# An Integrated Passive (Battery-Free) Tag-and-Seals-and-Sensor (TSS) for International Safeguards

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**Abstract.** The ability to reliably and securely automate the monitoring of sensitive nuclear materials (SNM) is an important goal in International Safeguards applications. In this paper, we report on a new advanced secure passive (battery-free) RFID tag integrated with fiber optics seal and a variety of sensors that allows real-time monitoring of items through secure wireless communications that employs *AES encryption* and *dynamic authentication*. This unique passive tag-seal-sensor (TSS) offers real-time monitoring of sensitive assets and securely provides valuable information (a data set consisting of the tag ID, seal tampering state, temperature and accelerometer data, and time stamps) ***without the need for batteries***. The TSS units not only aid the inspectors to perform their tasks effectively, but would also allow real-time inspection in large-scale facilities as they can be used in both continuous monitoring as well as in on-demand monitoring scenarios.

## 1. Introduction

The ability to reliably monitor seals remotely improves the efficiency and effectiveness of current containment and surveillance approaches. Although conventional seal technology has been used on containers in International Safeguards applications, they lack effective continuous monitoring of seal status. Passive seals, such as metal seals and Cobra seals that do not need batteries, require visual inspection and do not provide real-time monitoring capabilities. On the other hand, seals with remote monitoring capability such as Remote Monitoring Sealing Array (RMSA) depend critically on batteries for their operations. Figure 1 shows examples of some passive and active seals currently used by the IAEA.

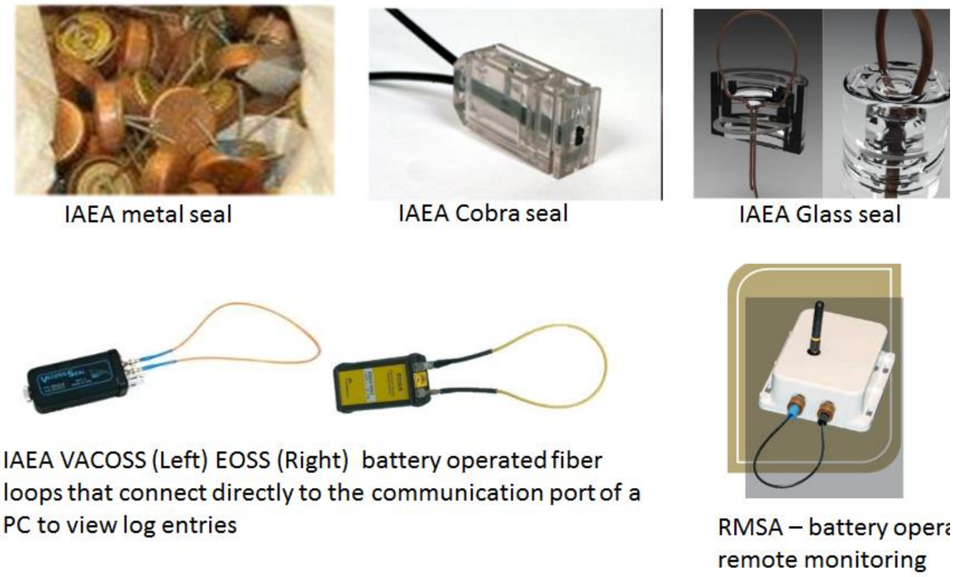


*FIG.1. Conventional seals either require visual inspection or depend on the lifetime of their batteries.*

The passive RF Tag-and-Seal-and-Sensor (TSS) introduced in this paper is a unique system developed specifically for international safeguards by LLNL and its industrial partner, Dirac Solutions Inc. (DSI). The TSS allows remote monitoring of a fiber optics seal status, data from a variety of sensors (including temperature, accelerometer, and possible gamma gross rate), and unique ID using a secure AES encrypted and dynamically authenticated wireless channel without the need for a battery. In addition, the TSS has an optional physical security feature, which is called "self-destruction upon removal". This unique tamper resistant feature allows the RFID chip to break irreversibly with any attempt to remove the tag from the container. Figure 2 shows the concept of operation for continuous monitoring and on-demand monitoring using TSS.

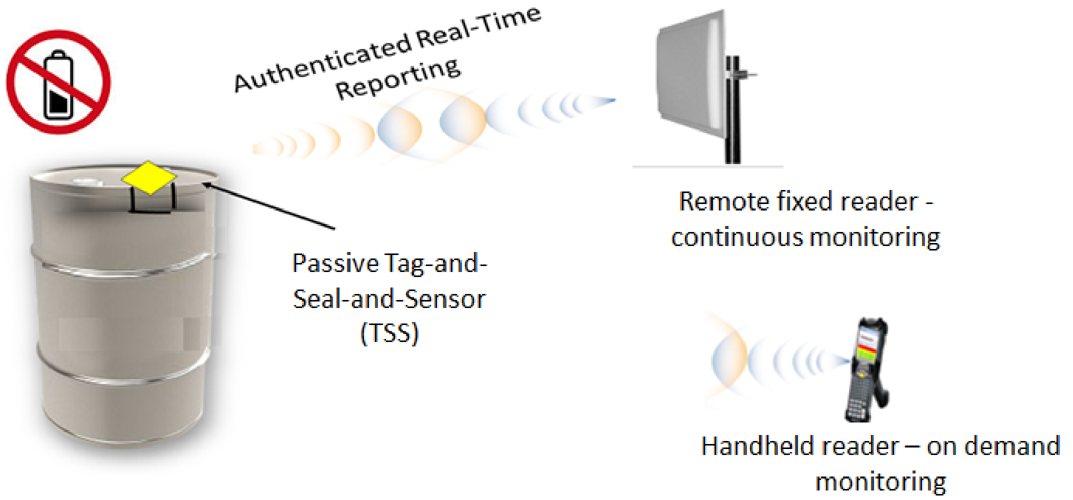


*FIG.2. Concept of operations for long-range passive (battery-free) tag-and-seal-and-sensor with data and physical security. Continuous monitoring can be performed using the remote fixed readers, and on-demand monitoring is available with handheld readers.*

As discussed above, TSS has the same capabilities as active seals in that it allows real-time monitoring. However, the battery lifetimes of conventional active seals are limited or unpredictable. As the long-term storage of SNM might last for several years, the TSS extends the lifetime of the physical seals and tags and sensors indefinitely, while getting the same performance of active seals and tags. Furthermore, the data and physical security features of TSS are countermeasures against the two typical RFID threats: (1) man-in-the-middle threat, and (2) cloning threat. Therefore, the TSS system is transformational in addressing a critical need in the Safeguards area for long-term real-time and on-demand monitoring.

## 2. Advantages of Passive (Battery-Free) TSS

Passive TSS has significant advantages for IAEA applications, as the active tags and seals that need a battery to operate pose the following challenges in various operational scenarios:

1. Operational lifetime is limited by fixed capacity of their battery.
2. Depletion of battery is dependent on both transmission and computation and the stated lifetime in battery specifications might be much shorter depending on the number of transmissions or the tag's level of operation. For example, computational requirement is increased with the need for authentication, encryption, and sensor operation.
3. Life expectancy of batteries and therefore, the tag and seal unit is unpredictable.

4. Battery health status is difficult to predict and monitor.
5. Active RF transmission is undesirable in nuclear facilities, as active transmission by 1000's of tags can lead to security issues and also increase the noise floor in the facility.

It's important to note that, TSS units do NOT actively transmit any signals and their communications with a reader is based on "backscattered technology". This means that *one reader actively transmits signals and 1000's of TSS units only reflect or modulate the transmitted signal (like a mirror).* So the level of active signal transmission is much less in TSS systems.

Furthermore, in any successful system design reducing the number of critical components in a system always increases its reliability over a long period of time; therefore, removal of the batteries brings additional reliability to various monitoring applications.

## 3. Anatomy of TSS System

The TSS system consists of a TSS sensor unit and an RFID reader, where one reader is capable of reading thousands of TSS units. The data collected by the reader from TSS units will be displayed on a monitor screen in a command and control station, or a mobile unit, such as an iPad, for inspector's convenience. This system was developed from ground up to satisfy IAEA's need for remote monitoring of SNM containers with the following requirements for RFIDs:

1. **Reliable operations on metallic containers:** As the conventional RFID signals fail to operate reliably when it's placed directly on metallic objects (multipath attenuation and signal cancellation).
2. **Long lifetime, ideally passive (no batteries):** eliminating the need for batteries provides a maintenance free and indefinite lifetime for the monitoring tag.
3. **Long communications range:** In order for tags to be useful for remote monitoring applications, they have to communicate in long range with their readers. Even in on-demand monitoring scenarios readers needs to be in a standoff location to prevent inspectors and operators to be close to possible leaky containers.
4. **Data security:** Strong encryption and dynamic authentication eliminates the man-in-the-middle threat and unauthorized readers cannot detect or misuse the messages between tag and reader.
5. **Self-Destruction upon Removal:** This requirement is based on the "Cloning Threat" for typical RFID's as it conventional RFID tags can be removed and cloned to spoof the system.
6. **Ability to work in harsh physical environment:** Many SNM containers (for instance $UF_6$ cylinders) experience very harsh physical environment such as extreme heat, or exposure to radiation levels, so the RFID tags have to be resilient to such environments with proper packaging.

### *3.1 TSS Unit*

The TSS unit is a passive (battery-free) RFID tag that is integrated with a fiber optics seal and a variety of sensors that operate without the need for batteries. The RFID tags, seals, and sensors are powered-up remotely by the reader antenna, from a distance of 6 meters or more. These sensor units do NOT actively emit RF signal, instead they reflect the received RF signal from their reader with a unique modulation scheme providing unique ID and other data. The communications between the tag and reader is achieved very securely by strong encryption and dynamic authentication. The passive TSS is also equipped with a mini-Guillotine under the RFID chip that gets activated when the unit is lifted by 1 mm, hence, the RFID board irreversibly breaks and memory is destroyed, and the tag becomes completely unreadable and mechanically destroyed.

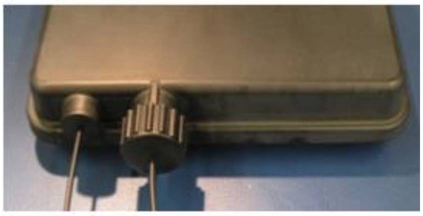

*FIG.3. (Left) Passive TSS (Right) detail of weatherproof, field-serviceable fiber ingress/egress.*

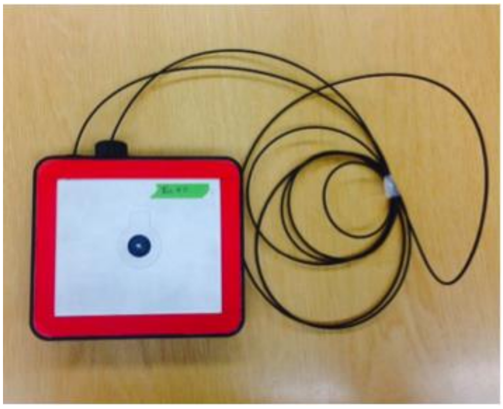

*FIG.4. Passive TSS is equipped with self-destruction upon removal capability to prevent cloning threats.*

The TSS units are developed by LLNL and DSI through DOE funding satisfies all the requirements mentioned in Section 3 and is now at Technology Readiness Level (TRL) 7. The units are under production for small and large scale manufacturing at DSI (www.Diracsolutions.com). Figures 3 and 4 show the TSS pre-production working units. DSI is also pursuing development of TSS units with internal Application Specific Integrated Circuit (ASIC) that can improve the range and reduce the size of the system.

### *3.2 The Stand-alone Reader Unit*

The reader unit is a stand-alone reader that includes a customized secure RFID reader capable of encrypted and dynamically authenticated communications, specialized dual polarity antenna for seamless detection of TSS units regardless of their orientation, and a single-board computing platform that allows for high level signal processing for improved signal to noise ratio detection. Figure 5 shows that stand-alone reader.


*FIG.5. Stand-alone RFID reader platform consisting of customized secure reader, antenna, and single-board computer.*

This reader is easily deployable in various facilities, and includes a backup emergency battery for continuous operation when there is an interruption of power in the facility. It is also capable of reader networking through TCP/IP and specialized communication backbone for reporting to centralized data collection and analysis centers. Multiple readers can be networked for large facility monitoring.

Figure 6 shows examples of seal closed and open (tampered) and authentic vs. suspect (unauthenticated) tag detection through network communications. In this experiment, the reader reports the seal status and presence of a commercial (unauthenticated tag without any sensor) through network communications when authenticated TSS units are monitoring two containers. This experiment shows that the reader immediately reports on the presence of a broken seal and an unauthenticated tag; therefore, not only the container cannot be tampered with, also the TSS unit cannot be replaced by an unauthorized tag and thereby is protected against intrusions and cloning attacks.

| Material Tracking and Authentication | | | | | | |
|---|---|---|---|---|---|---|
| Date | Time | Location | ID | Tag Authenticity | Seal Status | Temperature |
| 10/11/13 | 20:15:16 | Storage "1" | Cylinder "1" | Authentic | Closed | 30° C |
| 10/11/13 | 20:15:23 | Storage "1" | Cylinder "2" | Authentic | Closed | 30° C |
| 10/11/13 | 20:15:47 | Storage "1" | Cylinder "3" | Authentic | Closed | 30° C |
| 10/11/13 | 20:17:11 | Storage "1" | Cylinder "1" | Authentic | OPEN | 30° C |
| 10/11/13 | 20:17:31 | Storage "1" | Cylinder "2" | Authentic | Closed | 30° C |
| 10/11/13 | 20:17:45 | Storage "1" | Cylinder "3" | Authentic | Closed | 30° C |
| 10/11/13 | 20:17:55 | Storage "1" | EPC0011287 5 | SUSPECT | N/A | N/A |

*FIG.6. Reader GUI reports on the date, time, location, unique ID, tag authenticity, seal status and temperature. Broken seal (red), and "unauthenticated tag" (yellow) are reported.*

## 4. TSS Characteristics and Benefits

Table I. Summary of the characteristics and benefits of TSS system

| Characteristic | Benefit |
|---|---|
| Totally Passive (Battery-free) | Indefinite lifetime |
| Designed for metallic assets | Reliable communications on metallic objects |
| Dynamic authentication | Defeats tag cloning threat |
| Strong encryption | Secure wireless channel |
| Conformable tags | Adapts to the curvature of the container |
| Tamper resistant base, self-destruction upon removal | Physical security |
| Multiple tags detection(1000s) | Automated monitoring |
| Long range (> 6 m with encryption, 70 m without encryption | Standoff monitoring |
| Integrated fiber optics seal | Battery-free automated remote monitoring of the seal status |
| Integrated sensors (temperature, humidity, accelerometer) | Both sensor and the tag are powered remotely by the RFID reader antenna |
| Standalone customized reader with internal battery and single board computer | Rapidly deployable, continuous operation in the absence of facility power |
| Networking through TCP/IP protocol | Remote end-to-end monitoring |
| Multiple antennas provide longer read range | Large area monitoring |
| TRL 7 | Mature technology |
| ASIC implementation will further improve range or reduce size | Longer range standoff monitoring or securely monitoring smaller assets |

## 5. Applications of TSS in International Safeguards

The passive secure TSS system can improve many safeguard monitoring applications including containment and surveillance (C&S) of items, radiological source replacement application in medical and geo-explorations, and waste management for nuclear safeguards. These units provide confidence that C&S is maintained between established boundaries at many locations within a facility and that the nuclear material remains unopened (not tampered with) and follows the expected predetermined route within a facility, and therefore allows tracking of items. Without an effective authenticated seal, a monitored item would have to be re-analyzed between key measurement and inspection points within a facility to maintain materials balance. TSS provides a tracking mechanism with a unique identifier and location to an item, and can improve the safeguards monitoring scenarios and supporting various concepts of operations. Securing the SNM containers with TSS units mitigates

material movement concerns and adds confidence to continuity of knowledge (CoK) while reducing personnel requirements in continuous monitoring scenarios. Automated real-time unique ID and location of the high value assets is identified through secure reader networking, and any tampering attempt is reported immediately to a local and remote monitoring stations. The remote powering capability eliminates batteries in the tags-and-seals; secure, authenticated wireless link to a monitoring station reduces current 'eyes-on' inventory needs.
Furthermore, the on-demand stand-off monitoring with handheld capability ensures immediate identification and compliance in inspection scenarios. In summary, the TSS system reduces or eliminates concerns of unattended monitoring; secure remote monitoring greatly reduces demands of labor-intensive tasks for the inspectors.

## 4. Conclusions

Although item level monitoring of SNM requires seal-and-tag and sensor technologies, the combination of all technologies thus far have been developed more or less independently, and had been a lack of an integrated compact system. An integrated tag-and-seal-and-sensor that does not rely on batteries and provides data security through an encrypted and dynamically authenticated wireless channel can potentially revolutionize Safeguards monitoring applications. The TSS system reported in this paper, not only aids inspectors to perform their tasks effectively, they also allows real-time inspection in large-scale facilities.


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