Nano Devices & Concepts for Condition-Based Maintenance of Military Systems

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ABSTRACT

There is a continuous need for the Department of Defense (DoD) and its associate weaponry supply organizations to consistently evaluate the usability of weapons that exhibit deteriorative characteristics over a period of time. Along the same lines, enhanced condition-based maintenance evaluation procedures are necessary to mitigate the risk and reduce the cost of catastrophic failure of varying inventories of military systems. One significant area of research is the verification of the existence of sufficient concentrations of propellant stabilizer in the motor of stored missiles. Results from developed apparatuses can help collect degradation information to establish indicators that the missile's double-based solid propellant is still functional after long-term storage. Other mechanisms are being developed for the assessment of degradation in gun barrel rifling. The research outlined in this paper summarizes the Army Aviation and Missile Research, Development, & Engineering Center's (AMRDEC's) investigative approaches relative to the use of spectral-optical and acoustical methodologies for detecting deteriorations in both propellant and the apparatus that engages munitions. A spectral-optical sensing approach is presented that is based on distinctive light collecting optical fiber –based developments designed to detect the concentration of propellant ingredients. The use of diagnostic acoustic sensing mechanisms is delineated to include the use of commercially available transducer-based readers to collect information that is indicative of the distance that acoustic waves travel through weaponry components. In collaboration with several AMRDEC industry and academia supporters, this paper outlines sensing methods that are under consideration for implementation onto weapon systems. Conceptional approaches, experimental configurations, and laboratory results are presented for each initiative. Cost-savings and improved weaponry health monitoring capabilities are expected to derive from each sensing mechanisms.

Keywords: Nano devices, condition-based maintenance, propellant stabilizer, acoustic, spectral sensing,

1. INTRODUCTION

Over a period of time the chemical, electrical, and mechanical properties of missiles and rockets can change, degrade, and eventually result in the units becoming unusable. Throughout the life cycle of military armaments, weaponry health surveillances and shelf-life evaluations are implemented in order to evaluate the weaponry's properties, characteristics, and sustained performance. The functionality of missiles and munitions are often evaluated by live firings and/or destructive disassembly at routine time-periods after long-term storage. Destructive testing for determining long-term rocket motor aging and shelf-life is extremely costly.

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The missile's motor solid propellant key chemical ingredients include nitrate (nitrogen dioxide, i.e., NO_2), carbon (C) and sulfur (S). During long-term multi-year storage of missiles, the composition of the propellant can change due to the chemical reactions among the propellant ingredients and reactions with storage environments. Propellant ingredients' degradations may include depletion of propellant stabilizer, materials cracking, and material/inert surface de-bonding. In order to ensure successful firing of the weaponry/missiles, it is critical to be able to monitor the health of the propellant and ensure proper propellant composition prior to use by the warfighter. The optimal sensing system should be capable of nondestructively evaluating propellant degradation, rocket motor off-gassing, and measure (in real-time) the current percentage of propellant stabilizer.

Many missile systems utilize double-base propellants [containing nitrocellulose (NC) and nitroglycerin (NG)] that have minimum smoke signature. However, due to the slow chemical reaction between the stabilizers [e.g., 1,2,4-Butanetriol trinitrate (BTTN), 2-Methyl-4-nitroaniline (MNA)] and NOx released by NC and NG, the stabilizers are gradually depleted (i.e., aging effect). Depletion of stabilizer is shown as the linear dashed line in Figure 1 (below).

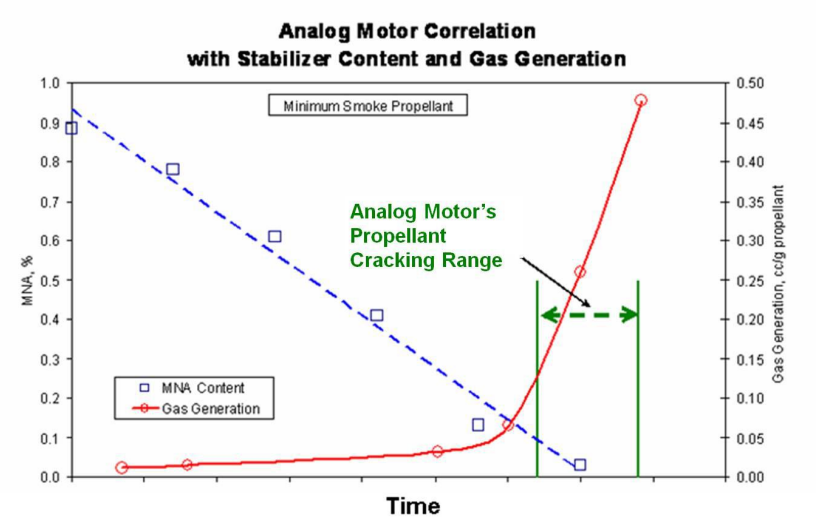


Figure 1. Stabilizer depletion (dash line) verses propellant generated off-gassing

After the concentration of stabilizer reaches the below threshold level (e.g., 0.05%), the propellant is no longer safe to use. For that reason, it is critical to monitor the aging effect of double base propellants. The US Army AMRDEC team has continuously investigated methods to assess the degradation of the missile's solid propellant [1,2]. Innovative methods to nondestructively evaluate the energetic materials that make up rocket motor propellant are of great interest to the Army and researchers at the AMRDEC.

The AMRDEC team is also looking at methodologies to monitor erosion of the inner portion of gun barrels used in weapons that are designed for counter rocket and munitions threats. When bullets (as shown in Figure 2) are fired from a typical Gatling gun type weapon system, continued rapid combustion of gun powder and friction between the bullet and gun barrel instigate substantial erosion of the inner portion of the gun barrel or bore. Such substantial erosion causes the potential issues of inaccuracy and risk of possible loss of angular momentum.

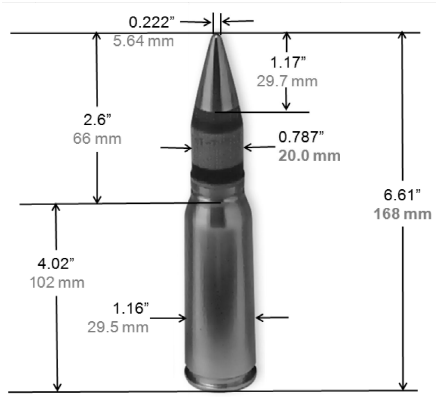


Figure 2. Typical munitions/dimensions for a popular M940 Bullet

As previously shown in Figure 1, the production of gas from a degrading propellant is outlined in relationship to the depletion of the stabilizer (i.e., MNA). The time-frame is in aging units of years. After the cross-over point between the gas generation curve (increasing exponentially) and the stabilizer consumption line, the propellant reaches the cracking point and the motor cannot be safely fired.

For research associated with methodologies for monitoring propellant degradation and measuring gun barrel erosion, the researchers are working to subsequently develop sensing systems that can partially include lab-on-a-chip components. The resulting systems are expected to be deployed across a wide spectrum of hardware platforms for degradation monitoring and ensuing integration into weaponry health monitoring devices. The overall program can generate potential cost-savings for the Army while providing a timely approach to enhance the Army's methodologies for measuring both propellant stabilizer depletion and cumulative erosion of gun barrels. Resulting sensors are expected to enhance the warfighter's' ability to monitor and predict the longevity of weaponry.

2. OPTICAL SPECTROSCOPY SENSING

The spectral optical sensing techniques utilize a non-invasive fiber optic spectroscopy methodology to monitor the status of double-base propellants' stabilizer levels. In order to obtain real time noninvasively determinations of concentration levels of stabilizer in double-base propellants, several novel non-invasive inspection methods (based on volume back scattering spectroscopy) were developed. One of AMRDEC's patented fiber optic spectroscopy methods is outlined in Figure 3.

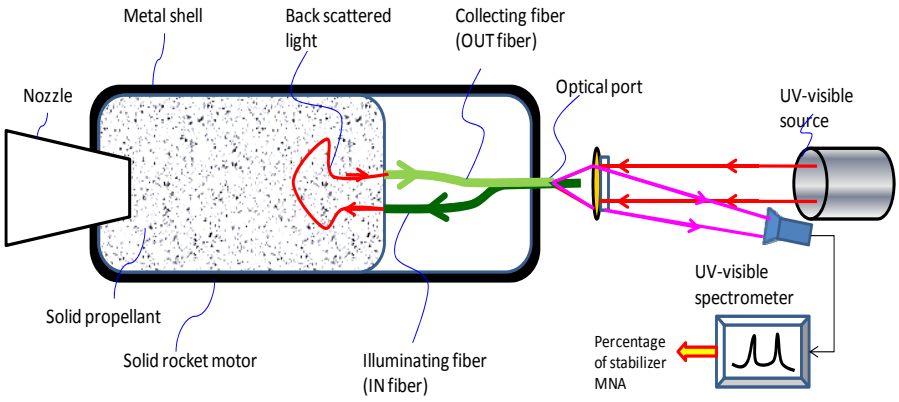


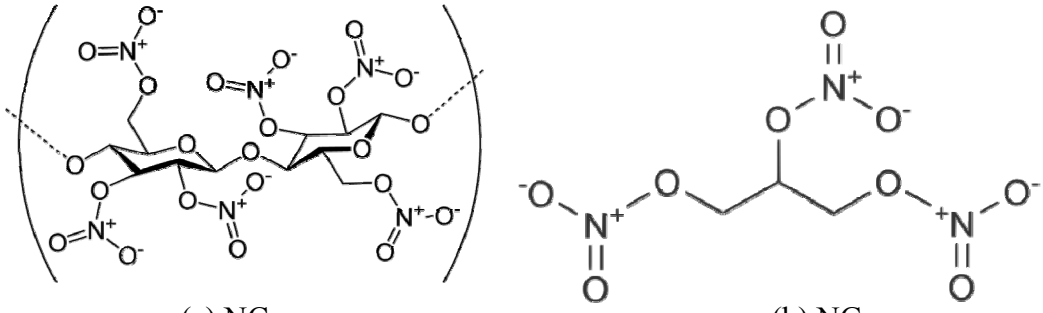
Figure 3. AMRDEC patented fiber optic spectroscopy method for measuring light intensity during heavy absorption of light by MNA, particularly at the UV/blue spectral

Throughout the propellant's degradation process, gases such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O) are released. The rate of evolution of N_2O, for example, is a direct indicator of the available amount of stabilizer that remains in the propellant. As N_2O is generated by the degrading rocket propellant, the stabilizer binds to the N_2O such that the N_2O is neutralized; however, once the stabilizer is depleted, the amount of N_2O increases exponentially.

The fiber optic spectroscopy methodology utilizes the concept that the absorption property of propellant is directly related to its chemical composition. During the propellant's aging process, the chemical composition of the propellant is constantly changing due to the chemical reaction between the stabilizer and mono-nitrogen oxides (NO_x) out-gassing. When one measures the volume back scattering spectrum, the concentration level of the stabilizer can be detected; and thus, the potency of the double-base propellant can be determined.

While looking at the previous diagram of the fiber optic spectroscopy setup, notice that the sensor head includes two fibers. One optical fiber is the illuminating fiber while the other fiber is the collecting fiber. The fibers are situated close to each other with a separation of about a couple of hundreds microns. The fibers are generally placed such that they can be in contact with the propellant surface. The collecting fiber can thus be used to collect the back scattered light from the illuminating fiber. The collected back scattered light is related to the absorption coefficient of the propellant's ingredient(s).

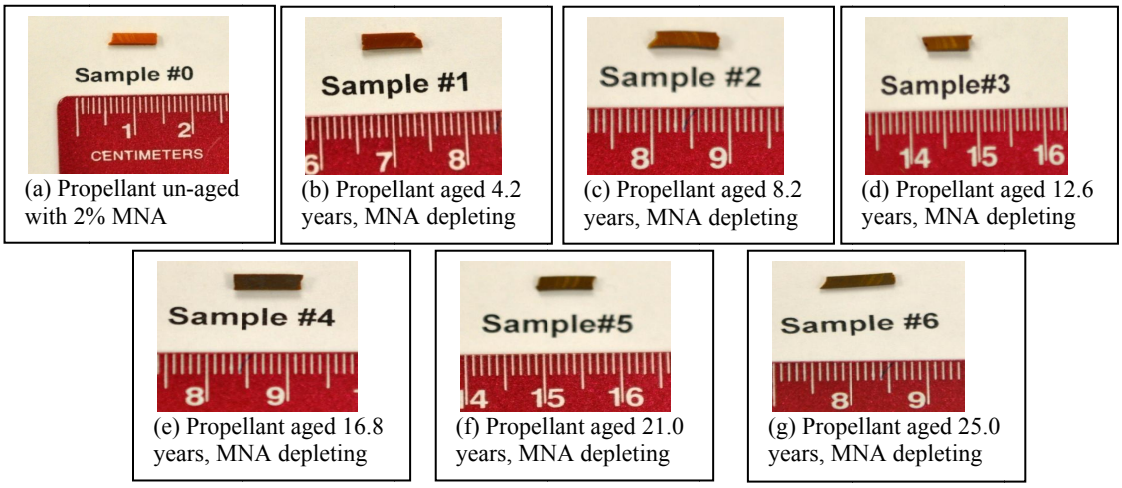
The stabilizers are consumed during the storage/aging of nitrate ester propellants that are widely used as low emission signature solid propellants. The double-base solid M9 propellant (used for a portion of this research) includes ingredients such as nitrocellulose (NC) and nitroglycerin (NG). The molecular structure of NC and NG are illustrated in Figure 4 [3,4].



(a) NC (b) NG

Figure 4. Molecular structures for (a) nitrocellulose and (b) nitroglycerin [3,4]

Experiments were conducted using the nitrate ester M9 grain propellants. The propellant is the minimum smoke and low signature brand produced by the Alliant Techsystems (ATK) motor manufacturer. The stabilizer used was the typical 2-methyl-4-nitroaniline (MNA). Figure 5 shows unpolluted (i.e., fresh) and aged propellant samples.



(a) Propellant un-aged with 2% MNA

(b) Propellant aged 4.2 years, MNA depleting

(c) Propellant aged 8.2 years, MNA depleting

(d) Propellant aged 12.6 years, MNA depleting

(e) Propellant aged 16.8 years, MNA depleting

(f) Propellant aged 21.0 years, MNA depleting

(g) Propellant aged 25.0 years, MNA depleting

Figure 5. Photos of propellant samples that have not been aged (sample #0) and samples accelerated aged up to 25 years

As indicated in Figure 5 (above), propellant that had not been aged (sample #0) was initially manufactured with the normal amount of two percent 2-methyl-4-nitroaniline (MNA) stabilizer. After undergoing accelerated aging (to simulate long term storage), the other samples (including samples # 1-6) show the resulting discoloration of the same sampled lot for the propellant after 25 years of replicated aging. The resulting aging is approximately equivalent to the normal aged shelf-life of the propellant.

A series of experiments were conducted to verify the fiber optic spectroscopy absorption methodology utilizing light sources with wavelengths of 473 nm and 532 nm. The back scattered spectrum was collected by way of an Ocean Optics 2000 UV/visible spectrometer. The concentration of MNA was determined by observing and capturing the ratio between the detected light intensities.

Results from absorption measurements (Figure 6) clearly show that the absorption coefficient of MNA has strong absorption in the UV/blue spectral range [5]. Determining the concentration of MNA by measuring the reflection, or back scatter, or transmission spectrum within the UV/visible/IR region of the propellant is possible [6]. The higher the concentration of MNA, the larger the absorption within this spectral range will be. Furthermore (and conversely), for the absorption spectrum at other wavelengths (e.g., green or red), the absorption of MNA will be compatible to other propellant ingredients (including NC, NG, and carbon). As a result, one can determine the concentration of MNA by measuring the spectrum at the UV/visible/IR spectral range. Figure 6 shows the measured results indicative of absorption spectrums for samples of un-aged propellant (sample #0) and the varying propellant samples that experienced up to 25 years of accelerated aging.

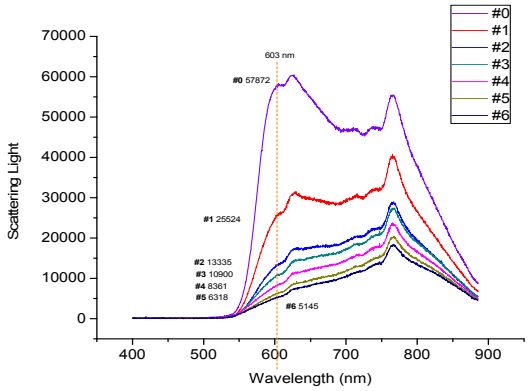


Figure 6. Measured results showing absorption spectrums for samples of un-aged propellant (sample #0) and propellant samples that experienced up to 25 years of accelerated aging

In the graphs (above), the decrease in magnitude of scattered light is due to the depletion of stabilizer. After approximately 25 years of storage (i.e., 6 weeks of accelerated aging at 75 ^{o}C), the stabilizer is depleted from 2.0% concentration level (fresh sample) to 0.05% concentration level. The propellant can become unstable, fragile (cracks), and may not be usable after the stabilizer depletes to less than 0.05%.

A second of AMRDEC's fiber optic spectroscopy methods (in collaboration with Alabama A&M University and General Opto Solutions) outlines the same type of setup as in the patent except for the use of a laser source (continuous-wave 785nm laser) through the illuminating fiber in order to obtain varying Raman spectrum results. The foundation associated with the setup is outlined in Figure 7 [7].

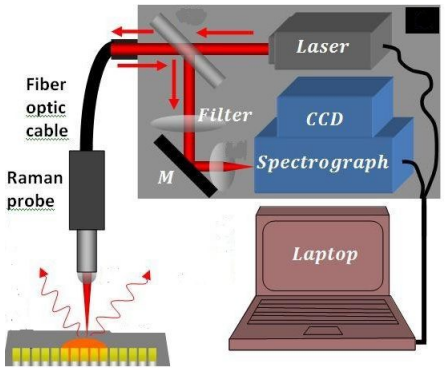


Figure 7. Fiber optic spectroscopy method for obtaining Raman spectrum results for propellant stabilizer (i.e., MNA)

The Raman fiber optic spectroscopy methodology utilizes the concept that the amount and wave numbers of the backscattered Raman light from the propellant are directly related to the propellant's chemical composition. During the propellant's aging process, the amount of propellant stabilizer is constantly degrading due to the chemical reaction between the stabilizer and NO_x out-gassing. When the Raman backscattering spectrum is captured, the concentration level of the stabilizer is displayed; and thus, the potency of the double-base propellant can be determined.

While looking at the Raman fiber optic spectroscopy setup in Figure 7 (above), one must note that the Raman probe also houses two optical fibers. As with the previous patented spectral optical configuration, the two optical fibers are closely positioned such that one fiber illuminates the specimen, while the other optical fiber collects the Raman back scattering. The fibers do not have to be placed in positions that allow for direct contact with the propellant surface.

Experiments were conducted utilizing the Raman technique to collect the backscattering spectrum for several samples of Methyl-Nitro-aniline (MNA) diluted with aluminum oxide. In order to avoid the use of actual energetic materials, the samples' ingredients only included percentages of MNA and aluminum oxide (and no nitroglycerin and nitrocellulose). Also note that aluminum oxide is generally not used in the real propellant. The key sample consisted of 2 percent MNA and 98 percent aluminum oxide (Al_2O_3) in order to simulate new propellant that generally has only 2 percent MNA. In addition to the 2 percent MNA sample, the other samples consisted of approximately 1.5 percent down to 0 percent MNA (in order to simulate the missile/rocket motor's MNA depletion scenario). Laboratory samples that were created by General Opto Solutions are shown in the photo (Figure 8, below). The actual Raman backscattering spectrum was collected for the samples with 2 percent, 1.5 percent, 1 percent, 0.5 percent, 0.1 percent, and 0 percent MNA.

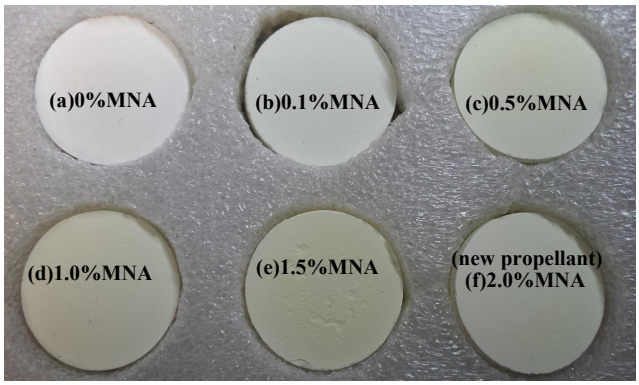


Figure 8. Photo of laboratory samples that have (a) 100% Aluminum Oxide (Al_2O_3), (b) Al_2O_3 & 0.1 % MNA, (c) Al_2O_3 & 0.5 % MNA, (d) Al_2O_3 & 1% MNA, (e) Al_2O_3 & 1.5 % MNA, and (f) Al_2O_3 & 2% MNA

As can be seen in Figure 8 (above), pure imitation propellant (i.e., MNA stabilizer mixed with Al_2O_3), is the darker sample ("f") that emulates propellant has not been aged. Sample "f" equates to initially manufactured propellant that generally has two percent 2-methyl-4-nitroaniline (MNA) stabilizer. After being deprived of MNA in order to simulate aging (associated with long term storage), samples "a-e" show the resulting discoloration associated with reduced amounts of stabilizer. Sample "a" is the pure Al_2O_3 that has no MNA (simulating total depletion of stabilizer and 25 years of aging). The simulated aging is typically equivalent to the full-fledged shelf-life of the propellant.

Laboratory investigations were conducted to verify the fiber optic Raman spectroscopy methodology utilizing the system's built-in continuous-wave 785nm laser. The back scattered spectrum was collected by way of the spectrometer housed in the system and laptop software. The concentration of MNA was determined by capturing and observing each wavenumber / cm^{-1} associated with the backscattered light intensities.

Collected wavenumbers associated with the Raman measurements clearly illustrate that the Raman peaks for MNA are depicted at approximately 1267 cm^{-1} and results agree with those observed by other scientists [8,9].

It is obvious that the higher the concentration of MNA, the greater the amplitude of the Raman peak. As a result, determining the concentration of MNA was accomplished by capturing and observing the Raman spectrum for the samples shown above in Figure 8. Figure 9 (below) shows the measured results indicative of Raman spectrums for the samples.

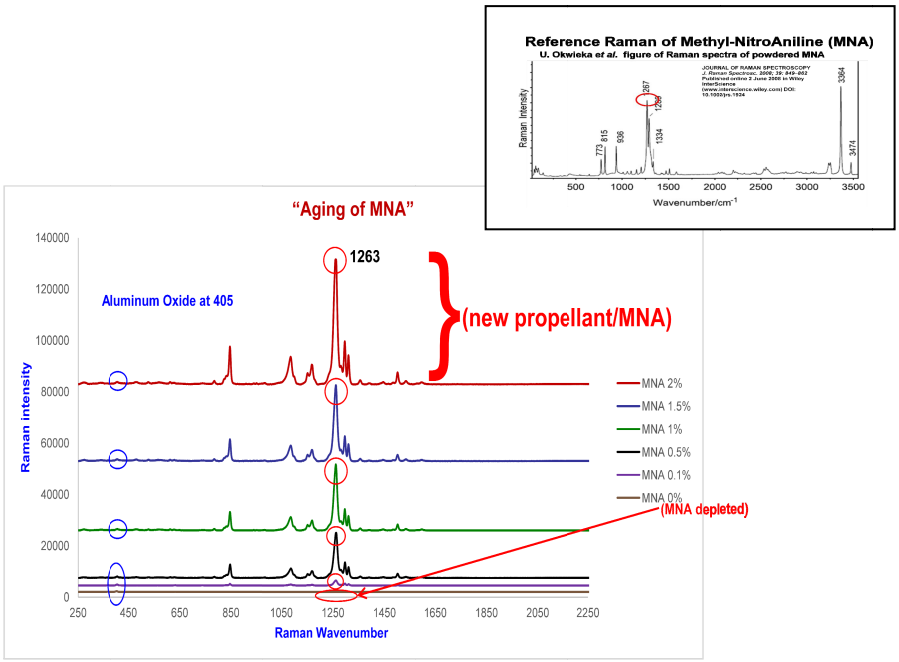


Figure 9. Measured results indicative of Raman spectrums for the simulated propellant samples

For the Raman spectrums (above), the decrease in magnitude of the MNA wavenumbers are due to the depletion of stabilizer. After long-term storage, the stabilizer is depleted from concentration levels of 2.0% (fresh MNA) to below 0.05%. At and below concentration levels of 0.05%, the propellant is unstable, fragile (cracks), and unusable.

Ascertaining the degradation in the concentration of propellants' MNA by capturing and observing the Raman spectral backscatter is an acceptable approach that yields consistence depictions of the stabilizer's wavenumber value of approximately1267 cm^{-1}. Szostak and others recorded the Raman spectra of powdered (ground) MNA excited with eight lines of an Ar/Kr Ion laser (their powers in parentheses) including 676.5 (at 15.7 mW), 647.1 (at 16.1mW), 568.2 (at 11.6mW), 530.9 (at 12.9mW), 514.5 (at 13.8mW), 496.5 (at 10.0mW), and 488.0 (at 12.3mW) [9]. Szostak's Raman spectra results are in Figure 10 (below) and are in agreement with the authors' MNA wavenumber results previously shown in Figure 9 (above).

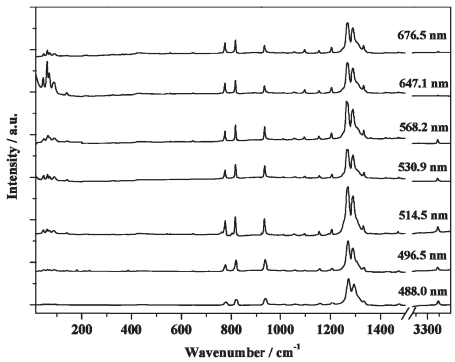


Figure 10. Measured results by Szostak et al of the Raman spectra of powdered MNA

3. ACOUSTIC SENSING OF GUN BARREL DEGRADATION

As with the previous optical spectral techniques, the acoustic sensing methodology is also non-invasive and utilizes the well known ultrasonic approach that equates the thickness of a material to the amount of time it takes for a series of high frequency sound waves to pass through the material. In addition to obtaining the thickness of an entity, acoustic sensing results can be used to differentiate the object's physical properties, degradation, integrity, and certain degenerative properties. The acoustic sensing methodology can been used to ultrasonically examine a material for corrosion, dimensional accuracy, and other characteristics, especially when defects can't be detected from the outside of the object. Acoustics transducers are generally used, along with acoustic thickness instrumentation, to engage an ultrasonic wave form through the material-under-test (as shown in Figure 11, below).

Figure 11. Acoustic sensing technique equating thickness to time it takes for the wave to pass through material (Reference Olympus Manual, DMTA-10022-01EN-Rev.B, October 2013)

The authors' primary goal was to utilize the acoustic sensing methodology to monitor the changing thickness of gun barrels after projectiles are excessively propelled down the tapered length of each barrel. During perpetual firing of the gun system, continued combustion of gun powder and friction between the bullets and gun barrel instigate substantial erosion of the inner portion of the barrel. One key objective was to decide whether to make measurements in real-time (with mounted sensors on the barrels during firings) or between bursts (with a single sensor held onto each barrel) utilizing a handheld device. In either case, the setup would incorporate an acoustic transducer. The targeted acoustic transducer had rapid feedback capabilities. Although the barrels being tested are manufactured from a Chromium-Nickel-Vanadium (CrNiV alloy), the chosen sensing transducer was designed specifically for thickness measurement of steel (the type of alloy was not critical).

Due to the unavailable of the actual gun barrels, personnel from the AMRDEC laboratory developed mock gun barrels and an accompanying mock bullet. The key objective was to conduct an actual proof of concept, testing, and demonstrations with an acoustic sensor. Due to limited material availability, the mock barrels were unfortunately made of a different steel alloy than the alloy used for the actual barrels. Although matching inner diameters were somewhat achieved, the outer diameters of the mock barrels were larger than those of the actual barrels. This was due to machining limitations at the AMRDEC facility. The mock barrels and bullet are shown in Figure 12 (below). Desired testing included acoustic sensing in conjunction with both thermal and humidity sensing. However, as a result of time restriction and funding, acoustic sensing (with one possible modifiable sensor) was completed and remaining efforts are part of future planning.

Figure 12. Mock gun barrels of approx. ~4inch length; outer diameters of all three barrels are 1.000 inch; inner diameters are 0.787 inches (simulating a new barrel), 0.805 inches (simulating a used barrel), and 0.825 inches (simulating a condemned/worse case barrel)

As outlined above in Figure 12, the mock gun barrels were each machined to a length of approximately 4 inches with outer diameters of 1.000 inch. The inner diameters are 0.787 inches (simulating a new barrel), 0.805 inches (simulating a used barrel), and 0.825 inches (simulating a condemned/worse case barrel). The best laboratory achievable thicknesses were 0.107inches (for the simulated new barrel); 0.098 inches (for the simulated used barrel); and 0.089 inches (for the simulated condemned barrel).

Initial measurements were taken utilizing an Olympus Ultrasonic Thickness Sensor/Gage that has good durability, rapid feedback capabilities, precise thickness range, and wide temperature range. The thickness values manufactured by the AMRDEC machinist are outlined in table 1 (below) and later compared with the actual thickness measurements taken in the laboratory. For the user's convenience, it should be noted that the Olympus acoustic sensor has an alarm that can alert the soldier when a thickness threshold has been breached.

Table 1. Thickness values associated with the AMRDEC machinist measurements compared to three trails of measurements obtained using the Olympus thickness devices

	Machinist Measurements (inches)	Candidate Modifiable Acoustic Sensor Measurements (inches)		
Trial	----------	1	2	3
New Mock Barrel	0.107	0.108	0.107	0.108
Used Mock Barrel	0.098	0.098	0.098	0.098
Condemned Barrel	0.089	0.089	0.089	0.089
*Note: There were minimal fluctuations in the thousandths place				

In the overall assessment, AMRDEC personnel successfully conducted a preliminary approach for embedded sensors to detect and monitor the thickness degradation of gun barrels. The goals of identifying, utilizing and incorporating digital sensors to monitor gun barrel degradations were achieved.

4. SUMMARY

Ongoing AMRDEC research and development of nano devices and concepts for condition-based maintenance of military systems have been presented. Two comparable and yet different design approaches for assessing the aging and shelf-life of missile and rocket components have yielded promising results. Sensing techniques for the detection of rocket motor off-gassing, as well as for toxic industrial chemicals, have been successfully demonstrated via laboratory experiments. Preliminary results are summarized below for each sensing method.

Optical Spectroscopy Sensing & Absorption

- Utilized optical fiber and absorption to detect varying propellant stabilizer
- Successfully detected diminishing amounts of various propellant ingredients
- Successfully obtained critical experimentally measured absorption spectrum of stabilizer
- Effectively demonstrated the feasibility of embedding fiber optic sensors in rocket motors

Raman Techniques with Optic Spectroscopy Sensors

- Successfully developed non-invasive fiber optic spectroscopy sensing system to monitor the shelf-life status of double-base propellants
- Successfully tested, collected and compared data from Raman spectrum of stabilizer degradation

Relative to the use of acoustic sensing methodology and laboratory assessments of gun barrels, the authors successfully outlined a preliminary approach for embedded sensors to detect and monitor the thickness degradation of gun barrels. The goals of identifying, utilizing and incorporating digital sensors to monitor gun barrel degradations were achieved.

5. ACKNOWLEDGMENTS

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