Health Management Issues and Strategy for Air Force Missiles

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Abstract:

As so-called "wooden rounds", which are intended to sit stably in storage for extended periods and then function precisely as desired, at a moment's notice, Air Force missiles would appear to be an ideal application for health monitoring. However, solid rocket motors that serve as the propulsion system for these missiles present a number of unique challenges for the development of integrated vehicle health monitoring systems. Mechanical and chemical complexity, long service lives, aging materials, and designs with small margins are typical for solid motors. But the payoff for health monitoring is extreme as well. Maintaining a healthy and capable fleet—ensuring the viability of the missiles in the fleet while not retiring or destroying good assets before it is necessary could save as much at 50% in costs over a 50-year life cycle. In this paper, a number of the unique aspects of solid rocket motors will be explored, the difficulties and successes in development of sensors and diagnostic systems will be discussed, and a path to further continue development of these systems will be proposed.

1. Introduction:

The current Minuteman III strategic missile fleet was designed with a service life of 12 years. The fact that there have been individual boosters in the fleet that have achieved lives more than twice as long is a tribute to the robustness of the design. But it also illustrates a significant lack of understanding in the aging processes of these missiles. And while this lack of understanding was beneficial in the case of Minuteman (service life was extended for financial/political reasons, not due to improved analysis), there have been other missiles that have suffered early and unexpected failures, either through aging or damage, which could have been prevented or avoided by an accurate assessment of the current state of the asset.

A health monitoring system for Air Force missiles must be able to address both of these issues: current state assessment and future state prediction. Over the last eight years, the Air Force Research Laboratory has managed a number of projects under the Technology for the Strategic Systems Program to address this challenge. The Service Life Prediction Technology program examined environmental, mechanical, and chemical sensors, as well as developed constitutive theories for accurate modeling of solid rocket motor propellants, including the effect of aging and chemistry on the mechanical properties. The Non-Destructive Evaluation/Data Processing program developed a high-resolution computed tomography capability for strategic missiles and the Automated NDE Data Evaluation System (ANDES 2), which reads the CT data and makes an assessment as to the structural integrity of the motor. The Critical Defect Assessment program has developed a computer code that couples structural, thermal, and ballistic models for a high-fidelity SRM simulation. And the Sensor Application and Modeling programs are taking commercial-off-the-shelf (COTS) and near-COTS sensors and developing a methodology for manufacturing and using them on solid rocket motors.

With these tools in place, the government and industry have sufficient knowledge and background to move towards the next step: application of integrated vehicle health monitoring (IVHM) to operational systems with the overall goal of reducing life cycle cost and improving reliability. But significant challenges remain. The purpose of this paper is to examine some of those challenges, particularly those unique to motors and present a way forward, identifying key needs for the future. In the first section, an introduction to solid rocket motors will be presented with a description of some of the most critical issues affecting motor structural integrity. Special focus will be given in areas where IVHM has been applied or would be beneficial. Next, a description of the current and potential future service life methodology will be presented. Then, approaches for acquiring the necessary data and using it to make an informed service life assessment are given. Finally, a short "wish list" of potential technologies that would enhance these efforts will be discussed. In general, discussions will focus on strategic/space launch application of IVHM technology, as this is where the Air Force Research Laboratory's research has been applied, but where applicable, or where other organizations have or are applying this technology to tactical (small air-to-air,

air-to-surface, surface-to-surface, and surface-to-air) missiles, this will be noted. In addition to the motor (propulsion system), there is ample opportunity for health management to be used on the entire missile system, from electronic safe and arm (ESA) devices to monitoring for the guidance or TVA systems. These will not be covered in this paper but are left for better qualified individuals to develop.

2. Rocket Science 101

Solid rocket motors are deceptively simple devices, particularly from a structural point of view. A rigid case, typically made of metal or organic composite, encloses the propellant, an energetic solid. During combustion, this energy is released and is converted to propulsive force through a nozzle. Each of these components has their own structural issues, individually and with respect to the entire missile system that are discussed below. Figure 1 presents an idealized solid rocket motor for reference.

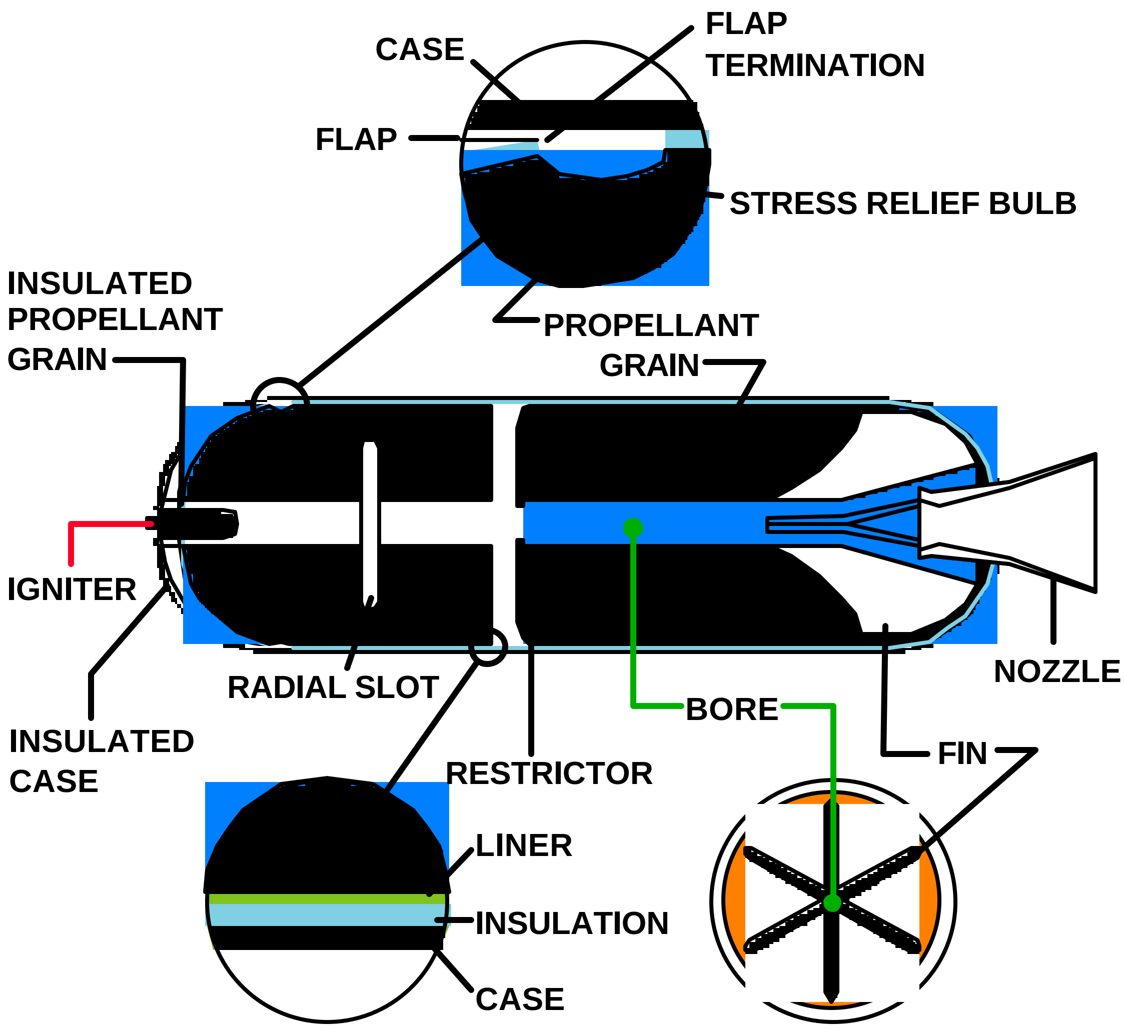

Figure 1: Idealized Solid Rocket Motor

2.1 Cases

The case of a solid rocket motor is a pressure vessel, maintaining the integrity of the motor at high pressures during operation. Cases typically are made from materials such as D6AC steel, 6Al-4V titanium, or various fiber composites such as Kevlar, glass, or carbon fiber. Generally, the cases for larger motors have a greater potential to be composite, although this is driven by mission requirements rather than the size itself. For example, tactical missiles tend to have metal cases because of the need for longitudinal stiffness during maneuvering, while the space shuttle RSRM boosters are steel simply so they can be reused on future missions.

The use of composite materials, as in many other applications, is strongly driven by the high specific strength of these materials. Reduction in the inert weight of a system directly enables improved capability for the missile. But use of these materials also entails new risks. Unlike metal cases, composites can be fairly easily damaged by impact, and damage severe enough to cause a catastrophic motor failure can result while still not being detectable to the naked eye. In addition, due to anisotropy and complexity of design, the fidelity of analyses of composite pressure vessels is not as mature as that for metals. Composite cases are regularly over-designed in the dome region to ensure failure in the cylinder, where predictive models are more accurate.

2.2 Propellant-Liner-Insulator

Working inward from the case, the first material encountered is the insulation, typically a rubber material such as EPDM. The main purpose is for thermal resistance as the burning surface of the propellant approaches the case wall. This layer prevents the case from heating and losing structural integrity before the propellant is completely consumed. In addition, flaps of insulator material are often used at the head or aft ends of the motor to reduce the stress on the propellant in the dome region. Next is the liner, a thin layer of polymeric material the main function of which is to facilitate the adhesion of the propellant to the insulator. The next layer is then propellant itself.

The most common type of propellant, particularly for use in Air Force ballistic missile and space launch applications, is composite propellant. Typical composite propellants are composed of a crystalline oxidizer, often ammonium perchlorate (AP), ground to a nominal particle size. 200 microns is typical, although many propellants have bi- and tri-modal distributions of sizes to improve mixing properties and tailor burn rates. Aluminum powder is added to the mix as a fuel, and both are held together by a polymeric binder. Commonly used binders include hydroxyl-terminated polybutadiene (HTPB) or polybutadiene acrilonitrile (PBAN). These materials are mixed, along with appropriate curatives and other chemicals such as burn-rate modifiers, cast into the motor, and cured. The resulting material is nonlinear, viscoelastic, prone to damage and debonding of the particles from the binder, as well as generally non-uniform in properties due to material flow and particulate segregation during the casting process.

Both structurally and chemically, the propellant-liner-insulator (PLI) system is one of the most complex in a solid rocket motor. Following cure, a motor may undergo a long post-cure period (weeks to months) during which time material properties of any of the materials may change significantly. And during the initial life of a motor, as much as five years after manufacture, mobile reactive species in the different layers migrate and can sometimes cause significant property changes, all the way down to making the interfaces zero-strength. In fact, motors are chemically active throughout their entire lives, leading to issues of motor aging perhaps far down the road. In addition to internal chemistry, propellants often harden over time due to oxidative cross-linking, and the introduction of moisture into the system can be extremely destructive to material properties in both the bulk materials and at the interfaces.

There are two general classes of flaws in the PLI system. The first is a void or inclusion, typically in the bulk propellant. The second is a fracture or debond. These will be treated separately below.

2.2.1 Voids and Inclusions

Voids in propellant often occur as a result of insufficient settling of the propellant during the casting process. Trapped air bubbles are not fully eliminated and a small area is formed which contains no propellant. If small enough, these are not typically of great concern, although if they are proximate to an interface or other high stress or strain region can contribute to the formation of cracks. Inclusions are objects which end up in the propellant which should not be. These can be large pieces of propellant ingredients or other motor materials, but also include anomalous objects. Notable inclusions that have appeared in motors include lead shot, a crumpled paper cup, and a wrench. Regardless of the source, these objects are often poorly bonded to the propellant and cause perturbations to the stress/strain field of the motor in a similar fashion as voids. If the item is large enough or likely not to be fully consumed in the motor, damage the item could do inside the case and to the nozzle becomes a major concern. Depending on the material in the inclusion, the combustion process in the region can be significantly changed. In some cases, this has been intentionally used to advantage, such as placing fine metal wires in the propellant to increase the burning rate by augmenting thermal conduction and providing a flame path.

2.2.2 Cracks and Debonds

Cracks can occur throughout the motor, although they are often seen in the bore, particularly in motors that have undergone thermal cycling. When a crack occurs, there are two scenarios. In the first case, when the combustion surface reaches the crack, the flame speed exceeds the crack propagation velocity. In this situation, the crack tip is blunted by the burning and does not propagate, so the concern is simply the increase in pressure of the motor due to additional burning surface area. If the crack area is small compared to the surface area of the motor, the pressure will not be significantly increased and this will not a major issue. In the case that the crack propagation speed is greater than that of the flame, the crack will propagate. In this situation, burning surface is exposed deeper in the motor before it was expected. Since the insulation thickness is determined by the time of exposure to the hot gases (with an appropriate factor of safety), early exposure can overwhelm the insulation, heating the case and creating an opportunity for failure. Cracks also occur in the propellant near the propellant-liner interface. This compounds the problem, as not only is there hot gas near the wall, but if the crack propagates, it detaches the motor grain from the bonding surface.

Debonds are similar to the cracks described above, but result from insufficient or incomplete bonding between two of the propellant-liner-insulator materials. As with cracks, the concerns are augmented burning near the case wall and the structural impact of the decreased bonding.

2.3 Nozzle

The purpose of the nozzle is to accelerate the hot gas generated by the propellant combustion process from subsonic speeds in the motor, through supersonic speed at the exit, converting thermal energy into propulsive force. Strategic/space launch nozzles are usually made of composite materials such as carbon phenolic. Carbon-carbon is often used to reduce weight and provide thermal resistance. Also as with the case, these materials are easily damaged. There are multiple bonded interfaces between nozzle components that can degrade with age. In tactical applications, nozzles are frequently manufactured from lower grade phenolics to keep costs down. Also, in tactical motors, the nozzles are usually contained within the metal case and are much less likely to be damaged than strategic/space launch nozzles.

3. Implementation of IVHM, Current and Future

The Air Force is interested in developing health management technology for solid rocket motors to reduce system life cycle costs while improving safety and reliability. The ultimate goal is to be able to tell which assets have aged out or otherwise need to be replaced, and which assets are still viable. Currently, a typical missile aging program will take a small number of motors, fire some and dissect others for verification. This is performed periodically, and as long as the verification firings and dissection data are nominal, the entire lot is considered viable. Otherwise, following further investigation, the entire lot of missiles may be condemned and destroyed. While attempts are made to chose motors which are expected to be “bad”, i.e. which have seen more time in service, or excessive thermal cycling, often the precise history of any given motor is not well known, making such attempts problematic. Since a statistically meaningful quantity of verification motors are not used, there is a strong probability that viable motors will be destroyed and have to be replaced at significant cost to the government, or that despite “successful” verification of the system, failures will occur, potentially causing mission failure, destruction of government property, or loss of life.

Changing to a condition-based paradigm has potentially enormous payoffs. Take the following notional example (numbers are used for illustrative purposes and do not relate to any current policy or system): Assume a missile fleet of some size X. The fleet is considered non-viable at approximately 20 years, at which time (say) 2.5% (0.025X) will not successfully complete the mission due to age-out of a structural material. Currently the entire fleet would be retired and replacements procured, rather than culling and replacing the bad missiles and leaving the rest. As those original missiles age, more will need to be retired more rapidly, but never as many as replacing an entire fleet in a short period to maintain readiness. Simple analysis assuming this 20 year service life and motors aging out in a Gaussian distribution means we have built approximately 2X missiles at the end of year 60. But following the current paradigm, we will have built the original fleet and replaced it entirely three times (total of 4X missiles). While this is a very simple example, it reveals some of the enormous benefits that could be realized.

3.1 Use of IVHM for Strategic/Space Launch Systems

The major health monitoring activity for current strategic motors is the Automated Non-Destructive Evaluation System (ANDES 2) at Hill Air Force Base, Utah. ANDES is the second generation of a NDE data analysis system currently examining computed tomography (CT) data and capable of inspecting motors larger than five feet in diameter, detecting voids, inclusions, debonds, or other flaws as small as 10 mils. One of the benefits of this second generation of ANDES is the capability to be "trained" on any type of NDE data, be it digitized film X-ray, CT, or ultrasound. Any identified flaws are reported to the user and a recommendation is provided as to whether these meet the motor specification. These data are maintained by Hill AFB and provide a zero-time assessment of motor structural state. The ANDES system has historically been used for inspection of the current Minuteman III fleet. Unfortunately, due to cost and logistical difficulties, these inspections are not performed regularly, but only when the system needs to be brought back to the depot for other maintenance. A photograph of the computed tomography facility at Hill AFB with a prototype high resolution imager is shown in Figure 2.

Figure 2: Hill AFB High Resolution 3D Computed Tomography (HR3DCT) Facility Inspecting Large Steel Case Boost Motor

Marks measured and evaluated by ANDES are converted into faceted surfaces which can be transferred directly to the Air Force's Structural/Ballistic Analysis System (SBAS II). SBAS is an analysis code that solves coupled fluid-structural-thermal-ballistic problems. Of particular interest to structural analysis, SBAS reads the marks detected by ANDES and can take a baseline motor mesh and automatically integrate the flaws, remeshing the model as necessary without user intervention. As the analysis proceeds, if integrated continuum failure or fracture propagation models determine that a crack will form or propagate, this too is performed automatically, significantly reducing the time required for an analysis.

Other non-destructive techniques are rarely used on deployed systems. Eddy-current or ultrasound are sometimes used for quality control by the motor manufacturers during the manufacturing process, but are not typically used once a motor has been fielded. Embedded sensors have been frequently used in demonstrations on subscale articles, but are not used on deployed systems. Chemical sensors are currently being developed, but remain at a low technology readiness level (TRL). All chemical data used in aging models is acquired in a destructive fashion, usually by dissection of the motor, after which the desired properties (e.g. cross-link density, sol-gel, chemical concentrations as a function of position) can be determined in laboratory experiments. Chemical aging models have been significantly improved in the last decade, allowing not only a high reliability prediction of the current chemical state of the PLI system, but also a prediction of the mechanical state of the motor as a function of the chemical state. This type of modeling is critical to the prediction of motor service life, but currently is limited in functionality as the motor of interest is always destroyed in the process of acquiring the necessary data.

3.2 Development of an "Instrumented Motor"

An "instrumented motor" would be a motor that has periodic surveillance, most likely with embedded sensors, although a system with fully external measurements could easily be envisioned. While a number of subscale motors with embedded sensors have been manufactured and fired, placement of sensors in operational motors will require significantly more background development effort. A critical question that must be answered is what effect the sensor has upon the motor. This question includes the simple long-term effects of the sensor materials on the PLI materials as well as the effect of embedded power and data lines on the burning characteristics of the propellant and the perturbation of the motor strain field by the sensors themselves. In order to minimize these effects, motors must be designed and manufactured with sensors in mind from the beginning. These types of issues are being examined under the Air Force Research Laboratory's Sensor Application and Modeling programs.

A necessary component to the use of sensors is the computational models to turn sensor data into useful information. Even in the best possible situation, there will never be, at least in the eyes of analysts, a sufficient number of sensors in motors. Conversely, in the eyes of the users of these assets, any intrusive technology is too much—unless the case can be made clearly and unequivocally for a tangible benefit. In addition, sensors are unlikely to be able to be placed in the location of greatest interest, as their presence would significantly change the local configuration and could cause the very failure the diagnostics are present to protect against. In essence, how to best use sensors to get motor data is a massive inverse problem: "How can you maximize the information about the internal state of the motor while minimizing the effect of sensors on the motor." Typically, we will be able to place sensors in regions of uniform strain, far from the points of interest and be left to compute or infer the information actually desired.

3.3 Design for Sensors and Implementation Challenges

For an operational motor to be deployed with a health monitoring system, a shift of paradigm will be necessary, beginning with the design process. Any health monitoring system, either embedded or external, will require significant changes to the motor design and require infrastructure support. For this reason, current systems typically will not be very good targets for this type of monitoring, unless it is fully external and self-contained, e.g. data loggers and environmental monitoring systems shipped with motors in shipping containers, or the ANDES Computed Tomography system, which resides at the depot, and to which motors are brought for inspection.

For embedded sensors, such as stress/pressure sensors embedded at the bondline, careful consideration of the placement of the sensor is critical to ensure minimal impact to the motor, as well as to ensure validity of the acquired data. As discussed previously, the location of the sensors themselves can be problematic in this sense. Modern stress transducers can be quite small. For example, a typical gauge that the Air Force has investigated is the Micron Instruments Dual Bond Stress Temperature (DBST) sensor, a steel disk 7.6 mm in diameter and 2.0 mm thick. Even at this small size, corners and edges of the sensor cause stress raisers that can serve as locations for failure initiation. To avoid this issue, a "cap" of steel or liner materials has been used to minimize abrupt geometric changes. However, to ensure that for future systems the sensor will not be the cause of a failure, detailed models, which include the health monitoring system, must be used from the outset. Placement of the sensors after the fact constitutes a significant change to the motor geometry and would likely require requalification, making it extremely unlikely.

Lines for sensor power and data acquisition are also a potential challenge. As described previously, inclusions are potential sources for cracks or debonds, as well as paths for flame to travel along. The wire or fiber optic line will most likely run a significant length within the motor, as it is generally believed to be structurally safer to egress these lines through a port in the head or aft end of the motor than to create one or more egress points in the cylinder, where they could decrease the case strength. Fiber optic strain gauges are good example of sensors where this is potentially a huge issue. For ease of manufacture, maintenance, and to reduce cost, a multiplexed sensor (multiple sensors on a single fiber) would potentially be beneficial, as long as any issues with a single line weaving a substantial distance over the inside of the case can be addressed.

Chemical compatibility of the sensors themselves is a third concern. Sensors must be inert to the various chemicals present in motors throughout a potentially very long lifetime. This has presented an interesting conundrum for the development of some types of chemical sensors. Sensors that respond to the presence of chemical species by physical changes, for example coatings on fiber optics that change strain state in response to a particular species, must obviously interact with the motor environment. But it is currently unknown whether these types of sensors would achieve equilibrium with their surroundings, or act as a sink (or source), driving the reactions that are being measured. And, of course, it is vital that none of the materials in the sensors themselves react with their surroundings.

3.4 The Sensor-Motor Inverse Problem

Deployment of health monitoring technology should never be a means unto itself, and the vision for its use in solid rocket motors is no exception. Without an understanding of what data is necessary to make an intelligent service life or system health prediction and the means in place to perform the necessary analyses, the data will be unused, or worse, used in an unwise fashion. In this section, I will describe one approach.

In general, the sensing technology which we have investigated for solid rocket motors, for example, sensors for stress or strain, chemical concentration, configuration in the form of X-ray or 3-D computed tomography data, measure the current state of the motor. The data that is really desired, and necessary to make predictions for future behavior, is that of the motor state, e.g. the various moduli of materials, diffusion parameters, or cross-link density. The reason for this becomes more apparent when one contrasts the data available for a more typical structural analysis with that of an SRM. In a general sense, when analyzing a structure, say a bridge or building, the structural materials are well understood, and if the properties are variable, they would be characterized. In addition, uncertainty in these values can be overcome by designing to larger margins of safety, as the application is rarely weight-limited. Of course, this is a very broad characterization as well as a gross oversimplification, but even in situations where it is not totally accurate, for example, composite structures for aircraft, periodic inspection and replacement is the norm. In the case of solid rocket motors, the properties of materials are not often well known. One rule of thumb is that propellant can have properties which vary ~5-10% batch-to-batch, as well as by a similar amount at different locations within a given motor. The materials are chemically active throughout their entire lives, interacting both with other materials in the motors as well as with the environment. And in many cases, the history of a motor may not be well known, so the loads (physical, thermal, and chemical) may be completely unknown, although this is less true for strategic assets than tactical. Finally, most portions of solid rocket motors cannot be subject to periodic maintenance. Once a motor is cast, only in very rare situations could it be repaired and returned to service.

A second aspect of this problem concerns the need to determine the condition of the motor while minimizing cost, time, or other impact to the system or its readiness. For example, the CT facility at Hill Air Force Base takes approximately 24 hours to fully scan a large motor and analyze the results. Before that can be accomplished, a team must travel to the silo, extract the entire missile, transport it back to the depot at Hill, disassemble the missile, and transport it to the CT facility. Following the scan, the process is reversed, with the overall result of one asset out of a fleet of 500 deemed healthy, days to weeks of effort including hazardous operations, and potentially hundreds of thousands of dollars expended. Another example would be that of a damaged case. Since many SRM cases are composites, impact during transport or handling could significantly decrease the strength without leaving visible evidence. While it would theoretically be possible to scan every motor with a combination of eddy current and ultrasound to ensure no damage, it is again, not a feasible solution. In both cases, a far better solution would be a small number of (relatively) inexpensive sensors, unobtrusively placed, and detailed analysis which could, if not provide definitive answers to the state of the motor, identify with high reliability those which are off-nominal and require additional scrutiny.

This ideal is the essence of what has been called the sensor-motor inverse problem—determining global information about the motor from a small number of distinct data points. Dr. Timothy Miller has performed significant preliminary work at AFRL along these lines. Dr. Miller modeled a 5” center-perforated motor (0.25” steel case, 0.5” inner bore diameter) in plane strain in a baseline (uncracked) configuration as well as with bore cracks ranging from 0.25” to 1.0” in depth. Data was acquired at the model bondline, which served as a series of virtual sensors—specific sensors were not modeled in this analysis. In the uncracked configuration under isotropic loading (pressure or thermal), the stress field of the motor exhibits radial symmetry. In the cracked configurations, the radial symmetry is broken and the radial stress at the bondline is relieved measurably, even inches away from the crack, lending credence to the idea that sensors need not be placed so close to critical locations that they could potentially be the instigator of failure. Examples of this analysis for thermal loading are shown in Figure 3. Depending on the type of loading, the minimum critical crack size, and the sensitivity of the sensors, the number of sensors necessary varies, but generally with a small number of well-positioned sensors and carefully considered analysis, large amounts of information can be acquired with minimum impact and cost.

Figure 3: Stress Fields in Uncracked and Cracked Thermal Analog Motors (Case Not Shown)

3.5 Potential Model for Deployment of IVHM on SRMs

Because sensors have not been deployed on operational systems before, it is extremely difficult to convince end-users to adopt new and unproven technology. And this is an extremely reasonable response. Given a technology that may have only been demonstrated on a prototype or in a laboratory environment, few program managers would be willing to risk billions of dollars of assets, not to mention their careers, on a technology with uncertain payoff. Part of the solution is to address the potential payoff in light of the risk, a task which has been attempted at various times in the past with varying degrees of success, mostly due to the difficulty in quantification of both the payoff and risk. The other portion of the solution is a measured, spiral approach to deployment. A possible path to this implementation is described below. It should be noted that what is described is simply one of a number of possible paths as conceived by the author—it in no way is either the only approach, or one that the Air Force intends to go forward with.

3.5.1 Step 1: Environmental Monitoring

As has been described previously, SRMs are chemically complex and chemically active throughout their lives. Motors, which begin with identical properties when cast, can age in entirely different fashions based upon the environmental factors each sees over a 20+ year deployment. Acquisition of those environmental histories is therefore critical to any non-destructive evaluation of a motor's state. Environmental monitoring systems which measure and record temperature and humidity are easily deployed, as they do not need to be embedded in the motor, but can be attached to the inside of the weather seal in the bore of the motor. When the propellants have a known breakdown or outgassing product, a chemical sensor in the bore of the motor should be considered as well.

For tactical motors, this environmental information is far more critical then for strategic or space launch motors. While strategic systems generally live in a benign environment in a silo and space launch motors are in controlled storage, tactical assets live a far more interesting life. They can be exposed to hundreds or thousands of hours of thermal cycling during captive carry on airplanes, deployed to the Middle East or Alaska for an extended period, or be exposed to the high-humidity environment of a ship at sea. For these systems, the addition of accelerometers to record transportation loading is critical as well. The Army is currently exploring environmental monitoring devices for deployment on the Patriot (PAC-3) missile, with sensors and a datalogger placed inside the shipping container. Coupled with measurements of the initial properties of the motors and chemical aging models, a first cut could be made at identification of off-nominal motors in an entirely non-destructive fashion.

3.5.2 Step 2: External Sensors

The next step is to attempt to acquire internal data about the motor in a non-destructive fashion. Unlike the costly and time-consuming (but highly effective) approach of bringing assets to a depot for non-destructive evaluation, techniques need to be used which either deploy external sensors with the asset or bring a portable inspection system to the location. For assessing the integrity of a composite case, fiber optic and piezoelectric arrays have been demonstrated. In the case of fiber optic arrays, changes in the strain field of the case can be correlated to the size and extent of damage caused by an impact. For the piezoelectric system, with one element acting as a transmitter and others acting as receivers, variations from a baseline wave propagation measurement can triangulate the location of damage. In both cases, detected defects would be identified and could be examined in more detail with other technologies (ultrasound or eddy current) as necessary.

Measurements of the internal state of the motor, e.g. cracks, voids, and debonds, is much more difficult. Portable X-ray or computed tomography systems could be used with a version of the ANDES system and transported to the silo, although this would likely still be a sufficiently difficult proposition that fleetwide inspections may not be feasible. Ultrasonic techniques, in particular a hand-held compact UT camera also could be deployed, but whether usable data could be acquired through the case and external protection systems is yet to be determined. It is clear that portable, non-invasive assessment of the motor internals still requires significantly more work.

3.5.3 Step 3: Internal Sensors on Surveillance Assets

The challenges inherent in deployment of an internal sensor system for SRMs have been covered extensively previously in this paper—we will not rehash it here. Instead, we propose an interim step between no sensors and a fully instrumented fleet that will provide significant information for those making fleetwide service life assessments without risking the integrity of the fleet on unproven technology.

Current aging programs make use of “plug motors”, assets which have sections of propellant removed for mechanical assessment, as well as full up motor dissections to estimate the current state of the fleet. These motors are taken from the population and are assumed to be representative, so decisions regarding the entire fleet are sometimes made on the basis of these few assets. Since these representative motors are already part of the fleet, a new version of this paradigm should have these motors fully instrumented as well. While deployed, these sensors would take all the necessary data for service life assessments. And when motors are plugged or dissected, those data could be correlated to destructive test results on these representative motors. This serves to not only prove that embedded sensors could be safely deployed, but also improves the aging models by acquiring data on real, deployed assets. These instrumented assets could be as few as 5-10% of the fleet population and still be of extraordinary benefit without the concerns of impacting readiness.

3.5.4 Step 4: Full Coverage

Once IVHM systems are demonstrated on operational assets, the way is paved for fully instrumenting the fleet. Since embedded sensors need to be installed at manufacture, this would likely only occur as part of a propulsion replacement program or on a follow-on system. By that time, improvements in both sensor technology and computational power would make acquisition of even more data possible, but also brings in the potential of taking the diagnostics, data processing, data maintenance, and aging predictions and placing them on board the asset. Motors would self-diagnose, assess their own health, and make predictions as to their future state. A simple “red light-green light” might be all that the end user sees.

4. Future Technology Needs:

While there are certainly tools that could be used immediately for IVHM of solid rocket motors, development of new sensors or techniques would significantly improve the process and reduce computational overhead. These are not presented as near-term, nor even necessarily feasible, but as an illustration of perceived needs and an opportunity for others to come forward with good ideas and advanced technologies.

1) Modulus sensors: Stress and strain can be measured, but prediction, these are only a means to establish the moduli. The material moduli (as a nonlinear viscoelastic material, there are several) are what evolve with the changing chemical state as the motor ages, and an independent measurement of them in-situ would be invaluable. Bonus points for the development of a sensor which can determine the moduli as a function of strain rate, one which can assess both elastic and viscous moduli, or one that can determine these properties in a field, not just at a single point.
2) Chemical sensors: These are the least mature of the sensor technologies which have been examined, but potentially have the greatest benefit. Whether measuring oxidative cross-linking or stabilizer depletion in bulk propellant or assessing diffusion of chemicals across the PLI interface, a non-destructive method of getting chemical data is necessary for a complete understanding of how the aging process occurs. Preliminary work has been performed on Raman spectroscopy and other types of probes, but issues with large probe size and propellant heating will keep this in the laboratory for a while yet. In the same vein as the modulus sensors, knowing the properties (diffusion parameters and polymer cross-link density) as opposed to the response state (local chemical concentration) would be a huge achievement.
3) Data manager: More a philosophy change than a technology issue, before any IVHM system is implemented, all the data management and retention issues must be addressed. Who is in charge of acquiring, maintaining, and analyzing the data for each missile? How will data be maintained such that technology changes will not render the data inaccessible (e.g. punch cards)? In the past, some data that has been taken on systems has either been lost or maintained as processed data, without keeping the original raw information. As new models and techniques are developed, maintaining this raw data is imperative, as it can be used with the new models, whereas processed data may not be (and has not historically been) as useful.
4) Non-contact sensors: In general, external sensors or sensor systems are only capable of taking gross measurements of structure or configuration. For example, X-ray, CT, or ultrasound can reveal changes in the structure, cracks, debonds, and the like, but cannot determine the local stress or strain or chemical concentration.

5. Summary and Conclusions

Significant progress has been made in the last decade in the understanding of solid rocket motors, laying the groundwork for development of a viable integrated vehicle health monitoring system that can be used on Air Force systems. Sensors have been demonstrated on subscale and experimental platforms without negatively affecting the motors and models are being developed which allow detection of off-nominal conditions from a small number of sensors. Work still remains, particularly in the area of sensor development, where new, smaller sensors are always desirable and improvements in chemical sensors for SRM specific materials are necessary to fully realize the benefits of improved chemical aging models without destroying assets. Non-invasive sensors also lag behind other technologies but would be of huge benefit, as they could allay all concerns involved with embedment.

Before an IVHM system is deployed on an operational system, all the parties involved, the motor manufacturers, the system integrators, and the end users must work together to determine the challenges and payoffs of this new technology. And all these groups must work with sensor designers and manufacturers to tailor sensor technologies to this particular application. Where the benefits outweigh the risks, it should be implemented wholeheartedly—doing it as an afterthought or without a coherent plan would likely cause more problems than it solves. But successful implementation can move missiles to a new paradigm with potential savings of billions of dollars.

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