A “Proof-of-Concept” Demonstration of RF-Based Technologies for UF_6 Cylinder Tracking at Centrifuge Enrichment Plant

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ABSTRACT

This effort describes how radio-frequency (RF) technology can be integrated into a uranium enrichment facility’s nuclear materials accounting and control program to enhance uranium hexafluoride (UF_6) cylinder tracking and thus provide benefits to both domestic and international safeguards. Approved industry-standard cylinders are used to handle and store UF_6 feed, product, tails, and samples at uranium enrichment plants. In the international arena, the International Atomic Energy Agency (IAEA) relies on time-consuming manual cylinder inventory and tracking techniques to verify operator declarations and to detect potential diversion of UF_6. Development of a reliable, automated, and tamper-resistant process for tracking and monitoring UF_6 cylinders would greatly reduce the risk of false or misreported cylinder tare weights, diversion of nuclear material, concealment of excess production, utilization of undeclared cylinders, and misrepresentation of the cylinders contents.

This paper will describe a “proof-of concept” system that was designed show the feasibility of using RF-based technologies to track individual UF_6 cylinders throughout their entire life cycle, and thus ensure both increased domestic accountability of materials and a more effective and efficient method for application of IAEA international safeguards at the site level. The proposed system incorporates RF-based identification devices, which provide a mechanism for a reliable, automated, and tamper-resistant tracking network. We explore how securely attached RF tags can be integrated with other safeguards technologies to better detect diversion of cylinders. The tracking system could also provide a foundation for integration of other types of safeguards that would further enhance detection of undeclared activities.

INTRODUCTION

It is well known that existing uranium enrichment plants could 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 creates a large global demand for reactor fuel that has already brought about challenges and concerns that the IAEA and world community must address.

The existing safeguards regime for uranium enrichment plants was negotiated as part of the Hexapartite Safeguards Project (HSP) effort completed in 1983 by the countries commercializing uranium enrichment technology at the time. It is a system that for a period of time worked well, when enrichment plant capacities were in the range of up to the 1,000,000 separative work units (SWU)/kg and were limited to a few established corporations and states. However, based on the projected growth required to fuel the current global nuclear renaissance, the enrichment capacity requiring safeguards in the next few decades will easily surpass the current capabilities of the IAEA to provide those services. 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 the IAEA has the capabilities that it needs to support this renaissance, effort must be invested in developing and deploying better remote containment and surveillance (C/S) monitoring technology. It is very important to the global safeguards community that the IAEA have the technologies and methodologies needed to provide timely assurance that significant quantities of nuclear material from peaceful or declared nuclear activities have not been diverted for the manufacture of nuclear weapons[2].

A RF-Based UF_6 Cylinder Tracking System (CTS)

The goal of providing and implementing adequate safeguards at uranium enrichment facilities presents unique challenges that are vital to the global nonproliferation effort. The current nuclear material accounting and control procedures for tracking uranium hexafluoride (UF_6) cylinders typically involve the manual entry of cylinder data into logbooks or computer databases. This approach is inherently problematic and many times requires follow-up effort to fix errors from the manual data entry process. The IAEA also relies on labor-intensive containment verification and surveillance techniques, such as conventional seal and weight checks, to verify UF_6 cylinder contents to establish some level of continuity of knowledge (CofK).

The current inspection regime for enrichment plants under IAEA safeguards consists of physical inventory verification (PIV), performed annually, interim inventory verification (IIV), performed approximately monthly, and a number of limited frequency unannounced inspections (LFUA) performed on a random basis each year. Annual and periodic scheduled inspections (such as PIVs and IIVs) are intended to establish a material balance for the IAEA to determine whether nuclear material has been diverted by the operator. The risk of detection provides deterrence and mitigation against proliferation and misuse by the facility operator. In order to achieve this, the IAEA spends a significant portion of its inspection efforts at enrichment plants verifying inventories, shipments, and receipts of UF_6 cylinders[1]. These types of efforts will only increase with the future growth in enrichment services: creating a strong need to develop dynamic real-time approaches that improve the efficiency and effectiveness of current efforts.

To this end, the original HSP effort is currently being enhanced. New options to improve the current safeguards regime for enrichment plants were discussed during an IAEA technical meeting in April 2005, and documented in a final report,[3] as well as in the revised model safeguards approach to gas centrifuge plants[4]. These new approaches will improve the efficiency and effectiveness of safeguards applied to enrichment plants, and close gaps in the HSP safeguards. The IAEA's updated model approach outlines the following three safeguards objectives to address proliferation concerns at gas centrifuge enrichment plants:

1. the timely detection of the diversion of significant quantities of natural, depleted, or low enriched UF_6 from the declared flow through the plant, and the deterrence of such diversion by the risk of early detection;
2. the timely detection of the misuse of the facility in order to produce undeclared product (at the normal product enrichment levels) from undeclared feed and the deterrence of such misuse by the risk of early detection; and
3. the timely detection of the misuse of the facility to produce UF_6 at enrichment higher than the declared maximum, in particular HEU, and the deterrence of such misuse by the risk of early detection.

To help achieve the above goals, the IAEA has expressed interest in the development of "smart tags" for monitoring material flow and inventory via the tracking of UF_6 cylinders[3]. Tracking UF_6 cylinders is an ideal way to monitor the flow of uranium throughout the enrichment process. It helps maintain CofK of the material at each stage in the enrichment process, such as the input of natural feed material, the withdrawal of product material (including blending operations), the withdrawal of depleted tails, and the withdrawal of material for sampling[5]. Previous efforts to track protected assets using RF technology are occurring within the Department of Energy facilities, and this experience is being utilized for this effort [6].

The utilization 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 the IAEA with a more effective and efficient method for site-level application of safeguards. The CTS could also be part of the overall safeguard system design that integrates data from other 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 to around a site-specific rules-based architecture. The key benefits of such a system for the application of safeguards are discussed in the following section.

Effectiveness vs. Efficiency: How much value can an RF-based CTS add to IAEA safeguards and how effective it is in mitigating proliferation? *Effectiveness* can be improved by closing the gaps in the current HSP safeguards approach such as detecting undeclared feed. Currently the only method the IAEA has to detect undeclared feed is during unannounced inspections. A CTS can provide improved detection beyond what random inspections offer if (1) all authorized cylinders were tagged, (2) the movement of cylinders in and out of the process areas is monitored, and (3) a surveillance system is in place to detect the presence of an unauthorized cylinder being connected to the feed and withdrawal systems. This last item is needed to determine whether material is being fed into the enrichment cascade using an unauthorized cylinder.

Efficiency can be improved by decreasing the amount of time that an IAEA inspector spends at enrichment plants verifying cylinder inventories. A CTS can greatly improve the efficiency of cylinder verification by significantly shortening the time an inspector spends physically verifying a cylinder's identification and containment integrity and reconciling data entry errors. In this way, the inspector is more likely to detect anomalous activities that could be indicative of material diversions and facility misuse which would, in fact, also improve the effectiveness of safeguards.

Wireless vs. Wired Systems: Wireless systems are really the only choice for monitoring assets that move. A RF-based system typically is more cost-effective to install in exiting or future facilities when compared with hard-wired installations. Wired installations at facilities typically involve wall penetrations, some very long wire runs (that may require physical inspection by inspectors to make sure they are connected to the right device), and additional physical security to monitor materials while existing systems are powered off to support the installation. The costs for maintaining and sustaining wired systems typically are higher than wireless systems.

System Integration: By providing rules-based tracking with integrated surveillance, site-specific rules can be designed to monitor activities at each facility with greater precision. Timely detection of the asset is greatly enhanced, which is critical in today's world of increasing threats where the only way to ensure an appropriate response (for any potential theft or diversion event) is to have near real-time detection at the asset. Effective tracking of UF_6 cylinders within a facility would provide a foundation for other safeguards systems to build upon and would thus become part of an integrated safeguards approach that could better provide an indication of undeclared activities.

Developing a Path Forward—UF_6 Cylinder Tracking System

The United States is undertaking efforts to improve the current safeguards regimes at enrichment plants. The National Nuclear Security Administration (NNSA) is promoting exploration of technologies and approaches that could be applied to develop the application of advanced safeguards technologies such as a UF_6 CTS. In December 2006, an expert team of representatives from the national laboratories met in Washington, D.C., to formulate a systematic approach to explore the usefulness of RF-based technologies for use in IAEA safeguards[7]. This team defined the safeguards needs, discussed potential RF-based solutions, identified weaknesses and vulnerabilities in RF-based technologies, and identified key system design requirements. A draft report issued in February 2007 summarized the meeting findings and provided recommendations on a path forward[5]. The expert team stated that it would need a thorough understanding of the existing commercial-off-the-shelf (COTS) RF technologies that could potentially address IAEA requirements prior to considering new technologies. It was also recommended that any RF-based system be considered within the context of an integrated safeguards system that could be enhanced by other containment and surveillance (C/S) and process-monitoring technologies. To design a system that increases the efficiency and/or effectiveness of IAEA safeguards, the report defined the following parallel paths forward:

1. identify and address IAEA needs by testing existing RF-based technologies and develop a baseline for future improvements in safeguards system performance; and
2. based partly on the testing results and other systematic analyses, develop new technologies and approaches to address vulnerabilities and improve system robustness and effectiveness.

Vision for Future CTS Design within Enrichment Plant

A proposed system installed at a gas centrifuge enrichment plant would provide the capability to monitor the movement of all cylinders within an enrichment facility, including feed cylinders, parent product (or intermediate) cylinders, customer cylinders, sampling containers, and tails cylinders. In the proposed CTS field design, a unique, robust, and tamper-resistant RF tag is attached to each cylinder either before it enters the enrichment facility or at the point of entry. A series of RF interrogators are strategically placed throughout the facility to monitor the process flow of the cylinders to the desired level. The data automatically transmitted from the RF tags to the interrogators provide a positive and unique identification of each cylinder.

Figure 7 shows a proposed concept for tracking an monitoring cylinders during transport to and from enrichment facilities that will be discussed in a later section of this paper..

Process Flow of UF_6 Cylinders in a Gas Centrifuge Enrichment Plant

As feed cylinders arrive at an enrichment facility, the CTS positively identifies the RF-tagged cylinders using an RF interrogator. As the cylinders enter the feed storage area, the RF interrogator automatically reads and records all relevant cylinder data, such as tare weights, accountability weights, and any nondestructive analysis (NDA) that has been performed. When cylinders are ready to be attached to the feed system to feed material to the cascades, the CTS registers that the cylinders have moved out of the feed storage area and into the cylinder processing area. (It should be noted that the hypothetical CTS can receive and integrate other containment and surveillance and process data, such as the status of door switches, crane movements, and signals from video cameras.) An RF interrogator automatically identifies cylinders as they are placed into the autoclave/hotbox, where they are attached to the process line. This provides positive identification of cylinders that are attached to the cascade—one of the main needs identified in the IAEA revised model safeguards approach for gas centrifuge plants. Additionally, the CTS can monitor the operation of the autoclave/hotbox using position limit switches and can record the total time that the cylinder is in process. The operation of the feed valve to the cascade, as well as any flow monitors on the feed header, can also provide data points for the CTS. When feeding is completed, the operator closes the transfer valve, opens the autoclave/hotbox, and places the feed cylinders on an accountability scale. Cylinders are identified again by the CTS, and are then weighed to determine the UF_6 heels remaining. The mass measurements are automatically entered into the CTS, and the amount of UF_6 that entered into the cascade is determined and logged. The empty feed cylinder is then moved to the storage location and, subsequently, either shipped back to the supplier or used to store tails material. The CTS can monitor all of the movements described above. It would also track samples taken from the feed cylinders and associate the analysis results automatically with the source cylinders. Figure 1 depicts a conceptual model of a CTS employing RF-based technology for feed cylinders.

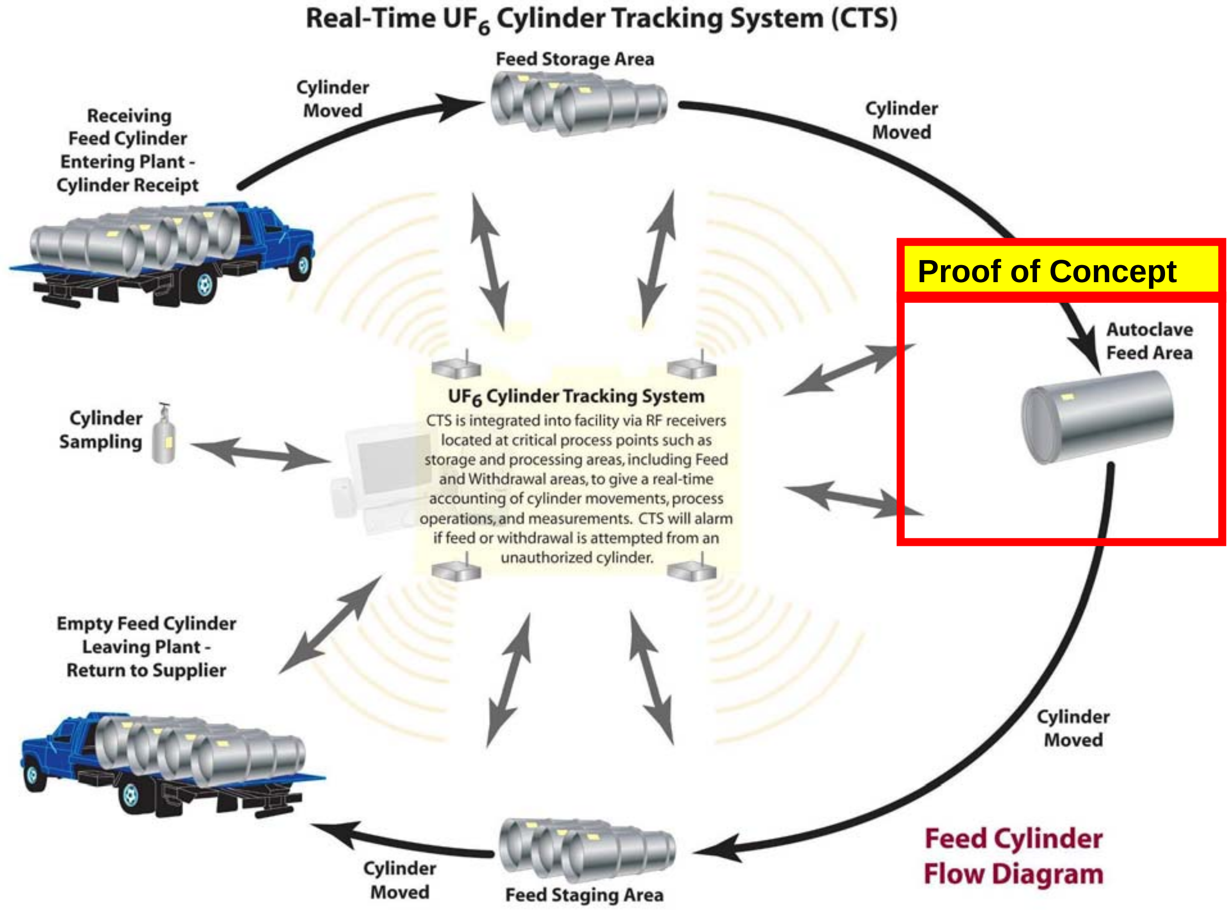


Figure 1: Proof-of-Concept RF CTS Field Test.

Laboratory and Field Testing Efforts

Preliminary tests of available RF tags were conducted at ORNL in 2006 under conditions to simulate the worst-case operating conditions at an enrichment plant[8]. These tags were also tested for read range, orientation with antennas, and physical durability. Many of the COTS tags did not adequately survive the temperature and humidity tests (designed to simulate conditions in an autoclave). Consequently, ORNL commissioned one of the vendors to create a custom enclosure designed to protect the RF tag in extreme temperatures while providing at least a 2-m read range. The RF tag is a Gen 2 UHF passive tag (i.e., no batteries), shown in the custom enclosure in Figure 2. It is also affectionately referred to as the "hockey puck" tag.

The proof-of-concept test (depicted in Figure 1) is designed to evaluate the feasibility of using RF technology to track cylinders. This test is focused on determining how well the technology (with minimum effort expended to protect it) can survive the temperatures of repeated autoclave cycling and repeated operational handling. The test facility for conducting these evaluations is located in Portsmouth, Ohio, and shown in Figure 3.

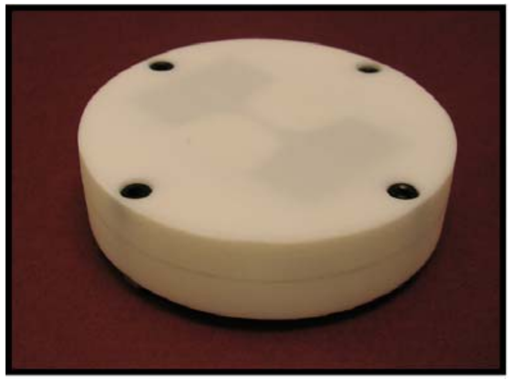


Figure 2: Custom-Enclosed “Hockey Puck” RF tag.

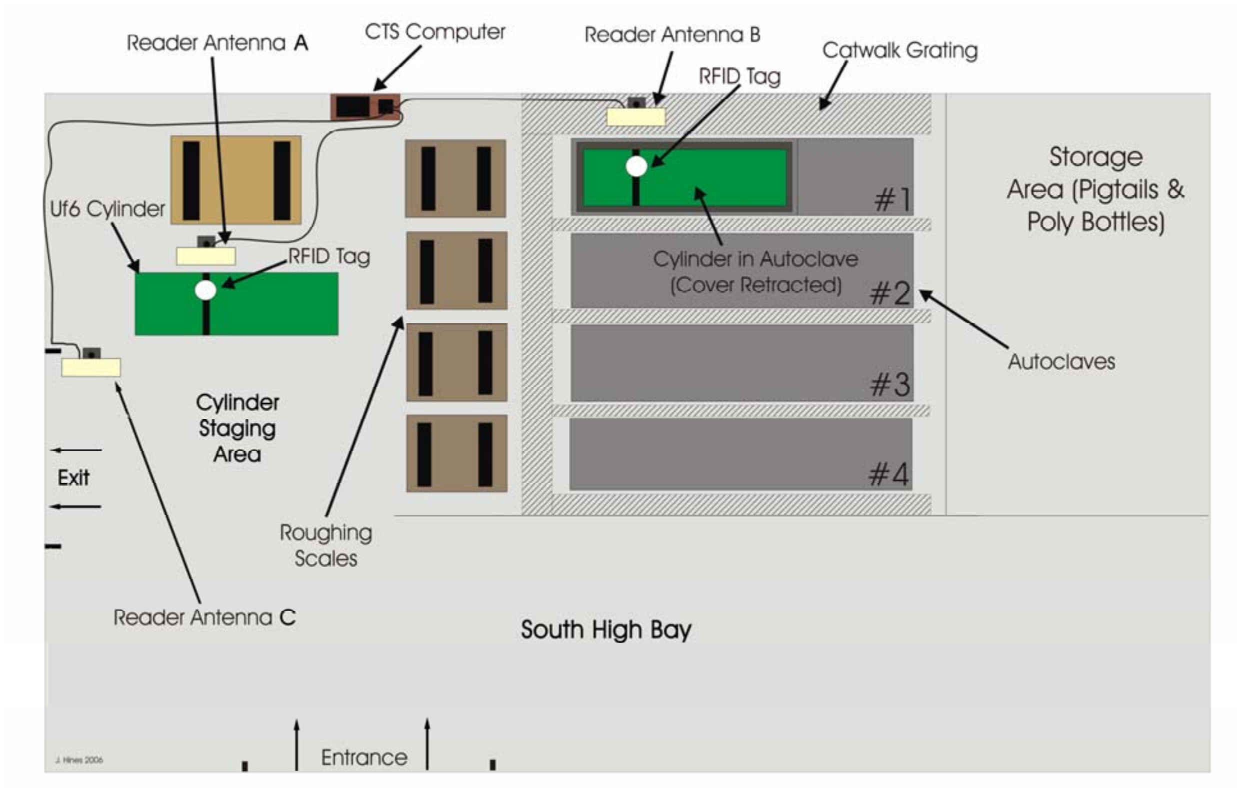


Figure 3: Proof-of-Concept Test Facility for RF-based CTS.

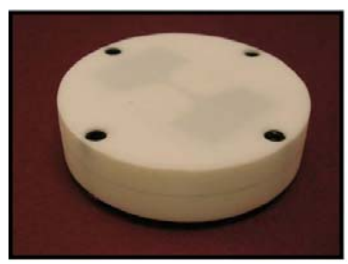
An RF-based system will be installed in the near future at the Portsmouth, Ohio, centrifuge enrichment plant for the purpose of determining the operational issues of implementing an RF system in a facility of this type. The initial goal of this effort is to evaluate the feasibility of COTS RF technology and obtain knowledge that will help identify what should be included in future efforts. The proof-of-concept test will begin with a pre-tagged cylinder arriving into the staging area depicted in Figure 3. The cylinder next would move to the scales and be read by the RF antenna mounted at that location. The equipment to be installed for this effort is shown in Figure 4. Next, the cylinder would be placed in the autoclave, and its tag would be read by the antenna mounted at that location. When the door for the autoclave closes, the tag will be shielded by the metal of the autoclave door and will not be able to be read. This event starts a clock that can be used to measure time in the autoclave. When the metal autoclave door re-opens (prior to removing the cylinder from the autoclave), the tag should again be readable by the antenna placed near the autoclave. This event stops the clock measuring time in autoclave. This type of information may be useful for detecting events that violate process rules associated with a facility. The rules-based feature is inherent in the ORNL software and can also be used to trigger other safeguard technologies (i.e., cameras) to collect data.

After the tag is detected, the cylinder is removed from the autoclave and placed on the scale, where the tag is read to record the event along with the weight of the cylinder. The cylinder is then moved to the cylinder yard and the tag is read upon exiting the autoclave facility.

Antenna Mounting for Autoclave

Antenna Mounting for scales and entry and exit points

RF Reader that supports up to 4 Antennas



Thermally protected RF Tag

Figure 4: System Components for CTS Proof-of-Concept Demonstration.

The user interface for the software for the proof-of-concept test is shown below in Figure 5. This interface has been designed for growth. It supports the requirements of modern data management systems and rules-based event processing and is not specific to any particular type of RF technology.

After the proof-of-concept test is completed, results and recommendations will be published for review. It is clear to the project team that additional technology development and testing must be continued to mature this approach and ensure that it covers all the important aspects that are needed for a complete IAEA-ready cylinder tracking system. It is known by the authors that the tag attachment must be tamper resistant and must not require modification to the cylinder. Current efforts are following the commercial efforts to provide RF-based seals like the one shown in Figure 6. The evolution of these RF-based technologies should make cylinder tracking a feasible option for IAEA consideration.

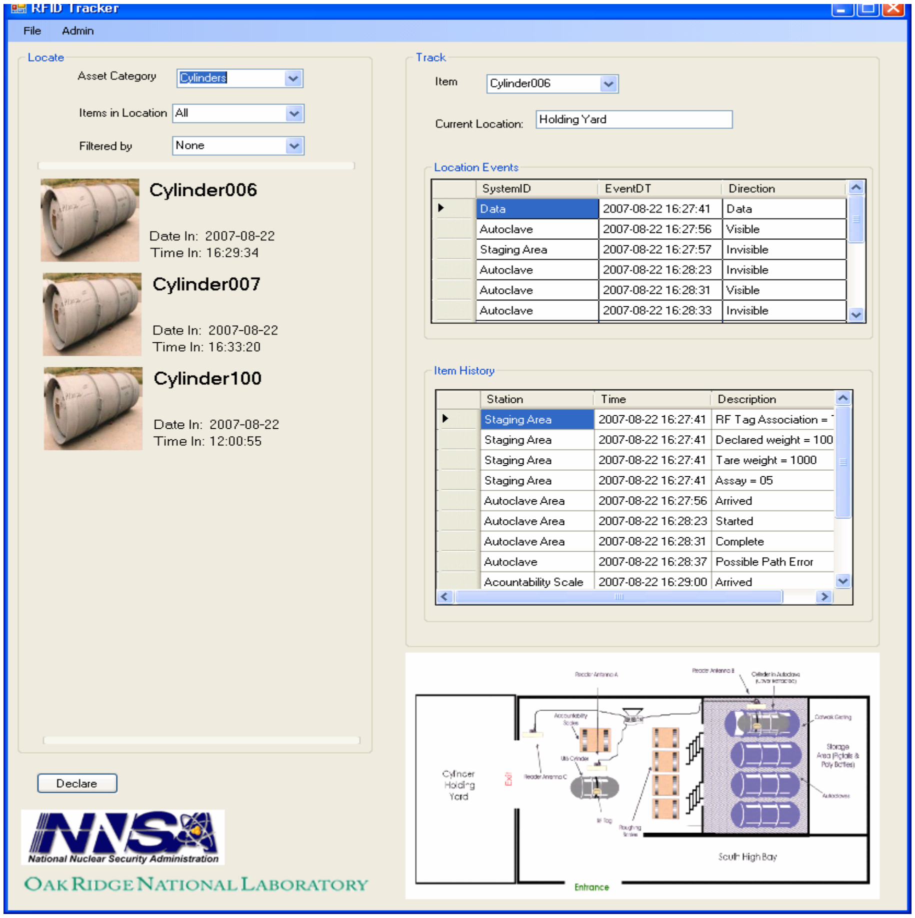


Figure 5: Current User Interface to RF-Based CTS.

The additional work will include developing the following specifications for the attached RF-device:

- ability to withstand washing in cylinder cleaning facilities
- survivability from repeated heating and cooling cycles at temperatures expected in an operating environment
- best location for attachment
- survivability after exposure to hydrogen fluoride gas and to other corrosive gases
- functionality in the presence of electromagnetic/radiofrequency interferences and ac/dc magnetic fields
- survivability from operational (vibration, dropping, and rough) handling at the plant and during transport
- resistance to software viruses
- resistance to tampering
- multi-year durability, including long battery life, if applicable

The field testing efforts will investigate the best RF-based technologies and safeguards approaches for the development of a full-system prototype. The full prototype will provide complete system performance evaluation and a determination of how cylinder tracking can best be applied by the IAEA for safeguards. The later phases will progress toward full system integration and will incorporate additional layers of safeguards technologies. Ultimately, a pilot system should be deployed in an operating centrifuge facility under IAEA safeguards.

Figure 6: An Example of a Commercial RF-Based Seal.

Issues and Vulnerabilities of RF-Based CTS

In moving forward with a proposed CTS concept, it is important that issues and vulnerabilities be clearly identified. 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. However, the effectiveness and the added benefits of RF technology as a security measure needs 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 the requirements necessary to design a robust system. 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 in use by the IAEA should be analyzed to gain a perspective of the IAEA's existing and future safeguards requirements.

Implementation of acceptable encryption and authentication methods may require some development to address the management of cryptographic keys in IAEA monitoring scenarios. Diversion path analyses and "red/blue teaming" to highlight the weaknesses and corrective actions of proposed safeguards approaches should be performed to provide credible tools for meeting the requirements of international safeguards. The following are some additional issues and concerns that must be addressed.

- **Security and Cultural Issues—**Wireless systems will need to be evaluated to determine whether they constitute an inventory or a security risk. Cultural resistance to using wireless technologies exists, largely because of questions regarding security and reliability. The IAEA and the host country must be assured that the RF system will work as declared. The RF technologies must be compared with current approaches and existing systems to demonstrate clear advantages.

- **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 study.

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

- **Frequency limitation—**The frequencies allowed for use at a facility or in a country must be known and factored into a system using RF.

- **Tags versus seals—**Criteria for when to use RF-based tags versus RF-based seals are needed. These criteria should include a design-based threat type of analysis and a cost-versus-performance evaluation.

- **Reliability—**Reliability of RF technologies must be compared with current approaches and existing systems. Tags must be durable enough to survive the environmental and operational environments at a facility.

- **IAEA authentication—**The system must be certified in a manner that assures the IAEA that the system is operational and the data is trustworthy.

CONCLUSION

As outlined in this paper, an RF-based CTS can provide the IAEA with technologies that improve the timely detection of diversion by providing a method to help verify the processing and storage of uranium at an enrichment plant. To achieve this, the vulnerability concerns of using RF-based cylinder tracking will have to be addressed and the system will have to demonstrate reliability that it can provide enhanced data and remote monitoring capabilities to the IAEA. If successful, RF-based monitoring systems have the potential to revolutionize the tools available to the IAEA for conducting international safeguards inspections.

Future work will include efforts to utilize RF technology for tracking UF_6 cylinders as they are transported. One concept for accomplishing this task will be to install an RF reader onto a cylinder transport vehicle and track the vehicle via a global positioning system (GPS). This concept is shown in Figure 7. The RF reader on the transport vehicle detects the identity, presence, or non-presence of the cylinder.

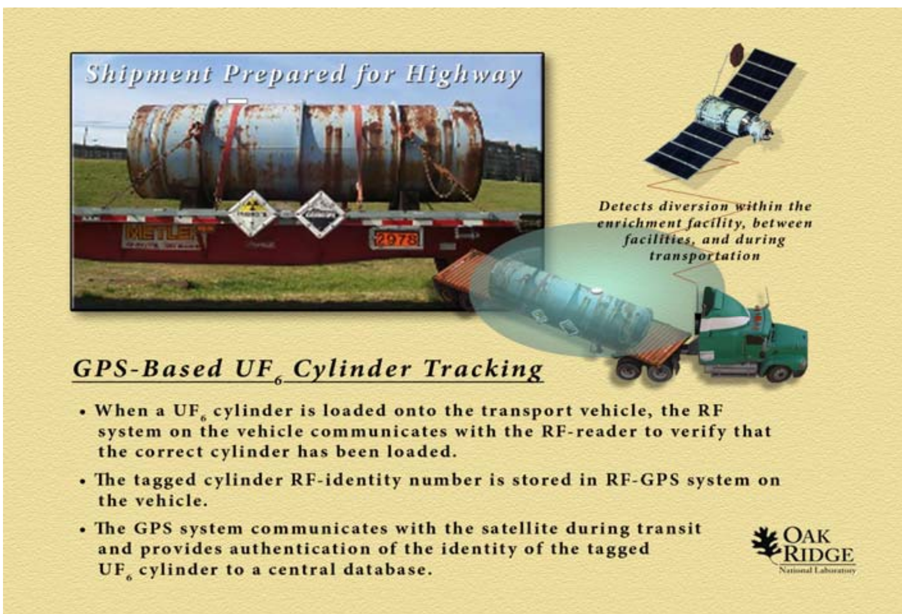


Figure 7: GPS-Based Cylinder Tracking Concept.

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