Comprehensive Nuclear Material Surveillance with a Radiation Detector-Equipped ARG-US RFID System*

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ABSTRACT

Comprehensive monitoring and tracking of sensitive nuclear materials can be achieved with radio frequency identification (RFID) technology, resulting in significant improvement of the operating efficiency of nuclear and radiological facilities. A system, called ARG-US, has been developed by Argonne National Laboratory for the U.S. Department of Energy (DOE) Packaging and Certification Program, for use in managing sensitive nuclear and radioactive materials. Several ARG-US RFID systems are in various stages of deployment and advanced testing across DOE sites. ARG-US utilizes a suite of sensors in tags to continuously monitor the state of health of the packaging and promptly disseminates alarms to authorized users and responsible parties via a secured local network and/or the Internet. In conjunction with available in-vehicle cellular and satellite communication packages and global positioning system receivers and the management infrastructure available from DOE-TRANSCOM, the ARG-US RFID platform can monitor and track assets in transit as well.

Many of the sensitive nuclear materials under surveillance are emitters of neutron and gamma radiation. This trait allows inconspicuous monitoring measures for the materials themselves, in addition to the other more overt packaging monitoring measures such as seal and shock. This monitoring can result in improved protection of materials and stricter safeguards implementation, when required. To realize these benefits, development was undertaken to incorporate a gamma dosimeter and a neutron detector in the ARG-US RFID tag platform. A dedicated expansion board was developed with a specially designed universal asynchronous receiver/transmitter interface to accommodate the two types of detectors. Just as importantly, the existing tag form factor was retained and the additional battery power requirements for the detectors were optimized. The selected detectors have sensitivity and measurement ranges suitable for nuclear materials monitoring. Both can initiate alarms for either a high or low radiation level and for a high cumulative dose. In a large installation, strategically located radiation-detector-enabled tags can yield an accurate, real-time, 2D or 3D dose field map. Any perturbation of the field distribution can be used to alert the operator. As radiation data are constantly available, manned surveillance with portable instruments may be appropriately curtailed, at least for high-dose-rate areas, conforming to As-Low-As-Reasonably-Achievable (ALARA) practice. In conjunction with the other sensors in the ARG-US platform—for seal (a tamper-indicating device), shock, temperature, and humidity—comprehensive autonomous monitoring of sensitive nuclear materials is now feasible with the ARG-US RFID system.

*Proc. INMM 54th Annual Meeting, Palm Desert, CA, July 14-18, 2013. The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357.

INTRODUCTION

Environmental remediation and radioactive waste management entail the collection, storage, processing, and disposal of a variety of materials, ranging from legacy weapons stocks, fuel cycle products and by-products, and medical and industrial radioisotopes to radioactive wastes. The packages holding these materials, governed by International Atomic Energy Agency (IAEA) regulations for international transport activities [1, 2], are classified as Excepted, Industrial, Type A, Type B, and Type C, with Type C being the most stringently regulated. Many of the IAEA member states adopt the same standards for their domestic transport and handling as well.

In addition to regulations on packaging, IAEA mandates physical protection against tampering or unauthorized removal of materials [3, 4]. The physical protection measures consist of a combination of hardware (security devices), procedures, and facility design fortifications. On the basis of the types and quantities of materials, the degree of protection is classified as Category I, II, or III, with Category I being the most tightly guarded.

Radio frequency identification (RFID) [5–9] is a technology that can augment the existing safeguards and security measures and further enhance the protection of both the materials and personnel. It is particularly well-suited for some of the more difficult and monotonous tasks and can greatly assist in the surveillance and verification processes.

An RFID system consists of three components [5, 7, 8]: tags that are mounted on the packages, readers that communicate with the tags, and software that manages the flow of data and instructions between the tags and readers. With RFID, unlike some of the other tagging or recording methods, a line of sight with the tagged item is not required. Battery-powered tags may have an effective work range of >100 m from the readers. The system tracks the tagged objects and queries their state of health autonomously and continuously. An alarm is triggered when the threshold of any sensor in the tag is exceeded. The control computer, in conjunction with a secure network, can send real-time information thousands of kilometers away. In transportation applications, the information, including event location, can be relayed via cellular or satellite communication networks and be shared by multiple users remotely in near-real time.

For monitoring sensitive nuclear materials with RFID, possibly the most critical element in the implementation is the selection of sensors. As the “eyes” of the system, sensors yield the raw data from which information can be processed and synthesized for actions.

ARG-US RFID System

“ARG-US,” meaning a watchful guardian, is an automated remote sensing and monitoring platform [10-12] developed by researchers at Argonne National Laboratory for the U.S. Department of Energy’s Packaging Certification Program, Office of Packaging and Transportation, Environmental Management. The system is designed to continuously monitor the state of health of containers for sensitive nuclear and radioactive materials, using the suite of sensors in the ARG-US RFID tags mounted on the containers. Reliability, long life, versatility (i.e., customizability for specific applications) and a user-friendly interface are key features of the platform.

The tags for the ARG-US RFID system are battery powered, with built-in sensors for tamper indication (seal), temperature, shock, and humidity, and the recently incorporated radiation sensors for gamma photons and neutrons. The front of the tag is covered by a plastic chassis to facilitate radio frequency transmission, and the back is sealed with a strong metal plate with a flange for attachment. Figure 1 shows the construction of an ARG-US tag with the optional radiation sensors. The form factor of the ARG-US tags is nearly universal; one can accommodate drum-type packages by merely modifying the back plate. Figure 2 shows ARG-US tags mounted on certified drum-type packages for nuclear materials.

Figure 1. Interior view of an ARG-US RFID tag, with the metal back plate and seal sensor removed. The two devices in the left compartment are the gamma dosimeter (top) and neutron detector.

Figure 2. A near-universal form factor allows ARG-US RFID tags to be mounted on multiple types of certified packages—Models 9975, 9977, 9978, ES-3100, DOT 7A, and others.

The radio transceiver in the ARG-US tag operates at 433 MHz and complies, for the most part, with the ISO 18000-7 standard [13]. This frequency is globally accepted and widely used. Of particular significance is its suitability for use near metallic objects, such as metal drums or containers. Other components on the tag's mother board (Figure 1, center compartment) include nonvolatile memories, a temperature sensor, a humidity sensor, a cantilever piezoelectric shock sensor, and the circuitry for processing signals from all sensors including the seal sensor (not shown). The nonvolatile memories can be programmed to store encrypted user data (e.g., contents manifest), sensor data, and event histories. When the stored information is programmed, it may be used as the basis for an automated tickler system that addresses compliance with processing or maintenance requirements and schedules.

Low-self-drain, high-capacity lithium thionyl chloride ($Li\text{-}SOCl_2$) primary cells are mounted on a "cartridge" board (Figure 1, right compartment) for ease of replacement. To extend battery service life, the board has a smart battery management circuitry which, by auto-switching, keeps only one battery on duty at any time. When the last battery is nearly depleted, an alert to call for replacement is automatically issued. It is projected that under normal usage, up to 10 years of service is attainable without requiring the batteries to be changed.

To communicate with the tags via radio frequency, one or more interrogators (readers) are used. The communication is two-way: the readers can receive signals from the tags, and they can send instructions to the tags. The readers may be permanently mounted in a building structure or on mobile carts. The reading range can be >100 m, and no line of sight is required. Mobile handheld readers may also be used when the need arises, for example, at loading docks.

Software provides the vital link between the technology and the end user and is a key component in implementing ARG-US. The ARG-US software package consists of a program called ARG-US OnSite, local and central databases, and web applications for storage, processing, and transportation. ARG-US OnSite is the basic building block; it controls the readers via the control computer and provides an intuitive graphical user interface to operate the hardware. Within the secure Internet, information from multiple rooms, buildings, or sites can be linked together by using the ARG-US web applications. The information can be accessed by authorized users located anywhere at any time. ARG-US TransPort, a subset of the ARG-US system, can monitor and track nuclear or radioactive materials in transport. It incorporates mapping and a global positioning system (GPS) and uses mobile communication equipment in the transport vehicle. Sample displays of ARG-US web pages are shown in Figure 3.

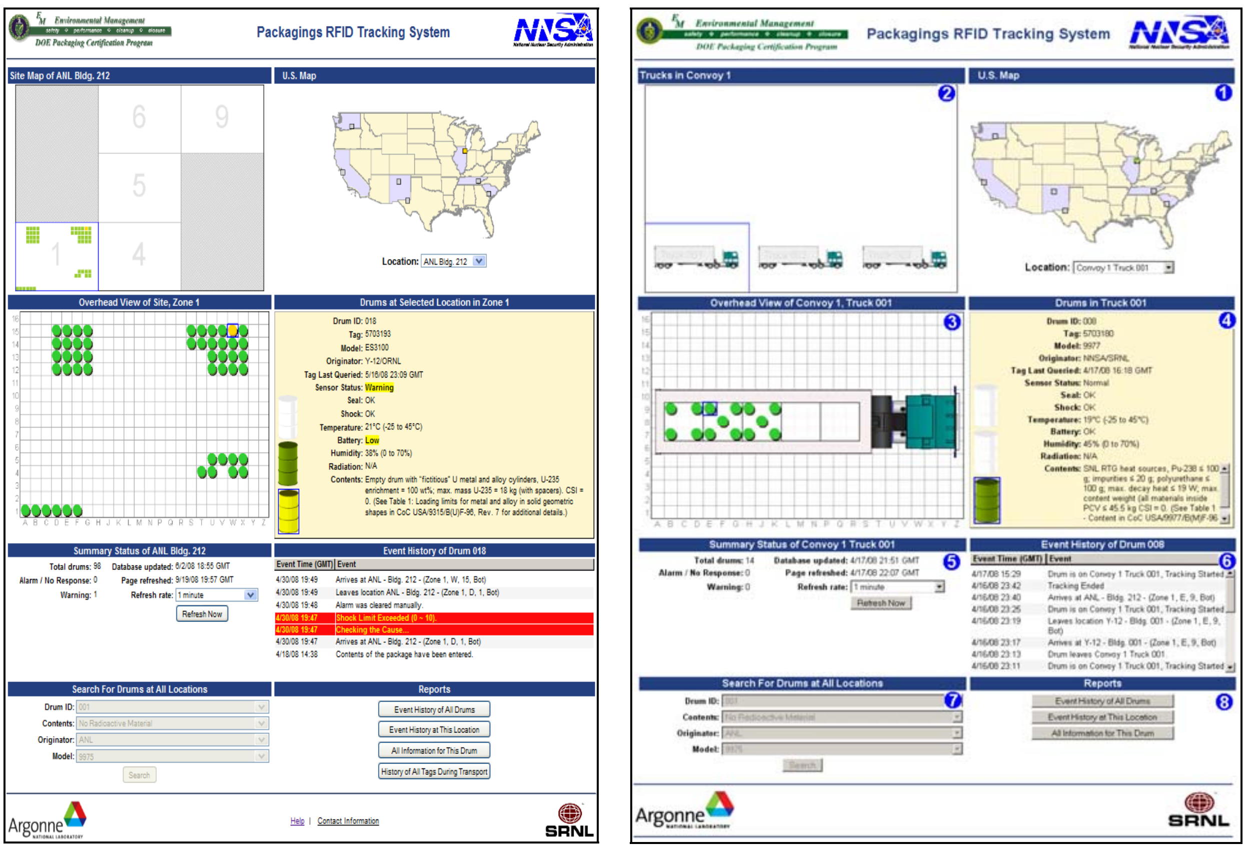

Figure 3. Sample web pages for ARG-US OnSite (left) and ARG-US TransPort (right).

DEVELOPMENT OF RADIATION DETECTOR-ENABLED RFID SYSTEM

With the addition of gamma and neutron detectors, the ARG-US RIFD platform can provide real-time monitoring of radiation levels of packages with sensitive nuclear and radioactive materials. The detectors regularly sample the gamma and neutron dose rates and accumulate total dose estimates that are stored in nonvolatile memory. Accurate exposure histories of tagged packages can be used to schedule surveillance activities for efficient aging management. In facilities with a large number of packages, dose rate readings from the tags can be collected to precisely map the radiation field—any significant perturbation from the norm can be used to generate alarms, thereby enhancing the safety, security, and safeguards posture of the operation. Because the radiation-field data are always available, the scope and number of routine manned inspections with hand-held detectors may be curtailed, thus reducing the exposure of personnel to radiation.

The gamma detector module selected for incorporation into the ARG-US tag is a modified compact personal dosimeter. The key features considered in the selection included compact size, low battery power consumption, suitable operating dose-rate range, high reliability, and reasonable cost. The selected detector is sensitive to x-ray and gamma radiation in an energy range of 50 keV to 6 MeV and has a wide dynamic measurement range—from 0.1 mSv/h to 8 Sv/h.

For the neutron detector, a newly commercialized solid-state device was chosen [14, 15]. While most of the selection criteria for the gamma dosimeter apply to the neutron detector, one added consideration is counting efficiency. The sensing element of the selected detector has multiple micro-channels that are impregnated with ^{6}LiF to increase the interaction surface area and volume. As a result, a relatively high counting efficiency, up to 20% for thermal neutrons, could be attained. Other desirable attributes for the neutron detector include high saturation threshold for neutron flux and low sensitivity to co-existing gamma radiation.

An expansion board that fits inside the tag enclosure (see Figure 1) was developed. The board holds both radiation detectors and provides proper data and command interfaces with the tag motherboard. The expansion board can be populated with just one of the two detectors, or it can be completely removed from the tag. This design flexibility allows options for different deployment needs.

The data from the detectors are collected by a low-power micro-controller unit (MCU) on the expansion board. The nonvolatile memory implemented within the MCU allows the accumulated dose rate information to be retained when the power is off. Careful power management and a judicious selection of components limit the impact of the detector operation on battery performance. In the low-power mode of the expansion board, the MCU is set at regular programmable intervals to wake up either one of the two detectors and read the instantaneous dose rate. The data are passed along through the tag to the reader network whenever those values are requested. The requested data are then displayed at the operator terminal and stored in the system database. Data on alarm events that have resulted from high or low dose rates or a high accumulated dose are stored in both the MCU and the database. Figure 4 shows a simplified block diagram of the detector integration in the tag structure and photos of the expansion board with and without the radiation detectors. The MCU provides additional interface possibilities to facilitate development of new sensor features, and the expansion board is designed with an internal separation to allow modular expansion capabilities, including external sensors. A variety of interface methodologies are available, including universal asynchronous receiver/transmitter (UART), inter-integrated circuit (I2C), serial peripheral interface (SPI), and universal serial bus (USB), plus direct analog voltage and digital signal interface.

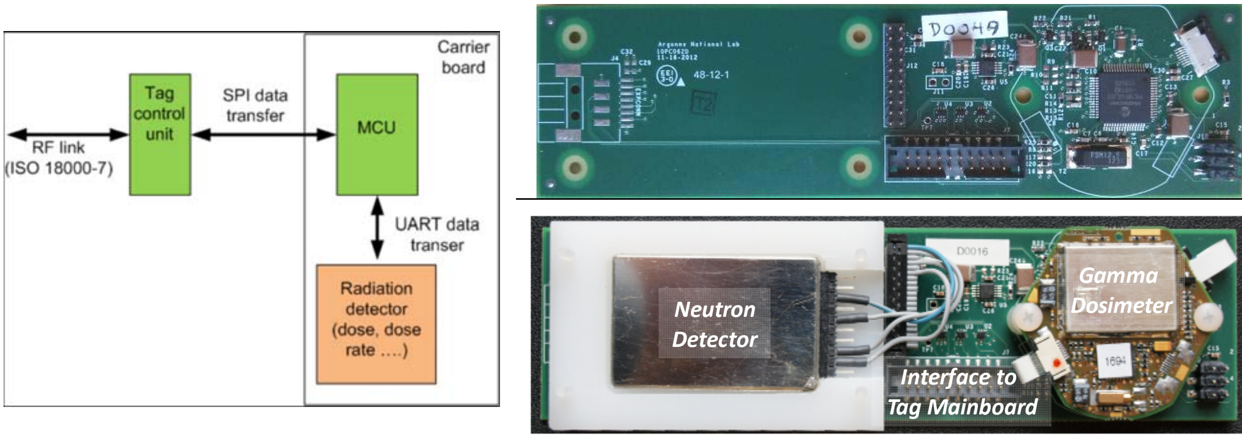

Figure 4. Sketch of interconnections and photos of bare and detector-populated expansion boards.

BENCHMARK TESTING OF INTEGRATED DETECTORS

Benchmark testing with a certified Cs-137 gamma source and an AmBe neutron source confirmed that both the gamma and neutron detectors function properly and that the integration at the board, firmware and software levels is successful. Figure 5 shows the experimental setup in a cave with tags mounted on a precision draw table.

The two principal parameters for the benchmark testing were exposure time and distance to sources. Additionally, concurrent neutron and gamma exposure was performed to verify the low sensitivity of the neutron detector to gamma radiation. ARG-US software and user interfaces, which were modified to accommodate the radiation detector options, were verified in the benchmark testing.

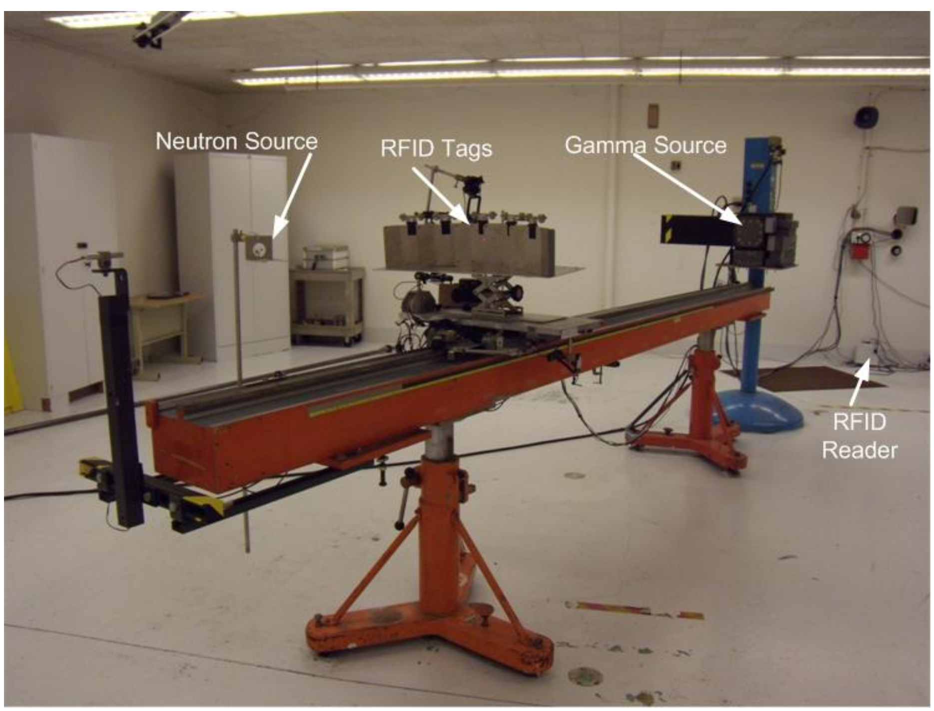

Figure 5. Benchmark testing of integrated-detector tags with a certified Cs-137 gamma source and an AmBe neutron source.

Figure 6 shows the readings of two integrated dosimeter tags at a constant distance from the gamma source over a period of 24 h. The gamma dose-rate readings were steady (100 mR/h) and the recorded cumulative dose increased linearly over time. By changing the distance to the gamma source and by using attenuators, the performance of the gamma dosimeters over a range of the anticipated dose-rate conditions was verified. These results, shown in Figure 7, were found to be highly satisfactory.

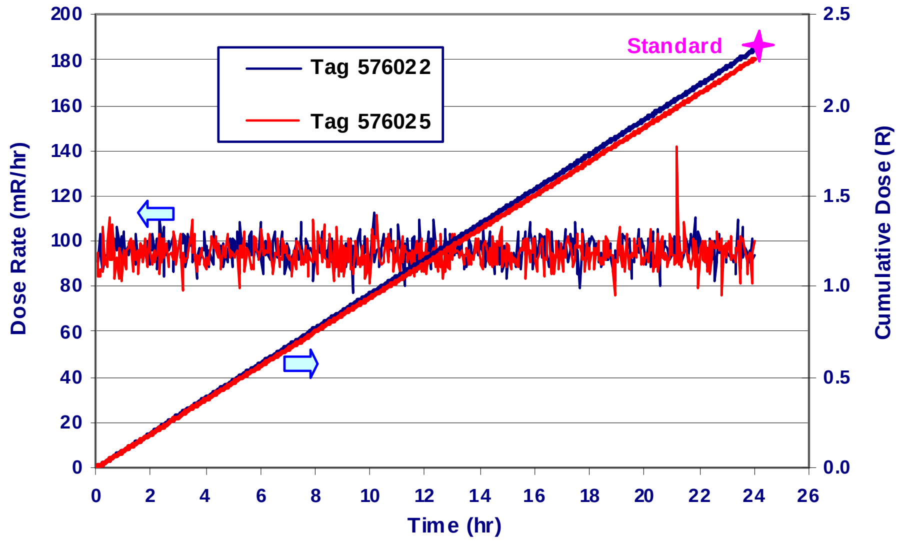

Figure 6. Response of integrated dosimeter tags at a steady dose rate of 100 mR/h for 24 hours (Self-shielding of the front plastic chassis of the tags accounted for the ≈4% reduced readings for both the dose rates and cumulative doses.)

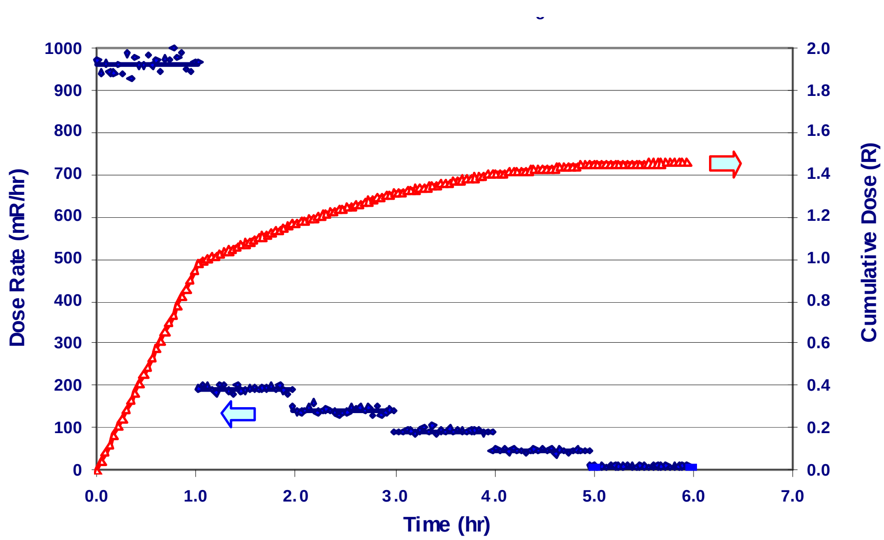

Figure 7. Response of an integrated dosimeter tag at dose rates ranging from 10 to 1000 mR/h. (Self-shielding of the front plastic chassis of the tags accounted for the ≈4% reduced readings for both the dose rates and cumulative doses.)

Measurement results for neutron detection as a function of source distance are shown in Fig. 8 for two of the integrated neutron detector tags. As the emitted neutrons from the AmBe source were mostly fast (>≈3 MeV) and continually underwent scattering and moderation in the test cave environment, as expected, the attenuation versus distance was not as pronounced as $1/r^2$. Figure 9 shows accumulation of total counts over a period of 12 h for four of the neutron detector tags at 300 cm from the source. The results confirm the steady performance of the neutron detectors over the period. In a separate effect test with only the gamma source, the integrated neutron detector tags displayed adequate lack of sensitivity to the gamma radiation.

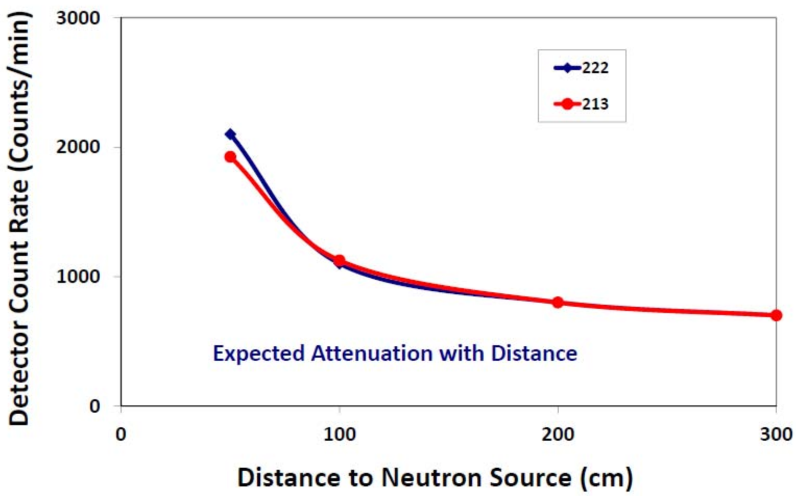

Figure 8. Response of integrated neutron detector tags as a function of distance to the neutron source.

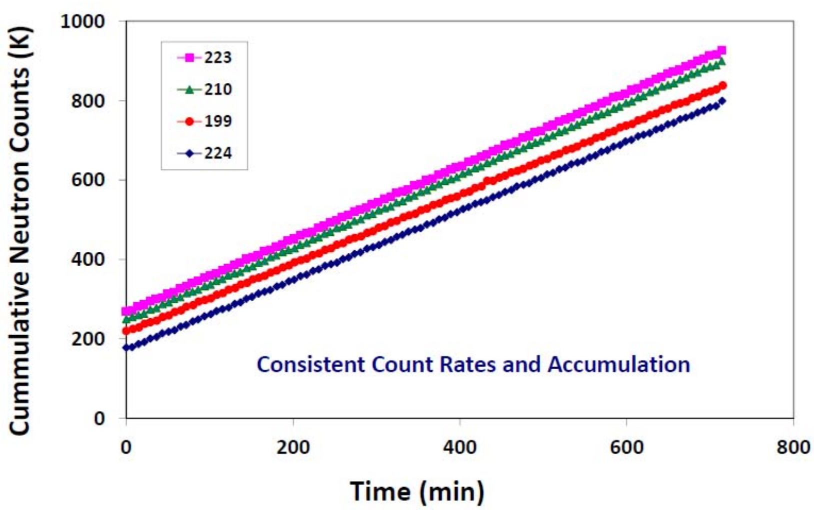

Figure 9. Reliable neutron detector performance as indicated by steady count rates and linear count accumulation over a period of 12 h.

DISCUSSION

Comprehensive monitoring of sensitive nuclear and radioactive materials can be attained with advanced RFID technologies such as represented by the ARG-US platform. The advantages of the technology are numerous—streamlined operation; improved record-keeping; enhanced safety, security, and safeguards; cost savings; and As-Low-As-Reasonably-Achievable (ALARA) dose rates to personnel. Capitalizing on the fact that most of the nuclear materials under surveillance are radiation emitters, the incorporation of gamma and neutron detectors further enhances the ability of the ARG-US RFID platform for monitoring and tracking. The modular approach and the flexible expansion interface adopted by ARG-US allow new sensor types to be added, as needed, without requiring redevelopment of the core technology.

As mentioned earlier, demonstrations and field-testing of the ARG-US RFID systems for storage and transportation applications have been conducted at selected DOE sites since 2010 [16]. The field-testing conducted at the K-Area Material Storage (KAMS) Facility at the DOE Savannah River Site, Aiken, SC, involved two phases in 2010 [17] and 2012 [18]. During Phase I field-testing, 20 Mk-II RFID tags (without radiation sensors) were deployed in the Category-I vault to monitor temperature and other environmental parameters of the 9975 packages over a span of six months. The RFID tag-recorded temperature data throughout the period corroborated the data obtained by independent temperature monitoring and testing equipment; the same was true of the humidity data. Other sensory functions of the tags, such as drum-lid closure and shock, were also verified to perform reliably in tests randomly conducted during the period.

During Phase II field-testing, 12 Mk-III RFID tags with radiation dosimeters were distributed in the Category II vault (910B) at KAMS. Much smaller than the Category I vault, this vault contains significantly fewer 9975 packages, but the movement of packages is more frequent. Unlike Phase I field-testing, during which the tag data were collected weekly by the operator, the Mk-III tags were programmed to be polled automatically every six hours from the beginning of the testing. The RFID tag-recorded data on temperature, humidity, dose rates and accumulated doses were collected over a period of six months and they all showed consistent patterns, and as expected, the doses increased monotonically with time; the occasional slight change in slopes reflects the configuration changes that occurred in the 910B vault. The overall performance of the system, from sensors to communication, has been proven robust and reliable, even as the new radiation dosimeters were incorporated into the modular platform of the Mk-III tag.

Progress has been made recently to qualify the ARG-US RFID tag as a tamper-indicating (TID) seal for the 9975, 9977, 9978, 9979 and ES-3100 packagings. The qualification followed the guidelines in the USNRC Regulatory Guide (RG) 5.80, “Pressure-Sensitive (PS) and Tamper-Indicating Device Seals for Material Control and Accounting of Special Nuclear Material,” December 2010 [19]. Evaluation of seal functionality and limitations defined in RG 5.80 revealed that the ARG-US RFID tag seal meets or exceeds all of the performance criteria for the PS/TID seal. The accreditation of the ARG-US RFID tag as a TID seal for Types B and AF transportation packagings can significantly reduce the cost of verification and exposure of workers to radiation, after a shipper-receiver agreement on its use for verification purposes is reached between sites. These benefits add to those enabled by the ARG-US RFID system regarding extension of the maintenance intervals for periodic leakage rate testing of radioactive material transportation packagings from one year to as many as five [20]. The extension not only enhances safety and contributes to ALARA dose rates by reducing handling by, and exposure of, workers to radiation, but it also reduces annual operating costs during the storage phase of such packagings by US$2500–3000 per package per year.

In July 2012, progress was also made in technology transfer when Argonne National Laboratory and Evigia Systems, Inc., reached a licensing agreement on the ARG-US RFID technology. As a result of this agreement, the ARG-US RFID system is now available commercially to customers around the world. Potential markets for ARG-US RFID tags include civilian nuclear industries; hazardous materials and chemicals companies; or any high-risk, high-value materials handlers.

FUTURE WORK

RF portal monitors, handheld readers, and video camera capabilities are among the items on the development path of ARG-US RFID for future applications in general, and domestic and IAEA safeguards in particular. RF portal monitors and handheld readers can help maintain the chain of custody and continuity of knowledge of special nuclear materials in packages. They complement fixed RF readers that need to be deployed to cover large facilities, such as KAMS. For example, facility configurations and operations may require (1) RF portals that register only entry/exit of a package into a vault or building, or (2) a handheld RF reader that can perform key functions at the package loading docks of the shipper and receiver sites. Development of software that integrates the fixed RF readers, portal monitors, and handheld readers has been initiated, as has the investigation of video camera capabilities and their integration into a web-based ARG-US system for remote sensing and facility monitoring.

Field-testing of ARG-US RFID systems at KAMS will continue in 2013, moving toward applications in areas with high radiation fields and multiple reader networks to validate the performance and reliability of the systems in facility operations.

TRANSCOM is the DOE’s unclassified Tracking and Communication Web Application, which is used to monitor the progress of "high-visibility" shipments, such as spent nuclear fuel and high-level and transuranic radioactive waste. Therefore, tracking and monitoring of ARG-US tagged packages with sensitive nuclear and radioactive materials during transport for DOE has been done via TRANSCOM using communication gear provided by Qualcomm. Up to now, the prevalent Qualcomm gear available in the transport vehicles has been the “OmniTRACS” and “OmniVision” platforms. Since TRANSCOM is making a gradual switch to a newer Qualcomm platform called Mobile Computing Platform (MCP) 200, ARG-US TransPort is being updated accordingly. The results thus far, including speed of response, have been highly satisfactory. Full integration and acceptance confirmation are expected in summer 2013.

CONCLUSIONS

Comprehensive monitoring and tracking of sensitive nuclear materials can now be achieved with the ARG-US RFID technology developed by Argonne National Laboratory for the DOE Packaging and Certification Program. ARG-US utilizes a suite of sensors in tags to continuously monitor the state of health of the packaging and promptly disseminates alarms to authorized users and responsible parties via a secured local network and/or the Internet. In conjunction with available in-vehicle cellular and satellite communication packages and GPS receivers and the management infrastructure available from DOE-TRANSCOM, the ARG-US platform can monitor and track assets in transit as well.

Recently, compact neutron detectors and gamma dosimeters have been successfully incorporated into the ARG-US RFID tags. In conjunction with the existing sensors, which include seal (a tamper-indicating device), shock, temperature, and humidity sensors, the enhanced platform provides broad protection of materials and strict safeguards implementation. A dedicated expansion board was developed with a specially designed universal asynchronous receiver/transmitter interface to accommodate the two types of radiation detectors plus other sensors in the future. Both gamma and neutron detectors can initiate alarms for either a high or low radiation level and for a high cumulative dose. In a large installation, strategically located radiation-detector-enabled tags can yield an accurate, real-time, 2D or 3D dose field map. Any perturbation of the field distribution can be used to alert the operator. As radiation data are constantly available, manned surveillance with portable instruments may be appropriately curtailed, conforming to ALARA practice.

ACKNOWLEDGMENTS

This work is supported by the U.S. Department of Energy under Contract No. DE-AC02-06CH11357. The authors wish to acknowledge the excellent leadership and strong support provided by DOE-EM for this project.

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