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Puck Passive Loop Seal

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ABSTRACT

Sandia National Laboratories (SNL) is advancing technical capabilities used in passive loop seals. The "Puck" seal uses a set of International Atomic Energy Agency (IAEA) requirements for new passive loop seals published in 2020 as a design guide. The seal is based on an oxygen-sensitive inner mixture encased in an oxygen-impermeable shell, is monolithic rather than two-part, incorporates self-capturing wire features, contains colored water beads and bubbles formed during processing as unique identifiers, and visually indicates tamper (whether from seal body penetration or from seal wire removal) by irreversibly changing the seal body from multi-colored to black. SNL is currently designing and developing prototypes of the Puck seal. Further, SNL is working together with Oak Ridge National Laboratory (ORNL) on another seal version, Puck/SAW, that uses the same seal body and incorporates a surface acoustic wave (SAW) chip that can monitor wire continuity and provide a unique identifier upon standoff interrogation. This paper will provide details on the design and development of Puck prototypes.

INTRODUCTION

Tamper-indicating devices (TIDs, or seals) are an essential tool deployed for international nuclear safeguards, arms control, domestic security, and other (including commercial) regimes to ensure monitored items are not accessed without detection. Seals should continually technically advance in all these regimes since adversary capabilities continually advance and new technologies may provide enhanced effectiveness (e.g., advanced tamper-indication or unique identifiers) and efficiency (e.g., verification in less time, more obvious tamper features, or easier installation and maintenance); furthermore, the IAEA has specifically expressed its desire for more advanced seals.

Passive loop seals are extensively used in international safeguards to maintain the continuity of knowledge of declared material and equipment. While there are a plethora of loop seals available commercially, the IAEA has extremely stringent requirements that are not met by commercial offerings. One of those requirements is that the unique identity of the device can be proven to ensure that it is not a counterfeited replacement; the identity element of the seal must be non-reproduceable and cannot be remanufactured but can be measured and verified. Another requirement is that the seal employ tamper-indicating features such that the seal wire cannot be removed and replaced without detection, thereby preventing illicit access to the monitored item.

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For reference, the most ubiquitous loop seal deployed by the IAEA is the metal cup seal (also called CAPS)—a small, robust, simple device that captures sealing wire between two metal cup halves, Figure 1. Unique identification characteristics are manually added to the long-used metal cup seal prior to being deployed to the field. Significant effort and cost are required to verify the identity and integrity post-mortem after seal removal and return to IAEA Headquarters (HQ). A best practice for seal programs is to periodically refresh seals; the longer a seal is used, the more time for an adversary to formulate an attack, or, if an attack already exists, the longer an adversary has to take advantage of it. An effort has been underway to replace various IAEA seals for these reasons, particularly to create an economical seal that combines robust tamper-indicating mechanisms with unique identification-characteristic materials. The IAEA has been seeking a replacement for the metal cup seal for many years and has identified a need for a passive loop seal with general high-level requirements of in-situ verification, minimal use of external tools, unique identification, and tamper-indication of the seal body. The IAEA published a set of approximately 40 seal requirements in mid-2020 [1] - see Table 1 for a subset of these requirements. Our goal is to use these published seal requirements and our significant subject-matter expertise in tamper-indication and seals to research, design, develop, and environmentally test a new passive loop seal. The impact is improved effectiveness (tamper-indication of seal body, inherent unique identifiers) and efficiency (quick tamper detection through visually obvious tamper responses, easy installation with minimal external tools required) providing benefit to the IAEA and to other regimes utilizing seals. We do note that the IAEA has developed a new passive loop seal very recently (first sharing details at the 2022 Safeguards Symposium) based on its requirements – our project was proposed and funded during the same time period that the IAEA was designing and developing the Field Verifiable Passive Loop Seal (FVPS), see Figure 1. However, we have designed and are developing features that differ from the IAEA's seal that provide value to advancing technical capabilities.

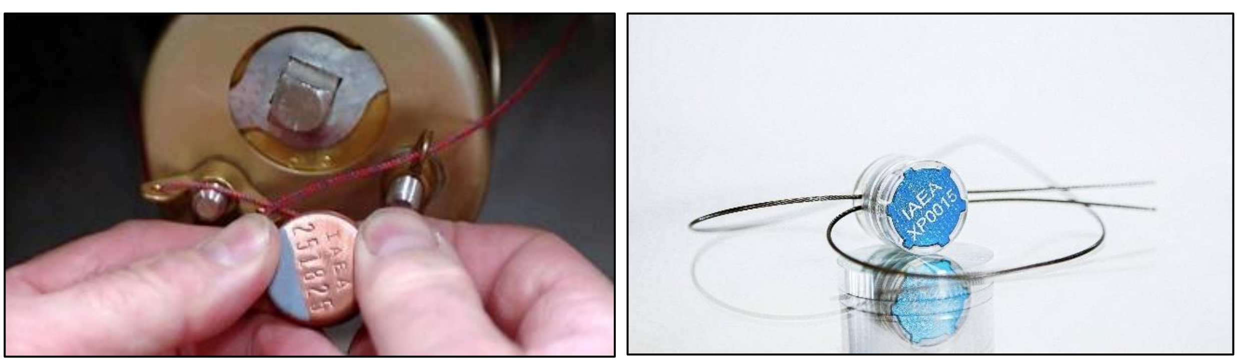

Figure 1: (Left) metal cup seal, image from IAEA, 2020, (Right) FVPS, image from https://www.iaea.org/bulletin/small-device-big-effect

Table 1: Subset of IAEA requirements versus the Puck seal design concept.

IAEA Requirement	Puck seal design
Seal body shall enable reliable and irreversible connection of sealing wire ends in tamper indicating manner	Once pierced with wire, oxygen-sensing mixture is penetrated and if wire is removed will be exposed to air, turning the seal body black. Wire is self-captured in seal body upon insertion.
Sealing wire shall be automatically captured inside seal body when latter is fully closed	Seal design incorporates wire capture mechanism
The seal shall be closed manually without any tools	Wire goes through monolithic seal body and cinches to secure it to object being sealed
Closing shall be clearly indicated by a tactile and, optionally, audible or visual feedback	Seal body does not require "closing"—instead it is monolithic
Seal body shall conclusively indicate any attempt to open and reclose it	Seal is monolithic so cannot be opened and closed; if seal body is penetrated or if wire is removed, tamper is indicated by an irreversible color change from multi-colored to black
Seal body integrity verification shall be performed by visual inspection	Seal body integrity is visually obvious as seal body will turn to black upon tamper
The seal body shall have unique identification features making its duplication (cloning) practically impossible with state-of-art techniques	Inherently unique identification features (colored water beads) and bubbles formed during manufacturing

SEAL BODY

Based on the IAEA requirements, we have designed Puck as cylindrical shaped with dimensions 30 mm diameter by 15 mm height. Figure 2 shows a functional drawing of the seal on the left and a computer-aided design (CAD) drawing on the right, with annotations that will be described by each section in this paper.

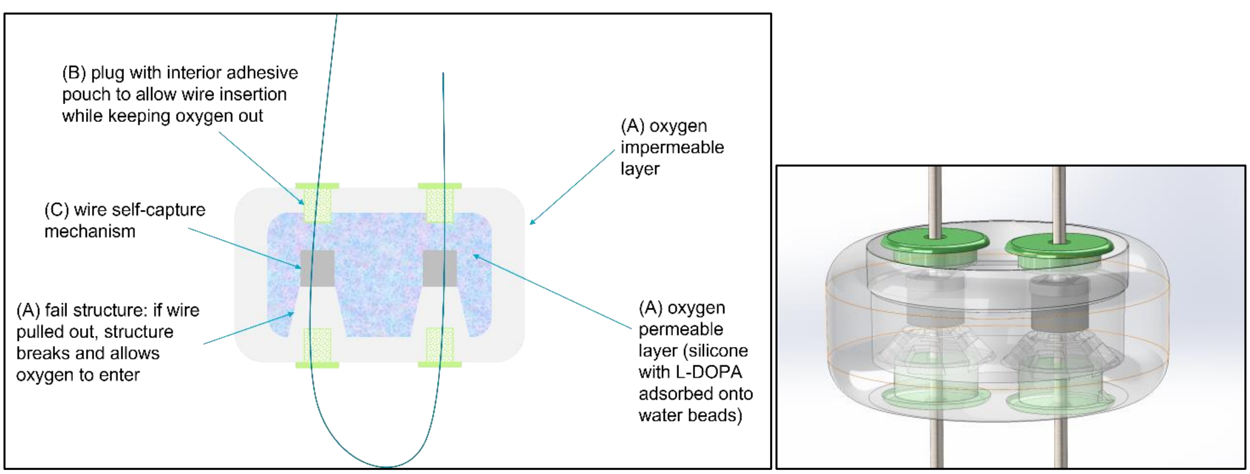

Figure 2: Puck design concept – (Left) cartoon drawing, (Right) CAD drawing. Images from SNL.

The seal body encompasses letter "(A)" in Figure 2—an outer oxygen impermeable shell (shortened to outer shell throughout remainder of paper), an inner oxygen-permeable sensing mixture (inner sensing mixture), and a structure (Figure 3) built into the outer shell that catastrophically fails if wire removal is attempted, thereby causing significant influx of oxygen into the inner sensing mixture. The inner sensing mixture is encapsulated such that any oxygen entering the inner sensing mixture (whether from outer shell penetration or removal of wire) causes an irreversible color change from light multi-colored to dark brown/black, as shown in Figure 4, where we drilled into the seal body.

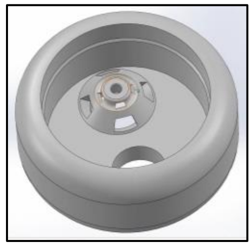

Figure 3: Fail structure allows increased oxygen flow into the inner sensing mixture if seal wire is removed. Image from SNL.

Figure 4: (left of each image) Material samples showing outer shell and inner sensing mixture; (right of each image) material samples demonstrating tamper event, which causes seal to irreversibly turn black. Note the unique identifier patterns formed from both the colored water beads and the bubbles. Pictures from SNL.

The inner sensing mixture and outer shell material were studied under a previous project called "Bleeding Materials," where the basic feasibility of materials (in terms of tamper-indication) was demonstrated [2]. To initiate a visible and drastic color change, the tamper-sensing mechanism utilized an oxygen-sensitive compound, 3-(3,4-dihydroxyphenyl)-L-alanine (L-DOPA). In an inert environment such as a glovebox, L-DOPA solution was mixed with an oxygen-permeable silicone. The solution was poured into an epoxy tray and then capped with additional epoxy to finalize the encapsulation process. A material sample from the previous project is shown in Figure 5.

Figure 5: Material samples from prior Bleeding Materials project, whose goal was to develop tamper-indicating enclosures with visually obvious tamper response. (Left) untampered sample, (right) sample after drilling into inner sensing mixture (tampering). Pictures from SNL.

For the current project the previous approach was modified to create a tamper-indicating device by designing wire insertion and capture mechanisms into the seal body, as shown in Figure 2 above. In addition to mechanical design for the wire insertion and capture, the current project requires additional R&D on processing techniques and concentration studies for consistent tamper response. The processing aspect of the sensing mixture has been optimized by evaluating a range of amounts for each of the three main components: colored water beads (a material addition from the Bleeding Materials project to improve processing), L-DOPA color-changing solution, and oxygen-permeable silicone. An optimal ratio of these three components has been established, along with a defined production protocol including L-DOPA soaking time, which will ensure desired performance and consistency of the sensing mixture moving forward. Additionally, the processing of the water beads themselves has been made consistent by utilizing a commercial blender to chop hydrated out-of-the-box beads to a suitable size for their incorporation within the sensing mixture. Figure 6 shows some of the processing studies to determine optimal material ratios (size of the water beads, silicone amounts, and L-DOPA amounts) and ensure consistency of production.

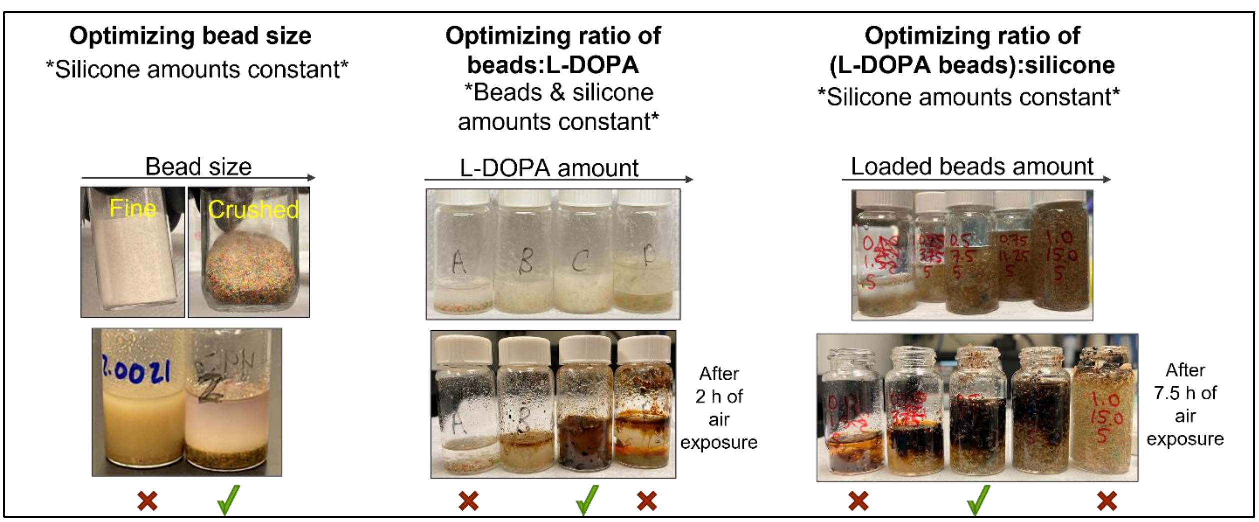

Figure 6: Processing studies to determine optimal material ratios and ensure consistency of Puck production. Pictures from SNL.

OXYGEN PLUG

To prevent oxygen from entering the seal's inner sensing mixture as the wire is inserted through the seal body, we are designing and developing an oxygen plug constructed of rubber with an embedded adhesive pouch. The rubber will allow the seal wire to puncture into the seal, and the adhesive pouch is intended to keep the oxygen out as the wire is inserted. Initially, the team considered the adhesive as a wire capture mechanism as well as oxygen barrier, but later decided that the IAEA requirement "sealing wire captured inside the seal body shall not be pulled out under the constant load up to at least 30 kg" might be too high for the adhesive to hold the wire in place. A separate wire-capture mechanism is under design, and the adhesive will only serve as the oxygen barrier.

As shown in Figure 7 and Figure 8, the plug has been designed and a prototype has been developed. This prototype is first being tested with simple seal features—the outer shell is 3D-printed with a single hole on the top and bottom of the seal, the plug is pushed in that hole, the seal is filled with the inner sensing mixture, and a top piece is adhered. The team will perform testing to ensure that the plug (no wire) prevents oxygen from entering the seal, then will insert a wire and repeat the test, and finally will remove the wire and repeat the test again, noting whether the seal turns black and the time it takes to do so.

Figure 7: (Left) 3D-printed outer shell with single hole for plug testing, (Right) assembled seal body with inner sensing mixture included. Pictures from SNL.

Figure 8: 3D-printed body with plug inserted and wire penetrating through the plug. Picture from SNL.

The adhesive pouch is not yet included in the above testing. However, studies are ongoing to determine the composition of the adhesive and time/depth of curing. It may be beneficial to cure the adhesive more rapidly using an ultraviolet (UV) penlight, which can also serve to improve depth of cure. The need for a UV penlight during seal application is not ideal (since the IAEA requirements dictated that the seal should not require external tools for application); however, the penlight may be necessary to ensure the adhesive is stable and in a "known state" within the seal.

For the purposes of this project, UV-curable resins based on acrylate and methacrylate chemistries were investigated for the adhesive, due to several factors. Notably, these chemistries are widely available and display fast, yet controllable curing kinetics. Also, they are often used in adhesives formulations due to their excellent adhesion to a wide variety of substrates. Due to the large variety of acrylate and methacrylate chemistries available to the adhesives formulator, certain criteria of the adhesive's performance envelope can be easily dialed in. For this project, one of these criteria centered around oxygen permeability, and the team ultimately selected methyl methacrylate (MMA). In addition to the selection of a resin for the adhesive, a photoinitiator is also needed to initiate UV curing. Nine photoinitiators were down selected for testing, and of those nine, only one successfully allowed UV curing at the 365 and 395 nm wavelengths available in commercial UV penlights.

WIRE CAPTURE

The wire capture mechanism is designed to allow wire to be inserted one way through the seal, but not pulled back out, and to do so without any external instruments (self-capture). From the IAEA requirements, "sealing wire captured inside the seal body shall not be pulled out under the constant load up to at least 30 kg". Several designs are under consideration and currently being mechanically tested. Ease of manufacturing will be considered as well.

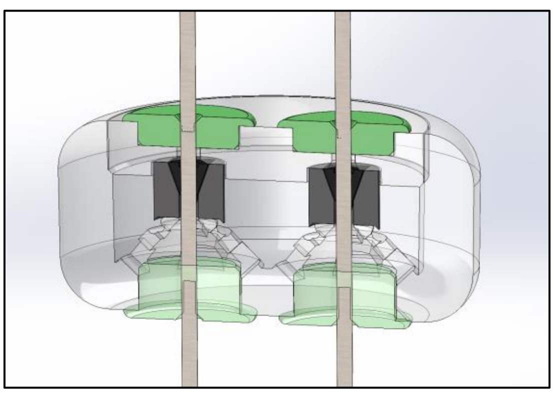

Figure 9: CAD drawing of seal – one wire capture mechanism design is shown in gray/black. Image from SNL.

TESTING

Various iterations of the seal (material sample only, with no penetrations as in Figure 4; seal body with single oxygen plug on top and bottom as in Figure 7; seal body with oxygen plugs and wire capture mechanism; fully assembled seal body with wire inserted as in Figure 9) will be environmentally tested, including the following types: thermal, radiation, mechanical, accelerated aging via UV exposure, and chemical/solvent/corrosion. Some of the environmental requirements are listed in the IAEA requirements document [1], but the document also references another testing document [3]. After each test is performed, we will be cautious to test for the possibility of false positives in the seal (no color change to black due to environmental stimuli) and that tamper response remains (no false negative, by drilling into post-tested object and ensuring color changes to black). Table 2 provides high-level testing information and does not include every test that will be performed. Testing will be conducted in replicates, and some tests will involve multiple test stimuli, such as performing mechanical and UV testing after radiation testing.

Table 2: High-level testing

Test type	IAEA requirement	Notes
Thermal	–50°C to +150°C (up to 3 years exposure in this range)	• Range based on available facilities and to mimic IAEA's thermal testing range of FVPS –30°C to +70°C • Testing will span various combinations of temperature, relative humidity, and ramp rates
Radiation	Seal shall maintain tamper indicating properties after receiving doses in the range of 0.1, …, 20 Gy/h for gamma radiation	• This range corresponds to 10–2000 rads/h or 0.003–0.56 rad/s • We will work with an SME to determine length of exposure
Mechanical	Drop test—seal body shall receive no damage if dropped onto concrete surface from height of 1.2 m	
	Seal body shall not be destroyed or deformed when person wearing protective shoes steps on it	
	Sealing wire shall have tensile strength of no less than 1570 N/mm^2	IAEA indicates 7 bundles of 19 wires, jacketed with nylon as one wire possibility. SNL testing similar types of wire.
	Sealing wire captured inside seal body shall not be pulled out under constant load of at least 30 kg	Wire self-capture mechanism will be tested against this load
Accelerated Aging via UV		Suntest XLS equipped with Xenon lamp and filter to allow wavelengths between 300–400 nm with irradiance range 30–65 W/m^2
Chemical	Seal shall maintain tamper indicating properties after up to 3 years exposure to	• May mean humid and/or salty environments

	corrosive environments typical of nuclear facilities	• Salt Fog and Salt Spray instruments may be used
Weight	Seal body weight shall not exceed 25 g	Figure 4 body weighed 10 g

SUMMARY AND NEXT STEPS

We are advancing technical capabilities used in passive loop seals by designing the Puck seal according to IAEA requirements for passive loop seals. The seal is based on an oxygen-sensitive inner mixture encased in an oxygen impermeable outer shell, is monolithic rather than two-part, incorporates self-capturing wire features, contains colored water beads and bubbles formed during processing as unique identifiers, and visually indicates tamper (whether from seal body penetration or from seal wire removal) by irreversibly changing the seal body from multi-colored to black. We have designed many of the seal features and are currently developing and testing prototypes. While this paper addressed just the Puck passive loop seal, ORNL is designing and developing a SAW chip, antenna, and wire, that will allow stand-off interrogation of the seal identifier and wire continuity status. Next steps include finalizing oxygen barrier plugs and the wire self-capture mechanism, and testing all components against a test plan, which is based on [1] and [3]. A prototype Puck seal will be completed by mid-to-late 2023.

REFERENCES

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[2] H.A. Smartt, et al, "Tamper-Indicating Enclosures with Visually Obvious Tamper Response: Final Report," Sandia National Laboratories Technical Report SAND2021-4322, Albuquerque, NM, April 2021.

[3] Qualification Test of IAEA Safeguards Equipment, SG-PR-12145, ver. 1, 2014-03-28

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