RADIONUCLIDE OPERATIONAL RESEARCH & DEVELOPMENT

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ABSTRACT

The development team responsible for creation of the automated aerosol and xenon sampling systems is continuing to solve problems related to the operation of automated systems for nuclear explosion monitoring. Several typical problems are presented here to characterize that effort. First, the development of tools for the efficient use of state-of-health information is in progress. Second, first-generation code segments useful for authenticating data have been developed and are discussed. Finally, the computations and experiments quantifying the effects of cascade summing in the operation of aerosol monitoring radiation detectors are discussed.

Both the Radionuclide Aerosol Sampler/Analyzer (RASA) and the Automatic Radioxenon Sampler/Analyzer (ARSA) gather state-of-health data (Miley, 1998; Bowyer, 1999). These data are stored and forwarded to a data center, such as the US National Data Center. Tools to simply visualize (with template eye guides) have been constructed. State-of-heath data from operational RASA units and specially designed experiments have been analyzed to demonstrate the ability to detect minute trends leading to failure. This analysis should allow systems maintenance staff some predictive capability.

Providing a digital signature on a data transmission serves to authenticate both that the message comes from a trusted source and that it has not been altered in any way. In addition, digital signature also makes the message undeniable: that is, it cannot be disputed that this message came from some other source or was fabricated. Authentication software has been produced in collaboration with Sandia National Laboratories and has undergone extensive testing on operational and test RASA units. Authentication code must implement the policy logic of an overall authentication infrastructure. Policy decisions for data authentication have not been completely set at this time. Because of this and the rapidly changing standards environment for authentication code today, this work will likely require extension to cover other authentication standards.

Cascade summing occurs when two gamma-rays emitted in the decay of a single nucleus both deposit energy in a detector. In addition to (or instead of) the familiar set of peaks and continuum usually uniquely associated with an isotope, higher energy peaks and continuum are observed. This effect occurs predominantly where the source is located close to the detector for maximum sensitivity, as in the International Monitoring System aerosol stations, including the RASA. The size of the effect may be computed by various means, including Monte Carlo simulation. Computations have been compared to experiment to show that in most cases the effect of summing is modest but perceptible. Certain extreme cases can show dramatic effect. The impact on efficiency measurements and certain fission products will be shown.

Key words: radionuclide, aerosol, SOH, cascade summing, authentication

OBJECTIVE

State-of Health Data

The general goals of State-of-Health (SOH) data gathering are to detect failures in the monitored process and to predict failures sufficiently ahead of time to minimize downtime. These goals can be separated into three distinct components: bounds checking on current SOH values, trend detection in SOH values, and fault detection/prediction based on detailed system knowledge. The philosophy of SOH development taken at Pacific Northwest National Laboratory (PNNL) is first to facilitate development, then to gradually analyze SOH parameters for failure-prediction capability. Finally, the production of tools to automatically examine SOH data will greatly reduce staffing needs while maximizing uptime. Because of the limited field experience with the RASA and ARSA, it is not well known what the most likely failure modes will be. Thus, as the operational experience base expands, more SOH parameters can be studied meaningfully.

Bounds checking of SOH values can be implemented relatively easily by creating a software process that compares each new SOH value to a pre-established range. This function in the RASA, for instance, automatically generates an alert e-mail to a pre-specified e-mail address describing the anomaly. The bounds range was originally established by histogramming a one-year sample of 5-minute resolution values. The 4 sigma limits of these values were chosen to limit false alarm alerts. This approach created a fairly narrow operation range. Unfortunately, conditions such as extreme weather, air conditioning failure, or other factors unrelated to the RASA directly have the ability to force the SOH values out of a narrowly defined range.

After a single system generated 600 alert e-mails in one weekend, it became generally acknowledged that the SOH value range needed to be sufficiently broad to limit alerts to obvious problems. The current idea for setting this range is to specify the nominal range of values (temperatures, currents, etc.) specified by subsystem suppliers. This is less sensitive to excursions but does not produce too many false alarms.

While bounds checking can and should be done on the monitored system, trend analysis need not be done on the RASA or ARSA. It may be sufficient to operate well-known process control software at the Data Center to examine these data. However, many of the SOH parameters are not naturally steady: for example diurnal variations are found in all RASA SOH temperatures. ARSA components normally undergo sizeable temperature swings every eight hours (Fig. 1). Thus, strong recurring patterns need to be mathematically nulled or accounted for in the mathematical trend model. Nulling can be accomplished effectively by taking the difference of two similar SOH parameters. It is preferable that one is not dependent on system performance. Outdoor air temperature or room temperature would be good examples of independent parameters.

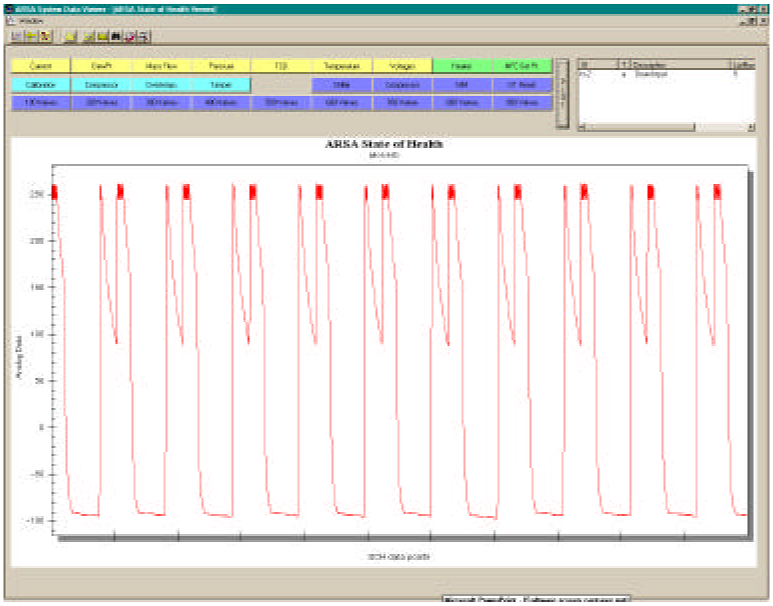

Figure 1. ARSA SOH Viewer

Because the development teams of the RASA and ARSA are still involved with the successful technology transfer to industry, it is possible to combine the RASA and ARSA development experience with mathematical and statistical methods to explore system failure predictions. Exploratory work of this sort has begun with the analysis of the temperature of the RASA blower motor and the current drawn by the RASA filter advance motor. Although the germanium detector seems to be the most failure-prone item, these motors are the critical mechanical components of the RASA. The goal of the SOH analysis is to predict failures far enough in advance to allow a service call that eliminates or minimizes downtime.

Blower Motor Thermal Test

To produce unambiguous data for the blower motor temperature analysis, researchers agreed that the commercially produced RASA would be left undisturbed for one month. In the fourth week, heat would be gradually applied to the motor to simulate or perhaps cause a bearing failure. Fortunately or unfortunately, a real failure occurred about 450 hours into the test (Fig. 2). The failure was of a type unknown on the PNNL prototype: when one or more filter strips terminates unexpectedly and the RASA continues to draw air, the blower motor can rapidly increase in temperature and emit a hot smell. After a cool-down period and replacement of the filter strip, the motor will return to normal operation.

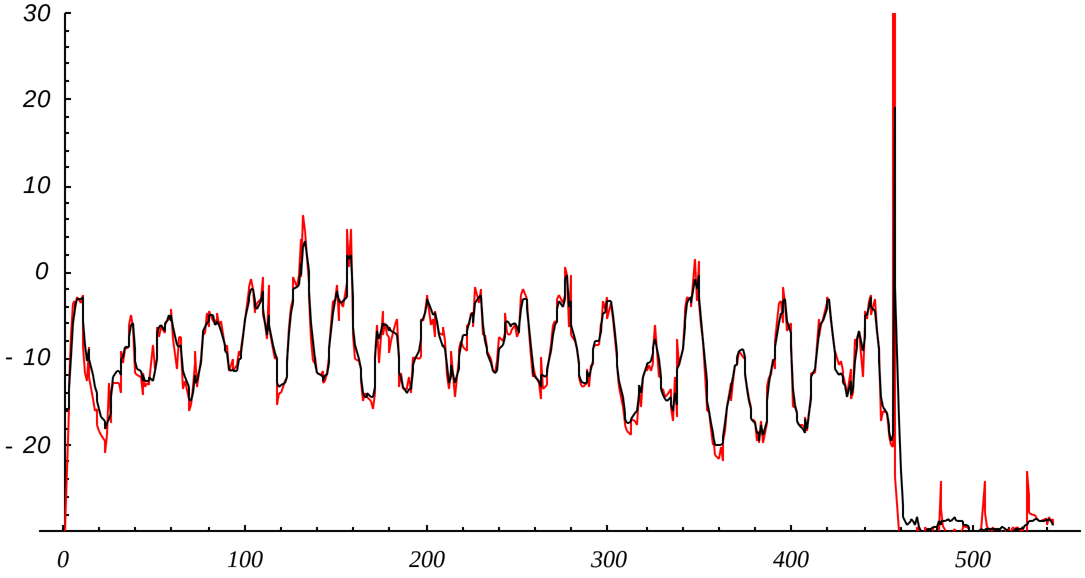

Figure 2. Temperature difference in degrees Celsius (black) vs. SARIMA predictions (red). Model was trained on first 240 hours data.

The strong diurnal variation in the raw blower temperature was suppressed by subtracting the inlet air temperature. Multiplying the inlet air temperature by some factor and also subtracting a fixed offset could have nulled the remaining diurnal variation more effectively. However, models were selected which naturally included diurnal variations. The time series models employed are formally known a seasonal autoregressive integrated moving average (SARIMA) models.

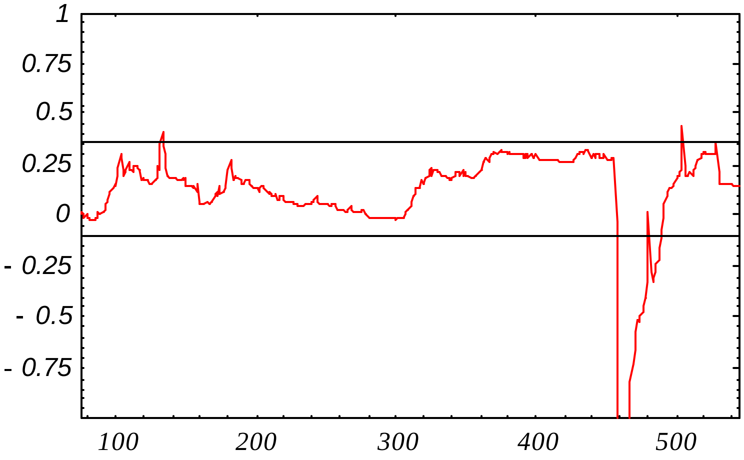

Figure 3. Cuscore statistic showing blower failure detection.

Obviously, this method has excellent predictive power, but the predictions are not sufficiently far out in the future to say that we have reached our goal of failure prediction, at least for this sudden-onset phenomenon. However, this model can be tuned to find patterns super-imposed on normal diurnal variation and to generate an alarm. As a crude example, the cuscore statistic is shown for the blower failure example below. The failure is seen in figure 3 as a dramatic excursion of the cuscore with a minor accidental excursion at about 133 hours. The bounds on the cuscore represent a much tighter bound than that in the simple alerts. Furthermore, the cuscore can be tuned to be sensitive to expected failure onset patterns.

Advance Motor Current Analysis

As a surrogate indicator for RASA filter paper jams, advance motor current can be used to identify excessive motor load. Minimum, maximum, and average current during motor operation comprise the SOH monitoring data (Fig. 4). These three measurements should be used since the range of motor current can be indicative of filter paper jam as well as the average motor current. Outlier data from the USX01 advance motor were identified as real failures or false failures (maintenance activities can produce unusual advance motor current). Once the real and false failures were determined, the false failures were removed from the data set.

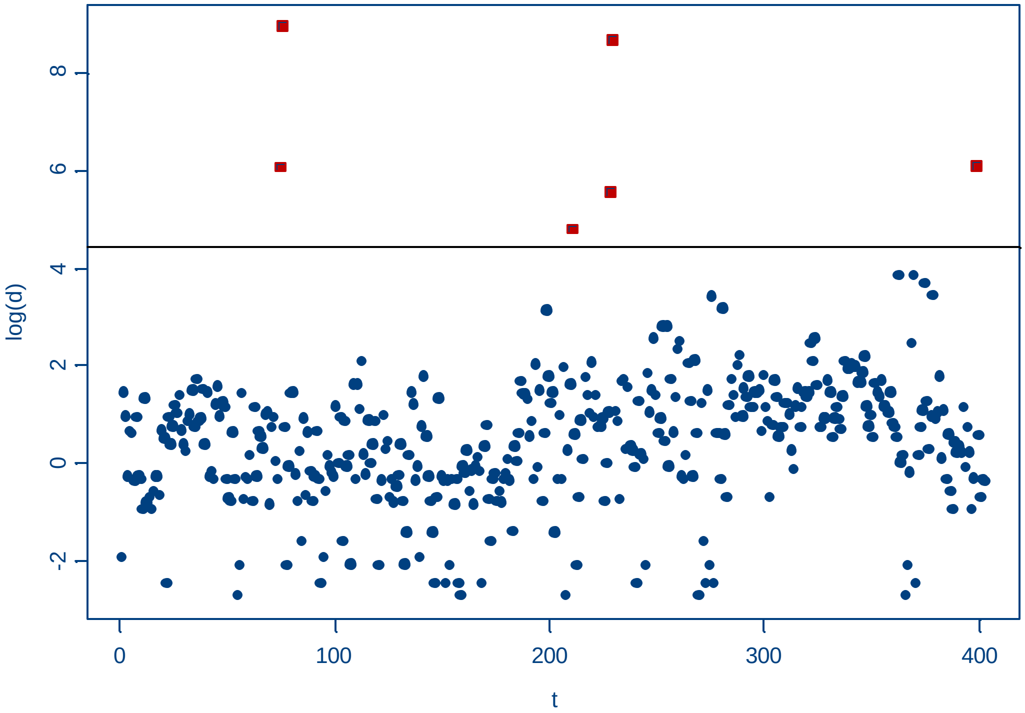

Figure 4. Advance motor SOH measurements (Mahalanobis distance) derived from advance motor current data. Extreme SOH measurements correspond to filter paper jams. Extreme SOH measurements serve as surrogate indicator for filter paper jams.

The Mahalanobis distance (relative to the nominal data) of the 403 observations are plotted versus time (Fig. 4). The known failures for the USX01 advanced motor stand apart from the nominal data in an obvious manner. We have found that all three SOH measures (minimum, maximum, and average current) are necessary to identify excessive motor load. If only one metric had been used, the entire behavior of the data would have never surfaced.

Based on this preliminary analysis, a simple rule can be used to identify excessive advance motor load (which has a strong possibility of being a filter paper jam):

If $(\mathbf{x}-\mu_{\text{Nominal}})'\,\Sigma^{-1}_{\text{Nominal}}\,(\mathbf{x}-\mu_{\text{Nominal}}) > \chi^2$, where

- $\mathbf{x}$ is the vector of SOH measurements (min, max, and average current)
- μ_{Nominal} and Σ_{Nominal} are the mean vector and covariance matrix computed from a large number of nominal SOH measurements
- $\chi^2 = {(\mu_{\text{Nominal}}-\mu_{\text{Failure}})'\,\Sigma^{-1}_{\text{Nominal}}\,(\mu_{\text{Nominal}}-\mu_{\text{Failure}})}\big/{4}$

In reality, most of these advance motor failures were the result of allowing the polyester sealing tape to run out, which causes the filter to wind around the drive rollers. This particular failure mode should be quite rare in real monitoring use. However, it stands to reason that increased motor current over a few days may indicate an imminent jam or other maintenance condition.

These two exploratory analyses show that there is real potential in a mathematical/statistical approach to system management. The future of SOH operation research for the radionuclide systems includes about 50 more parameters and their interdependency. However, the approach of choice is to determine the first few most likely failure modes, as they become apparent, then design detection and then prediction tools for them. A list of analog SOH parameters for the ARSA and RASA can be found Miley (1998) and Bowyer (1999).

Authentication

RASA Authentication Software applies a digital signature to all normal outgoing messages that are e-mailed from a RASA system on which it is installed. This digital signature can be used to verify that the message actually came from the source that it claims to have, and that the contents of the message have not been altered.

The digital signature conforms to the S/MIME (Secure/Multipurpose Internet Mail Extensions) standard, version 2. It specifies adding a digital signature and public key certificate as a MIME attachment to the e-mail message. S/MIME is a developing standard of the Internet Engineering Task Force (IETF) S/MIME working group that has been widely adopted in industry. S/MIME specifies procedures for signed and/or encrypted data and X.509 public key certificates to be transmitted as MIME data types. All public key information needed to verify digital signatures is embodied within ISO (International Standards Organization) X.509 certificates.

The signature function is performed by a tamper-evident hardware cryptographic token (the U.S.-Government-developed Fortezza Card) in the form of a PC Card processor card obtained from a commercial supplier (Spyrus, http://www.spyrus.com/). The card is configured to use the Digital Signature Standard (DSS) with a public key size of 1024 bits and is capable of self-generating a private key and communicating the new public key.

The Authentication Software is constructed on the client-server model. There is one authentication server program. It manages interactions with a Fortezza card, X.509 certificate handling and PKCS #7 (Public-Key Cryptography Standards) signature generation, and maintains a database of public key certificates for use in verifying signed messages. Other RASA programs connect to the authentication server using a socket interface and can request that operations be performed. The OpenSSL (http://www.openssl.org/) software package is used as the basis library for certificate processing

The authentication software operates as a plug-in to existing RASA control software (version 2.2). When properly installed, the authentication software is automatically recognized by the RASA control software and is used to sign outgoing e-mail messages. When the authentication plug-in is not present, or is removed, the RASA control software automatically reverts to sending unsigned messages. A hardware interface card to receive the Fortezza PC Card processor card must be installed on the RASA control computer.

Implementation to Date

The original work on the authentication software was performed at Sandia National Laboratories (SNL). A prototype version of the software that could operate on a RASA system was constructed in collaboration with PNNL and demonstrated in the third quarter of 1999 (Harris 1999). Subsequently, the demonstration prototype was further modified by PNNL to operate in a production mode with RASA control software.

Modifications for the demonstration included porting the Sandia software to the operating system that RASA uses (QNX, http://www.qnx.com). The standard driver software for the Fortezza card (the CI Library) was also ported to QNX. This allowed software that already uses the Fortezza card with CI Library calls to be easily ported and used on the RASA.

Subsequent modifications focused on reliable operation of the software under actual operating conditions and upon the "plug-in" interface that allows it to be easily added to or removed from an existing RASA installation. Most of the modifications needed to achieve reliable operations were due to the differences between QNX and Unix (for example, a limitation on the maximum size of a message sent via a socket connection).

Version 1.0 of the RASA Authentication Software has been tested on the two RASA stations at Hanford (USX01 and USX03) using a Spyrus Fortezza card. The software was installed and used to sign normal outgoing RASA e-mail messages. Results were observed for several days of operation. The e-mail reader functions of both Netscape and Internet Explorer browsers were used to verify that the signatures for the e-mail messages would authenticate. Only the initial self-signed X509 certificates have been used for these tests. Third-party signed certificates have not been tested.

Future work being considered includes: Modifying the software to work with hardware tokens that conform to the PKCS #11 token interface standard; testing the system with authentication-only hardware tokens (subject to lesser cryptographic export regulation); and fully supporting X509 certificate management (signature by approved certificate authority using approved methods).

Cascade Summing

Cascade summing was brought up in Working Group B as an important issue that could stall efforts to implement final software at the International Data Centre for automatic radionuclide analysis (Miley et al, 1999). Cascade summing can be an important consideration for measuring isotopes that decay by emitting two or more gamma-rays in succession. Many important fission products and calibration isotopes have this property. Cascade summing is negligible when the source of radiation is at a reasonable distance from the detector, say as little as 10 cm for a point-like source and a 10-cm diameter detector. However, systems designed for detection of trace levels of radiation usually have maximal contact between the source and detector.

Table 1. Measured cascade summing effect for some fission products of interest.

Fission Product	Energy (keV)	Gammas /sec @ 10 cm	Gammas /sec @ 0 cm	Expt Ratio
Zr-95	756.7	203.0	196.0	0.966
Nb-95	765.8	64.0	62.6	0.978
Mo-99/Tc-99m	140.5	1388.0	1035.0	0.746
Ru-103	497.1	288.7	270.9	0.938
Rh-105	319.1			N/A
Ag-111	342.1	-	-	-
Cd-115m	933.8	-	-	-
Sn-125	1067.1	-	-	-
Sb-125	427.9	-	-	-
I-131	364.5	569.9	486.5	0.854
Ba-140	537.0	355.7	340.5	0.957
La-140	1596.2	1343.0	1030.0	0.767
Ce-141	145.4			N/A
Ce-143	293.3	114.4	86.5	0.756
Nd-147	531.0	84.7	80.5	0.951
Pm-149	286.0	-	-	-
Pm-151	340.1	-	-	-
Sm-153	103.2			N/A

An experiment was carried out to estimate the size of the summing effect in several geometries. A point-like fission product source was made and measured at 0 cm and 10 cm from the front face of a RASA gamma-ray detector.

The fission product spectra were analyzed in the usual way with an automated spectral analysis code and with human analyst review. The comparison of 0 cm and 10 cm results is found in Table 1. The significant (~25%) effect in Mo-99, La-140, and Ce-143 would be less in the RASA because of the lower gamma-ray efficiency, particularly at low energies.

Interestingly, gamma-ray detectors with good efficiency at low energies can have a significant problem with Ba-140. Every decay of Ba-140 which emits the characteristic 537 keV gamma-ray has to emit another 43 keV worth of gamma-rays. If the source is at the front face of the detector and if the detector has essentially no absorber on its front face, many or most of the 537-keV gamma-rays will sum with all or part of the 43 keV, thereby greatly diminishing the 537-keV line. This can be easily rectified by adding absorber material to replace the normal 0.7 mm of useless Ge on a P-type detector.

The effect of cascade summing on calibration data has been estimated by use of the Monte Carlo code, CraZy (Miley, 1993). These computations show that the effect of summing at 10 cm is negligible, at 0 cm is worthy of consideration, and for the RASA geometry is one-half to one-third as large as at 0 cm. It should be noted that the 1-sigma statistical uncertainties in the 10-cm values are of the order of 30% because of the relatively low efficiency of that geometry. Around 10 million histories each for 8 scenarios were required to compute the 10-cm values even that well.

Table 2. Simulated corrections in calibration lines

Energy	0 cm	RASA	10 cm
898	29%	12%	2.6%
1173	31%	10%	3.4%
1332	32%	12%	1.6%
1836	32%	12%	2.4%

CONCLUSIONS AND RECOMMENDATIONS

The authentication work done to date will likely require follow-up to extend the cryptological hardware supported. In addition, reasonable structures for key management need to be addressed throughout the International Monitority System. This will be observed as an evolving process of standard selection and adoption, with trickle down occurring into the field hardware over a period of years. Command authentication will also likely require investment and will have a similar implementation profile.

Analysis of state-of-health parameters has great potential rewards in uptime and effective cost of ownership of the radionuclide systems. Additional development in SOH data management is required to allow the SOH data to be useful. In particular, the payoff in germanium detector uptime alone is worth a considerable investment into the understanding of its failure modes.

Finally, it will likely be necessary to revisit basic topics in gamma-ray spectrometry several more times before the small errors, approximations, and short-cuts in the analysis of the radionuclide data are ironed out. The best approach to take when these events occur is to seek expert guidance, perform simple experiments and calculations, and to engage the expert community as early as possible to prevent wildly non-optimal procedures and policies from being posited.

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