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Development of an Advanced Ceramic Seal for Maintaining Continuity of Knowledge in Treaty Verification and Safeguards Applications

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Abstract:

Sandia National Laboratories and the Savannah River National Laboratory are collaborating on research and development of technologies for an advanced capability prototype tamper-indicating device known as the Ceramic Seal. Advanced capabilities include multiple levels of tamper indication such as a frangible seal body, surface coatings, and an active detection of seal status; and unique identification via electronics as well as non-reproducible surface features. The innovation of the Ceramic Seal is the inclusion of multiple advanced capabilities in a volume comparable to the ubiquitous metal cup seal. Our advanced capability small volume seal has application in treaty verification and safeguards regimes for maintaining continuity of knowledge. Once attached to a monitored item, the seal's identity and status can be verified in-situ rather than requiring removal and analysis at an inspectorate location.

The Ceramic Seal has evolved from a first generation prototype constructed of alumina to a second generation prototype manufactured from low-temperature co-fired ceramic (LTCC). LTCC allows integration of passive electronic components into the seal construction material. Vulnerability reviews have been conducted periodically throughout the project and results used to guide the design. This paper will describe the capabilities of the current generation Ceramic Seal.

Keywords: Tamper-indicating devices; seals; Containment and Surveillance

1. Introduction

Containment/surveillance (C/S) measures aim to ensure Continuity of Knowledge (CoK) or Chain of Custody (CoC) during inspector absence on the movement of nuclear or non-nuclear material, weapons throughout their lifecycle, equipment and samples, and preserving the integrity of relevant data. Viewed as complementary to nuclear material accountancy, C/S is a critical element of many non-proliferation regimes. C/S equipment and approaches require continuous improvements because (1) the adversary continues to technically advance (which could render C/S equipment obsolete with a single technical advancement), (2) requirements could change based on the introduction of new procedures or approaches, and (3) as technology advances there may be new options for C/S equipment, including options that provide efficiency gains.

The Ceramic Seal [1,2], a collaborative effort between Sandia National Laboratories (SNL) and the Savannah River National Laboratory (SRNL), integrates multiple advanced technologies into a prototype next generation loop seal with various technical options available depending on the deployment. One possible deployment is as a replacement for the ubiquitous metal cup seal (Figure 1) used by various organizations. 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 advancements (tamper indication and unique identification) and efficiency improvements (in-situ verification and ease of application). Its innovation is the integration of these advanced 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 identification number verified in-situ through a contact reader, and physical identification via non-reproducible surface features. This paper will discuss the status of the research and development of the various technologies and integrated prototype loop seal.

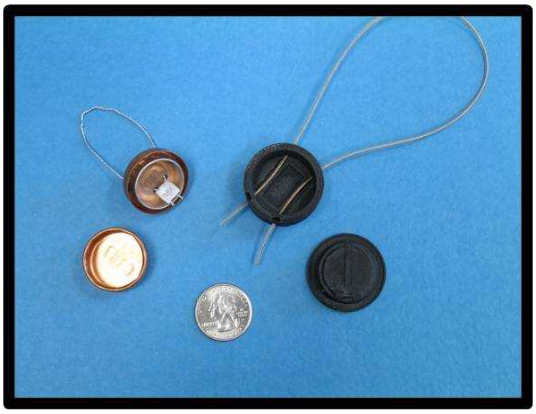

Figure 1: Size comparison of a metal cup seal (left), rapid prototype of an early model of the Ceramic Seal (right), and a U.S. quarter (bottom).

2. Advanced security

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. The following subsections describe the advanced tamper-indicating features in use by the Ceramic Seal.

2.1. Seal body

The body of the Ceramic Seal is fabricated using a low-temperature co-fired ceramic (LTCC) process. With LTCC, passive components such as resistors, capacitors and inductors along with conductive line traces can be integrated into a monolithic package, thereby freeing valuable space for active components and the battery. Furthermore, LTCC packaging can reduce electronic noise and radiated emissions from the device [3].

The properties of the material used in LTCC 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 might result in difficult-to-reassemble fragments. Other materials also meet these requirements; however, they do not have the added benefits of LTCC, namely the ability to integrate electronics. The first prototype of the Ceramic Seal was constructed of 99.8% Al_2O_3. The current version, using DuPont 951 LTCC Green Tape™ material, is manufactured using, by weight, 50.3% Al_2O_3, 31.3% SiO_2, 11.9% PbO, 1.1% K_2O, and 5.4% CaO [3].

The LTCC manufacturing process involves punching unfired or green ceramic sheets with via holes, screening with a conductor, stacking with excellent precision, laminating the result into a monolithic three-dimensional structure, and firing in a furnace. Figure 2, Figure 3, and Figure 4 show the Ceramic Seal during the LTCC process.

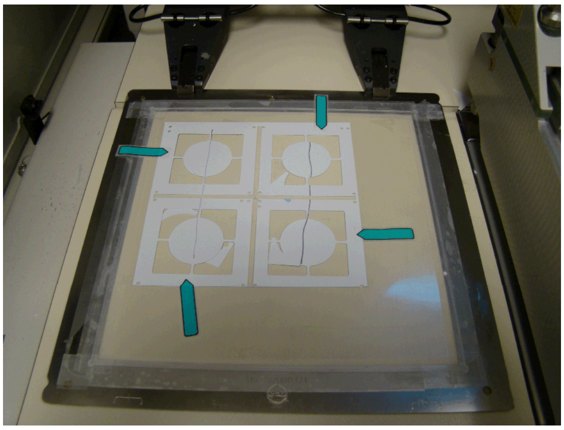

Figure 2: LTCC Green Tape™ punching process.

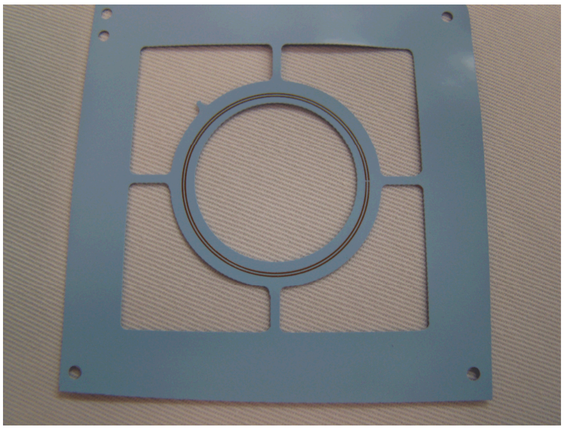

Figure 3: Conductive trace screen printing.

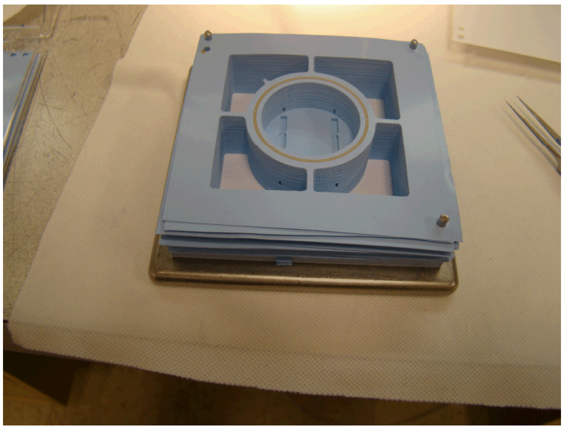

Figure 4: Green Tape™ stacking prior to lamination.

2.2. Tamper planes

As mentioned above, conductive line traces can be integrated into the LTCC – some are used to connect electronic components and a separate set are embedded throughout the body of the seal for tamper indication (tamper planes). These tamper planes are connected to the electronics and if disrupted, i.e., signals cannot pass, software within the electronics impacts performance.

2.3. Active tamper indication

The Ceramic Seal provides active tamper indication. Physically, the electronic components are attached to the embedded line traces in the seal cap (see Figure 6 for electronics housing). The Ceramic Seal utilizes a single microcontroller. Two battery springs make contact with a battery directly below the electronics.

Seal firmware is programmed prior to deployment; however, the Ceramic Seal requires “personality programming” in-situ, meaning configuration must happen via the RS232 serial communication vias located on the cap of the seal. Personality programming loads the secret keys onto the seal, sets message creation interval, and sets absolute time. The electronics will not be powered until the seal cap and base is connected, so personality programming the seal must happen after it has been closed. However, for added security, we have designed the seal to accept personality programming only one time, i.e. cryptographic keys can only be loaded a single time.

The seal creates several message types – state-of-health (configurable), anomalous events, and the seal interrogation history. As messages are created, we append a message authentication code (MAC) using the 128-bit CMAC algorithm with AES cipher (and optionally encrypted using 128-bit AES) before storing in flash memory. The MAC derives its uniqueness from the secret key, the seal’s 8 byte ID, a non-repeating message count and a clock. The 8 byte ID is assigned during firmware programming and can be a unique number by procedure. The MAC ensures that the seal itself can be uniquely identified due to the combination of the 8 byte ID with the cryptographic key.

A seal reader, which will also have the secret keys, will be able to send an authenticated command to the seal (over the serial port), receive the requested message(s), and authenticate them using its copy of the secret key.

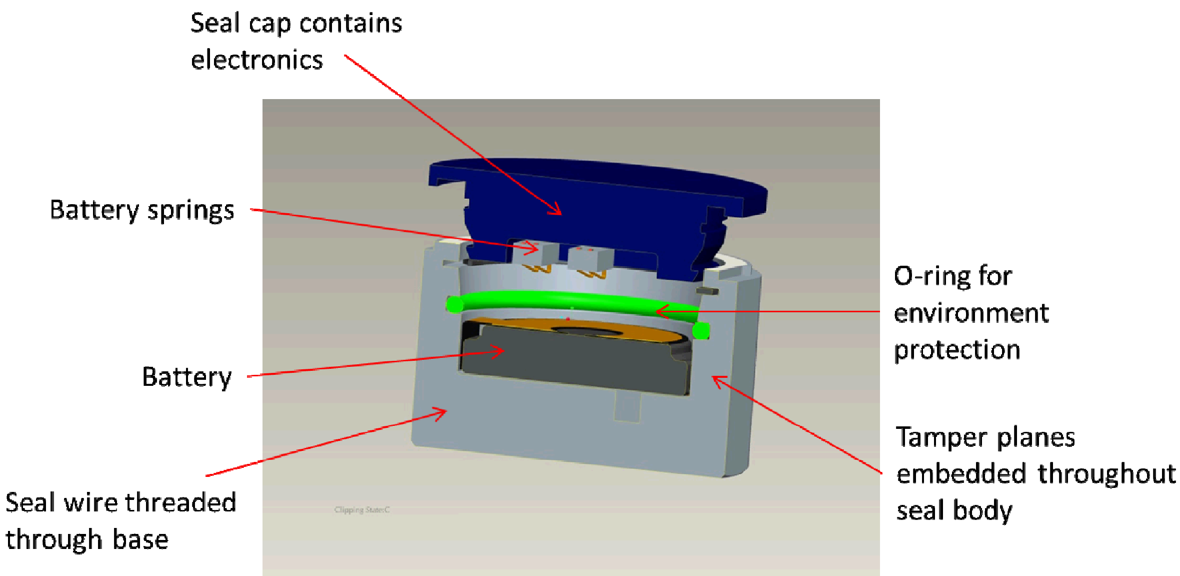

Figure 5: Seal concept. Image courtesy SRNL.

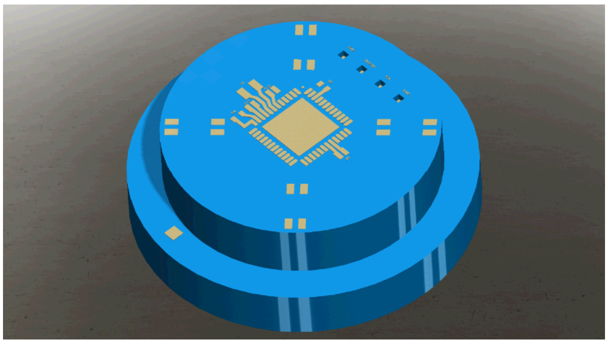

Figure 6: Seal cap, fabricated using LTCC, with electronics underside.

2.4. Coatings

SRNL is developing coatings [4,5] for application to the outer surface of the seal body. Modification to the seal body will be noticeable under a fluorescent light. As the coatings are in development, they will not be discussed in this paper.

3. Improved efficiency: self-securing wire

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. The design team and SNL vulnerability review (VR) team iterated on several designs before choosing the method shown in Figure 7. The wire itself is important as well. Active research in identifying appropriate wires is on-going and commercial candidates have been identified.

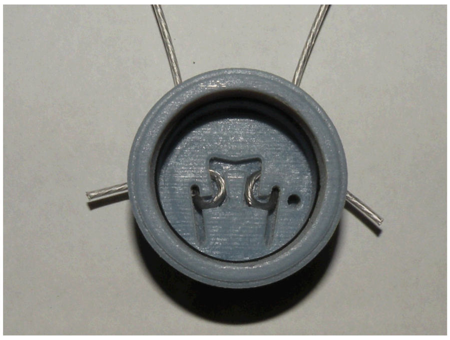

Figure 7: Rapid prototype of seal base highlighting self-securing wire mechanism. Image courtesy SRNL.

4. Improved efficiency: in-situ verification

The Ceramic Seal allows in-situ verification with a contact reader to verify its integrity. Currently, the reader is implemented using a serial connection and a laptop computer. As described in section 2.3, the seal reader will contain the same secret keys as the seal. It will be able to send an authenticated command to the seal over the serial port, receive the requested message(s), and authenticate them using its copy of the secret key. The reader supports the following commands: request latest sensor state of health, request a specific message number from the seal, request that the seal send the latest anomalous/tamper message, request that the seal send all anomalous/tamper messages stored on the seal, and personality programming.

5. Next steps

The next step in the design is to complete development of the Ceramic Seal software. Once complete, the VR team will review the electronics and software and provide guidance for any modifications, if any, to the electronic and software design team.

The seal prototype will be fabricated and assembled using LTCC and will consist of tamper planes, the electronics, battery, and coatings from SRNL. The completed prototype will undergo functional testing, and then a comprehensive VR. Final modifications will be made to the seal based on guidance from the VR team.

6. Acknowledgements

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Unless otherwise noted, all pictures or images have been taken or created by Sandia National Laboratories.

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