Return-on-Investment Potential for US Army Missile Health Monitoring

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Abstract—Application of health monitoring technology and the capability to predict failures can potentially improve the efficiency and effectiveness of US Army missile sustainment. Sustainment functions throughout the weapon’s lifecycle and across the spectrum of different Army missiles such as field testing, lab testing, inspections, retrograde, maintenance, reliability improvements, and supply functions offer many opportunities to better the sustainment status quo in both cost and performance. New technology solutions must however accrue benefits associated with metrics such as total life cycle cost, as well as other readiness-type metrics such as reporting accuracy, timeliness, uncertainty, and other factors. Application of health monitoring and failure prediction must provide an acceptably high return in benefits as compared to the investments needed upfront for development and deployment. Given those constraints, only the most innovative and well engineered applications of existing, emerging, and new technology will suffice in context even though overall sustainment improvements are highly desired. The information in this paper is intended to notionally describe the US Army’s missile logistics and supply such that feasible and effective technology solutions can be targeted at specific processes, and thereby provide maximal quantifiable effect. The paper will also briefly address applied research currently being conducted that targets Return-on-Investment (ROI) risks and thereby better enable technology transition.

I. INTRODUCTION

The US Army produces and fields various type weapon systems that enable many diverse capabilities, and support both current and future operations. In the case of Army missile systems, it’s critically important that the readiness of Army assets is assessed in a consistent and periodic manner. The Army at present therefore conducts surveillance of missile stockpiles, and within today’s constrained budget environment it’s highly desirable to increase the efficiency and improve the effectiveness of those activities to achieve both functional and economic tangible benefit. Similarly, improvements are also desired for the many other related missile logistics and supply processes where tangible benefit can accrue. Because of limitations in available data, the current surveillance and other related sustainment processes result in reactive versus proactive decision making. Surveillance for maintaining reliability and shelf life of missiles as well as other sustainment activities can however be enhanced by implementing proactive tools such as health monitoring, in conjunction with real time predictive evaluation of it’s critical assets.

To address these needs, the US Army has transitioned technology solutions to some of its tactical missile systems that provide the first new fielded capability to monitor health or condition with the intent to improve overall missile sustainment. These initial applications were an outcome of applied research solutions first developed by the Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC). The AMRDEC is actively conducting follow-on research to address shortfalls and constraints seen in fielded applications, as well as to optimize the performance and efficiency of existing technologies.

Even though great strides have been made introducing missile health monitoring, severe challenges exist in formulating predictive/proactive sustainment capabilities that not only target the most significant sustainment drivers for greatest effect, but also create solutions which in themselves are highly efficient and effective [1]. It is generally recognized and accepted that health monitoring, prognostics, and embedded diagnostics can replace/optimize traditional corrective or preventive maintenance to enhance system availability, lower logistics footprint, and reduce operating and support costs. However, capabilities derived from new technology solutions must provide acceptably high return in benefits as compared to the upfront investments needed for development and deployment. Since achieving a high Return-on-Investment (ROI) in this context is very difficult, for new technology transition to occur and sustainment benefits to be realized solutions must be suitably constrained. In a fully integrated logistics and supply enterprise with health monitoring, the Army logisticians can better identify/predict system failures; achieve accurate and timely asset visibility, and utilize condition-based processes that improve overall sustainment efficiency and effectiveness. Given the constraints inherent to achieving an acceptable ROI only the most innovative and well engineered applications of existing, emerging, and new technology will suffice in achieving sustainment benefits even though highly desired by the Army.

Missile health monitoring in its most basic form is comprised of the collection and distribution of source data related to the usage and exposure stresses experienced by an individual asset. The Army’s missiles are subjected to long
durations of stress from usage and environmental exposure, which contribute to the increasing potential of critical failure. Similarly, many of the technical risks associated with implementation of health monitoring relate to the very severe operational constraints mandated for Army missile field applications. Those constraints include low volume, extreme operating environments, limited data processing, and long operating life. For these unique applications related to Army missiles, operational life presents the most significant challenges, and typically also drives other major constraints. The tradeoffs between performance within constraints vs. the level of sufficiency to indicate and/or predict failure is the core challenge that must be addressed.

To address these challenges, the AMRDEC has partnered with industry leaders in this area in the development of new health monitoring technologies that focuses on design and development of new sensors capable of detecting root cause failure modes, and presenting this information to the warfighter in an effective and efficient manner. New low power, low cost and small form factor sensors are being designed and evaluated along with commercial solutions to meet military requirements for long life, broad environmental operation and integration into existing missile systems. The sensors solutions are tested and balanced against power, volume; communication, data storage and root cause detection to maximize health monitoring capability.

The intent of this paper is to describe the US Army’s missile logistics and supply processes in a notional manner such that feasible and effective technology solutions can be identified that target specific processes, and thereby provide maximal quantifiable effect. The paper will also highlight the most significant ROI risks from a technology standpoint that potentially effect transition, as well as briefly outline the current applied research that targets those risks. This information will hopefully establish a dialog among industry, academia, and government so the most feasible and effective means of where and how technology solutions can positively impact Army missile sustainment can be determined.

II. BACKGROUND

The sustainment processes referenced herein relates exclusively to the US Army’s missile systems; however basic concepts can be applied more broadly to other Army systems with similar outcomes. As with other Army commodities, for missiles to achieve mission requirements various logistics and supply functions are mandated throughout the life cycle. These sustainment functions applied in conjunction with a weapon’s inherent performance characteristics define its state of readiness. The core function being addressed herein relate to the processes that assure US Army missiles attain a specific readiness level as mandated by relevant Army authority to meet mission needs. Minimizing statistical uncertainty is a critical element in defining and characterizing mission capabilities and readiness as pertaining to Army missile systems.

By providing Army sustainment managers the ability to anticipate missile sustainment requirements in a proactive manner would increase the efficiency and improve the effectiveness of missile-related logistics and supply processes. These “anticipatory” sustainment decisions would be enabled from knowledge derived from the analysis of data/information using prediction and/or forecasting techniques and methods. In its most basic form these techniques would transform information into knowledge that is directly relevant to critical sustainment decisions, thereby resulting in more efficient and effective process outcomes.

These general techniques and methods for maintenance-specific processes are generally characterized as Condition Based Maintenance (CBM) where requirements for a system are derived solely upon an “evidence of need”. In other words, maintenance is performed only when mandated vs. in a periodic fashion. The “evidence of need” is acquired through an accurate assessment of the system’s condition which is established functionally through a relevant set of tests and/or measurements. Certainly, an existing anomalous condition warrants maintenance; however further CBM optimization can be achieved by the prediction of future condition, and that optimization would likely improve as prediction capability improves. Within Army missile sustainment, maintenance-type processes do exist and CBM is directly applicable in those cases to attain optimization. Missile sustainment also involves other processes not entirely equivalent to maintenance; however those processes can be similarly optimized using predictive methods.

This discussion relates to US Army missile systems characterized as fielded systems, and can be further characterized as either deployed operationally or in a stockpile with a “ready” status. A complete categorization of Army missile status types related to sustainment can be fairly complex. However, a general high level of categorization for “serviceable” Army missiles would be either of the following: (1) deployed for tactical use. (2) stockpile storage in a “ready” stand-by state for potential future deployment as needed. Additionally, there would be “unserviceable” missiles that are not considered operational for various reasons, and those would be identified as such and segregated from the serviceable assets. In some cases, a subset of “unserviceable” assets while still considered segregated would be undergoing a logistics action such as being repaired to return to a “serviceable” status. In other cases, the “unserviceable” assets would not likely be returned to “serviceable” status, and undergo a demilitarization for final disposal. In this context, Army missiles require both temporary and long-term storage, and various forms of tactical and non-tactical transportation/handling to support both storage and deployment functions. A final distinct categorical status would be that of a missile
being “in-operation” which is very dependent on missile type. The in-operation status has the weapon being “ready for use” by soldiers. For some Army missiles, “in-operation” is comparable to conventional munitions and encompasses just tactical handling and transportation. For other missiles in-operation might include added tactical transportation not experienced otherwise such as captive flight, as well as the potential active functioning of components in manner similar to other equipment that operates more continuously over long periods.

As alluded to previously, it is critically important that the Army assess the readiness of its missiles in a consistent and periodic manner for each and all the status categories described above. Therefore, the Army undertakes a regular periodic assessment of the reliability of its missiles through a dedicated program of surveillance [2]. Within the fielding phase of its missiles, the Army collects pertinent reliability data utilizing a variety of surveillance methods such as inspections, testing, and other monitoring that occurs in both the deployment and stockpile storage fielding categories. These on-going assessments of all the Army’s missiles serve as the following: (1) a basis in determining its readiness for current and future needs; (2) a basis in establishing what potential mitigation may be required during the lifecycle to maintain a level of readiness; and (3) a basis for determining potential future procurement that might be needed to replace existing missiles to maintain readiness levels. If a missile system continues to perform reliably and safely based on surveillance data, for each missile type a recommendation to that effect is made to major Army decision makers. Conversely, if surveillance analysis indicates undesirable trends, whole missile populations or subsets of populations could be suspended for further use or restricted for special use only. Therefore, this surveillance function in relation to identification of degradation for missile populations and its effect on readiness of the stockpile has potentially very significant economic implications in addition to obvious war-fighting implications.

To further complicate matters, in the last few decades there has been a significant shift in how the Army builds and fields its missiles which affects the Army’s missile surveillance function. This change has made a major impact on the factors affecting degradation of Army missiles, as well as the considerations needed to manage and assess readiness. Prior to Operation Desert Storm, the Army’s missiles were designed for long term storage in depots without extensive deployments. Additionally, these generations of missile were designed and built to government-owned specifications resulting in highly homogeneous stockpile configurations. Since Operation Desert Storm, missile deployments have become more frequent resulting in a greater stratification of aging and performance within the stockpile. Compounding the problem, government acquisition has reduced or eliminated control of lower level specifications. The result is a further reduction in stockpile homogeneity. These changes in the Army’s design, production and fielding of its missiles makes for a less certain and more costly assessment of the readiness of missile stockpiles.

Factors Effecting Army Missile Readiness and Reliability –

In association with the fielding scenarios described previously, Army missiles are exposed to highly variable and extreme environments as well as induced stresses from those environments during storage, transportation, handling, and operation. Additionally, some highly critical missile component material properties degrade with age, and environments can influence those aging effects. Instantaneous overstress conditions as well as cumulative stresses due to long term environmental exposures have impacts that degrade Army missile reliability over time. The typical environments of interest include cyclic exposure to extreme temperatures and extreme humidity, dynamic loading from vibration and shocks, corrosive atmospheric conditions, and other exposures.

A number of failure modes induced by environmental exposure have been identified within missile surveillance testing, and subsequent data trend and/or failure analysis. These failure modes are divided into three component categories and include the following: (1) mechanical/structural components, (2) electrical components, and (3) energetic components such as rocket motors and explosive warheads. The mechanical category includes missile structural components which are subject to damage during transportation and handling. The critical electrical components include guidance and control systems, which are susceptible to failures due to corrosion, temperature, and humidity effects on sensors, wearing of electromechanical parts, and battery failures. Energetic components can be damaged by dynamic loading, or can degrade through chemical processes.

Enhancement to Army Missile Surveillance and Assessment

As noted above, the Army’s current surveillance and periodic test programs have identified several failure scenarios which include manufacturing defects, contamination during manufacturing, and most important of all degradation due to aging and exposure to extreme environments inherent to fielding. In the case of environmental degradation and aging effects, the failure mechanisms point towards accumulated damage resulting from exposure to temperature, humidity, shock and vibration. Therefore, these failure mode analyses indicate that real time monitoring of exposure, and the analysis of that data can provide tools to identify defects with better accuracy as well as predict the onset of defects, with an overall improvement in reliability determination.

In this context, the Army has therefore initiated and continues applied research to monitor exposure and stress parameters that can be measured real time with an integrated health monitoring system. The data from these monitoring systems can then be utilized to develop predictive models
for components health and integrity and determine the missile reliability before use in operations, as well as anticipate needed sustainment actions to maintain the needed state of readiness for its weapons. The first of these systems to collect source data has already been fielded on several missile systems, and will in all likelihood be incorporated in all future Army missiles. The data resulting from these systems already provides benefit in planning sustainment; however a great deal of additional effort is required to achieve a predictive capability that can further optimize sustainment efficiencies and effectiveness.

Since the Army has already fielded missile health monitoring systems, and is presently fielding additional health monitoring systems, the source data related to environmental exposure is becoming available and will potentially increase in scope. However, adding predictive capabilities to Army sustainment comes only with costs which include upfront development/acquisition/integration, but also recurring costs in infrastructure, data transfer, and sustainment of the monitoring capability itself. Those costs need to be significantly offset by the benefits in sustainment that are possible with the capability. Therefore, significant challenges exist in identifying where health monitoring and predictive capability can positively impact missile sustainment, and also in what monitoring capability outcomes are achievable to make those positive impacts. The many constraints involved already mentioned need to be addressed, but also the certainties in the condition indications and predictions play a major role in how great an impact can be made, and how much benefit can accrue. In other words, the need exists to provide certainties with predictive methods so that the status quo can be impacted for greater efficiency and effectiveness.

Therefore, AMRDEC applied research in health monitoring plays a major role to enable the certainties needed for condition indication and prediction, and to enable capabilities that are targeted at the sustainment processes with the greatest potential benefit (again within the many constraints involved). A successful AMRDEC applied research in this area increases the likelihood that new technologies related to missile health monitoring will transition to existing and emerging future missile systems as a means to foster their affordability. Much work still needs to be done in the following (1) identifying where the greatest potential benefit can occur, (2) defining how those benefits accrue functionally in the sustainment processes, and (3) determining the specific monitoring capability and/or prediction methodology that will provide the “actionable” information at the needed level of certainty to enable those functional benefits.

III. SPECIFIC MISSILE SUSTAINMENT PROCESSES

As previously mentioned, each Army missile system employs unique sustainment processes tailored to the inherent utility of that weapon to a certain extent. However, a listing of specific sustainment activities can be generated that applies across the spectrum of logistics and supply scenarios somewhat consistently for all Army missiles. Figure 1 gives a graphic depiction of various Army missile sustainment processes described in the following paragraphs:

Figure 1. Graphic Overview of Missile Sustainment Processes

**Depot Processes**

The Army depot system encompasses numerous facilities, with the majority located within the United States, and some with a similar functionality as the US facilities located overseas where there’s a strong US military presence. Typically, each Army missile system has one specific depot designated to support that weapon exclusively, and generally that depot serves the following key functions.

1) The Army depot is the initial government destination for new Army missile production assets. For some situations an acceptance could occur at the production source, in some cases at the depot. The final assembly of new production Army missiles could occur at the depot as well, where a government acceptance would then follow. Individual munitions will typically enter temporary storage for these new production assets. Various handling and transportation by forklift/truck occurs as a result of depot movements. Visual inspections are performed during these processes to check humidity indicators and the shipping/storage container identification markings. Temporary storage conditions can be in earth covered storage “magazines”, or possibly in MILVAN/ISO containers that are not located in a “magazine”.

2) The Army depot serves as the long-term storage location of assets described earlier as in a “ready-to-use” stockpiled state for potential future deployment. Operations within this scenario are very similar to the temporary storage above, but typically assets in long-term storage are located in earth covered “magazines”. Stockpiled assets are visual inspected on a periodic basis similar to the checking of humidity indicators and the shipping/storage container identification markings.
with temporary storage. For some missiles, a mobile test van has been developed that performs functional testing of the missile, and those tests will also occur on stockpiled assets on a scheduled basis.

3) The Army depot serves as a repository for the supply of assets to other storage locations as well as deployments. This can occur for new production assets after a temporary storage and/or for stockpiled assets. In these scenarios, the original pallets of missiles may be broken down and re-palletized to accommodate the follow-on shipments. Follow-on shipments from the depot are either by truck or rail modes of transport, for later potential transport by ship or air, depending on the intended use of the assets to be shipped. Visual inspections would occur prior to any out shipment from the Army depot. In a similar manner, the Army depot would also receive assets returned from other locations related to several scenarios, one significant scenario being the retrograde of previously deployed assets. The extent of operations performed on returning assets varies and is described below.

4) In many cases, facilities to perform detailed testing, rework and/or repair of Army missiles are co-located at the Army depot. For the returning of assets just described, the Army depot depending on the situation would perform inspections of those assets, and potential rework/repair as warranted for those assets. However, in some cases rework/repair may occur elsewhere, and the depot would accommodate those operations as warranted. Where the depot has the facilities to perform extensive repair and rework, they would also have the ability to do the functional testing capabilities needed to adequately support those operations.

**Assets Organic to Continental US (CONUS) Operational Units**

Missiles to be utilized by operational units as what’s termed their organic load are shipped from the depot to the installation in the continental US that serve as its home base. Those installations have facilities called Ammunition Supply Points where their organic assets are stored. In most cases, these storage facilities are similar to those of the depot (earth covered magazines), but are less expansive than at the depot. The ASPs would be supplied from the depot as described above. Operations are also very similar to those at the depot, and organic assets would be derived from stocks at the local ASP and would be either shipped by sea and/or air transport with the unit’s other basic load materiel. Similar to depot operations, pallets of missiles are offloaded by forklift, and transported by truck within ASP movements. Visual inspections are performed during these processes to check humidity indicators and the shipping/storage container identification markings. For missiles with a mobile test van, the ASP would be scheduled to functional test those assets on a scheduled basis.

Missiles going to OCONUS, that are not organic with CONUS based operational units, are transported to the designated debarkation locations from Army depot by truck or rail. Transportation and handling occurs at debarkation locations, as well as in-transit (visual) inspection. In some cases, shipments will be made to and from sea ports to support the Preposition (PREPO) ships maintenance and resupply cycle. These ships contain Army war reserve stock and are deployed worldwide. Ammunition containers aboard PREPO ships will be stored with a climate control system that is designed to maintain a stable climate of less than 69% RH and less than 100 deg F in the cargo spaces. Round inspection occurs during PREPO ship maintenance cycles, and 100% inspection of the box/pallet exterior and humidity indicator will be performed.

For air transport, upon asset receipt a truck will be assigned to a temporary holding area and an in-transit (visual) inspection will be performed. They will be held in storage until country clearance is obtained and then pallets will be uploaded to an appropriate trailer or loading scheme for a particular aircraft, and transported to the aircraft.

The assets will arrive at an OCONUS theater supply activity, and will be inspected and transported to the Reserve Storage Activity. Assets will either be sent to ASPs or other theater locations. Unlike permanent magazine storage, ammunition assets in field storage are most often stored on the ground on unimproved surfaces such as roadside or barricaded above ground magazines. Ammunition distribution areas will be provided for the tactical units at the brigade, division, and corps level.

Assets will be transported from the Army theater level storage area by truck to the corps storage area located in the corps ready area. Located in the rear, it is more fixed than the forward combat ASP it supports. For this reason, it is usually a more permanent storage facility such as an earth covered magazine, even though it can be stored on the ground with tarp coverage. The assets will be handled by crane or forklift at this location. They will then be transported from the corps storage area to the division ASP by truck and offloaded by crane or forklift. During peacetime, ammo would be stored in earth covered magazines, and outside storage otherwise. Assets may also be delivered from the theater level directly to the division ASP. Those shipments of palletized missiles will be within either MILVAN or commercial ISO containers or as break-bulk. MILVAN/ISO containers will be used for shipments to OCONUS locations by ship transport, and occasionally for large shipments to CONUS locations; otherwise, they will be shipped as break-bulk. The most frequent shipping method is by common carrier truck; however in some cases rail transport will be used for large shipments and some missiles will be air transported. Inspections will be performed upon receipt and out shipment, and every two years for depot storage and monthly at ASPs.

**Assets to be Shipped Outside the US (OCONUS)**

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These assets will remain at the division ASP unless delivered to the operational units described below; determined to be unserviceable and scheduled for return to the depot; or to be retrograded after completion of the deployment. Similar to CONUS ASP operations, visual inspections are performed during these processes to check humidity indicators and the shipping/storage container identification markings. For missiles with a mobile test van, the ASP would be scheduled to functional test those assets on a scheduled basis.

**Missiles At-Unit**

At the battalion level, missiles will be delivered to the operational units (companies), offloaded by crane and uploaded to the firing platform. The battalion basic load will be kept on trucks or downloaded to the ready storage area. The assets will be transported by truck from the division storage area. The assets will remain “at-unit” until fired, determined to be unserviceable, or to be retrograded after completion of the deployment. They would be returned to the division ASP for eventual return to the CONUS depot responsible for that type of missile.

**Specialized Testing and Evaluation**

The final sustainment process to be discussed completes the cycle of missile surveillance to assess readiness by complementing the various missile lifecycle processes just described in the previous sections with dedicated testing and evaluations. This testing and evaluation is typically conducted at Army laboratory and/or specialized test facilities, and is tailored to the specific system. These tests and evaluations at times consist of dedicated flights on an “all-up-round” both with extensive instrumentation and/or without instrumentation. The bulk of the specialized testing however is conducted at the component level both as destructive testing, and non-destructive testing. Components selected from representatives samples of the stockpile are tested such that key parameters critical to a given missile’s function can be assessed as a function of factors most relevant to the sustainment decision making process, such as a missile’s age and/or a missile’s stress exposure profile. All the information gleaned from the many lifecycle processes, as well as the dedicated specialized testing that’s performed are utilized to provide the most complete and accurate understanding of the state of readiness for Army missile systems. Additionally, this complete portfolio of assessments would be critical towards identifying, planning, and programming any mitigation that might be deemed necessary to assure proper readiness.

**IV. EXAMPLES OF CURRENT APPLIED RESEARCH**

The Army’s applied missile research team has focused on the development of new technologies associated with Condition Based Maintenance and missile sustainment. This work coincides with the Army’s focus to gain the necessary knowledge to assess missile readiness levels as efficiently as possible, and with the greatest effect. Therefore researchers are addressing the Army’s need to obtain critical surveillance data within the unique challenges involved such as power, size, measurement timing, data storage and finally collection and analysis of this information. An important factor being addressed is to utilize commercially available components to the greatest effect possible to optimize unit cost, and transition timelines. Therefore, temperature, humidity, pressure, high-g and low-g accelerometers, and chemical detectors from currently available commercial companies have been tested and characterized. Evaluations have identified those products that could meet the military operational environment requirements and those that needed modification or special consideration to be functional over the life cycle of the missile. The commercial solutions were also evaluated for accuracy across operational range to better understand the false alarm impact from shifts in response due to operating at the edge of the sensors design. The temperature, humidity, and pressure sensors solutions provided several options that met or exceeded the environmental operational requirements as well as accuracy over required conditions. Further evaluation for low power operation, required calibrations and recalibrations over the lifecycle narrowed the sensor solution options. The final sensor solution evaluation compared size, communication method and enclosure ruggedness. Of these three sensor types; Temperature, Humidity and Pressure a commercial solution was found that meet all the environmental, power, size and accuracy requirements.

**Embedded Propellant Chemical Sensing**

Another important factor being addressing focuses on a key driver for Army missile sustainment related to low-smoke propellant cracking and failures caused by environmental exposure and aging. An evaluation of the failures shows that a chemical signature could be used as a nondestructive means for health evaluation [3], [4], [5]. Therefore, evaluation of commercially available chemical solutions was conducted. The commercial chemical sensor options showed a unique challenge in the accuracy and power requirements needed for a health monitoring unit. The accuracy of the chemical sensor is a significant issue and is still under investigation today as we work towards a solution that can uniquely identify the specified chemical as well as survive in long term exposure of low levels during certain storage modes such as at the depot in earth covered magazines. The commercially available solutions often detected other chemicals present and would “false trigger” resulting in potentially unnecessary maintenance or testing of the missile system. In addition, the chemical sensor solutions often required excessive power and long calibration cycles to accurately detect. The power requirements were most often a heating coil required to elevate the reacting chemical temperature for detection to occur. This chemical sensor requirement made the commercially available solutions incompatible with the
A potential solution still under evaluation and testing was designed and developed with the help of NASA Ames Research Center in California [6],[7]. The chemical sensor being tested is a functionalized carbon nano-tube based sensor that doesn’t require heating for operation and is much smaller than current commercial solutions. Still under investigation is the accuracy for functionalizing to a particular chemical element, and long term exposure effects on the accuracy. This research continues and shows high potential to provide a low power, long life, chemical sensor. This carbon nano-tube based chemical sensor technology not only applies to missile health monitoring but can be applied to other areas such as detection for homeland security, industrial exhaust monitoring and other EPA-type applications. Shown in Figure 2 is the chemical sensing module developed as part of AMRDEC’s applied research.

Composite Rocket Motor Impact Detection

Another sensing modality that provides a significant payoff in missile sustainment decision making is damage to composite rocket motor cases. Because of the many attributes these composite materials bring to missile applications, rocket motor cases of this type are now being utilized frequently. As part of AMRDEC applied research, solutions optimized for low volume and lower power were developed utilizing a methodology that has emerged from the Small Business Innovative Research program [8]. Shown in Figure 3 is the Army’s current composite rocket motor case impact detection module which demonstrates the capability, and employs a commercially available low cost high-g piezo accelerometer. Another configuration that uses a low-g accelerometer to activate a high-g accelerometer offers a good solution to address many inherent component and operational constraints for this capability. However, there are operational scenarios that don’t include an initial drop such as an impact during handling, the impact of another container being loaded or stacked, etc. that causes a significant impact event to damage the missile system that challenge this configuration in terms of power usage. The performance requirements mandated to accurately resolve an impact event drove the need for the accelerometers, both high-g and low-g to always be active and ready for an impact. The power requirements and processing of this data presents a significant issue for long term data storage and health monitoring system. To address these power issues, a MEMS based shock trigger that requires no power to operate but at set thresholds indicates an impact of significance has occurred is being developed. The no-power shock sensor solution was designed to trigger at four different thresholds, 20g, 60g, 120g, and 800g, and these thresholds are reconfigurable at design. Each threshold level is independent of the others and can trigger different events such as the high-g accelerometer capture for a possible significant impact (when the 20g threshold is exceeded), or the detection of a launch event by the 800g trigger to shutdown sensors or save data off to a black box for review after testing. The MEMS solution offers a long term power savings capability, is electronically readable and resettable for multiple trigger events over the life cycle of the missile system.

Missile Health Monitor Usability Improvements

Another focus area for missile health monitoring research is the improvement of data collection and memory storage to thereby enhance the usability of this technology, and foster its transition. The storage and accessibility of sensor data is critical to identifying the environment inducing failure modes during the missile life cycle. The demonstration system that has been designed and developed includes a
removable micro SD card for depot level maintenance and review. This solution provides long term mass storage of data collected during the different life cycle modes; storage, handling and operational readiness seen by the missile assets. The micro SD card option provides easy transport of large historical log files, readily expandable storage based on new larger micro SD sizes and rugged non-volatile storage suitable for rough handling and operation. The micro SD card is not accessible from outside the missile system and designed for historical review at the depot level once an indication of an event of significance has occurred and the war-fighter has evaluated the system and determined it is in need of repair or testing.

In the context of improved usability, US Army applied research has developed solutions to enhance the war-fighters ability to access the health of the missile system. The first solution was a touch screen LCD display embedded in the front side of the health monitor, as that device might be notionally integrated into a tactical missile. The touch screen provided a solution for the war-fighter in the field with no tools in hand the ability to quickly and easily assess the health of the missile system. The basic display was enabled with a touch similar to current cell phone capacitive touch screen interfaces. This enabled the display to show a single color health monitor indication; green for mission ready, yellow for caution and a list of the sensor that had triggered the caution indication, and finally red for indication of a significant event that should be reviewed more thoroughly possibly at the depot. The red condition also displays the sensor or sensors that triggered the failure rating to allow in the field assessment of the severity of the impact on operational readiness of the system. These indications are not resettable in the field and all data is logged to the SD card for historical review. There were several displays evaluated and none provided the ruggedness required for operational solutions. The first solution reviewed and evaluated was the cell phone LED backlight LCD micro screen. The display power requirement also exceeded the power supply capacity available for continuous operation. The backlight LCD display also had issues with view ability in direct sunlight, scratching in blown sand and debris conditions. Several of these issues have been addressed by developing a cover option for the display that provided shielding from airborne particulate; sand, dust and debris. The shielding could also be utilized as a sun visor to provide shade for easy reading of the display. The power management options implemented to increase operation life included short display timeouts and disabling the backlight in sunlight conditions, however power remains an issue for this type of display. Another option evaluated was the E-ink solution that only requires power to change state. This provided a significant power savings solution along with moldable curved design options for improved integration on the side of the missile cylinder. The E-ink display was also direct sunlight read-able; however there wasn’t a multi-color version to provide the easy health status indication and low temperature operation required a heater to keep the fluids from freezing. The demonstration unit continues to utilize the LCD backlight solution for demonstration of the capability to provide the war-fighter a tool-less indication option even though further research will be required to field a tactical solution with this option. Shown in Figure 4 is the demonstration display unit described in the previous narrative.

![Figure 4. Enhanced Display Integrated Into a Missile Health Monitor](image)

The second method developed for easy user assess of a missile’s health status was through a wireless mobile application for smart phones and PDAs. The wireless solution transmitted both current conditions as well as allowing the download of all historical data. The radio solution offers the user the ability to query multiple assets at one time, with this data then being pushed to database storage for logistics and others on the health of their assets. The integrated radio solution is a major power consumer and therefore power management techniques were implemented to reduce the effects on operational battery life. The first and most significant solution was to disable the radio until enabled by another sensor such as magnetic sensor, low-g accelerometer (double tap) or key/physical switch. The demonstration system that was built utilized the embedded low-g accelerometer to detect a double tap event to disable the display and enable the radio operation.

The US Army’s applied research initiatives, as well as other partner initiatives continues to develop and integrate logistics solutions to aid the war-fighter in providing mission capable weapons when needed most. The sensor suites and demonstration systems designed, developed, and built by AMRDEC, CGI Federal and its partners prove those enabling solutions that are capable of improving operational readiness and allow for more efficient and effective Army sustainment.

V. SUMMARY

Technology-based solutions have potential to increase the
efficiency and improve the effectiveness of missile logistics and supply processes. The monitoring of a missile’s health is the basic capability that results, and that monitoring provides Army sustainment managers relevant data collected from individual missiles as well as decision-support knowledge derived from that data. In its most basic form these technologies would transform information using predictive methods (termed “prognostics”) into knowledge, which is directly relevant to critical sustainment decisions. Missile health monitoring and prognostics applied broadly over the entire missile sustainment enterprise affects those processes which have traditionally driven weapons systems availability, logistics footprint, and sustainment costs. An enhanced missile sustainment enterprise ensures more efficient and effective lifecycle management by:

- Improvement of missile inherent reliability through targeted design change, elimination of preventable issues that warrant maintenance, and the prevention of “no evidence of failures” false alarm events.
- Streamline maintenance processes through proactive and accurate condition indication of Army assets, being able to quickly and effectively diagnose the maintenance required, and effectively plan and implement those maintenance actions.
- Maximize the serviceable life and shelf life of Army missiles through proactive mitigation of preventable conditions that effect and ultimately shorten shelf life.
- Perform more effective missile surveillance/mission assessment to achieve a better knowledge level assuring a state of readiness.
- Perform a reduced level of surveillance/assessment achieving the same level of knowledge as before (minimum needed) that assures a state of readiness or better.
- Reduce the required size of “in-theater” logistics support needed to sustain the force, also known as the logistics footprint.
- Streamline retrograde processes through proactive and accurate condition indication of Army assets, being able to quickly and effectively diagnose the maintenance required, and effectively plan and implement the return of assets from deployment.
- Reduced O&S costs from better utilization of available material assets and enabled by dependant demand forecasting based on real asset health status and history rather than artificial supply demands.
- Improved availability prediction of impending failures so that questionable components can be replaced before they fail.

The key challenges facing US Army researchers, developers, and engineering managers are to match highly innovative technology with specific potential problems. That approach overcomes both the non-recurring and recurring costs with application of new technology so that efficiency and effectiveness improvements can be realized. The researchers and acquisition managers in the US Army are currently taking that approach to greatly enhance the affordability of the weapons they have responsibility for.

VI. REFERENCES


VII. BIOGRAPHIES

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