Results from a "Proof-of-Concept" Demonstration of RF-Based Tracking of UF_6 Cylinders during a Processing Operation at a Uranium Enrichment Plant

C.A. Pickett, D.N. Kovacic, J. M. Whitaker, J.R. Younkin, J. Hines, M.D. Laughter
Oak Ridge National Laboratory

J. Morgan
Innovative Solutions

B. Carrick, K. Whittle
United States Enrichment Corporation

B. Boyer
Los Alamos National Laboratory

Abstract
Approved industry-standard cylinders are used globally for processing, storing, and transporting uranium hexafluoride (UF_6) at uranium enrichment plants. To ensure that cylinder movements at enrichment facilities occur as declared, the International Atomic Energy Agency (IAEA) must conduct time-consuming periodic physical inspections to validate facility records, cylinder identity, and containment. By using a robust system design that includes the capability for real-time unattended monitoring (of cylinder movements), site-specific rules-based event detection algorithms, and the capability to integrate with other types of monitoring technologies, one can build a system that will improve overall inspector effectiveness. This type of monitoring system can provide timely detection of safeguard events that could be used to ensure more timely and appropriate responses by the IAEA. It also could reduce reliance on facility records and have the additional benefit of enhancing domestic safeguards at the installed facilities.

This paper will discuss the installation and evaluation of a radio-frequency - (RF-) based cylinder tracking system that was installed at a United States Enrichment Corporation Centrifuge Facility. This system was installed primarily to evaluate the feasibility of using RF technology at a site and the operational durability of the components under harsh processing conditions. The installation included a basic system that is designed to support layering with other safeguard system technologies and that applies fundamental rules-based event processing methodologies. This paper will discuss the fundamental elements of the system design, the results from this site installation, and future efforts needed to make this technology ready for IAEA consideration.

Introduction
It is well known that uranium enrichment plants can easily be modified to produce direct-use material for nuclear weapons. The current global resurgence in nuclear power has peaked interest and created demand for constructing uranium enrichment facilities in countries that currently do not have this capability. This resurgence has created safeguards concerns and challenges that the International Atomic Energy Agency (IAEA) and global community must address.

Based on the projected growth required to meet the projected global demand for energy in the next decade, enrichment capacity requiring safeguards will easily surpass current IAEA safeguards capabilities. This is particularly true when considering the changing nature of the fuel cycle, current geopolitical dynamics, and the potential for new players to become involved.[1] To ensure IAEA has the capabilities that it needs to support this renaissance, investments are required for developing and deploying better remote containment and surveillance monitoring technologies. It is paramount to the global safeguards community that IAEA have the tools needed to provide timely assurance that significant quantities of nuclear material from peaceful, declared nuclear activities have not been diverted for the manufacture of nuclear weapons.[2]

Previous work documented the details and installation of an RF-based system designed to determine the feasibility of using RF technology in a uranium enrichment facility.[3] This paper will discuss the results

obtained to date from that effort, including some of the lessons learned from using the technology within the facility and the operational issues and benefits to the site.

Why Track UF_6 Cylinders?

One reason it is important to consider tracking uranium hexafluoride (UF_6) cylinders at enrichment facilities is the contents of these cylinders represent the bulk of the material inventory available for further enrichment processing (or possibly diversion). Tracking cylinders (in a near real-time manner) as they move around a site requires implementation of methodologies that provide timely detection of unauthorized activities. Implementing near real-time tracking technologies also creates options for using remote unattended monitoring methods for inspection, which typically are less intrusive to the facility owner and more cost effective for the IAEA.

For enrichment facility safeguards systems to be effective, they must be able to provide timely detection of known indicators associated with unauthorized highly enriched uranium (HEU) production, such as the following.

- Diversion of UF6.
- Undeclared low enriched product at amounts greater than declared.
- Production of HEU that may be indicated by
  - reduced throughput,
  - portable feed and withdrawal equipment/stations in cascade area,
  - extra UF_6 cylinders in cascade area,
  - valve settings,
  - piping reconfigurations (e.g., intercascade piping, feed/ withdrawal points), and
  - radiation measurements or swipes indicating HEU.

The following traditional safeguards technologies and methods are typically used during on-site inspections of enrichment facilities.

- Radiation monitoring and nondestructive assay (NDA) measurements.
- Sampling.
- Application and verification of seals.

Additional safeguards measures for enrichment plants have been added since the Hexapartite Safeguards Project, including the following.

- Environmental sampling.
- Continuous online enrichment monitors.
- Portable neutron uranium hold-up counters.

Implementation of a reliable, automated, and tamper-resistant RF-based cylinder tracking system (CTS)—designed to track UF_6 cylinders throughout their entire life cycle—will improve domestic accountability of materials and provide IAEA with enhanced detection of material diversion and the potential for detection of undeclared product. Such a CTS also could be part of an overall safeguards system design that integrates data from other monitoring systems and sensors (such as radiation detectors, gamma spectrometers, pressure and temperature sensors, accelerometers, limit switches, cameras, accountability scales, and other pertinent devices) that are designed around a site-specific, rules-based architecture.

Current nuclear material accounting and control procedures for tracking UF_6 cylinders typically involve manual entry of cylinder data into logbooks or computer databases. This approach is inherently problematic and, many times, requires follow-up efforts to find and correct errors from the manual data-entry process. IAEA also relies on labor-intensive containment verification and surveillance techniques, such as conventional seal and weight checks, to verify UF_6 cylinder contents and to establish some level of continuity of knowledge (CofK).

To help achieve the above goals, the IAEA has expressed interest in developing “smart tags” for monitoring material flow and inventory via the tracking of UF_6 cylinders.[4] Tracking UF_6 cylinders

represents one possible way to monitor the flow of uranium throughout an enrichment facility. It helps maintain CofK of material location at each step in the enrichment process[5]. Ongoing efforts to track other protected assets using RF technology are occurring within Department of Energy facilities, and experiences from these efforts were used for this project.[6]

Basic Operation of the RF-Based CTS installed at Portsmouth, Ohio

The RF-based system installed at the uranium enrichment plant in Portsmouth, Ohio, has demonstrated the capability to track cylinder movements within an autoclave facility. A depiction of this facility is shown in Figure 1. In this facility, a series of RF readers (antenna and reader pairs) were strategically placed at key detection points in the facility to detect and record tagged cylinders that passed through these points. The data were transmitted automatically from the RF tags to the readers and then passed to a central data collection computer.

This proof-of-concept test began with an RF tag being installed on a cylinder arriving in the cylinder staging area (located near the entrance depicted in Figure 1). The cylinder is then moved past the first RF antenna (Reader Antenna A in Figure 1) and read as it is raised by an RF-controlled crane on its way to the autoclave (see Figure 2). The cylinder then is placed in the autoclave, and the antenna (Reader Antenna B in Figure 1) mounted at that location reads the tag. When the door for the autoclave closes, the tag is shielded from the antenna by the metal of the autoclave door. This event is time–stamped and is used to calculate the lapsed time in the autoclave. When the metal autoclave door reopens (before the cylinder is removed from the autoclave), the tag again is readable by the antenna (B) placed near the autoclave. From these event times, the time in the autoclave is determined. This timing information may be useful for detecting events that violate process rules associated with particular equipment. This type of rules-based feature is inherent in the Oak Ridge National Laboratory software and can be used to trigger other safeguards technologies (e.g., cameras) to collect additional data to further support verification. After the cylinder is removed from the autoclave, it is moved to an accounting scale (see Figure 3a), where the tag is read by a reader antenna (unlabeled in Figure 1) at the data collection computer to log the activity, along with the recorded weight of the cylinder. As the cylinder exits the facility, the tag is read for the last time by an antenna (Reader Antenna C in Figure 1) located near the exit (see Figure 3b).

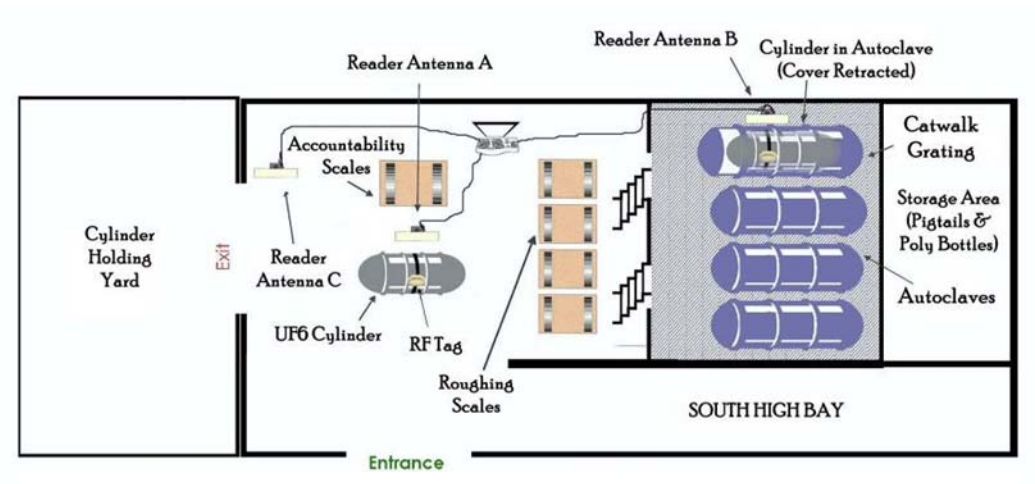


Figure 1. Radio-frequency-based proof-of-concept cylinder tracking system within an autoclave facility.

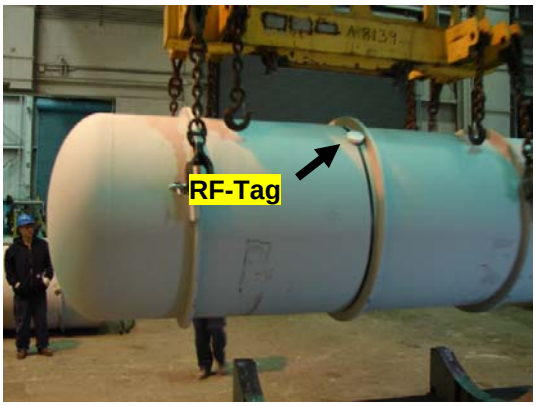
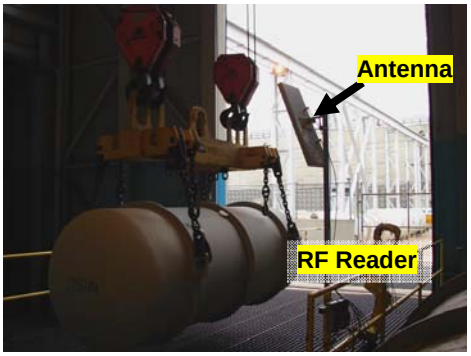


Figure 2. A radio-frequency- (RF-) tagged UF_6 cylinder passing the staging area antenna and being raised to the autoclave.



(a) **(b)**

Figure 3. (a) Radio-frequency detection as cylinder is moved to scale for post process weighing. (b) Detection of cylinder exiting facility into the cylinder yard.

Preliminary Observations and Lessons Learned from the Portsmouth CTS Installation
The CTS was installed at the Portsmouth, Ohio, autoclave facility in January of 2008. The tags were attached to cylinders as they entered the autoclave facility. All tags were removed from cylinders in the cylinder yard (after exiting the facility) and reused on cylinders entering the facility.

The data collected and observations to date from the proof-of-concept evaluation can be summarized as follows.

Tags

- Some tags did not survive their initial autoclave process exposure (which involved being heated for up to 30 hours with pressurized steam to approximately 230°F).
- Some tags began to fail after multiple runs exposing them to the autoclave process conditions.
- Tag performance did not seem to be affected by thermal shock (of leaving the autoclave and moving into the cylinder yard during January temperatures of less than 10°F).
- No tags showed any significant damage due to operational handling and cylinder moves.
- Tags that survived the initial autoclave process continued to operate properly for many successive autoclave process cycles until they eventually failed due to warping of the tag housing.

All tags tested were listed by their manufacturers as high temperature tags, but some tags failed upon exposure to moisture in the autoclave. The pressurized steam in the autoclave seeped through the tag sealing and delaminated the antenna structure of the tag, causing the failure. This only affected paper-based tags. One tag that was sealed with a cork gasket tended to absorb water, which attenuates RF

transmissions, and therefore, it could not be read when it exited the autoclave. Several tags did survive multiple runs through the autoclave and failed only after the sealing wore out and let in the hot steam. Future efforts will focus on ensuring hermetic sealing of the tag and its associated components. Thermal shock did not seem to be an issue during this phase of testing, but could have been a factor in some of the sealed tags beginning to leak over time.

In addition to being able to withstand the operating environment, future cylinder tags must support tamper-resistant attachment without modification to cylinders. Tags also will require tamper-resistant packaging and, more than likely, some form of data authentication. Current work involves following commercial efforts to provide these types of features along with technology development efforts. The rapid progression of technology should make cylinder tracking an attractive option for near-term IAEA consideration.

RF Interferences at Portsmouth

Before the RF-based CTS could be put into operation at the autoclave facility, several tests for RF-interference with operating equipment had to be conducted. The first set of tests involved turning on all of the CTS equipment and then turning on all RF-based systems in the autoclave facility—one device at a time. The first device tested was the radio-controlled bridge crane used to move the 14-ton cylinders. This crane operated at a different frequency from the 900-MHz CTS equipment and exhibited no effects from the CTS.

The next device tested was an RF-based portable radiation dosimeter, which was a crucial component of the radiation safety system. There were two versions of this device at the site, one was an older analog-based model; the newer one was primarily composed of digital electronics (see Figure 4a). The analog model did have problems while the CTS was operating, but the newer, digital one did not. Therefore, during operation of CTS, only digital dosimetry was used.

(a)

(b)

Figure 4: Equipment in the Autoclave Facility that was susceptible to RF-interference: (a) RF-based dosimetry and (b) nondestructive assay measurement cart.

The other device found to be prone to RF interference was the equipment on an NDA measurement cart (see Figure 4b). This equipment also was analog based, but was required for use in the facility. The decision was made to turn off the RF readers when NDA measurements were made. As with the dosimeters, digital-based NDA equipment in the area seemed to be immune to RF interference.

Future Efforts and System Design Issues to Address

A team of RF technologists and safeguards professionals met in Oak Ridge, Tennessee, during May of 2008 to discuss vulnerability issues and functional requirements for a next generation RF-based CTS. The following are some of the near-term steps that were identified.

- Engaging stakeholders (operators, IAEA, etc.) in developing full system requirements.
- Integration of system with continuous load cell (weighing) measurements.

- Working with Los Alamos National Laboratory on supporting global positioning system tracking of cylinders from a shipping site to a receiving site.
- Evaluating other RF technologies.
- Developing some tamper-resistant attachment options.

Vulnerability Issues—Vulnerabilities include spoofing, counterfeiting, transfer, and cloning. The extent to which system design can mitigate these concerns will be an important aspect of this work. Below is list of some known vulnerabilities that need to be addressed, along with some potential solutions.

Tag attachment	Solutions: Embedded technologies
Tamper detection	Solutions: Tamper indicating packaging, smart tags
Battery lifetime	Solutions: Passive tags, low power circuitry, batteries with extended life
Environmental concerns	Solutions: Improved packaging technologies
RF interference	Solutions: Site and route survey, ultrawide band and spread spectrum
Shielding	Solutions: Low frequencies, heart-beat (for an active tag), multiple antennas
Spoofing/authentication	Solutions: Advanced cyber security techniques
Data security/integrity	Solutions: Advanced cyber security techniques
Orientation and range	Solutions: Distributed readers, ultra-wide-band antenna design
Location of Readers	Solutions: Tamper-resistant packaging and location sealing

It also will be important to better define the system requirements for cylinder tracking within facilities around the globe. Such requirements include which radio frequencies are acceptable for use, best locations for secure attachment of antennas and readers, and appropriate implementation of site-specific rules-based data processing. All solutions will require repetitive testing and system evaluations. The implementation of red/blue team evaluations for all proposed system designs is recommended.

Some issues that need to be addressed for system acceptance include
- operator and state or IAEA acceptance,
- international standards,
- export control, and
- system costs.

Security and Cultural Issues— Cultural resistance to using wireless technologies exists, largely because of questions regarding security and reliability. Therefore, wireless systems will need to be evaluated to determine whether they constitute an inventory or security risk. In addition, IAEA and host countries must be assured that RF systems will work as specified. And finally, RF technologies must be compared with current approaches and existing systems to demonstrate clear advantages.

Reliability—Reliability of RF technologies must be comparable to current approaches and existing systems. Tags must be sufficiently durable to survive the environmental and operational environments at a facility.

CTS Functional Requirements—Some functional requirements for CTS components were identified along with some optional design parameters that may later need to be specified. These are summarized, by category, below.

Tag mounting/attachment
- Ability to withstand environmental exposures
- Does not degrade tag performance
- Resistant to normal handling and transportation procedures
- Will not compromise the integrity of the container

Tamper detection
- Detects modification, removal, and replacement
- Advantages of passive versus active RF devices (with regard to recording tamper)

- Real-time indication of tampering

Battery lifetime
- Ability to track status of battery life
- Shelf life
- Operational life
- Replaceability

Environmental concerns (temperature and other weather issues, radiation)
- Temperature ranges at -50°C to +150°C for anticipated cycles per year
- Steam bath at 10 psi
- Other cylinder heating ranges (hot box)
- Radiation (X-rays, high energy)
- Weather exposure (rain, extreme sunlight)

Availability
- Commercially available
- RF identification standard versus proprietary
- Globally available (e.g., technology not subject to export controls)

RF Interferences—RF signals may interfere with existing systems and equipment. This interference depends on the RF band selected, which also can be a site-specific or a state-specific issue.

- Must work in international radio frequencies
- Must not interfere with other equipment frequencies or be vulnerable to other frequencies
- Must be resistant to jamming detection/denial of service
- Must be resistant to shielding
- Must include watchdog heart beat for active tags
- Must be resistant to spoofing/amenable to authentication
- Must include transport layer of security
- Must ensure data security and integrity
- Must be insensitive to orientation
- Location accuracy and read range

Diversion Scenarios—A number of diversion scenarios/paths and various operating conditions will have to be analyzed to determine the most effective uses for RF technologies.

- Feed/Withdrawal
- Extra (unidentified, undeclared, unauthorized) cylinders at the facility
- Abnormal processing paths
- Weigh stations
- In-processing facility
- Storage yards
- In transit onsite or during shipment in commerce
- Unusual operating conditions

Layered Technologies-System Effectiveness—A number of technologies that may improve system effectiveness have been identified.

- Load cells
- Reusable tamper indicating devices
- Radiation detection sensors
- Integrated Tamper technologies (such as reflective particle tag)

Continuous monitoring of an asset or sensitive material using RF-based technology is recognized as capable of providing direct security benefits through timely detection of diversion activities.[6] However, in moving forward with a proposed CTS concept, it is important that issues and vulnerabilities be clearly identified. The effectiveness and added benefits of RF technologies applied to security measures need to be evaluated at the safeguards systems level. Diversion path analysis and evaluation of effectiveness and efficiencies of RF technology in actual safeguards applications will help delineate requirements necessary to design robust systems. Vulnerability issues such as sniffing, spoofing, transfer, and cloning need to be evaluated relative to the effectiveness of RF tags at the systems level. Vulnerabilities of tags, seals, and surveillance systems currently approved/used by IAEA should be analyzed to gain a perspective on IAEA's existing and future safeguards requirements.

Conclusion

As outlined in this paper, RF-based CTSs have the potential to provide IAEA with advanced technologies fortimely detection of diversion of uranium at enrichment plants. To achieve this, vulnerability concerns surrounding RF-based cylinder tracking will have to be addressed, and systems will have to demonstrate reliability and enhanced data and remote monitoring capabilities. If successful, RF-based monitoring systems have the potential to revolutionize the tools available to IAEA for conducting international safeguards inspections.

Current work has indicated that an RF device can be fabricated that will survive multiple exposure to the operating conditions of the autoclave and be durable enough to survive the indoor and outdoor conditions associated with moving and storing cylinders. Future efforts will include efforts to utilize RF technology for tracking UF_6 cylinders as they are transported.

References

1. C.A. Pickett, J.R. Younkin, D.N. Kovacic, M.D. Laughter, J. Hines, B. Boyer, B. Martinez "Evaluation of an RF-Based Approach for Tracking UF_6 Cylinders at a Uranium Enrichment Plant," 8th International Conference on Facility Operations—Safeguards Interface, March 30–April 4, 2008, Portland, Oregon.
2. IAEA, *The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons*, INFCIRC/153 (Corrected) (IAEA 1972), p. 1, June 1972.
3. IAEA, *Final Report on the IAEA Technical Meeting on Techniques for IAEA Verification of Enrichment Activities*, Vienna Austria, April 18–22, 2005, Department of Safeguards, Division of Technical Support (SGTS), Division of Concepts and Planning (SGCP), November 2005.
4. I. Tsvetkov, W. Bush, R. Fagerholm, D. Hurt, M. Jordan, and J. Leicman, "Implementation of the IAEA's Model Safeguards Approach for Gas Centrifuge Enrichment Plants," 29th ESARDA Annual Meeting, Aix en Provence, France, May 22–24, 2007.
5. Oak Ridge National Laboratory, *Nuclear Material Safeguards for Uranium Enrichment Plants: Part 3 Uranium Enrichment Plant Description and Material Control and Accountability*, ISOP-347/R6, Program for Technical Assistance to the IAEA Safeguards, 2005.
6. C. A. Pickett, G. D. Richardson, B. J. Stinson, and J. R. Younkin, "Technologies for Real-Time Monitoring and Surveillance of High-Valued Assets," presented at the 48th Annual INMM Meeting in Tucson, Arizona, July 8–12, 2007.