition that the most likely failure modes may change with time. Square-root biased sampling (§ 6.3) may be helpful in designing a more efficient highly accelerated life testing (HALT) qualification strategy. Designs should be conservative with efforts made to maintain the use of earlier-qualified parts. Making transitions to newer-generation components should involve careful consideration, with recognition that the latest generation parts, because they are either near the limits of their specifications or have small feature dimensions, may either exacerbate existing, or give rise to new, failure modes, e.g., see the discussion in Chapter 5. Highly accelerated stress screening (HASS) should be optimized to ensure that screening does not create "walking wounded." In particular, the use of legacy MIL Standard HALT tests, for example testing capacitors at multiples of their rated voltage, is not advised unless it can be shown that such tests screen for likely dormant failure modes, e.g., § 5.5. This approach will also require that NNSA engage basic materials science research and characterization as new technologies in COTS devices evolve in order to develop the understanding of how these devices behave, their critical failure mechanisms, and possible new methods of testing for these failure modes that can augment currently used testing methodologies. These steps will ensure that NNSA applies the most appropriate testing to new technologies to ensure reliability.

6. What are the critical science areas that need further consideration and review (if any)?

   Answer: Reliability will be improved by developing a framework that extends from materials science to device physics to circuit engineering, which should be implemented by leadership at the top (see Chapter 9 and the strategies outlined in Chapters 6-8). Overall, the historical knowledge base for electrical, mechanical, and thermal simulations is well established. To move forward, component- and systems-level approaches to electrical, electromechanical, and acoustic internal materials characterization should be developed to provide new insights and surveillance capabilities (Chapter 7). Topics that are necessary for improving the long-time reliability of devices and components are characterization tools, models and frameworks for understanding and identifying failure modes, such as defect formation and evolution of structure in electronics materials, electrochemical reactions and corrosion, radiation effects, and the impact of coupled fields on device degradation.

As new materials are introduced, the dependence of the material properties as a function of the environment and stresses will be needed. Moreover, the changes in these properties over time, along with defect formation, will be key to determining the reliability of devices under dormant operating conditions. In carrying out this program, it is crucial to have a goal-based R&D process, which is focused on impact for effective screening and testing, and mitigation of aging.

11 FINDINGS AND RECOMMENDATIONS

In this section we summarize the Findings and Recommendations that were identified in the different chapters of this report.

11.1 Findings

1. The rapid design cycle for commercial off-the-shelf (COTS) electronics is aligned with the demands of commercial markets, but does not align with design cycles or lifetime requirements for weapons systems, nor does it enable a well-controlled supply chain for components (e.g., resistors, capacitors, printed wire boards, etc.) needed for weapons applications.

   (a) Traditionally, variability in the quality and reliability of parts, as well as concern about future availability of parts due to obsolescence, is partially mitigated by life-of-program buys for weapon systems, thus missing future upgrades in performance and capabilities possible with short design time cycles.

   (b) There can be corresponding challenges in assuring reliability in new electronic technologies using legacy military standard tests.

2. The challenges associated with ensuring high reliability of COTS electronics over long times, under demanding environmental conditions, and for high-consequence applications, are also found in the aeronautics, aerospace, automotive, and medical device industries. These industries have developed, and continue to develop, approaches to manage the challenges of aging and reliability assurance, including investigating the materials level processes that cause electronics to fail when stresses are applied. While each industry faces different environmental stresses (e.g., temperature, humidity, and atmosphere), there can

be significant commonality in the underlying mechanisms of aging and failure. Information sharing can accelerate each sector's work to assess aging under their specific stressors.

3. A goal of reliable performance after 40-60 years of un-monitored storage poses difficult, and perhaps unrealistic, challenges for electronic components to electrical subsystems and systems, whether or not COTS materials are utilized. Reliability in the presence of material aging can be improved by careful assessment of defects and their mechanisms of evolution, integrating self-tests into the system, monitoring characteristics at regular time intervals, and life-cycle replacements.

4. Understanding the aging of materials, components, and subsystems involves:

    (a) mechanisms that span from atomic to the micron (and larger) scales;

    (b) designs and material processing steps that introduce structural heterogeneity (including interfaces and defects);

    (c) manufacturing steps in assembling subsystems and systems from components that may be imperfectly compatible; and

    (d) the environmental conditions and history that introduce chemical and mechanical stresses that can drive changes.

    All of these factors should be assessed before new electronic devices or systems are introduced into a weapon system.

5. It is well known that most physical processes in electronic materials have rates whose temperature dependence is more complex than simple Arrhenius behavior, arising from multiple activated processes and their interactions. However, parametric testing design often relies on such simplified assumptions, which may lead to incorrect lifetime estimates.

6. The risk of failures due to aging requires increased attention because of rapid advances in miniaturization of electronic components and increased parts density in electronic systems. Components with smaller feature sizes can be more susceptible to degradation than larger ones, if these issues have not been addressed in their design, because:

   (a) In powered systems, voltages are applied over shorter device distances, leading to larger electric fields. This may lead to high field-induced materials changes, including local stresses.

   (b) Diffusion lengths over the decades of storage may be commensurate with critical materials or device sizes (e.g., a grain size or a metal thickness).

   (c) Larger components, containing multiple crystal grains or multiple ferroelectric domains (in capacitors as well as transducers), have parallel and redundant transport pathways, making their properties and performance more robust.

   Assessing electronic materials, devices, and systems requires increasing power characterization techniques to locate and assess possible pathways to failure.

7. The introduction of base metal electrode (BME) multi-layer ceramic capacitors (MLCCs), to replace traditional precious metal electrode (PME) MLCCs, achieved higher energy densities, compared with PME parts available at the time. But BME parts do not have the proven long-term reliability, and the electrodes' susceptibility to oxidation requires a very different manufacturing process that may introduce new long-term failure modes. PME capacitors with energy density comparable to MIL-SPEC BME capacitors are now available (except in the larger package sizes, above 0805), and are currently produced by American companies. By contrast, most BME capacitors are manufactured

in Japan, Korea, and China, and two major domestic manufacturers were recently acquired by Pacific Rim corporations.

8. Traditional over-voltage testing, which can reveal manufacturing variability, may not yield useful information about aging-related effects in dormant parts.

9. There is a trade-off in highly accelerated stress screening (HASS) between finding defects and not damaging the items that pass the test, i.e., creating “walking wounded.” In other cases, legacy tests may no longer be appropriate for modern electronics, so reconsideration of screening protocols for COTS components is warranted.

10. In qualification testing, a subset (or lot) of items is tested to identify poorly performing items, poor manufacturing processes, etc. A natural way to allocate resources is to assign the number of tests for a given failure mode in proportion to the corresponding a priori estimated probability of failure, which is “strong profiling.” However, a mathematically optimal strategy for screening, given a fixed resource, is “square-root biased sampling”, where the distribution of tests is based on the square root of the a priori probabilities.

11. Concepts such as *Physics of Failure* and *Design for Reliability* overcome some of the shortcomings of the standards-based reliability tests recommended in MIL handbooks. Industry continues to utilize and develop robust reliability programs that combine Physics of Failure and Reliability Growth processes seeking to ensure that qualified COTS components can perform over long periods and survive dormant phases. Simulation capabilities have shown promise in assisting the reliability analysis of electronics in industry, but it is not clear how well this approach has been adopted or is being developed within NNSA as part of their reliability activities.

12. A variety of physical processes, including electromechanical and acoustic resonance technology, can provide sensitive indicators of changes in electronic materials and circuits. The development of Power Spectrum Analysis techniques for exploiting such signatures should provide non-destructive means to identify internal defects, such as cracks, delamination, and voids, and other early signatures of aging-related failures, and may provide a route for periodic monitoring of stored components and systems.

13. Reliability Growth, as conceived by DoD and industry, aims to improve reliability over time; it is a practice and not a mathematical model. Reliability Growth has been proven to be an effective way to maintain a system from acquisition through to retirement.

14. The next generation of reliability management processes includes Design for Reliability and Design for "X," where X can be function, manufacturability, testing, reliability, or sustainment. DoD and industry have already adopted Design for Reliability. NNSA and SNL are interested in these processes and are considering their use, but JASON lacked documentation to understand whether the COTS Transformation Initiative would achieve the goals of Design for Reliability with respect to integrating COTS electronic materials into nuclear weapons systems.

15. Monitoring and surveillance of Stockpile weapons is used to identify signs of aging and to initiate mitigations for defects that are found. This approach compensates for the risk of incomplete understanding of the aging of materials and systems.

16. NNSA has multiple parallel paths addressing COTS certification and reliability with complex rules, unclear decision-making and reporting requirements. This perceived complexity can result in protracted timelines for solving problems that other industries solve effectively in months.

11.2 Recommendations

Below JASON provides 15 recommendations. The first recommendation provides an overall structure to a materials-science informed, Physics of Failure and Design for Reliability plan that is then amplified by the recommendations that follow.

1. NNSA should create an Electronic Materials Reliability Coordination Plan (EMRCP) under which the research efforts on electronic materials aging work cooperatively, and have well-defined responsibilities to support the use of COTS electronics in the Stockpile. Such a plan should include coordination among:

   (a) systematic research on the changing materials and designs of COTS electronics that will be available for future use in the Stockpile;

   (b) linked experimental and modeling research on defects and aging processes and development of predictive tests for various components and assemblies

   (c) materials evaluation and selection of reliable components;

   (d) component, subsystem, and system testing focused on the most likely failure modes and linked iteratively to modeling at relevant scales;

   (e) surveillance of both components and actual systems, and additional "witness" components and systems;

   (f) assessing life-cycle replacement for different electronics subsystems

   (g) with (a-f) linked via a Physics of Failure and Design for Reliability process.

   To accomplish these steps, NNSA's EMRCP should include a focused materials science research program that anticipates and addresses the evolving COTS technology landscape, which will likely be driven by non-defense market pressures. The program should have responsibility to characterize the relevant material properties, including failure modes, so that science-based understanding of new materials and component choices will already be in place when the need arises to use new COTS components. A framework should be established to share this knowledge with the responsible program teams.

2. NNSA should partner with the Department of Defense and NASA to support the formation of a COTS Reliability Consortium with aeronautics, aerospace, automotive, and biomedical device companies to share common knowledge and practices, and possibly create leverage with COTS manufacturers to produce designs with long lifetimes that enhance long-term reliability and minimize aging of both dormant and powered components and systems. Cooperation in the materials research relevant to the use of COTS electronics in reliability-critical applications should reduce unnecessary duplication, saving resources, and producing better results.

   (a) NNSA should form a "storage-aging advisory panel" with experts in materials science, electronics, and reliability, from government agencies and laboratories, universities, and industry, to evaluate the impact of the evolution in COTS electronics on systems reliability for high-consequence applications.

   (b) NNSA should invest in basic materials science research aimed at characterizing the reliability-impacting aging processes that occur at the ever-smaller feature sizes found in COTS electronic components. Experiments, theory and simulation must all play an essential role in such a program, with machine learning potentially offering new insights from data-rich experiments.

3. NNSA's EMRCP should accelerate the process by which new COTS electronics materials and devices can be assessed and qualified for use

in the Stockpile by systematically evaluating the changing materials, manufacturing, and designs against a baseline of trusted materials and devices. This work will require a well-designed plan of research with an integrated, iterative process of experimental characterization, modeling, and evaluation of outcomes of stress testing.

4. NNSA's EMRCP should include development of component and subsystem designs that enable regular monitoring through subsystem testing done in the field, in order to ensure reliable functioning of the electronics components. There should be a suitable plan for this surveillance activity, which allows only limited access to the interior of the system, with no further disassembly required.

5. NNSA's EMRCP should consider implementing continuous, automated recording of the environments to which all components and systems are exposed, including temperature, humidity, power, and vibration (accelerations) so that there are clear records that can inform characterization of any faults that are discovered.

6. NNSA should view with skepticism expectations of long-term stability and reliability when adopting COTS electronic components whose design and manufacture were predicated on applications in commerical products with limited service lifetimes. This is especially true for technologies like BME MLCCs, where commercial pressures for maximum energy density force the adoption of exceptionally small feature sizes, and where the reactivity of the materials requires processes and dopants whose impact on component lifetimes is not fully understood.

7. Given the proven long-term reliability of PME MLCCs and the near parity of MLCC densities of domestically-manufactured PME capacitors (except in the larger package sizes), (b) (5) [redacted] And, to the extent that there is a reduction in density, an essential part of the

design process must include an appreciation of the tradeoffs between reliability and reduced device size at the requirements phase.

8. The effectiveness of over-voltage testing of electronic components, e.g., as used in COTS Qualification, to determine suitability for long-term dormant reliability needs to be re-examined.

9. Stress screening in different tests should be targeted at the most likely modes of failure for a given component or system. Reconsideration should be given to tests that overstress parts, since these may introduce "walking wounded" in the Stockpile.

10. For qualification testing, NNSA should consider the mathematically optimal strategy of "square-root biased sampling", where the distribution of tests is based on the square root of the a priori probabilities.

11. During or before the design phase, SNL should develop a scientific understanding of the most probable failure modes of COTS components and the circuits assembled from them. An accurate model of the device and system must be created, i.e., coupled electrical, mechanical, and thermal responses, which should be used to improve designs and model behavior of stored systems. Experiments are needed to verify and validate the simulations.

12. NNSA's EMRCP should develop rapid, non-destructive testing methods designed to provide early warning of changes that are likely to result in component or system failures during storage aging. Establishing a database of such device "fingerprints"' will allow changes of individual units to be monitored over the life of a system.

13. NNSA should formalize their adoption and use of Design for X processes, including Design for Surveillance and, most particularly, Design for Reliability, in the design and management of their weapons systems.

This step requires broad collaboration from fundamental materials scientists to surveillance engineers. To succeed, the process needs to be intentional, documented, and tracked.

14. NNSA's EMRCP should consider complementing or extending the existing surveillence program by using "witness systems," whereby a large number of each of the electronic components, subsystems, and systems are assembled, placed in a representative test environment, left mostly unpowered as the actual systems of interest, and monitored periodically for the lifetime of the weapon system. The low cost of the electronic components and subsystems may enable a larger-scale supplement to the traditional surveillance program than is possible for fully operational systems.

    (a) NNSA's EMRCP should complement or extend the existing surveillence program by locating aged examples of components in storage, such as never-powered-up "old stock" and logistics stockpiles (not necessarily weapons stockpiles) that may contain components purchased 20-30 years ago, and test appropriately to establish failure rates and failure mechanisms. These contemporary aged components may not have been stored in as benign environments as the systems of concern, but helpful inputs to reliability assessments can come from these "witness components."

15. NNSA's EMRCP should evaluate the feasibility and advisability of a life-cycle replacement approach for each of the major electronic subsystems to reduce the risk associated with aging of COTS components.

12 APPENDIX 1: STATEMENT OF WORK

The following document is the Statement of Work for this Study.

NA 11 JASON Study Statement of Work

Electronic Materials Aging

Background

Nuclear weapon performance requirements include lifetimes spanning several decades. Commercial off the shelf (COTS)[1] parts are used more frequently within our modernization programs. Most of the electronic materials and components within the weapon system are electrically inactive for a majority of the system lifetime and only functioned for a relatively short time. Determining the reliability of successfully executing a long dormancy, highly demanding, short duration, operational sequence over extended lifetimes challenges our ability to model, predict and meet system performance requirements under Stockpile to Target Sequence[2] (STS) environments. Failure rates of modern electronics are assumed to follow a bathtub curve where failure occurs at increased percentages both early and late in life. Elevated voltages and temperatures are frequently used to accelerate component aging in order to probe the useful life between the infant mortality and terminal stages. This bathtub screening assumes a high duty cycle and that fundamental material or device failure modes are known and well understood.

New approaches to rapidly discover failure mechanisms and aging phenomena are needed to ensure high reliability electronics are fielded to the Stockpile. This increased materials science understanding is particularly important for COTS electronic materials. Increased understanding of electronic materials at the device and next level of assembly should reduce occurrences of as of yet, undiscovered failure mechanisms or unique aging behavior that limits service lifetime.

Study Focus

The JASON shall recommend rapid discovery processes to more effectively uncover material and electronic device aging and failure modes. Further JASON shall suggest methods to determine, verify and validate device reliability in an accelerated way. New approaches to improve electronic aging understanding is also desired to reduce reliability and qualification testing while increasing reliability evidence. Input on the use of modeling and simulation as predictive tools is also a desired outcome.

Candidate Study Questions:

1. For COTS electronic materials and components, how can we use material science knowledge to improve accelerated aging testing methods to better understand the impact of aging on reliability and confidently qualify components for deployments of 20 years or more?

---

[1] In this context, we consider Commercial off the shelf (COTS) to include commercial and military specification electronic components of passive (inductors, resistors, capacitors) and active (filters, diodes, switches, integrated circuits) types.

[2] Stockpile to Target Sequence (STS) environments include thermal, vibration, shock and radiation; both intrinsic and hostile.

2. Considering the long dormant periods of most system components, does NNSA's approach to accelerated aging in COTS electronic materials and components appropriately probe aging phenomena and uncover potential aging and failure mechanisms?
3. Are current techniques to determine and validate electronic material and device reliability estimates appropriate for long dormancy, short duration high demand operations over extended lifetimes?
4. Considering Reliability Growth Models, as used in DoD reliability methods, are there improvements to the current NNSA/DOE reliability methods to

   a) Accelerate qualification

   b) Increase confidence in reliability estimates by leveraging systems and sub system testing during development and qualification

   c) reduce qualification and/or production acceptance testing protocols.
5. What changes could be made to the NNSA COTS testing methods that would reduce the overall time to qualify, while preserving high reliability operation of electronic assemblies?
6. What are the critical science areas that need further consideration and review (if any)?

This Page Intentionally Left Blank

13 APPENDIX 2: BRIEFINGS TO JASON

Table 1: Briefings arranged by the Sponsor

Briefer	Affiliation	Title of Presentation
John Baima	Integra	Semiconductor Assembly and Test Service Die Prep – Assembly – Test & Qualification
Ed Cole	Sandia	Microelectronic Defect Detection and Localization
Terry Davis	KCNSC	Production Testing of COTS Parts and Electronic Assemblies and Sub-systems
Jesse Leitner	NASA GSFC[16]	Assuring the Reliability of Spaceborne Electronics for NASA Missions
Rudy Mijares	Air Force	DoD Reliability Growth Strategy
Scott Nicolaysen	Sandia	COTS Transformation
Heather Quinn	DOE	High-Reliability Design in DOE Systems
John Schwartz	Sandia	Surveillance Activities: Design For Surveillance (DFS) – Sandia's Approach to Developing a More Predictive Surveillance Program
Dawn Skala	Sandia	Materials Compatibility and Aging
Susan Trolier-McKinstry	Penn State	Reliability and Aging in Dielectrics and Piezoelectrics
Paul Vianco, I	Sandia	Materials Reliability and the US Nuclear Deterrence
Paul Vianco, II	Sandia	Application-Specific Integrated Circuit (ASIC) Plastic Ball-Grid Array (PBGA): Package Life Test (PLT) History and Rationale
Rena Zurn	Sandia	SNL Reliability Overview

Table 2: Additional briefings arranged by JASON

Briefer	Affiliation	Title of Presentation
Kerry Bernstein	formerly DARPA	Overview on Microelectronics Wearout, Ageing, and Reliability
Gordon Charles	formerly Analog Devices	HALT and HASS Purpose & Value
Alan Devoe	Presidio Components	discussion with JASON
Ed Dodd and Gil Sharon	Ansys Sherlock	Ansys Sherlock for DoD Applications
Clive Randall	Penn State	Reliability and the Vulnerability of Excessive Burn-in Strategies with BME MLCC's
Ann Swift	IBM	Basic Chip Reliability Concepts (Product RE "101")
Daniel Weidman	MIT Lincoln Laboratory	Failure Rate of Dormant COTS Components

14 APPENDIX 3: BRIEF REMARKS ABOUT LIFETIME AND RARE EVENT ESTIMATION

In addition to materials science, stakeholders should invite a closer look at modern approaches to lifetime estimation. This is a very large research and applications area and includes contributions from the aeronautics sector, because they have similar system-level concerns in predicting failure in expensive and hard-to-service systems; the automotive sector because, as indicated above, they have put effort into similar issues, offered solutions, made choices and worked with the semiconductor industry to make progress; and the semiconductor sector because they have looked at fundamental issues in testing for decades.

The use of information theoretic techniques [61] as well as Bayesian techniques to estimate rare events has a long history, e.g., [62] has a good summary of the literature; see also the references cited at the bottom of page 840 in [61]. The topic is present in studies in the aeronautics and aerospace industries [63] and the automotive industry.

As a generalization, pure Bayesian techniques need large data sets; modified techniques include information from models or expert input. A germane example is the application of Bayesian techniques to predict failure of a discrete package for insulated-gate bipolar transistor (IGBT) devices [64]. A recent relevant example develops "[a]n imprecise Bayesian nonparametric approach to system reliability with multiple types of components .... This allows modelling partial or imperfect prior knowledge on component failure distributions in a flexible way through bounds on the functioning probability." [65]. Another recent example hints at a path towards using this type of analysis to determine realistic lifetimes that should be expected from these components, which we note is in contrast to dictating that they must last 40-

60 years [66]. An additional example of trying to *a priori determine what the lifetime* should be for a system can be found in a study of truck systems [67]. One conclusion from these studies is that it may be desirable to continuously rebuild, or replace, certain subsystems on, say, N year cycles.

It would seem prudent to incorporate this body of literature in future thinking about strategies to improve reliability estimates. The NNSA and SNL staff challenged with leading the reliability efforts may wish to consider learning more about formal methods to components or systems where rare event failure dominates.

15 APPENDIX 4: PIEZOELECTRIC MATERIALS

Barium titanate ($BaTiO_3$) and other piezoelectric materials are used as dielectrics in multilayer ceramic capacitors (MLCCs), because they permit the fabrication of large value capacitors in a relatively small volume. At room temperature, barium titanate is a ferroelectric material. The Ba+ atomic cores move off-center of each atomic cell, creating an electric dipole. The large dielectric constant (>1000) for a fine-grained $BaTiO_3$ ceramic results from the response of many polarized grains. A structural phase transition occurs as the temperature is raised above the Curie temperature 125°C [68]. Above that temperature, an unpolarized phase occurs, and one would expect different activation energies than those found at room temperature. This should be noted for HALT or HASS characterizations.

15.1 Piezoresistive Materials

When a semiconductor is strained by an applied stress, the changes in the positions of the atoms alter the energy bands, including the minima of the conduction band and the top of the conduction band, and shape of the light and heavy hole bands. Changes in the band structure alter the conductivity, and spatially non-uniform strain can move charges from one place to another inside a device, changing its operation. In this way, a resistor or transistor is transformed into a strain sensor that can be used to detect failure modes in aging components and devices including diffusion, cracking or corrosion.

The conductivity of a semiconductor is given by:

$$\sigma = ne\mu_n + pe\mu_p, \qquad (15\text{-}8)$$

where n and p are the electron and hole concentrations and e is the electron

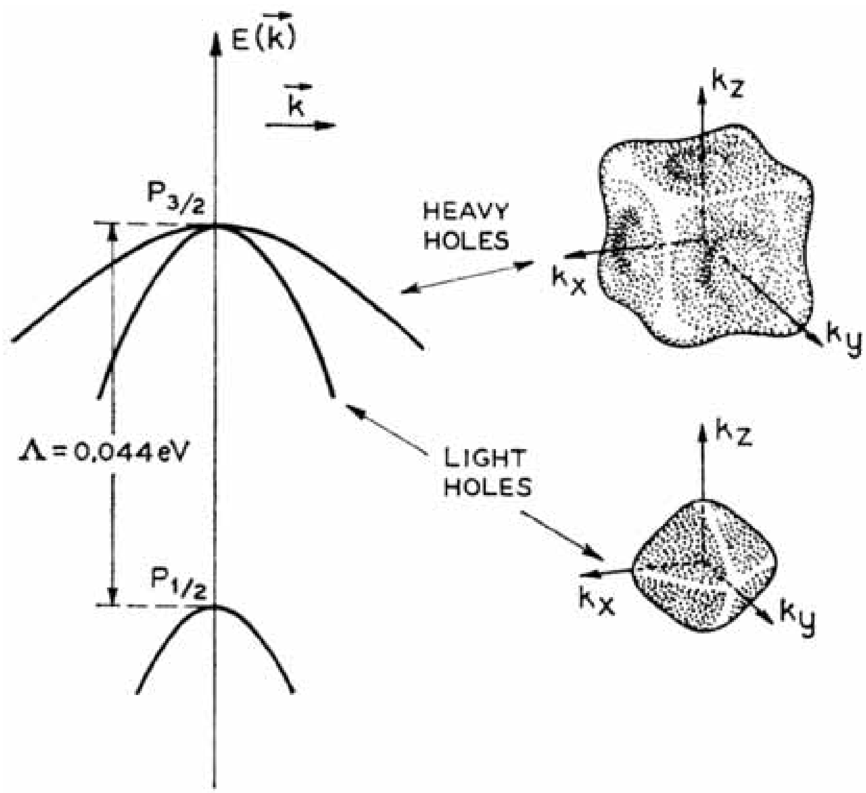


Figure 21: Effect of strain on the valence band in silicon: (a) Heavy and light hole bands in unstrained silicon, along with the band split off by spin-orbit scattering. The energy surfaces about $k = 0$, shown at right, are not ellipsoids and do not have well defined effective masses. (b) Split valence bands in silicon for uniaxial compressive stress; for tensile stress the order of the heavy and light hole bands is reversed. The energy surfaces are now ellipsoids about $k = 0$ with well-defined effective masses [69].

charge. The electron mobility is given by

$$\mu_n = \frac{e\tau}{m_e^*} \tag{15-9}$$

with μ_p given by a similar formula. Here τ is the momentum relaxation time, and m^* is the effective mass. Changes in the electron or hole concentrations or mobilities change the conductivity.

Silicon is a piezoresistive material for both electrons and holes. The conduction band has six valleys with minima located along the (100) directions in k-space. The energy surfaces are elongated paraboloids with longitudinal effective mass $m_{el} = 0.98m_o$ along the (100) direction and a transverse effective mass $m_{et} = 0.19m_o$, where m_o is the electron mass in a vacuum. Under an applied stress, the six valleys move in energy according to the strain direction. The electron mobility can increase substantially when two valleys have the lowest energy, because the small transverse mass leads to a large mobility in those directions. This effect has been used in CMOS circuit design.

The effects of uniaxial strain on the valence bands of silicon are illustrated in Fig. 21 [69]. For unstrained silicon, in Fig. 21(a), the heavy and light hole bands join at $\mathbf{k} = \mathbf{0}$. The energy surfaces, shown at right, are not paraboloids, the effective mass heavy holes is $m_{hh} = 0.49m_o$, and the effective mass for light holes is $m_{lh} = 0.16m_o$. For compressive uniaxial stress, in Fig. 21(b), holes flow into the heavy-hole band which lies above the light-hole band, and the mobility decreases due to the heavy mass. However, for tensile stress the order of the bands is reversed, and holes flow into the light-hole band increasing the mobility. Both processes change the measured conductance.

Spatially nonuniform strain can redistribute the location of carriers inside a device and alter its behavior; nonuniformity is expected for aging. Strain typically reduces the bandgap E_g, drawing carriers toward the regions of greatest strain. The shifts are determined by the deformation potential D and the strain ϵ through the relation $\Delta E_g = D\epsilon$. For silicon, the deformation potentials are $D_u = 2.0$ eV for uniaxial stress in the [001] direction and $D_{u'} = 2.7$ eV for stress in the [111] direction. For example, a 10 N force applied with your fingers to the ends of a Si rod with area 1 mm^2 creates strain $\epsilon \sim 10^{-4}$ and a bandgap change $\Delta E_g \sim 0.1$ meV. With pliers you can get $\Delta E_g \sim 10$ meV.

This Page Intentionally Left Blank

16 APPENDIX 5: SUPPLEMENTAL DOCUMENT ON CAPACITORS

The following document is "DLA Land and Maritime – VQ Supplemental Information Sheet for Electronic QPL-32535," dated 4/16/2020.

DLA Land and Maritime - VQ
Supplemental Information Sheet for Electronic QPL-32535

Specification Details **Date 4/16/2020**

Specification: MIL-PRF-32535
Title: Capacitor, Chip, Fixed, Ceramic Dielectric (Temperature Stable and General Purpose), Extended Range, High Reliability and Standard Reliability
Federal Supply Class (FSC): 5910
Conventional: No
Specification contains quality assurance program: No
MIL-STD-790 Established Reliability & High Reliability: Yes
MIL-STD-690 Failure Rate Sampling Plans & Procedures: No
Weibull Graded: No
Specification contains space level reliability requirements: Yes
Specification allows test optimization: No

Contact Information

Office of Primary Involvement: Passive Devices Branch, DLA Land and Maritime - VQP
Primary Qualifying Activity Contact: 614-692-2063, e-mail: vqp.ahc@dla.mil
Secondary Qualifying Activity Contact: 614-692-0619, e-mail: vq.chief@dla.mil

Notes

N/A

Part Configuration

Performance specification number	Slash sheet number	Characteristic	Voltage	Capacitance	Capacitance tolerance	Termination	Product level	Electrode
M32535	01	BX	B	103	K	Z	M	B

PART LISTINGS

GOVERNMENT DESIGNATION	MANUFACTURER'S DESIGNATION OR TYPE NUMBER	TEST OR QUALIFICATION REFERENCE	SPEC FI-CATION SHEET	SUPPL ER'S NAME (ADDRESS ON LAST PAGE)
M32535				
1000 pF thru 10000 pF; tols. J, K, M; in 4, 6.3, 10 volts; E2 rated temp. and volt. temp. limits; term. H, M, Z; electrode. P; product level M, T	SR0201	32535-5285-19	/1	Presidio Components
M32535				
2200 pF thru 6800 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50, 100 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	0402	32535-4924-17	/2	AVX Ltd.
8200 pF thru 27000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	0402	32535-4924-17	/2	AVX Ltd.
10000 pF thru 33000 pF; tols. J, K, M; in 4, 6.3, 10, , volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	0402	32535-4924-17	/2	AVX Ltd.
10 pF thru 330 pF; tols. F, G, J, K; in 4, 6 3, 10, 16, 25, 50, 100 volts; BP, E1 rated temp. and volt. temp. limits; term. G, Z; electrode. B; product level M, T	C0402	32535-4811-17	/2	Kemet de Mexico, S.A. de C.V.
390 pF thru 680 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50 volts; BP, E1 rated temp. and volt. temp. limits; term. G, Z; electrode. B; product level M, T	C0402	32535-4811-17	/2	Kemet de Mexico, S.A. de C.V.
820 pF thru 1000 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25 volts; BP, E1 rated temp. and volt. temp. limits; term. G, Z; electrode. B; product level M, T	C0402	32535-4811-17	/2	Kemet de Mexico, S.A. de C.V.
39 pF thru 6800 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. G, Z; electrode. ., B; product level M, T	C0402	32535-4811-17	/2	Kemet de Mexico, S.A. de C.V.
8200 pF thru 22000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. G, Z; electrode. B; product level M, T	C0402	32535-4811-17	/2	Kemet de Mexico, S.A. de C.V.

PART LISTINGS				
GOVERNMENT DESIGNATION	MANUFACTURER'S DESIGNATION OR TYPE NUMBER	TEST OR QUALIFICATION REFERENCE	SPEC FI- CATION SHEET	SUPPL ER'S NAME (ADDRESS ON LAST PAGE)
27000 pF thru 47000 pF; tols. J, K, M; in 4, 6.3, 10 volts; E2 rated temp. and volt. temp. limits; term. G, Z; electrode. B; product level M, T	C0402	32535-4811-17	/2	Kemet de Mexico, S.A. de C.V.
39 pF thru 4700 pF; tols. K, M; in 100 volts; E2 rated temp. and volt. temp. limits; term. M, Z; electrode. P; product level M, T	SR0402	32535-4966-17	/2	Presidio Components
33000 pF thru 100000 pF; tols. J, K, M; in 4, 6.3, 10 volts; E2 rated temp. and volt. temp. limits; term. H, M, Z; electrode. P; product level M, T	SR0402	32535-5285-19	/2	Presidio Components
5600 pF thru 27000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. M; electrode. P; product level M, T	SR0402	32535-4966-17	/2	Presidio Components
M32535				
2200 pF thru 18000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50, 100 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	0603	32535-4924-17	/3	AVX Ltd.
22000 pF thru 120000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	0603	32535-4924-17	/3	AVX Ltd.
150000 pF thru 180000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	0603	32535-4924-17	/3	AVX Ltd.
1 pF thru 82 pF; tols. B, C, D, F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100, 200 volts; BP, E1 rated temp. and volt. temp. limits; term. G, R, V, Z; electrode. B; product level M, T	C0603	32535-4811-17	/3	Kemet de Mexico, S.A. de C.V.
180000 pF thru 220000 pF; tols. J, K, M; in 4, 6 3, 10 volts; E2 rated temp. and volt. temp. limits; term. G, R; electrode. B; product level M, T	C0603	32535-4811-17; 32535-5463-19	/3	Kemet de Mexico, S.A. de C.V.
100 pF thru 2200 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100 volts; BP, E1 rated temp. and volt. temp. limits; term. G, R, V, Z; electrode. B; product level M, T	C0603	32535-4811-17	/3	Kemet de Mexico, S.A. de C.V.
2700 pF thru 3900 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50 volts; BP, E1 rated temp. and volt. temp. limits; term. G, R, V, Z; electrode. B; product level M, T	C0603	32535-4811-17	/3	Kemet de Mexico, S.A. de C.V.
4700 pF thru 5600 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25 volts; BP, E1 rated temp. and volt. temp. limits; term. G, R, V, Z; electrode. B; product level M, T	C0603	32535-4811-17	/3	Kemet de Mexico, S.A. de C.V.
1000 pF thru 47000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. G, R, V, Z; electrode. B; product level M, T	C0603	32535-4811-17	/3	Kemet de Mexico, S.A. de C.V.
51000 pF thru 150000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. G, R, V, Z, ; electrode. B; product level M, T	C0603	32535-4811-17; 32535-5463-19	/3	Kemet de Mexico, S.A. de C.V.
1000 pF thru 18000 pF; tols. K, M; in 100 volts; E2 rated temp. and volt. temp. limits; term. M, Z; electrode. P; product level M, T	SR0603	32535-4966-17	/3	Presidio Components
180000 pF thru 180000 pF; tols. K, M; in 25 volts; E2 rated temp. and volt. temp. limits; term. M; electrode. P; product level M, T	SR0603	32535-4966-17	/3	Presidio Components
22000 pF thru 150000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. M; electrode. P; product level M, T	SR0603	32535-4966-17	/3	Presidio Components

PART LISTINGS

GOVERNMENT DESIGNATION	MANUFACTURER'S DESIGNATION OR TYPE NUMBER	TEST OR QUALIFICATION REFERENCE	SPEC FI-CATION SHEET	SUPPL ER'S NAME (ADDRESS ON LAST PAGE)
M32535				
2200 pF thru 100000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50, 100 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	0805	32535-4924-17	/4	AVX Ltd.
120000 pF thru 470000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	0805	32535-4924-17	/4	AVX Ltd.
560000 pF thru 1000000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	0805	32535-4924-17	/4	AVX Ltd.
1 pF thru 470 pF; tols. B, C, D, F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100, 200 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C0805	32535-4811-17	/4	Kemet de Mexico, S.A. de C.V.
10000 pF thru 150000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C0805	32535-4811-17	/4	Kemet de Mexico, S.A. de C.V.
180000 pF thru 680000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C0805	32535-4811-17	/4	Kemet de Mexico, S.A. de C.V.
820000 pF thru 1000000 pF; tols. J, K, M; in 4, 6 3, 10 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C0805	32535-4811-17	/4	Kemet de Mexico, S.A. de C.V.
560 pF thru 8200 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C0805	32535-4811-17	/4	Kemet de Mexico, S.A. de C.V.
10000 pF thru 10000 pF; tols. F, G, J, K; in 4, 6 3, 10, 16, 25 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C0805	32535-4811-17	/4	Kemet de Mexico, S.A. de C.V.
10000 pF thru 100000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50, 100 volts; E2 rated temp. and volt. temp. limits; term. M, R, Z; electrode. P; product level M, T	SR0805	32535-4966-17	/4	Presidio Components
120000 pF thru 470000 pF; tols. K, M; in 4, 6 3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. M; electrode. P; product level M, T	SR0805	32535-4755-16	/4	Presidio Components
10000 pF thru 104000 pF; tols. K, M; in 4, 6 3, 10, 16, 25, 50, 100 volts; E2 rated temp. and volt. temp. limits; term. M, R; electrode. P; product level M, T	SR0805	32535-4966-17	/4	Presidio Components
M32535				
10000 pF thru 390000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50, 100 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	1206	32535-4924-17	/5	AVX Ltd.
470000 pF thru 1000000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	1206	32535-4924-17	/5	AVX Ltd.
1200000 pF thru 2200000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	1206	32535-4924-17	/5	AVX Ltd.
560 pF thru 1800 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100, 200 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1206	32535-4811-17	/5	Kemet de Mexico, S.A. de C.V.
2200 pF thru 18000 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1206	32535-4811-17	/5	Kemet de Mexico, S.A. de C.V.

PART LISTINGS				
GOVERNMENT DESIGNATION	MANUFACTURER'S DESIGNATION OR TYPE NUMBER	TEST OR QUALIFICATION REFERENCE	SPEC FI- CATION SHEET	SUPPL ER'S NAME (ADDRESS ON LAST PAGE)
22000 pF thru 27000 pF; tols. F, G, J, K; in 4, 6 3, 10, 16, 25 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1206	32535-4811-17	/5	Kemet de Mexico, S.A. de C.V.
100000 pF thru 3300000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1206	32535-4811-17	/5	Kemet de Mexico, S.A. de C.V.
390000 pF thru 1500000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1206	32535-4811-17	/5	Kemet de Mexico, S.A. de C.V.
1800000 pF thru 2200000 pF; tols. J, K, M; in 4, 6 3, 10 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1206	32535-4811-17	/5	Kemet de Mexico, S.A. de C.V.
M32535				
22000 pF thru 680000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50, 100 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	1210	32535-4924-17	/6	AVX Ltd.
820000 pF thru 1000000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	1210	32535-4924-17	/6	AVX Ltd.
1200 pF thru 3300 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100, 200 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1210	32535-4811-17	/6	Kemet de Mexico, S.A. de C.V.
3900 pF thru 33000 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1210	32535-4811-17	/6	Kemet de Mexico, S.A. de C.V.
39000 pF thru 47000 pF; tols. F, G, J, K; in 4, 6 3, 10, 16, 25 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1210	32535-4811-17	/6	Kemet de Mexico, S.A. de C.V.
82000 pF thru 680000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1210	32535-4811-17	/6	Kemet de Mexico, S.A. de C.V.
820000 pF thru 2200000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1210	32535-4811-17	/6	Kemet de Mexico, S.A. de C.V.
3300000 pF thru 3300000 pF; tols. J, K, M; in 4, 6 3, 10 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1210	32535-4811-17	/6	Kemet de Mexico, S.A. de C.V.
M32535				
100000 pF thru 2200000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25, 50, 100 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	1812	32535-4924-17	/7	AVX Ltd.
3300000 pF thru 4700000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	1812	32535-4924-17	/7	AVX Ltd.
5600000 pF thru 8200000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	1812	32535-4924-17	/7	AVX Ltd.
1000 pF thru 6800 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100, 200 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1812	32535-4811-17	/7	Kemet de Mexico, S.A. de C.V.
2200000 pF thru 3900000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. R, V, ; electrode. B; product level M, T	C1812	32535-4811-17	/7	Kemet de Mexico, S.A. de C.V.

PART LISTINGS				
GOVERNMENT DESIGNATION	MANUFACTURER'S DESIGNATION OR TYPE NUMBER	TEST OR QUALIFICATION REFERENCE	SPEC FI-CATION SHEET	SUPPL ER'S NAME (ADDRESS ON LAST PAGE)
4700000 pF thru 4700000 pF; tols. J, K, M; in 4, 6 3, 10 volts; E2 rated temp. and volt. temp. limits; term. R, V; electrode. B; product level M, T	C1812	32535-4811-17	/7	Kemet de Mexico, S.A. de C.V.
8200 pF thru 56000 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1812	32535-4811-17	/7	Kemet de Mexico, S.A. de C.V.
68000 pF thru 68000 pF; tols. F, G, J, K; in 4, 6 3, 10, 16, 25, 50 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1812	32535-4811-17	/7	Kemet de Mexico, S.A. de C.V.
82000 pF thru 100000 pF; tols. F, G, J, K; in 4, 6 3, 10, 16, 25 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C1812	32535-4811-17	/7	Kemet de Mexico, S.A. de C.V.
100000 pF thru 1800000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. R, V; electrode. B; product level M, T	C1812	32535-4811-17	/7	Kemet de Mexico, S.A. de C.V.
M32535				
1000000 pF thru 4700000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25, 50, 100 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	2220	32535-4924-17	/8	AVX Ltd.
5600000 pF thru 10000000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25, 50 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	2220	32535-4924-17	/8	AVX Ltd.
12000000 pF thru 22000000 pF; tols. J, K, M; in 4, 6.3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. R; electrode. B; product level M, T	2220	32535-4924-17	/8	AVX Ltd.
1000 pF thru 27000 pF; tols. F, G, J, K; in 4, 6.3, 10, 16, 25, 50, 100, 200 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C2220	32535-4811-17	/8	Kemet de Mexico, S.A. de C.V.
100000 pF thru 3300000 pF; tols. J, K, M; in 4, 6 3, 10, 16, 25 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C2220	32535-4811-17	/8	Kemet de Mexico, S.A. de C.V.
3900000 pF thru 4700000 pF; tols. J, K, M; in 4, 6 3, 10, 16 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C2220	32535-4811-17	/8	Kemet de Mexico, S.A. de C.V.
5600000 pF thru 10000000 pF; tols. J, K, M; in 4, 6 3 volts; E2 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C2220	32535-4811-17	/8	Kemet de Mexico, S.A. de C.V.
33000 pF thru 100000 pF; tols. F, G, J, K; in 4, 6 3, 10, 16, 25, 50, 100 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C2220	32535-4811-17	/8	Kemet de Mexico, S.A. de C.V.
120000 pF thru 150000 pF; tols. F, G, J, K; in 4, 6 3, 10, 16, 25, 50 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C2220	32535-4811-17	/8	Kemet de Mexico, S.A. de C.V.
180000 pF thru 180000 pF; tols. F, G, J, K; in 4, 6 3, 10, 16, 25 volts; BP, E1 rated temp. and volt. temp. limits; term. D, G, R, V, Z; electrode. B; product level M, T	C2220	32535-4811-17	/8	Kemet de Mexico, S.A. de C.V.
M32535				
100000 pF thru 100000 pF; tols. K, M; in 4, 6 3, 10, 16 volts; E2 rated temp. and volt. temp. limits; term. M, Z; electrode. P; product level M, T	SR0603	32535-4966-17	/9	Presidio Components

Manufacturer and Supplier Location Information

Manufacturer   AVX Ltd (CAGE Code U6827)

Location: Ballycastle Road, Coleraine BT52 2DA
Ballycastle Road,Coleraine, Ireland BT52 2DA, Ireland

Manufacturer   Kemet (CAGE Code 31433)

Location: 2835 Kemet Way, Simpsonville, SC 29681-2457,

Plants:

1. Kemet de Mexico, S.A. de C.V., Avenida Eloy Cavazos 7908 Ote., Col. Rancho Viejo, Guadalupe, N.L., C P. 61750, MX

Manufacturer   Presidio Components (CAGE Code 60212)

Location: PO Box 81576, 7169 Construction Court, San Diego, CA 92121,

This Page Intentionally Left Blank

References

[1] M. T. Bohr and I. A. Young, CMOS Scaling Trends and Beyond, *IEEE Micro*, **37**, 20–29 (2017).

(b) (5) [redacted]

[redacted]

[4] J. Minihan, E. Schmidt, G. Enserro and M. Thompson, Commercial Off-the-Shelf (COTS) Components and Enterprise Component Information System (eCIS) Federal Manufacturing & Technologies, KCP-613-8421s (2008).

[5] U. Abelein, H. Lochner, D. Hahn and S. Straube, Complexity, quality and robustness-the challenges of tomorrow's automotive electronics, in *2012 Design, Automation & Test in Europe Conference & Exhibition (IEEE)*, 870–871 (2012).

[6] U. Backhausen, O. Ballan, P. Bemardi, S. De Luca, J. Henzler, T. Kern, D. Piumatti, T. Rabenalt, K.C. Ramamoorthy, E. Sanchez, and others, Robustness in automotive electronics: An industrial overview of major concerns, in *2017 IEEE 23rd International Symposium on On-Line Testing and Robust System Design (IOLTS)*, 157–162 (2017).

[7] A. Swift, "Basic Chip Reliability Concepts (Product RE "101")," briefing to JASON, 13 July 2020.

[8] C. Hillman, The end is near for MIL-HDBK-217 and other outdated handbooks, *Design News*, 17 July

2018, https://www.designnews.com/electronics-test/end-near-mil-hdbk-217-and-other-outdated-handbooks.

[9] S.P. Carfagno and R.J. Gibson, A Review of Equipment Aging Theory and Technology (Research Project 890-1), Report EPRI NP-1558, Electric Power Research Institute (1980).

[10] *Long-Term Non-Operating Reliability of Electronic Products* , edited by J. Pecht, M. Pecht (CRC Press, New York, 1995).

[11] Book review by A.J. Rafanelli of *Long-Term Non-Operating Reliability of Electronic Products*, edited by J. Pecht, M. Pecht (CRC Press, New York, 1995).

[12] F.P. McCluskey, E.B. Hakim, J. Fink, A. Fowler, and M.G. Pecht, Reliability assessment of electronic components exposed to long-term non-operating conditions, *IEEE Transactions on Components, Packaging and Manufacturing Technology—Part A*, **21** (1998).

[13] *Reliability Growth: Enhancing Defense System Reliability*, NRC Report (The National Academies Press, 2015).

[14] Commercial Off-The-Shelf Airborne Electronic Hardware Issues and Emerging Solutions: Authority for Expenditure No. 75 Report, DOT/FAA/TC-16/57, September 2017.

[15] NASA NESC Technical Update 2014 (2014). www.nasa.gov/sites/default/files/atoms/files/techup2014_pdf9-1pageview.pdf

[16] M. White, Commercial off-the-shelf (COTS) parts risk & reliability user & application guide, JPL Publication 17-5 (2017).

[17] J. Leitner, "Assuring the reliability of spaceborne electronics for NASA missions," briefing to JASON, 29 June 2020.

[18] J.R. Wertz and W.J. Larson, *Space Mission Analysis and Design*, 93rd ed., (Microcosm, Torrance CA and Klewer, Dordrecht, 1999).

[19] M. Maćkowski and S. Krzysztof, Electromagnetic Emission Measurement of Microprocessor Units, in *International Conference on Computer Networks*, (Springer, Berlin, 2009).

[20] T. Belytschko, R. Gracie, and G. Ventura, A review of extended/generalized finite element methods for material modeling, *Modeling Simul. Mater. Sci. Eng.* **17** (2009).

[21] G. Charles, "HALT and HASS Purpose & Value," briefing to JASON, 22 June 2020.

[22] J.H. Weiner, *Statistical Mechanics of Elasticity* (Dover, 2002).

[23] H. Schmalzried, *Chemical Kinetics of Solids*, (VCH, New York, 1995).

[24] S. J. Klippenstein, V. S. Pande, and D. G. Truhlar, Chemical kinetics and mechanisms of complex systems: A perspective on recent theoretical advances, *J. Am. Chem. Soc.*, **136**, 528–546 (2014).

[25] E. Kaxiras, *Atomic and Electronic Structure of Solids*, (Cambridge University Press, 2003).

[26] C.A. Randall, R. Maier, W. Qu, K. Kobayashi, K. Morita, Y. Mizuno, N. Inoue, and T. Oguni, Improved reliability predictions in high permittivity dielectric oxide capacitors under high dc electric fields with oxygen vacancy induced electromigration, *J. Appl. Phys.* **113**, 014101 (2013).

[27] S.K. Kurtz, S. Levinson, and D. Shi, Infant mortality, freaks, and wear-out: Application of modern semiconductor reliability methods to ceramic multilayer capacitors, *J. Am. Ceram. Soc.* **72**, 2223–33 (1989).

[28] F. Bayle and A. Mettas, Temperature acceleration models in reliability predictions: Justification & improvements, in *IEEE 2010 Proceedings-Annual Reliability and Maintainability Symposium (RAMS)*,1–6 (2010).

[29] G.T. Galyon, A History of Tin Whisker Theory: 1946 to 2004, *SMTA Int. Conf. Chicago* (2004); `http://www.hlinstruments.com`

[30] A.A. El Mel, R. Nakamura and C. Bittencourt, The Kirkendall effect and nanoscience: hollow nanospheres and nanotubes *Beilstein J. Nanotechnol.* **6**, 1348–1361 (2015). doi:10.3762/bjnano.6.139

(b) (5) [redacted]

[redacted]

[33] D. Liu and M.J. Sampson, Some aspects of the failure mechanisms in BaTiO3-based multilayer ceramic capacitors, *CARTS International*, Las Vegas, p. 49–61 (2012).

[34] D. Liu and M.J. Sampson, Reliability evaluation of base-metal-electrode multilayer ceramic capacitors for potential space applications, *CARTS USA*, 28–57 (2011).

(b) (5) [redacted].

[36] D.J. Weidman (MIT Lincoln Laboratory), "Failure Rate of Dormant COTS Components," briefing to JASON, 20 July 2020.

[37] N. Muhammad, Z. Fang, S.Y. Shah, and D. Haider, Reliability and Remaining Life Assessment of an Electronic Fuze Using Accelerated Life Testing, *Micromachines* **11**, 272 (2018).

[38] W.H. Press, Strong profiling is not mathematically optimal for discovering rare malfeasors, *Proceedings of the National Academy of Sciences*, **106**, 1716–1719 (2009).

[39] E. Dodd, briefing to JASON, 21 July 2020, `https://www.ansys.com/products/structures/ansys-sherlock` and `https://www.reliasoft.com/resources/resource-center/design-for-reliability-overview-of-the-process-and-applicable-techniques` and A. Mettas, Design for reliability: Overview of the process and applicable techniques. *International Journal of Performability Engineering*, **6**, 577-586 (2010).

(b) (5) [redacted]

[41] P. Tangyunyong, E.I. Cole Jr., G.M. Loubriel, J. Beutler, D.M. Udoni, B.S. Paskaleva, and T.E. Buchheit, Power Spectrum Analysis (PSA), SAND2017-7761C (2017).

[42] C.S. Smith, Piezoresistance effect in germanium and silicon. *Phys. Rev.* **94**, 42 (1954).

[43] S.M. Hu, Stress-related problems in silicon technology. *J. Appl. Phys.* **70**, R53–R80 (1991).

[44] K.L. Ekinci and M.L. Roukes, Nanoelectromechanical systems, *Review of Scientific Instruments*, **76**, 061101 (2005).

[45] S. Levikari, T.J. K arkk ainen, C. Andersson, J. Tamminen, and P. Silventoinen, Acoustic Phenomena in Damaged Ceramic Capacitors, *IEEE Transactions on Industrial Electronics*, **65**, 570–577 (2018).

[46] M. Holler, M. Odstrcil, M. Guizar-Sicairos, M. Lebugle, E. Müller, S. Finizio, G. Tinti, C. David, J. Zusman, W. Unglaub, O. Bunk, J. Raabe, A.F.J. Levi, and G. Aeppli, Three-dimensional imaging of integrated

circuits with macro- to nanoscale zoom, *Nature Electronics*, **2** 464– 470 (2019).

[47] U.S. Department of Defense. *Department of Defense Handbook: Reliability Growth Management*. MIL-HDBK-189C. Washington, DC. (2011) https://www.dac.ccdc.army.mil/Documents/CRG/MIL-HDBK-189C.pdf

[48] https://www.document-center.com/standards/show/MIL-STD-785/history/REV%20B%20CANCELLATION%203 and https://www.weibull.com/mil_std/mil_std_785b.pdf

[49] National Research Council. 1998. Statistics, Testing, and Defense Acquisition: New Approaches and Methodological Improvements. Washington, DC: The National Academies Press. https://doi.org/10.17226/6037

[50] https://dsb.cto.mil/reports/2000s/ADA482504.pdf

[51] http://acqnotes.com/acqnote/acquisitions/dodi-5000

[52] https://www.dote.osd.mil/Portals/97/pub/reports/FY2016/other/2016DOTEAnnualReport.pdf?ver=2019-08-22-105134-547

[53] R. Mijares, briefing to JASON, 30 June 2020, and Directive-Type Memorandum (DTM) 11-003 – Reliability Analysis, Planning, Tracking, and Reporting, Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics (March 21, 2011).

[54] M. Silverman and A. Kleyner, What is design for reliability and what is not? In 2012 Proceedings Annual Reliability and Maintainability Symposium (pp. 1-5). IEEE (January 2012).

(b) (5)

(b) (5) [redacted]

[58] H. Hecht, *Reliability for Space Mission Planning in Space Mission Analysis and Design* (3rd ed., J.R. Wertz and W. J. Larson, Microcosm Press, Torrance CA and Klewer, Dortrecht, Netherlands, 1999).

[59] H. Hecht, *System Reliability and Failure Prevention* (Artech House, Boston, 2004).

(b) (5) [redacted]

[61] A.R. Sampson and R.L. Smith, Assessing risks through the determination of rare event probabilities, *Operations Research*, **30**, 839–866 (1982).

[62] D. Straub, I. Papaioannou and W. Betz, Bayesian analysis of rare events, *Journal of Computational Physics*, **314**, 538–556 (2016).

[63] T. Seitz, Predicting Rare Event Failures in Space Hardware using Common Event Data, `http://asq.org/asd/2017/04/predicting-rare-event-failures-in-space-hardware-using-common-event-data.pdf`

[64] S.H. Ali, M. Heydarzadeh, S. Dusmez, X. Li, S.A. Kamath and B. Akin, Lifetime estimation of discrete IGBT devices based on Gaussian process, *IEEE Transactions on Industry Applications*, **54**, 395–403 (2017).

[65] G. Walter, L.J.M. Aslett and F.P.A. Coolen, Bayesian nonparametric system reliability using sets of priors, *International Journal of Approximate Reasoning*, **80**, 67–88 (2017).

[66] G. Walter and S.D. Flapper, Condition-based maintenance for complex systems based on current component status and Bayesian updating of component reliability, *Reliability Engineering & System Safety*, **168**, 227–239 (2017).

[67] S.J. Vermeulen, *Software Tool for Predicting Component Lifetimes with an Application to Trucks*, Technische Universiteit Eindhoven (2016).

[68] M.G. Harwood, P. Popper, and D.F Rushman, The Curie Point of Barium Titanate. *Nature* **160**, 58 (1947).

[69] J.C. Hensel and G. Feher, Cyclotron Resonance Experiments in Uniaxially Stressed Silicon: Valence Band Inverse Mass Parameters and Deformation Potentials. *Phys. Rev.* **129**, 1041 (1963).

Department of Energy
National Nuclear Security Administration
Office of the General Counsel
P. O. Box 5400
Albuquerque, NM 87185

March 9, 2021

SENT VIA EMAIL:
saftergood@fas.org

Mr. Steven Aftergood
Federation of American Scientists
1112 16th St. NW, Suite #400
Washington, D.C., 20006

Dear Mr. Aftergood:

This letter is the National Nuclear Security Administration's (NNSA) final response to your December 4, 2020 Freedom of Information Act (FOIA) request for copies of the following:

> "We request a copy of a 2020 report entitled "Electronic Materials Aging." This report was performed for NNSA earlier this year by the JASON scientific advisory panel. I believe the NNSA points of contact are: Ross Agee (ross.agee@nnsa.doe.gov) and Matthew Johnson (matthew.johnson1@nnsa.doe.gov)."

Your request was received in this office on December 4, 2020.

We contacted the NNSA's Office of Defense Programs (NA-10) to conduct a search for responsive records. NA-10 searched and located the requested document entitled, "JSR-20-2B Electronic Materials Aging." The enclosed document is provided to you with redactions pursuant to 5 USC § 552 (b)(5) (Exemption 5 of the FOIA).

Exemption 5

Exemption 5 exempts from mandatory disclosure inter-agency or intra-agency memorandums or letters which would not be available by law to a party other than an agency in litigation with the agency. Exemption 5 incorporates the attorney-client privilege, attorney work-product privilege, and deliberative process (or pre-decisional) privilege. The general purpose of the deliberative process privilege is to prevent injury to the quality of agency decisions and provides protection for the decision-making processes of government agencies, where the exposure of that process would result in harm. In addition, pre-decisional information is exempt from disclosure to protect against premature disclosure of information that could cause confusion that might result from the disclosure of information that would not in fact be the agency's final decision. Information is pre-decisional if it was prepared to assist an agency decision-maker to arrive at a decision. Pre•decisional information that is exempt from mandatory disclosure is distinct from post-decisional information that sets forth the reason for an agency decision that has been made.

The information being withheld pursuant to Exemption 5 is intra-agency communications regarding the future of the Nuclear Weapons Program that is both pre-decisional and process deliberative information. With respect to the discretionary disclosure of deliberative information, the quality of agency decisions would be adversely affected if frank, written discussion of policy matters was inhibited by the knowledge that the content of such discussion might be made public. Disclosure of the deliberative material is not in the public interest because foreseeable harm to the Nation's nuclear weapons program and stockpile could result from such disclosure. Moreover, any facts intertwined into the recommendations contained in the document cannot be segregated because their very selection reveals the issue being deliberated.

The Department of Energy (DOE) regulations 10 CFR § 1004.1 provide that documents exempt from mandatory disclosure under the FOIA shall be released regardless of their exempt status, unless DOE determines that disclosure is contrary to public interest. For the reasons described above, NNSA has determined that release of the information described above is not in the public interest.

Pursuant to 10 CFR § 1004.7(b)(2), I am the individual responsible for the withholding of information pursuant to Exemption 5 of the FOIA.

You may appeal our withholding under Exemption 5 within 90 calendar days from your receipt of this letter pursuant to 10 CFR § 1004.8. Appeals should be addressed to Director, Office of Hearings and Appeals, HG-1, L'Enfant Plaza, U.S. Department of Energy, 1000 Independence Avenue, S.W., Washington, D.C. 20585-1615. The written appeal, including the envelope, must clearly indicate that a FOIA appeal is being made. You may also submit your appeal to OHA.filings@hq.doe.gov, including the phrase "Freedom of Information Appeal" in the subject line (this is the method preferred by the Office of Hearings and Appeals). The appeal must contain all of the elements required by 10 CFR § 1004.8, including a copy of the determination letter. Thereafter, judicial review will be available to you in the Federal District Court either: 1) in the district where you reside; 2) where you have your principal place of business; 3) where DOE's records are situated; or 4) in the District of Columbia.

You may contact me, the NNSA's FOIA Public Liaison, at 866-747-5994, or by mail at Department of Energy, National Nuclear Security Administration, Office of the General Counsel, P.O. Box 5400, Albuquerque, NM 87185 for any further assistance and to discuss any aspect of your request. Additionally, you may contact the Office of Government Information Services (OGIS) at the National Archives and Records Administration to inquire about the FOIA mediation services they offer. The contact information for OGIS is as follows: Office of Government Information Services, National Archives and Records Administration, 8601 Adelphi Road-OGIS, College Park, Maryland 20740-6001, e-mail at ogis@nara.gov; telephone at 202-741-5770; toll free at 1-877-684-6448; or facsimile at 202-741-5769.

There are no charges to you for processing your FOIA request. If you have questions regarding this response, please contact Ariana Gallegos by email at Ariana.Gallegos@nnsa.doe.gov or write to the above address. Please reference Control Number FOIA 21-00051-AG in your communications.

Sincerely,

Christina H. Hamblen
Digitally signed by Christina H. Hamblen
Date: 2021.03.07 14:20:18 -07'00'

Christina H. Hamblen
FOIA Officer

Enclosure