Application of a Relative Humidity Sensor for Monitoring Water Vapor Concentration inside Enclosures

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ABSTRACT

The presence of water can have adverse effects on the performance of mechanical and electrical hardware. Standing or condensed water can cause shorting or grounding issues in the short term and can accelerate corrosion in the long term. High humidity can also accelerate corrosion as well as cause swelling of electrical components, seals, or composite materials. Water exposure data can be used to actively intervene prior to degradation (e.g. to fix a water leak) or to calculate the remaining life of a system that has been exposed to water or high humidity. The U.S. Army has recognized the importance of environmental monitoring and failure prediction in weapon systems to ensure readiness, to enhance safety, and to improve weapon performance. Since 2000, Picatinny Arsenal has sponsored the development of specialized environmental monitoring sensors with on-board diagnostics in various new weapon/ammunition systems. In this article we present an effort at the Pacific Northwest National Laboratory to develop an asset health monitor to assess water concentration inside the storage container of an artillery shell. Desiccant is used in the container to maintain the water vapor concentration below 5000 parts per million; a higher water concentration would indicate container leakage or the need to replace the desiccant. Various types of water sensors, including standing water indicators, corrosion indicators, and humidity sensors, were identified and categorized according to type of water exposure, accuracy, and response time. A commercially available relative humidity sensor was identified as a cost effective approach to measuring water vapor concentration inside the container. Relative humidity can be converted to water concentration using the water vapor saturation pressure at ambient temperature. Using diurnal temperature simulations, it was determined that the accuracy of the relative humidity sensor would be unsatisfactory in high temperature/low humidity situations where a small change in relative humidity results is a large change in water vapor concentration. To overcome this obstacle, a strategic sampling technique was developed to increase the accuracy of the water concentration measurement that is based on relative humidity sensor data. The relative humidity sensor was integrated into the Remote Readiness Asset Prognostic/Diagnostic System (RRAPDS), which is an asset health monitor developed by PNNL to measure environmental conditions in munition containers. RRAPDS will be secured to the container with a probe that extends into the container to monitor internal temperature and humidity. RRAPDS includes a microcontroller to process environmental data and execute diagnostic routines. This paper will describe the approach that was developed to estimate water concentration using relative humidity sensor data and describe the sampling technique used to maximize the accuracy of the water vapor concentration assessment.

1. INTRODUCTION

The presence of water can have adverse effects on the performance of mechanical and electrical hardware. Standing or condensed water can cause shorting or grounding issues in the short term and can accelerate corrosion in the long term. High humidity can also accelerate corrosion as well as cause swelling of electrical components, seals, or composite materials. Despite efforts by industry to address the effects of water on electronics, corrosion of various electronic devices continues to cause

reliability concerns (Schnable et al 1979 and Osenbach 1996).

Water exposure data can be used to actively intervene prior to degradation (e.g. to fix a water leak) or to calculate the remaining life of a system that has been exposed to water or high humidity. The U.S. Army has recognized the importance of environmental monitoring and failure prediction in weapon systems to ensure readiness, to enhance safety, and to improve weapon performance (Erickson et al 2002, Mauss 2011, and Marotta et al 2005). Since 2000, Picatinny Arsenal has sponsored the development of specialized environmental monitoring sensors with on-board diagnostics in various new weapon/ammunition systems (Marotta & Erickson 2004). In this article we present an effort at the Pacific Northwest National Laboratory to develop an asset health monitor denoted the Remote Readiness Asset Prognostic/Diagnostic System (RRAPDS), which is an asset health monitor developed to measure the vibration, humidity, and temperature environment of munition containers.

Desiccant is used in the container to maintain the water vapor concentration below 5000 parts per million based on volume (PPM_v); a higher water concentration would indicate container leakage or the need to replace the desiccant. Various types of water sensors, including condensed water indicators, dew point indicators, and humidity sensors, were identified and categorized according to type of water exposure, accuracy, and response time. A commercially available relative humidity sensor was identified as a cost effective approach to measuring water vapor concentration inside the container.

The problem with detecting water vapor concentration with a humidity sensor is the amount of water needed to achieve saturation is much higher at elevated temperatures. Therefore, using a relative humidity sensor to measure water concentration is inherently less accurate at elevated temperatures. The problem is exasperated if it is desired to measure trace amounts of water concentration. This paper will describe an algorithm that was developed to improve the measurement of water concentration using relative humidity sensor data, describe the sampling technique used to maximize the accuracy of the water vapor concentration assessment, and provide an overview of the design of RRAPDS.

2. MONITORING MOISTURE CONDITIONS INSIDE ENCLOSURES

Early in the design phase of RRAPDS, existing moisture detection sensors and algorithms were viewed for potential integration. These methods are summarized below.

Many sensors have been developed to detect the presence of condensed water. These sensors fall into the categories of discrete, single point sensors, and distributed polymer rope-type sensors. These type of sensors are very useful for detecting water intrusion into a basement or enclosure. When water or conductive liquid contacts these types of sensors, the sensor will immediately turn on an alarm. Since RRAPDS needed to measure a rise in water concentration that would occur prior to condensation occurring, these sensors were deemed to be non-applicable. Furthermore, it was desired to provide a large margin between the maximum amount of water concentration allowable before desiccant replacement and the dew point condition. Therefore, sensors that measure condensation would not provide the desired margin of safety.

Moisture/preservation models were also investigated. Several are based on temperature, humidity, and dew point. The Image Permanence Institute (IPI) has developed algorithms that provide quantitative measures of the risk for specific modes of degradation, including natural aging, mechanical damage, mold, and metal corrosion (Reilly 2005). These algorithms use temperature, dew point, and relative humidity readings to predict the risk of damage for each specific degradation mode. IPI has incorporated the algorithms into software which is now in use in museums and libraries worldwide. The software has proven to be a useful evaluation tool for evaluating potential storage locations and for monitoring existing storage facilities, but does not apply to monitoring low water concentration levels inside closed containers in the presence of desiccant.

The use of a humidity sensor was then investigated. Relative humidity can be converted to water concentration using the water vapor saturation pressure at ambient temperature. However, using diurnal temperature simulations, it was determined that the accuracy of the relative humidity sensor would be unsatisfactory in high temperature/low humidity situations where a small change in relative humidity results is a large change in water vapor concentration. To overcome this obstacle, a strategic sampling technique, discussed later in this paper, was needed increase the accuracy of the water concentration measurement that is based on relative humidity sensor data.

3. RRAPDS OVERVIEW

RRAPDS, shown in Figure 1, was designed to fit in the existing volume at the aft end of a munition container. A primary objective was to install RRAPDS without any modification to the container. The novel shape of RRAPDS, with two separate compartments, was chosen to allow the enclosure to mount over the existing container end cap. RRAPDS is secured to the container using a pre-existing pressure and humidity test port.

The relative humidity sensor was integrated into RRAPDS using the mounting hole for an existing visual (blue/pink) humidity viewport. The humidity sensor selected for use in RRAPDS was the Sensirion SHT25 humidity sensor, which is a low cost, low power MEMS sensor designed for remote monitoring. The sensor is mounted to the bottom of the main PCB, and protrudes into the container as shown in the lower view of Figure 1.

RRAPDS makes use of low-power consuming electronics to help ensure an operational life of up to ten years using a lithium battery pack. The microcontroller has the ability to process environmental data and execute diagnostic routines. If pre-established thresholds have been breached, an LED indicator light can be tripped to red to make that situation clear to a field user.

Data will continuously be collected and stored on RRAPDS. Go and no-go LED indicators are provided on the cover of the device. An associated reader device will be able to collect data from the device via a hard wired connection or by wireless means. The later method will enable communication links with many RRAPDS devices simultaneously and make it easy to collect data from devices that are not physically accessible. Data will ultimately be deposited and stored in the Munitions History Program (MHP) for any and all authorized users to access and review as may be needed.

4. MONITORING WATER CONCENTRATION USING A HUMIDITY SENSOR

The planned function of the Sensirion SHT25 relative humidity and temperature sensor in the proposed health monitor is to measure the concentration of water vapor in the missile container and to indicate when it exceeds a predetermined level. The use of this type of sensor requires that the concentration of water vapor be calculated from measured values of relative humidity (%RH) and air temperature in the container. An unacceptable increase in the concentration of water vapor in the container would be detected as an excursion of the measured %RH value above the alarm level. That level, defined as a function of temperature, must be established with regard to the expected uncertainties in the measured values of %RH and the calculated values of water-vapor concentration.

The specified measurement uncertainty of the SHT25 sensor after calibration by the manufacturer is ±1.8 %RH at 25 ℃. However, given a nominal water-vapor concentration of 5000 PPM$_v$, this value increases to approximately ±4 %RH at temperatures near 0 ℃, and to approximately ±5 %RH at 50 ℃. The corresponding uncertainties in the water-vapor concentration are approximately ±260 PPM$_v$ at 0 ℃ and +5700/-5000 PPM$_v$ at 50 ℃.
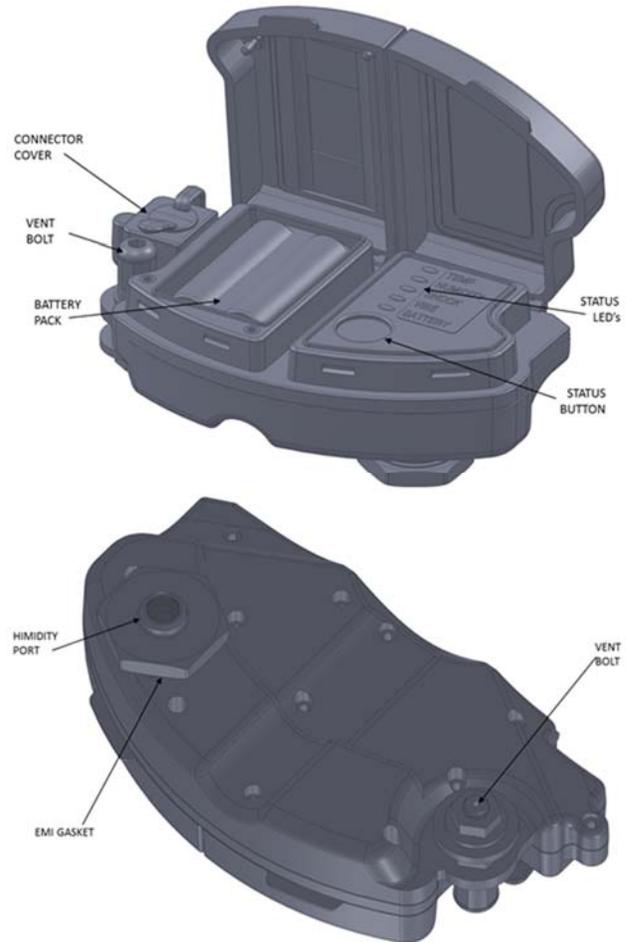

Figure 1. RRAPDS Overview

However, if the alarm level over the temperature range of interest were defined as the expected relative humidity plus its temperature-dependent uncertainty as given above, approximately 5% of all deployed monitoring systems would be expected to produce false alarms. This would occur because Sensirion defines the measurement uncertainty of their humidity sensors as the plus and minus deviations from the mean that bound 95% of the values measured by a large number of sensors. This is a reasonable approach, given that a large number of sensors, exposed to the same environmental conditions, produce a set of %RH values that approximate a normal distribution. In such a distribution, 95% of the values are within two standard deviations of the mean value.

Increasing the measurement uncertainties of the SHT25 sensor by 50% (to three standard deviations) would reduce the expected number of false alarms to 0.3%. A temperature dependent alarm level based on this approach is illustrated as the red curve in the following graph (Figure 2).
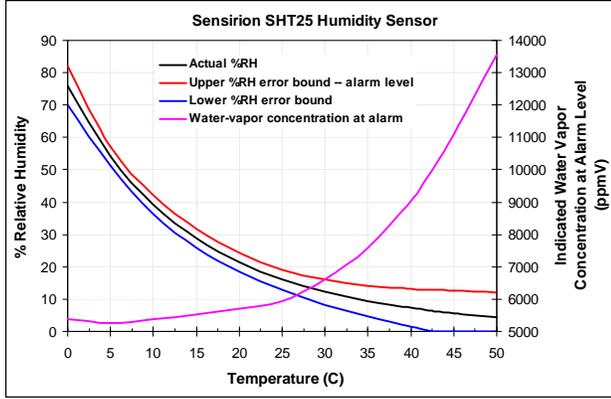
Figure 2. Temperature Dependent Moisture Threshold

The black curve shows the expected values of %RH as a function of temperature, given a water-vapor concentration of 5000 PPM$_v$. The blue curve shows the expected negative error bound. At container temperatures less than 25 ℃, the absence of an alarm would indicate that the concentration of water vapor in the container is within 1000 PPM$_v$ of the nominal value. At higher temperatures, the possible concentration would be substantially higher, rising to approximately 13,500 PPM$_v$ at 50 ℃, 8500 PPM$_v$ above the nominal value. This level would be of concern if a correspondingly high concentration were indicated at lower temperatures where the measurement is more accurate. An analysis of the reported values of %RH and the corresponding water-vapor concentrations should put a high weight on measurements made at low temperatures; e.g., at the low-temperature end of a diurnal cycle.

Periodic measurements by the SHT25 sensor will ensure that, at any temperature above freezing, a high water-vapor concentration in the container will be detected and reported at a level well below the level at which condensation can occur. This is graphically illustrated in Figure 3. Here, the plotted curve shows the trajectory of the dew point if the %RH in the container were to follow the alarm level (red curve in Figure 2) across the temperature scale. The dew point (given by the vertical scale) is always well below the air temperature in the monitored container (horizontal scale), so condensation cannot occur without an alarm being reported by the SHT25 sensor.
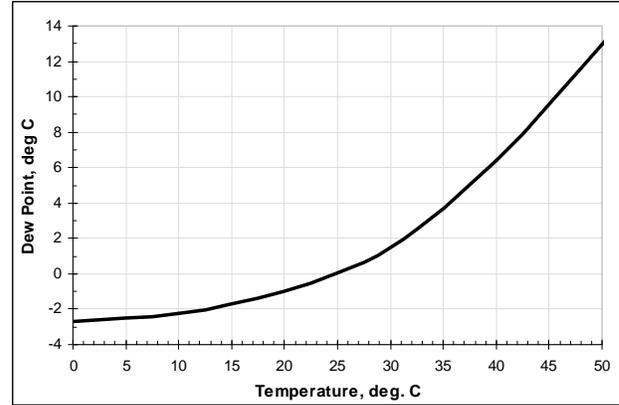

Figure 3. Dew Point if the %RH in the Container were to follow the Alarm Level (red curve in Figure 2)

5. WATER CONCENTRATION ALGORITHM DEVELOPMENT

An algorithm was developed that integrates the temperature dependent accuracy of the humidity sensor with a basic data acquisition and alarming functionality. The following is a description of the algorithm, which is graphically shown in Figure 4.

Humidity is sampled by RRAPDS every 6 hours. The sample time 6 hours was chosen to increase the likelihood of measuring PPM$_v$ during a colder time of day, when the PPM$_v$ calculation is more accurate. Water concentration is only calculated when the temperature is between 0 and 50˚C. Using the current temperature, water vapor pressure (in mm Hg) is determined using a lookup table. Water concentration is computed using the following equation.

$$PPM_v = \frac{P_w}{P_{tot} - P_w} 10^6 \tag{1}$$

Where

P$_w$ = Water vapor pressure
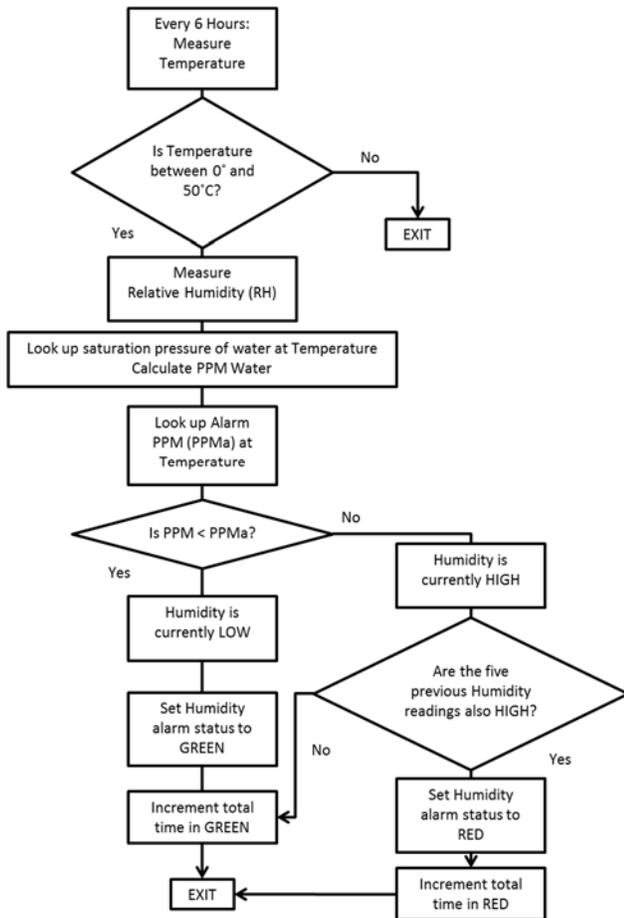
P$_{tot}$ = Total Pressure

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Figure 4. Humidity Concentration Algorithm

The humidity LED indicator will not indicate alarm status unless six consecutive readings are greater than the temperature dependent PPM alarm threshold. Since the moisture content alarm would require that the desiccant be changed, and the cost of replacing the desiccant was relatively high, requiring six consecutive readings reduced the likelihood of a false alarm.

The humidity indicator will switch from alarm back to non-alarm as soon as one reading of acceptable moisture content is detected. The moisture content alarm threshold was implemented as a hard-coded lookup table based on the pink curve of Figure 2. A humidity data table is also stored on RRAPDS that reflects the total number of days in non-alarm and alarm status and the number of times the status went from non-alarm to alarm. In addition, the following event data is recorded:

- Date of initial trip from alarm to non-alarm (once the container is assembled and sealed, it takes a finite period of time for the desiccant to dry out the internal volume of the container)

- Date of last non-alarm to alarm trip event

- Date of last alarm to non-alarm trip event

- Maximum humidity ever detected

6. ALGORITHM VERIFICATION

The algorithm was tested using a sequence of humidity/temperature pairs that were designed to mimic the response to desiccant life cycle consisting of a quick drying out phase, followed by a period of very low water concentration, and ending with a slow increase in water concentration due to desiccant degradation. This synthetic water content verification sequence is shown in Figure 5. The synthetic data also includes rapid increases in PPM_v to test the robustness of the algorithm. The algorithm would alarm only after six consecutive measurements were made that were greater than the temperature dependent water concentration alarm threshold. This would be a strong indication that desiccant replacement was needed. Note that the water concentration data could have been extrapolated to predict the time to critical condensation. This could have been used to establish the optimum time to replace the desiccant. The approach was not taken because it would have adversely increased the alarm response time in the case of a breeched container.

After the algorithm was verified, the system was installed in a container (see Figure 6) with desiccant. The internal air was monitored with RRAPDS and independently measured with a laboratory grade humidity sensor over a period of several days. The data is shown in Table 1. It was found that the desiccant dried the internal air to less than 1500 PPM_v in less than one day, and that the water concentration measured by RRAPDS lagged the humidity response of the laboratory grade humidity sensor, which was inserted directly into the container cavity. This discrepancy was attributed to a slow rate of air exchange between RRAPDS and the container.
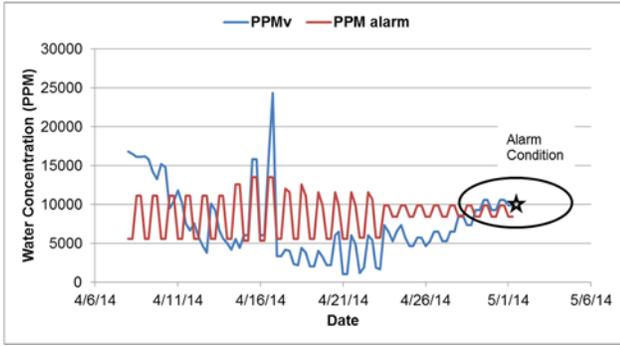
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Figure 5. Algorithm Verification Sequence

Figure 6. RRAPDS Installed on Container End Cap

Table 1. Humidity Response Test Results

Day	Lab Grade Humidity %RH	Lab Grade Temp, °C	Lab Grade PPM	RRAPDS %RH	RRAPDS PPM
1	25	22	6587	NA	NA
2	1.4	22	368	6	1581
4	1.3	22	342	5	1317
10	0.9	22	237	4	1054

7. CONCLUSIONS

In this article we present an effort to develop an asset health monitor to assess water concentration inside the storage container of an artillery shell using an economical, low power humidity sensor. Using diurnal temperature simulations, it was determined that the accuracy of the relative humidity sensor would be unsatisfactory in high temperature/low humidity situations where a small change in relative humidity results is a large change in water vapor concentration. To overcome this obstacle, a strategic sampling technique was developed to increase the accuracy of the water concentration measurement that is based on relative humidity sensor data. The likelihood of false

alarms was further reduced by constraining the temperature range of the humidity sensor and by requiring multiple consecutive alarm readings. The algorithm was subjective to verification by injecting synthetic data and by environmental testing.

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BIOGRAPHIES

Brian Hatchell joined the Pacific Northwest National Laboratory in 1991 and has been involved in a number of complementary areas involving optical-mechanical design, structural analysis, and electrical/mechanical systems engineering. In recent years he has managed several projects under the National Security Directorate involving the development of remote health monitor electronics for military assets. During the execution of these projects, Mr. Hatchell developed automated verification methods to accelerate environmental and vibration testing of asset health monitors. Mr. Hatchell has worked with graduate students to test vibration energy harvesting technologies for deployment on candidate transportation platforms, including the Apache Helicopter. Brian Hatchell holds a Master's of

Science degree in Mechanical Engineering from the Georgia Institute of Technology, is an INCOSE Certified Systems Engineering Professional, and has published several technical papers regarding the development of health monitors.

Eric Gonzalez is a lead senior technician at the Pacific Northwest National Laboratory and is involved in electronics development, fabrication, and testing. Eric's skills include: building and testing printed circuit boards, testing and validating electronic systems, and performing power measurements. Eric received an A.A. in Electronics Engineering Technology from ITT Technical Institute.

Anton Sinkov is an electrical engineer at the Pacific Northwest National Laboratory and is involved in electronics development, applications for RF transmitters, and advancement of graphical user interfaces. Anton holds a Bachelor's degree in Electrical Engineering from Washington State University.

Lorenzo Luzi is an intern at the Pacific Northwest National Laboratory and works on projects involving computer vision, digital signal processing, microcontroller interfaces, and machine learning. Lorenzo is currently a PhD student at Rice University where he studies Electrical Engineering.