

Assessment of the Impacts of Packaging, Long-Term Storage, and Transportation on Military MEMS

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ABSTRACT

The Army is transforming into a more lethal, lighter and agile force. Enabling technologies that support this transition must decrease in size while increasing in intelligence. MEMS are one technology the DoD will rely on to accomplish these objectives. Conditions for military MEMS utilization are unique. Operational and storage environments are significantly different than those found in the commercial sector. The impact of these environments on the functionality of MEMS has not been assessed. Furthermore, a standardized methodology for conducting these analyses does not exist.

To facilitate the insertion of MEMS technologies in weapon systems, the U.S. Army ARDEC is addressing these information gaps. The MEMS user community will benefit from data on failure modes induced by packaging, transportation and storage for selected devices. These data are being used to develop standardized methodologies for MEMS assessments. Activities include:

- Assessment of operational environments in which military MEMS device are utilized
- Determining & developing methods to preserve MEMS devices during long-term storage
- Independent assessment of reliability that cannot be obtained from private industry
- Establishment of reliability data that will be fed back into development & design to improve MEMS devices
- Production & design process can be vastly improved to increase yields that will drive costs down

Recent accomplishments of the program include an assessment of MEMS of interest to DoD, Test Guidelines for Environmental Stress Screening (ESS), Long-Term Storage Test Guidelines, Assessment of the Barriers to Implementation, and other tools and methodologies to facilitate the transition of MEMS to the Department of Defense. The MEMS assessment generated under this program will benefit the MEMS user community by filling the information gap that currently exists for reliability. With the rapid growth of the MEMS industry it is crucial to consider the reliability of this emerging technology and its applications in the early stages of its development.

Introduction

Recent conflicts in the Global War on Terror (GWOT) have demonstrated a need for a lighter, more agile and more lethal force. Therefore, the technologies that support these systems must afford a decrease in size while increasing in intelligence. Micro-electromechanical systems (MEMS) are an enabling technology that will allow the Army and Department of Defense (DoD) to meet these objectives.

The War on Terror has brought numerous issues to the forefront. A primary issue is the need to

rapidly respond and adapt to varying missions and operational environments. This necessitates secure, accurate, and timely transmission of information. The Army must transform into a lighter yet more lethal "objective force," that must be deployable, 70% lighter and 50% smaller than current systems while maintaining equivalent lethality and survivability [1].

Accordingly, the technologies embedded in military vehicles and weapon systems must be decreased in size and weight while providing improved reliability, capability, and intelligence. To meet these requirements, Army scientists and engineers need to capitalize on new technologies and

breakthroughs in emerging technologies such as MEMS.

The conditions military MEMS must operate in are unique. Operational and storage environments for the military are significantly different than those found in the commercial sector. Issues impacting the utilization of MEMS by the DoD include; high G-forces and spin associated with gun launch, extreme temperature and humidity ranges, extended periods of inactivity, interaction with explosives and propellants and stringent requirements for safety and reliability. The military operational environments in which MEMS will be stored or required to function are extreme and in general greatly surpass any commercial operating conditions.

To facilitate the insertion of MEMS technologies in weapon systems, U.S. Army ARDEC is addressing the information gaps delineated above. This will benefit the MEMS user community by providing data on failure modes induced by packaging, transportation and storage for selected devices. These data will then be used to develop a standardized methodology for conducting these assessments. Specific activities include:

- Assessment of the operational environments in which the military MEMS device may be utilized.
- Determining & developing methods to preserve MEMS devices during long-term storage before they are designed into products.
- Independent assessment of reliability that cannot be obtained from private industry.
- Establishment of reliability data that will be fed back into development & design to improve MEMS devices.
- Production & design process can be vastly improved to increase yields that will drive costs down.

Department of Defense Military Utilization

The transition within the DoD to lighter more capable devices has lead to an increased interest in MEMS. The rapid increase in potential MEMS applications have resulted in a greater need for an accurate assessment of quality, reliability, and survivability. The Army is not alone in facing these challenges. The U.S. Department of Defense (U.S. Army, Navy, Air Force, NSA, OSD, DARPA, ONR, Homeland Security, etc.), NASA, Health and Human Services Department, National Sciences Foundation (NSF), and Department of Energy (DOE) are implementing MEMS based technologies. With increased utilization, come increased requirements, qualifications, and safety considerations.

Besides being implemented as an enabling technology for new systems, MEMS technology is also being investigated for replacement of obsolete or unprocurable electronics, switches, sensors, storage devices, mechanical systems, and other components in current weapon systems.

Since MEMS technologies involve complex, systematic fabrication approaches while utilizing the advantages of wafer-based lithography for the miniaturization of multi-component systems and microelectronics, they allow one to create advanced devices with added capabilities. MEMS technology enables the manufacture of small systems with increased functionality that will lead to performance enhancement for both current systems and entirely new systems.

The DoD has identified several key benefits of MEMS utilization [2]. These include:

- Cost Savings
- Life Savings
- Weight Reduction
- Space Reduction
- Miniaturization
- Reduce Integration Risk
- Combination / Integration of Components
- Increase Plug and Play Capabilities
- Potential Reduction of System Risk
- Power Reduction
- Advanced Capabilities

The DoD is focusing on four primary areas of interest for MEMS utilization: 1) Inertial Measurement, 2) Distributed Sensing, 3) Power Systems, and 4) Information Technology [3]. While the majority of the DoD's MEMS efforts are focused in these areas, there are ongoing efforts in other areas such as Safing & Arming, Fuzing technologies, and Energetics. Some examples of advanced MEMS technology applications in DoD Systems include [4]:

- Acoustic Microsensors
- Velocimeters
- Magnetometers
- Micromechanical-Based Spectrometers
- Low Power Wireless Integrated Microsensors
- Surveillance Systems
- Multifunctional Electro-optical Sensors
- MEMS Infrared Remote Micro Sensors
- Magnetic Resonance Imaging Systems (MRI)
- MEMS Un-cooled Infrared (IR) Imaging Arrays
- Gyroscopes
- Embedded Sensor Systems
- Remote Weapon Systems

- Unmanned Vehicles (Land, Air, Space, Sea, etc.)
- Battle Space Awareness
- S&A Devices
- BITs (Built In Test)

The primary areas of focus are facilitated through cooperation with commercial industries. The adoption of the areas unique to the DoD, are rapidly increasing. With the Army's transformation to the Future Combat System (FCS) the need for robust, safe and reliable MEMS devices is essential.

Military Applications

Current and future military systems that may incorporate MEMS include: safety and arming devices, fuzing devices, various guidance systems, sensors/detectors, reduced power consumption/micro power systems, inertial measurement units, tracking devices, radio frequency devices, wireless radio frequency identification tags (RFIDs) and network systems, global positioning systems (GPSs), radar systems, mobile base systems, information technologies, satellites, and missiles. Incorporating MEMS into these applications will provide the military with new levels of speed, awareness, precision, lethality, and information dissemination. The system capabilities enhanced by MEMS will translate directly into tactical and strategic military advantages.

Although MEMS will be required to survive and function in harsh environments, the impacts of packaging, storage, transportation, and operating environments on the long-term performance of MEMS in DOD systems are not well understood. Performance of tests in accordance with standardized methodologies is essential to demonstrate the desired reliability for MEMS that are, or will be, used in critical military applications. These devices must often serve a number of functions within a particular system. The functions may be degraded by continuous operation and storage in aggressive environments as well as extended periods of dormancy.

The applications, operational, transportation, and storage conditions are vastly different between military and commercial sectors. Military MEMS systems must often function and survive after experiencing extended periods of inactivity and extreme transportation profiles. It is not uncommon for military MEMS to be expected to endure extended storage, which may be greater than 20 years, in extreme environments. These extreme conditions pose tremendous challenges. Corrosion, material migration, device anomalies, and other potential

failure mechanisms, are a direct result of these conditions. Mission profiles for Army weapon systems often include operation in harsh environments which may include any or all of the following [4]:

- Continuous operations in high humidity & moisture
- Continuous operations in areas of high wind
- Significant off-road driving
- Continuous operations in areas of high heat
- Continuous operations in sub-zero temperatures
- Extreme high & low pressured environments
- Continuous operations in sandy regions, where sand ingestion, infiltration, & contamination are commonplace
- Large variations and rapid changes in temperature due to diurnal cycles and deployment from aircraft
- Extreme G-forces due to airdrop delivery & gun launch

Shock, vibration, temperature extremes, environmental elements are all potential hazards and can greatly impact the quality and reliability of military MEMS. Transportation, shipping, and storage are prime induction points for these potential failures mechanisms. 70% of military vehicle mission profiles involve off-road conditions. An assessment of the environment in Iraq [5] recorded temperatures as high as 115 – 125 °F with 1.0 kW/m² of insulation. Average daytime temperatures ranged from 95 – 105 °F. Large diurnal cycles occur in the summer because of the inability of the dry air to retain temperature.

Military Standards have been developed to assist with the design and evaluation of military systems in harsh environments [6]. These standards were developed to cover 99% of the global environment that military operations are performed. Unfortunately, the conditions in the Middle East often fall outside these ranges. Besides the extreme temperature environments, another environmental condition is a serious concern, sand. Sand intrusion is a significant issue with all military equipment deployed in current operations. The operational environments of MEMS can adversely affect packaging & device reliability.

Another factor to be considered during the assessment of MEMS devices is long-term storage. Long-term storage should include compatibility of materials within and adjacent to the device, hermeticity of packaging, creep of materials, and stresses on interfaces caused by temperature, shock, or vibration.

Material compatibility may be the most critical issue with regard to long-term storage. The MEMS industry is employing numerous new material combinations in emerging devices, with minimal data on their compatibility. Such materials being incorporated include metallics, polymers, composites, ceramics, and numerous fluidics. Compatibility of these materials directly impacts their reliability. Potential material interfaces and their affects are being studied currently to gain a better understanding of the relationship between material compatibility, long-term storage and reliability.

Military MEMS Assessment

Currently, most MEMS development within the Department of Defense is derived from an enabling technology. The end user's inputs or requirements are usually not included in the process. The design is often a byproduct of the materials and manufacturing processes that facility possesses, rather than optimized selection criteria for the intended application. The end users' input is solicited after the device has been designed, manufactured, and packaged. This may lead to integration, performance, and reliability issues, retarding the implementation into DoD systems.

The combination of operational extremes and lack of end user feedback has resulted in a need to assess military MEMS beyond current commercial practices. Since devices will be transported, stored, and utilized in both packaged, and unpacked configurations using past integrated circuit tests, protocols, and standards is inadequate.

Engineers at U.S. Army ARDEC, and their partners throughout DoD and government agencies have been working on a comprehensive approach to MEMS Reliability Assessment.

Researchers have performed extensive literature searches, interviews, and data mining in an attempt to collect information about devices, reliability data, and test methods to baseline what we have and what we need.

As part of the team's efforts, Dr. Ivars Gutmanis, of Hobe Corporation, has written a report entitled, "*MEMS Standards, Tests, and Applications in U.S. Department of Defense Activities*," which provided a snapshot of the current state of MEMS.

Several team members performed a Lean Six Sigma Project entitled "*MEMS and NEMS Assessment Using Six Sigma*," to develop risk mitigation tools to facilitate the transition to and implementation of MEMS for the U.S. Army. Results included [7]:

- Materials of construction selection hierarchy

- Assessment of the impact of corrosion/material degradation on failure mechanisms
- Physics of failure for MEMS devices
- Environmental Stress Screening (ESS)
- Test Guidelines
- Barriers to Implementation Matrix
- Cause and Effect Analyses
- Assessment and Summary of Current MEMS practices
- Preliminary identification of DOD MEMS utilization
- Benefits of MEMS Utilization

Through this and other government support assessments several technology gaps and barriers to implementation were documented.

Barriers to Implementation

There are several primary barriers slowing the military's transition to MEMS. Beyond the physical barriers imposed such as gun launch, extreme operating environments, and costs, there are other "virtual" barriers that must be addressed. The lack of documented reliability data for MEMS has adversely affected the "trust" in MEMS and is and will continue to be a major obstacle to overcome. MEMS research has primarily been focused on development of new devices, little consideration has been paid to reliability, interfaces, or packaging. Vast arrays of devices types have been developed with little knowledge or consideration of the failure mechanisms, quality, reliability, or safety of these devices.

This lack of trust in MEMS has left many end users reticent to adopt this technology. System developers and program managers are unwilling to utilize MEMS since they are unwilling to assume the potential risks of an "unknown technology". Successful utilization of MEMS in military systems will be largely dependent upon their long-term performance within these systems. There are many aspects of MEMS performance in military applications that have yet to be explored. The unknown responses of MEMS to their storage, transportation, and operational environments must be determined if MEMS are to be widely implemented into DOD systems.

These barriers must be addressed for successful integration of MEMS into weapon systems. In response to this need, members of ARDEC have initiated a comprehensive program to reduce and eliminate these barriers. This program includes identification of devices for DOD applications, development of test protocols and

testing capabilities, assessment of modeling packages and guidance for design, manufacture and packaging.

Development of Methodologies for Assessing Military MEMS

As previously mentioned, ARDEC scientist and engineers are developing tools and methodologies to provide a comprehensive assessment of the impacts of packaging, long-term storage, and transportation on Military MEMS, and its affects on safety, survivability, and reliability.

To date several tools have been developed to assist with this assessment and hopefully increase the “trust” and utility of MEMS as an enabling technology for military systems. Test Plans and Guidelines were developed for several devices based on their class. Definitions for the classes can be seen in Table 1. When developing test guidelines, consideration was given to the process steps that comprise the manufacture, assembly and packaging of the device. The generic steps and potential issues of those processes are detailed in Figure 1.

Environmental Stress Screening (ESS) Test Plans are being developed for several candidate devices of interest to ARDEC and the DoD. ESS testing exposes devices or components to stresses (temperature, vibration, humidity, etc.) to force defects and failures during a screening process. These tests help identify infant mortalities and potential failure modes.

After devices are evaluated to ensure functionality, a portion of the devices are submitted to ESS Testing. After ESS the devices are tested

and/or evaluated to determine the effect of the environment stresses to the functionality and performance of the devices.

Besides ESS testing, several other tests are utilized to assess the reliability of the MEMS devices. Other testing includes materials characterization, properties, compatibility, and fatigue lifetime assessment, leading to a Long Term Storage/Accelerated Aging Guidelines. The results are being used to modeling the impacts of packaging and long-term storage on the reliability of MEMS.

The information gained from ESS and other test protocols and methods can be used for Failure Modes & Effect Analyses. were performed on the S&A devices. FMEAs are used to analyze the potential failure modes of the system and determine the severity of the failure’s effect to the system. A general Cause and Effects Diagram based on the ARDEC S&A device is illustrated in Figure 2.

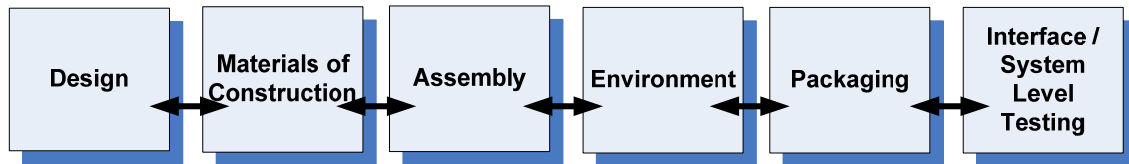
The information obtained from the testing and analyses are then to be incorporated into a series of reliability modeling efforts. Under these efforts, reliability modeling for MEMS S&A devices was performed. This involved identification of reliability data sources that can be employed to populate MEMS reliability models. Reliability modeling refers to the process of predicting and understanding the reliability of components and/or the system. Both physics of failure approach, as well as the components stress approach were undertaken. MIL-STD-785, MIL-HDBK-217, IEEE 1332, as well as some other common standards, were considered during the adaption of these models [8-11].

Class of MEMS	Characteristics	Examples
Class I	No moving parts	Pressure sensors RF IDs
Class II	Moving parts; no impacting surfaces	Gyros Accelerometers Resonators
Class III	Moving parts; impacting surfaces	Relays Valves Pumps
Class IV	Moving parts; impacting and rubbing surfaces	Optical switches Scanners Discriminators
Class V	Moving parts; interfaces with explosives, propellants, & Energetics	S&A Devices IMUs Fuzing

Table 1. MEMS Devices Classes

TEST HIERARCHY:

MEMS Test Guidelines



Issues

- | | | | |
|--|---|--|--|
| <ul style="list-style-type: none"> • Compatibility <ul style="list-style-type: none"> Thermal Chemical Electrical Physical • Quality / Uniformity • Structural Properties • Thermal Cycling • Modulus • Environment | <ul style="list-style-type: none"> • Tooling Effects <ul style="list-style-type: none"> Stresses Thermal Effects Quality Aspect Ratio • Process Method Effects • Thermal Cycling • Contamination | <ul style="list-style-type: none"> • Function (Class of Device) • Type • Processing • Contamination • Quality/ Tolerances • Compatibility • Stress/Strain • Thermal Cycling • Corrosion | <ul style="list-style-type: none"> • Processing <ul style="list-style-type: none"> Contamination Hermeticity Quality Compatibility Thermal Cycling Interfaces • Function (Class of Device) • Operational / Storage Environment |
|--|---|--|--|

Figure 1. MEMS Test Hierarchy

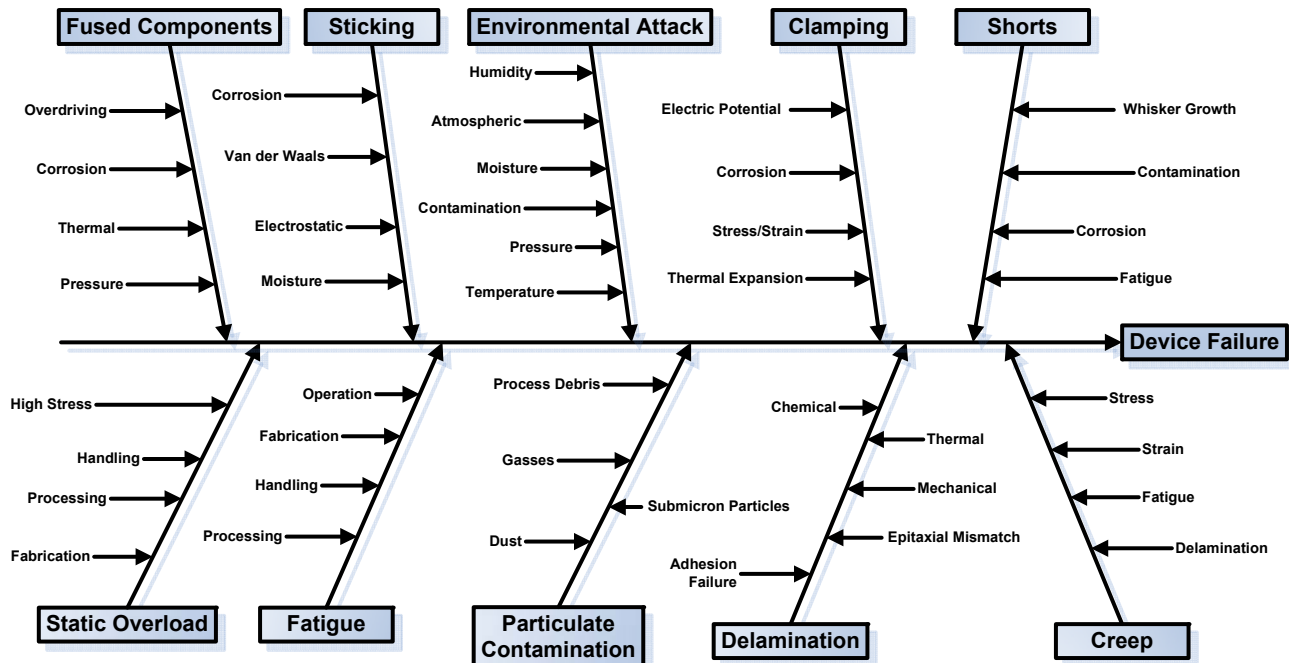


Figure 2. General Fishbone for ARDEC S&A

Commercial off-the-shelf (COTS) software is being used to generate models for MEMS devices of interest to DoD. One approach taken was to adapt PRISM[®] software for reliability. PRISM[®] software employs environmental parameters (duty cycle, cycling rate, etc.) and failure rate terms (operational, non-operational, and cycling) to generate a reliability analysis. Due to the relatively recent development and fielding of MEMS, software such as PRISM[®], which is based on Comprehensive System Reliability Prediction (CSRP), currently lacks some data necessary for reliability modeling of MEMS. One goal of the Army engineers working on the assessment of military MEMS is to modify and update the existing functionality and structure of the CSRP to best meet MEMS reliability modeling needs, as well as develop data warehousing critical to both DoD and industry.

Engineers from the Army, along with their partners, utilized a two-phase approach in developing a component-level model for the ARDEC MEMS S&A device. Phase one involved the collection of reliability information, failure data, and failure mode/mechanism data on the specific part type of interest. Raw material, design, manufacturing, and environmental data from previous efforts were considered as inputs. Phase two involved the analysis of available data and information using PRISM[®] based reliability models. The reliability modeling of interest to ARDEC is more application oriented, focusing on parameters such as materials, design, processes, and storage/use environment to predict the reliability of that device in actual operational conditions.

This approach resulted in the development of a theoretical model for Class V MEMS devices which uses PRISM[®] for MEMS reliability modeling (Figure 3). This process helped identify relevant modes of failure including stiction, structural breakage, contamination, package, and induced failure that are relevant to the S&A device. Operational, environmental, cycling, and induced factors were all considered. An example of a Safing and Arming MEMS reliability prediction model is illustrated in Figures 4.

$$\lambda P = \pi G(\lambda OB\pi DCO + \lambda EB\pi DCN\pi RHT + \lambda TC\pi CR\pi DT) + \lambda IND$$

Where:

λP = Predicted failure rate in failures per million "calendar hours"
 πG = Growth rate, reflects improvements in device manufacturing over time
 λOB = Operating base failure rate

πDCO = Operating duty cycle factor
 λEB = Non-operating (or "environmental") base failure rate
 πDCN = Non-operating duty cycle (proportional to time in the non-operating state)
 πRHT = Non-operating temperature and relative humidity acceleration factor
 λTC = Temperature cycling base failure rate
 πCR = Temperature cycling rate acceleration factor
 πDT = Temperature cycling delta-T acceleration factor
 λIND = Induced failure rate contribution

Figure 3. Theoretical Model for MEMS Class V Devices

$$\text{Model Form: } \lambda P = \pi G((\lambda O * \pi DC) + (\lambda EB * \pi RHT * \pi DCN) + (\lambda BC * \pi TC * \pi CR)) + \lambda IND / 10^6 \text{ calendar hrs.}$$

Where:

λP = MEMS component failure rate
 λO = Operating base failure rate
 λBE = Non-operating (environmental) base failure rate
 λBC = Temperature cycle base failure rate
 λIND = Induced failure rate
 πG = Growth rate Pi factor
 πDC = Duty cycle Pi factor
 πRHT = Relative humidity acceleration Pi factor
 πDCN = Non-operating duty cycle factor
 πTC = Temperature cycling Pi factor
 πCR = Temperature cycling rate Pi factor

Figure 4. Theoretical Model for ARDEC S&A MEMS Device

The predicted failure rate can then be expanded by the addition of component test data, experimental data, or field data. That data can then be compiled with PRISM[®], or similar software, to include unique assembly information of MEMS devices. The results are then used to develop process grade sets for specific devices.

The data and results obtained from the testing, modeling, and analysis can be used to assess the reliability of Class V MEMS devices for military applications. This information can then be incorporated into current and future designs to

improve component and systems functionality, producibility, and reliability.

Conclusions

The DOD is currently investigating enabling technologies, to meet emerging threats, enhance weapon systems performance, reduce life cycles costs and improve system reliability. Because of the benefits associated with miniaturization, MEMS, is one such technology the DOD may rely on to meet their current and future objectives. Before the military beings employing MEMS for utilization in weapon systems, MEMS must be highly reliable in extreme environments. Furthermore the reliability must be demonstrated and show repeatability and safety. As detailed above, ARDEC scientists and engineers are continuing to identify the devices, operational conditions, and applications of MEMS in military systems. The development of test protocols and testing of representative devices continues. Work towards the adoption of standards has begun. The information gained from these activities, and the data gained from failure analyses will aid in the transition of MEMS technologies from the labs to the field where it is needed.

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