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Ceramic Seal

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Abstract

Containment/Surveillance (C/S) measures are critical to any verification regime in order to maintain Continuity of Knowledge (CoK). The Ceramic Seal project is research into the next generation technologies to advance C/S, in particular improving security and efficiency. The Ceramic Seal is a small form factor loop seal with improved tamper-indication including a frangible seal body, tamper planes, external coatings, and electronic monitoring of the seal body integrity. It improves efficiency through a self-securing wire and in-situ verification with a handheld reader. Sandia National Laboratories (SNL) and Savannah River National Laboratory (SRNL), under sponsorship from the U.S. National Nuclear Security Administration (NNSA) Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D), have previously designed and have now fabricated and tested Ceramic Seals. Tests have occurred at both SNL and SRNL, with different types of tests occurring at each facility. This interim report will describe the Ceramic Seal prototype, the design and development of a handheld standalone reader and an interface to a data acquisition system, fabrication of the seals, and results of initial testing.

ACKNOWLEDGMENTS

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NOMENCLATURE

C/S	Containment and Surveillance
CoK	Continuity of Knowledge
DOE	Department of Energy
NNSA	National Nuclear Security Administration
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory

1. INTRODUCTION

Containment/Surveillance (C/S) measures are critical to any verification regime in order to monitor declared activities, detect undeclared activities, verify the integrity of equipment or items, reduce inspector burden, and to maintain Continuity of Knowledge (CoK) between inspections [1]. Equipment used in C/S can include tags, seals, tamper indicating enclosures, optical surveillance, and radiation detectors, and this equipment currently exists at varying levels of technological sophistication and maturity. Some C/S equipment, such as the metal cup seal, has been fielded for 50 years. Legacy optical surveillance equipment, based on the DCM-14 camera module, is currently undergoing replacement. It is critical that C/S equipment evolve given the technology advancements and capabilities available to potential adversaries. Development of new C/S equipment also allows use of new technologies to improve equipment efficiency and effectiveness for inspectors and to reduce burden on operators.

The U.S. National Nuclear Security Administration (NNSA) Office of Defense Nuclear Nonproliferation Research & Development has funded the Ceramic Seal [2-6] effort to address the technical containment requirements for securing access points (loop seals). Loop seals are common equipment used for C/S measures, as reflected by the tens of thousands of metal cup seals deployed globally, in addition to the Electronic Optical Sealing System (EOSS), the electronic Variable Coding Seal System (VACOSS), the passive single-use Cobra seal, and the electronic/wireless Remotely Monitored Sealing Array (RMSA).

The Ceramic Seal has been in development by SNL and SRNL for several years and prototypes for operational testing have now been fabricated. The Ceramic Seal can provide an improved and modernized alternative to the metal cup seal or other single use seals. The metal cup seal, although environmentally robust, inexpensive, and small in size, is operationally burdensome and its integrity is not able to be verified in-situ. The Ceramic Seal addresses issues with the metal cup seal and makes additional security improvements (tamper indication and unique identification) and efficiency improvements (in-situ verification and ease of application). Its innovation is the integration of these capabilities in a small volume, including a self-securing wire feature; multiple levels of tamper indication via a frangible seal body, surface coatings, and active detection of state through low power electronics; electronic unique identification verified in-situ through a contact reader, and physical identification via non-reproducible surface features.

2. CERAMIC SEAL BACKGROUND

The most critical element of a seal applied in a treaty verification regime is its tamper-indicating features. A loop seal will employ a wire or fiber-optic cable (FOC) threaded through a monitored item's hasp or otherwise secured, and the wire or FOC will terminate within the seal body. In single use seals such as the Ceramic Seal and metal cup seal (versus multiple use seals in which the seal wire can be removed and reattached), confidence must be maintained that the wire is unable to be removed from the seal body once secured without detection and that the seal body has remained intact such that the seal body has not been opened and the wire removed/replaced. Tamper-indicating features on the seal body serve the role of providing this confidence. It is important to note that a vulnerability review (VR) team iteratively worked with the design team to evaluate and guide the tamper-indicating features of the seal.

The properties of the alumina (99.8% Al_2O_3) material used in the Ceramic Seal body meet the requirements of "frangibility" – that is, upon deformation it tends to break into fragments rather than retaining cohesion, yet the material is strong enough to withstand the operational environment. Frangibility is important so that a tamper attempt is prone to result in fragments that are difficult to reassemble without evidence of tampering.

The Ceramic Seals are coated with spray coatings developed in partnership with Tetramer Technologies. These exterior fluorescent coatings [7-9] act as a tamper indicating feature as modification/tampering of the seal is visible under UV illumination. The coatings are transparent to allow Laser Surface Authentication (LSA) for unique physical identification of the seal body.

The Ceramic Seal provides active tamper indication by monitoring both "tamper planes" embedded in the interior of the seal, as well as monitoring connectivity between the cap and base of the seal (to determine if the seal has been opened). The tamper planes are connected to the electronics and if disrupted, i.e., signals cannot pass, software within the electronics records a tamper attempt.

Seal firmware is programmed prior to deployment; however, the Ceramic Seal requires personality programming in-situ, meaning configuration must happen via the RS-232 serial communication vias located on the cap of the seal. Personality programming loads secret keys onto the seal, sets the seal ID, message creation interval, and absolute time. The seal electronics are not powered until the seal cap and base is connected, so personality programming must happen after application of the seal in a facility.

A seal reader (two variations are currently under development and described later in this paper), which has the secret keys, sends a command to the seal (over the serial port), receives the requested message(s), and authenticates them using its copy of the secret key.

The capability of self-securing wire not only improves efficiency but touches upon security as well. The wire ends must securely terminate in the seal body in such a manner that they cannot be easily removed, and must do so in an efficient manner. In the Ceramic Seal design, the wire is routed through the monitored item and into the seal base, where it is secured by a tortuous path. Vulnerability reviews were performed on several iterations of the design before choosing a final design.

The wire itself is important as well, and appropriate commercial candidates have been identified. The current seal prototype does not have the capability to monitor the integrity of the wire using the internal electronics; however, such a capability is anticipated in future research. There are instruments available to externally connect to the wire after deployment and subsequently during verification to determine if the wire has been tampered with.

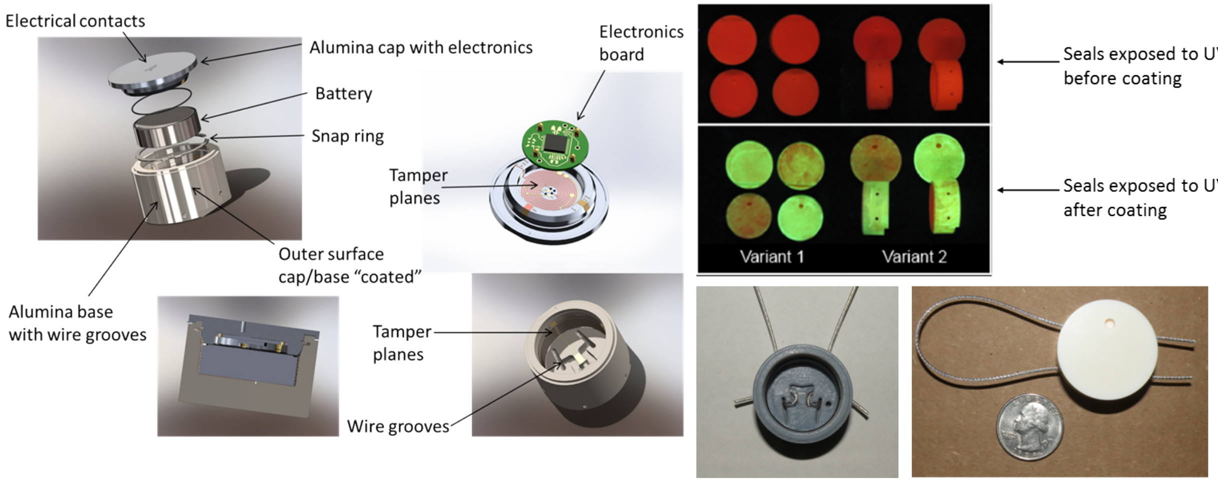

Figure 1: (Left and Bottom) Ceramic Seal design features. (Right, Top) Ceramic Seals are shown on top uncoated, with alumina based sol gel doped with terbium coatings on the bottom. Excited by 254 nm UV. Coatings images courtesy Tetramer Technologies.

The Ceramic Seal will operate as follows: the Ceramic Seal wire is looped around the item to be monitored and secured within self-securing grooves in the seal base. The battery is inserted into the seal base, and the seal cap is snapped onto the seal base, secured by a snap ring. Personality programming of the Ceramic Seal is then performed, and once that is completed the seal is ready for use. It is expected that the seal would be periodically inspected physically and electronically. An inspector would attach a reader to download state-of-health (SOH) and events. Physical inspection (visual or instrumentation) would reveal deformations in structure or coatings.

3. FABRICATION

As described above, the design of the Ceramic Seal is complete, and prototypes of the seal have been fabricated and tested. The fabrication has been an iterative optimization process. This section will describe some of the fabrication issues with the seal.

The fabrication of the Ceramic Seal consists of the following steps:

- Fabricate ceramic caps and bases
- Brazing of metal pins into cap for electrical contact
- Application of exterior, tamper-indicating fluorescent coatings
- Application of tamper planes onto seal cap
- Application of dielectric onto tamper planes
- Application of electrical patterning for circuit board onto dielectric layer
- Attachment of circuit board to cap
- Metallization of seal base interior for power contacts

The ceramic caps and bases are machined and fired by Astro Met, Inc. Brazing of metal pins into pre-determined slots on the caps for the electrical contacts occurs at SNL. Brazing is a joining process whereby a filler metal is heated above 450ºC and distributed between two or more close-fitting parts by capillary action. The caps with brazed pins and bases are sent to SRNL for application of the exterior, tamper-indicating coatings by Tetramer Technologies and characterization using Laser Surface Authentication by SRNL (Figure 2 and Figure 3).

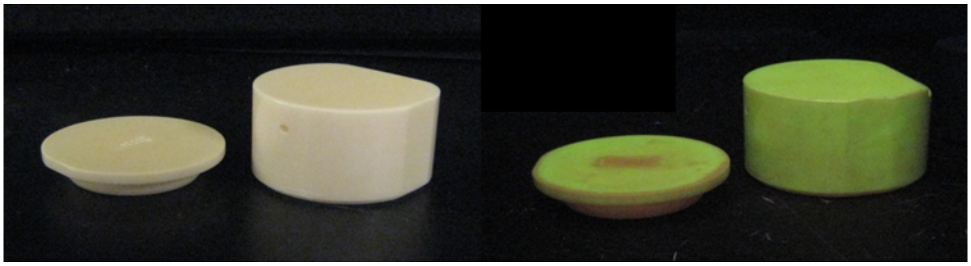

Figure 2: (Left) Tamper-indicating coatings under ambient light, (Right) under 254 nm UV illumination.

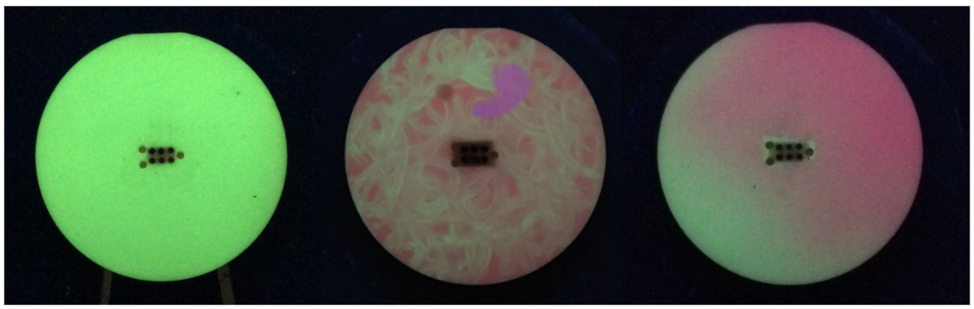

Figure 3: Tamper-indicating coatings illuminated with 254 nm UV. (Left) solid green, (Center) chaotic, and (Right) gradient.

Tamper planes have been challenging due to the fine lines, narrow line spacing, and small size of the seal. The team originally pursued direct write technology for application of tamper planes as the parameters (line width and spacing) could be easily adjusted. However, direct write was ultimately unsuccessful due to the geometry of the seal and substrate porosity. The team instead pursued physical vapor deposition which is more suited for manufacturing, but requires deposition masks. These masks are fixed and thus the line width and features need to be known in advance. The team developed laser cut masks at SNL, which is a simple and fast process. Sputtering techniques were used initially but tamper planes are now deposited using an e-beam technique.

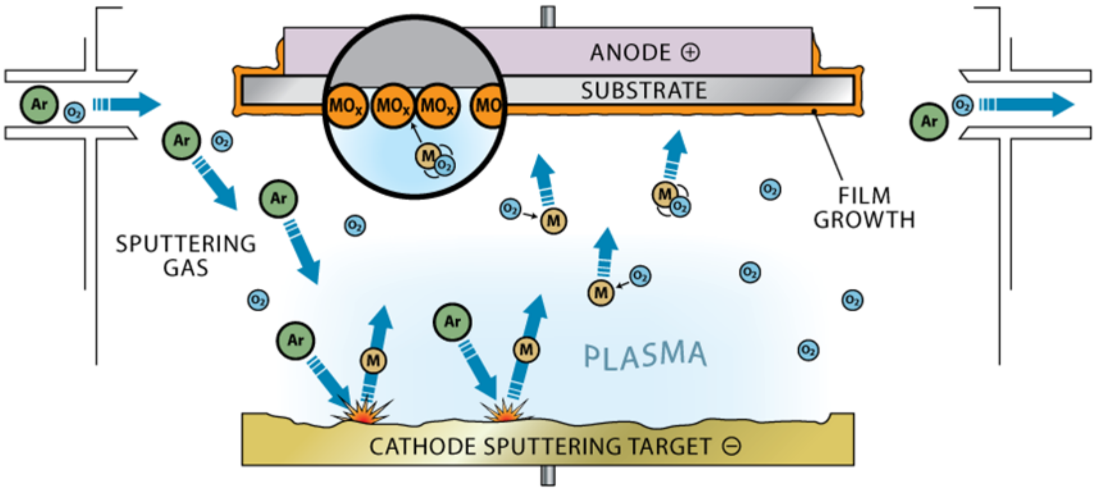

Figure 4: Physical vapor deposition process – requires physical mask to define pattern.

Figure 5: Masks. (Left and center) tamper planes use two separate spiral patterned masks. (Right) mask for circuit board electrical connections.

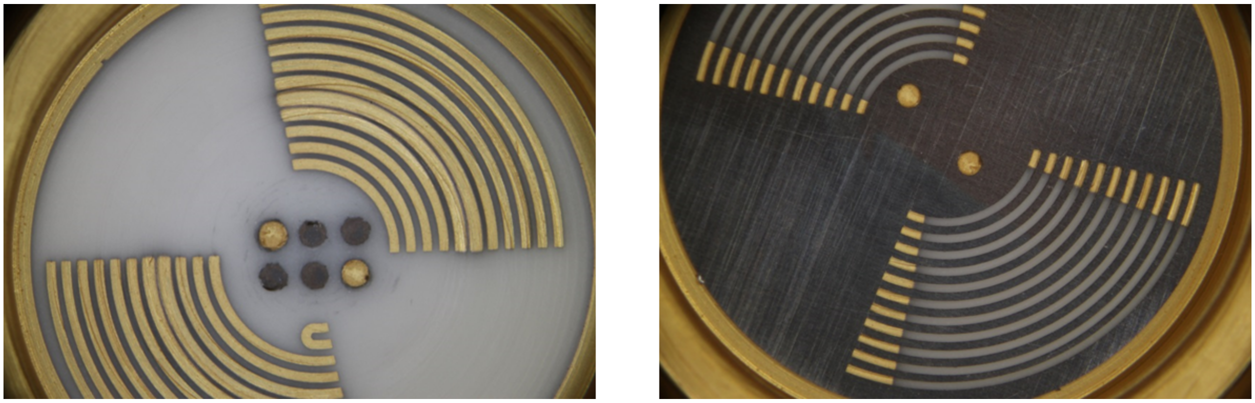

Figure 6: First and second half tamper planes.

Once the tamper planes are deposited, a dielectric coating is applied over the pattern, and baked. A second coating is deposited before hard-baking. Next the patterning for the electrical connections is deposited using e-beam techniques while another mask is in place. The circuit board is attached to the cap and aligned to the proper electrical connections.

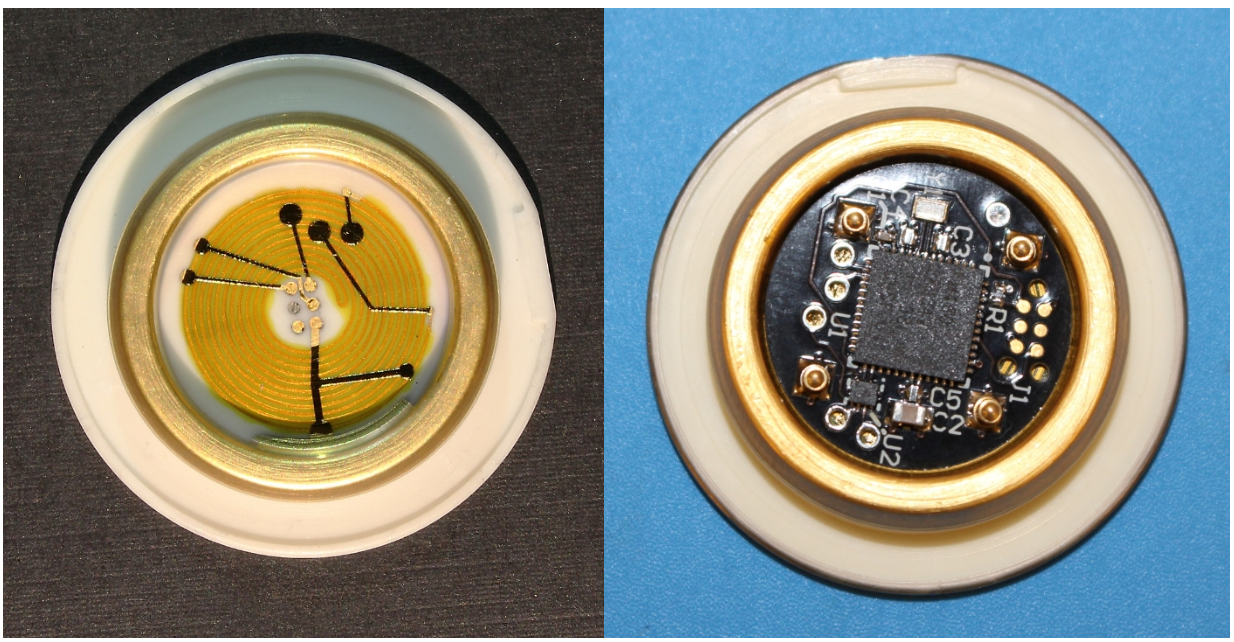

Figure 7: (Left) Electrical connection pattern on top of tamper planes, (Right) completed seal cap with circuit board attached.

For the base, a fixture is used to prevent metallization of all except the interior section of the base. See Figure 8.

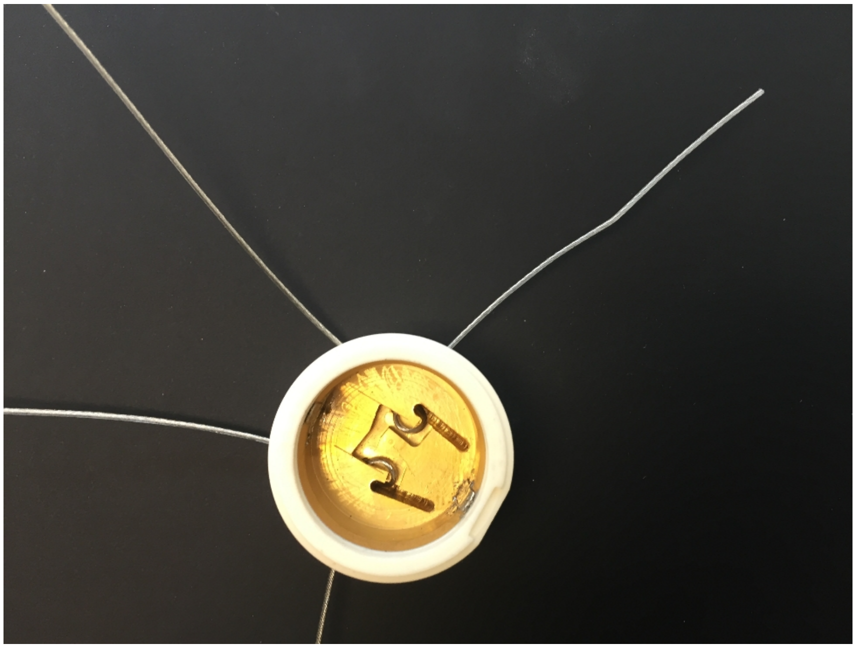

Figure 8: Seal base with wire threaded through tortuous path.

Fabrication of multiple functioning prototypes has been completed and the manufacturing process for these initial prototypes has been optimized. The manufacturing process will eventually have to be modified for mass production and to reduce the per-unit cost.

4. READER DEVELOPMENT

The Ceramic Seal is read in-situ by connecting an electronic reader to the pins located on the seal cap. SRNL is developing a handheld, standalone reader and SNL is developing an interface to a data acquisition system that is typically responsible for multiple devices. SRNL has also developed a seal module to facilitate the electrical connection between the seal and seal readers.

The standalone reader, developed by SRNL, uses an Archer 2 handheld computer from Juniper Systems with a custom seal module. The Archer 2 is designed for industrial use, is shock-resistant, waterproof, has a high visibility screen for outdoor applications, and can operate up to 20 hours on one charge. Rather than modifying the rugged Archer 2 case, it was decided to design a separate seal module to connect to the Ceramic Seal electrical contacts. This module communicates with the Archer 2 via USB. To use the seal reader, a seal is inserted into the seal module. The seal module is designed to automatically capture the seal and align the seal electrical contacts with spring-loaded contacts in the seal module. A knob on the seal module is then turned to make electrical contact with the seal. The module has internal electronics that alert the Archer 2 that a seal is connected. The Archer 2 displays the seal tamper status, battery voltage, and temperature and can provide more detailed information if desired. Seal information can also be output to a file if an inspector wants to evaluate seal data on a PC. If there is an error in communicating with the module, the Archer 2 will indicate whether it is unable to communicate with the module or the seal. Once the seal interrogation is complete, the knob is retracted and a lever on the seal module is pushed to eject the seal from the module.

SRNL has completed a second generation reader and is currently implementing a first generation crypto-token to help secure seal communications. The crypto-token employs a micro-controller to more securely perform cryptographic key management. It is responsible for validating the inspector via a passphrase and holds the secret keys necessary for reading and authenticating messages from the seal. Data on the token is encrypted until use, and the token will be held in a tamper indicating enclosure.

SRNL and Tetramer Technologies have also developed a first generation coatings reader. The coatings reader has an additively manufactured frame that holds a commercial UV lamp to illuminate the seal and an iPod/iPhone to obtain images. The seal is held by the reader and is surrounded by a reflective conical surface internal to the device. With the reflective conical surface, two images can capture the entire exterior surface of a Ceramic Seal. One image is taken with the seal cap facing the iPod and a second image is taken with the seal base facing the iPod. iOS software has been developed to compare reference and verification images obtained by the reader.

Figure 9: (Left) SRNL handheld standalone reader with seal inserted in module, (Right) Ceramic Seal Coatings Reader.

The SNL-developed tablet interface reader is a Nexus 10 tablet with a USB to serial connection to the Ceramic Seal. Once physically connected to the seal, the tablet downloads SOH and event messages, and passes the received data via Wi-Fi to a data acquisition system (DAS). The DAS may be responsible for multiple sensors/devices. SNL has completed a second generation reader that can personality program the Ceramic Seal prior to deployment (set seal ID, cryptographic keys, SOH interval), perform in-situ verification and transfer messages from the interface to the DAS.

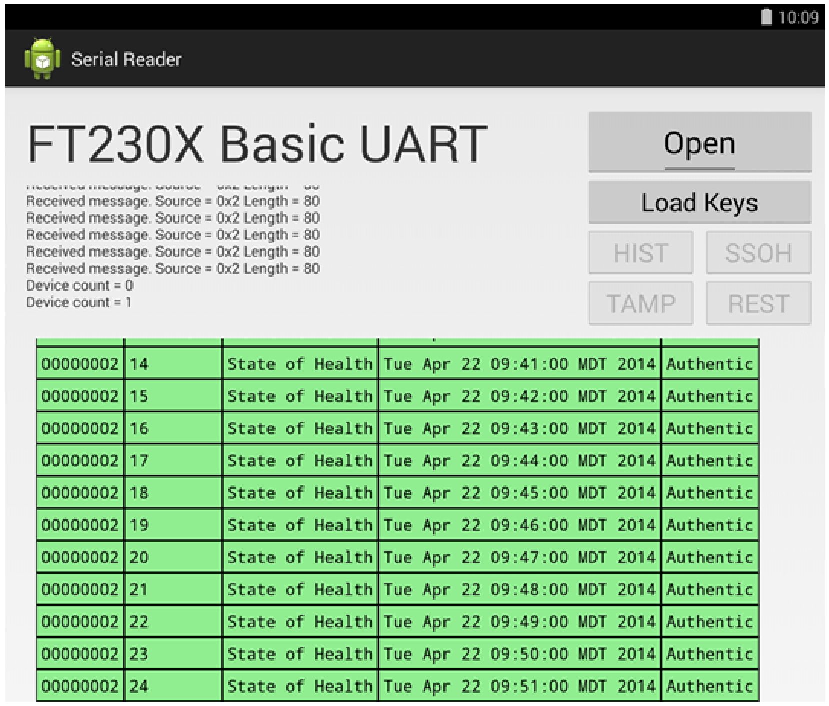

Figure 10: Tablet interface reader (screen shot of tablet applications). Messages are passed to data acquisition system (DAS).

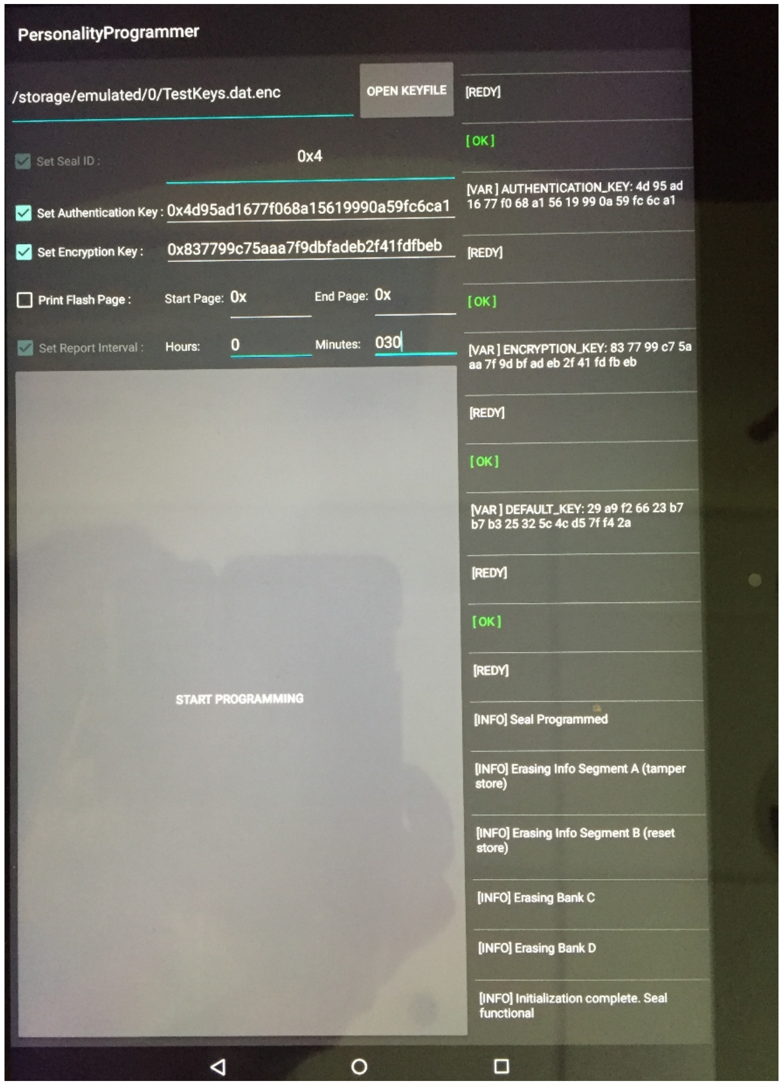

Figure 11: Personality Programmer Application on Nexus 10 tablet. Application allows user to set seal ID, authentication and encryption keys, and SOH reporting interval.

5. TESTING

As seals are fabricated, they are either sent to SRNL or kept at SNL. SRNL will perform in-depth testing in an operational environment in FY17. SNL has been performing basic operational testing – including programming seals, reading seals, reprogramming seals, user-friendliness of seals and readers, and interface to the data acquisition system.

Table 1 provides information about seals, their IDs, and their status and location. As shown, of the five seals located at SNL, three are currently operational. It is hypothesized that the other two seals lost power between cap and base and are no longer functioning, as expected. The first several seals used firmware that doesn't allow reprogramming, whereas reprogramming was allowed in subsequent batches for troubleshooting purposes.

Table 2 and Table 3 provide information on seal number 2 and 3, in particular their SOH as read by the tablet interface reader.

Table 1: Seal status

Seal #	Location	Operational	Reprogrammable?	Status or Notes
1	SRNL sent back to SNL	No (suspected power loss)	No	Will need to remove circuit board and rebuild to reinsert into inventory
2	SNL	Yes	No	Seal was initialized 11/2015 and has continuously operated
3-1	SNL	No (suspected power loss)	No	Seal was initialized 11/2015 and stopped functioning at some point. Suspect loss of power between top and bottom
3	SRNL		Yes	Shipped to SRNL 8/2016. Programmed and verified at SNL in 8/2016.
4	SNL	Yes	Yes	Reprogrammed and verified multiple times
5	SNL sent to SRNL	Yes	Yes	Operational at SNL for approximately 9 months and then sent to SRNL for further testing
8	SRNL		Yes	Shipped to SRNL 8/2016. Programmed and verified at SNL in 8/2016.
10	SNL	Yes	Yes	Programmed and verified at SNL
14	SRNL		Yes	Shipped to SRNL 8/2016. Programmed and verified at SNL in 8/2016.
17	SRNL		Yes	Shipped to SRNL 8/2016. Programmed and verified at SNL in 8/2016.

Seal number 2 is the only seal at SNL that has been continuously operating. The other seals have been used to test the personality programmer and reader applications on the tablet and therefore have been reprogrammed multiple times.

Table 2: Seal #2 SOH. Initialized Tuesday, November 17, 2015 at 14:04:14. SOH interval is every minute. Message buffer can hold approximately 1500 to 2000 messages and will overwrite messages when full.

Message #	Authentication Status	Voltage	Date	Time	Temp C	Notes
1	Pass	2.95	17-Nov-15	14:05		
1194	Pass	2.95	18-Nov-15	9:51		
2534	Pass	2.95	19-Nov-15	8:11		
3983	Pass	2.96	20-Nov-15	8:19	18.68	
7001	Pass	2.96	22-Nov-15	10:36	20.76	
10392	Pass	2.96	24-Nov-15	19:06	19.37	
10471	Pass	2.93	24-Nov-15	20:24	9.43	Left

						outside in 44 F for ~1.5 hours
12714	Pass	2.96	26-Nov-15	9:47	18.68	
25598	Pass	2.97	5-Dec-15	8:30	18.21	
35594	Pass	2.98	12-Dec-15	7:05	18.91	
52899	Pass	2.98	24-Dec-15	7:29	18.91	
78957	Pass	2.98	11-Jan-16	9:46	17.98	
99363	Pass	2.98	25-Jan-16	13:51	18.68	
119335	Pass	2.98	8-Feb-16	10:40	18.68	
143900	Pass	2.99	25-Feb-16	12:01	18.68	
161211	Pass	2.98	8-Mar-16	12:31	19.37	
171061	Pass	2.96	15-Mar-16	9:40	19.6	
303838	Pass	3.01	15-Jun-16	14:22	23.07	
354070	Pass	3.01	20-Jul-16	14:04	20.29	
354075	Pass	3	20-Jul-16	14:04	20.76	
445062	Pass	2.91	21-Sep-16	15:49	20.76	

Table 3: Seal #3 SOH. Initialized Tuesday, November 17, 2015 at 14:14:02. SOH interval is every minute.

Message #	Authentication Status	Voltage	Date	Time	Temp C	Notes
38	Pass	3.14	17-Nov-15	14:47		
1184	Pass	3.12	18-Nov-15	9:52		
2540	Pass	3.12	19-Nov-15	8:27		
3975	Pass	3.12	20-Nov-15	8:21	16.15	
6992	Pass	3.11	22-Nov-15	10:37	19.2	
10383	Pass	3.11	24-Nov-15	19:07	18.8	
12702	Pass	3.1	26-Nov-15	9:46	18.8	
25589	Pass	3.08	5-Dec-15	8:31	15.94	
35586	Pass	3.08	12-Dec-15	7:04	18.8	
52890	Pass	3.07	24-Dec-15	7:27	18.8	
78949	Pass	3.06	11-Jan-16	9:45	15.94	
99358	Pass	3.05	25-Jan-16	13:53	18.8	
119327	Pass	3.05	8-Feb-16	10:40	18.8	
			8-Feb-16			Removed kapton tape and suspect power loss

The Ceramic Seal reader and personality programmer applications on the tablet interface have functioned mostly as expected. Upon initial connection to a seal, the personality programmer application is started. The user enters the seal ID number, selects whether to use authentication and encryption (which populates the correct key from an encrypted file), and selects SOH interval. The only issue encountered to date has been a loose cable connection between the tablet interface and the seal, causing an error during programming. After programming, the Ceramic Seal reader application is used to verify the SOH of the seal. Typical commands used are SOH and HIST which result in the application displaying either the current SOH or all SOH commands since programming. The commands REST and TAMP will result in an error unless there has been a disruption to the tamper planes or a hardware reset in the electronics. The only issue with the reader application to date has been that it needs restarted occasionally or the reader application will not communicate with the seal.

The tablet interface is able to connect to a data acquisition system (DAS). It is established as a "node" on this DAS, along with many other device nodes. When a Ceramic Seal is connected to the tablet interface and read, assuming that the tablet interface is also connected via Wi-Fi to the DAS, data is passed from the tablet interface to the DAS for collection.

6. NEXT STEPS

SRNL will continue testing Ceramic Seals in an operational environment in FY17. SRNL will also continue development of the standalone reader, in particular implementation of cryptographic communications.

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