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RFID TECHNOLOGY FOR ENVIRONMENTAL REMEDIATION AND RADIOACTIVE WASTE MANAGEMENT

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ABSTRACT

An advanced Radio Frequency Identification (RFID) system capable of tracking and monitoring a wide range of materials and components – from fissionable stocks to radioactive wastes – has been developed. The system offers a number of advantages, including enhanced safety, security and safeguards, reduced personnel exposure to radiation, and improved inventory control and cost-effectiveness. Using sensors, RFID tags can monitor the state of health of the tracked items and trigger alarms instantly when the normal ranges are violated. Nonvolatile memories in the tags can store sensor data, event records, as well as a contents manifest. Gamma irradiation tests showed that the tag components possess significant radiation resistance. Long-life batteries and smart management circuitries permit the tags to operate for up to 10 years without battery replacement. The tags have a near universal form factor, i.e., they can fit different package types. The read range is up to >100 m with no line-of-sight required. With careful implementation, even a large-size processing or storage facility with a complex configuration can be monitored with a handful of readers in a network. In transportation, by incorporating Global Positioning System (GPS), satellite/cellular communication technology, and secure Internet, situation awareness is assured continuously. The RFID system, when integrated with Geographic Information System (GIS) technology, can promptly provide content- and event-specific information to first responders and emergency management teams in case of incidents. In stand-alone applications, the monitoring and tracking data are contained within the local computer. With a secure Internet, information can be shared within the complex or even globally in real time. As with the deployment of any new technology, overcoming the cultural resistance is part of the developmental process. With a strong institutional support and multiple successful live demonstrations, the cultural resistance has been mostly overcome. As a result, implementation of the RFID technology is taking place at several of U.S. Department of Energy sites and laboratories for processing, storage, and transportation applications.

INTRODUCTION

Environmental remediation and radioactive waste management entail collecting, storing, processing, and disposing of a variety of materials, ranging from legacy weapons stocks, fuel cycle products and by-products, medical and industrial radioisotopes to radioactive wastes. The packages holding these materials, governed by the 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 also 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 materials types and quantities, the degree of protection is classified as Categories I, II, or III, with Cat-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 personnel and materials. It is particularly well suited for some of the more difficult and monotonic 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 interrogate the tags, and software that manages the data and instructions flow between the tags and readers. With RFID, unlike many other tagging methods, line-of-sight is not required between the tags and the readers. Battery-powered tags may have an effective work range of up to >100 meters from the readers. The system tracks the tagged objects and queries their state of health autonomously and continuously. It triggers an alarm 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, the information, including event location, can be relayed via cellular or satellite communication networks and be shared by multiple users remotely near real time.

The benefits of an RFID system are many. By scaling back manned inspections, for instance, radiation exposure to personnel can be reduced, reinforcing the universally endorsed concept of ALARA (as low as reasonably achievable). Likewise, early warning of the health of the package can mitigate the consequences of an incident, thereby improving the security and safeguards of both the facility and the materials. Real-time access of status and history data of the materials can improve situation awareness and operational efficiency, reduce inventory control mishaps, and enhance overall cost-effectiveness. There is, therefore, a strong incentive to modernize the procedures and operations for environmental remediation and radioactive waste management by adopting the RFID technology.

ARG-US RFID SYSTEM

The RFID system [10,11,12] described in this paper was developed by Argonne National Laboratory under the auspices of the DOE Packaging Certification Program (PCP), Office of Packaging and Transportation of the U.S. Department of Energy Environmental Management (DOE-EM). The system is named ARG-US, which reflects its designed role of being a watchful guardian. The concept of monitoring and tracking nuclear and radioactive materials with ARG-US RFID system is shown in Figure 1. The intent is to follow the complete life cycle of the packaging – from initial contents loading, through interim transports and processing, to possible long-term storage and eventual disposal. With a secure network, the full records of inventory and history from all sites can be linked and archived and be remotely accessible by all authorized users.

Hardware Platform

The tags for the ARG-US RFID system are presently at the Mk-II version, shown in Figure 2. For demanding service conditions and functionality, and unlike many of the tags in commercial usage, the Mk-II tags are battery powered. The tags have built-in sensors that monitor temperature, shock, humidity, seal, and battery strength. The front of the tag is covered by plastic to facilitate RF transmission, and the back is sealed with a strong metal plate with a flange for drum attachment. With the available space and continuing shrinkage of electronic component sizes, Mk-II tags can be expanded in future with enhanced functionalities. The approximate dimensions of an Mk-II tag are 150 mm (H) × 210 mm (W) × 30 mm (T), and the tag weight is ≈900 g.

For nuclear applications, adequate resistance of tag electronics to radiation damage is a necessity. In gamma irradiation tests performed with a Cs-137 source, the tags were verified to function at a dose beyond 31 krad. This dose level corresponds to ≈17 years of service in a field of 200 mR/h, the regulatory dose rate limit on the surfaces of Type B packaging. Since the actual surface dose rates are often significantly lower than the statutory limit, the life span of Mk-II tags would be proportionally longer.

Monitoring the package closure integrity is an important requirement of the ARG-US system. A low-profile seal sensor is used in the Mk-II tags for this purpose. Its sensing element is a pliant, force-sensitive piezoresistive material whose electric resistance changes from kΩ when compressed to MΩ when decompressed. The sensor is positioned beneath the seal bolt(s) of the drum lid to monitor the bolt tension. In Figure 2, the seal sensor has a dual head for mounting under two adjacent lid bolts. In other applications, one or more lid bolts may be engaged. The seal sensor is produced by screen-printing, and the configuration can be readily updated. As only the seal sensor and the back plate's mounting flange need to be modified for different drum types, the Mk-II tags can fit on multiple packages. Figure 3 shows some of the different applications, including the widely used DOT 7A. When installed, the ribbon portion of the seal sensor is concealed behind the sheet metal back plate.

The transceiver in Mk-II tags operates at 433-MHz and complies, for the most part, with the ISO 18000-7 standard. This frequency is globally accepted and widely in use. Of particular consideration is that it can be used with metallic objects, such as steel drums. Other components on the tag's circuit board include several banks of nonvolatile memories, a temperature sensor, a humidity sensor, a cantilever piezo shock sensor, and the circuitry for processing the piezoresistive seal sensor signal. The nonvolatile memories can be programmed to store encrypted user data (e.g., contents manifest), sensor data, and event histories.

Low-self-drain, high-capacity lithium-thionyl chloride ($Li\text{-}SOCl_2$) primary cells are used in the Mk-II tags. To further extend the battery service life, a smart battery management board is incorporated. While up to four batteries may be loaded (Figure 2), auto-switching keeps only one fresh battery on duty at any time. When all batteries are nearly depleted, an alert is

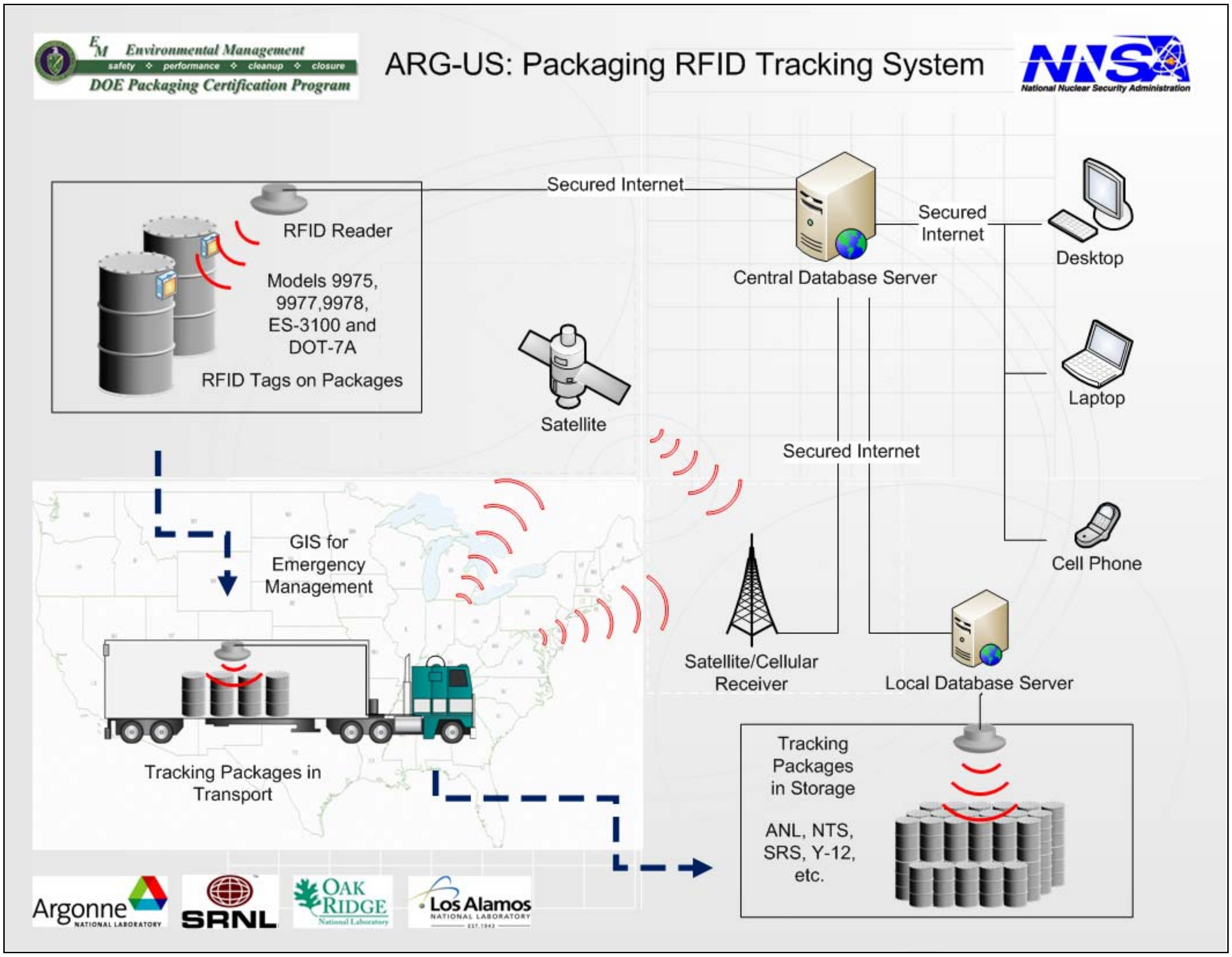

FIGURE 1. Concept of packaging RFID monitoring and tracking system for nuclear materials management

FIGURE 2. Mk-II RFID tag

FIGURE 3. Mk-II RFID tags mounted on multiple drum types (9975, 9977, 9978, ES-3100, DOT 7A)

issued to call for replacement. By using this method, up to 10 years of service life without battery change is projected under normal usage.

In storage applications, the reader, or a network of them, may be permanently mounted on the ceiling or walls. In some cases, a compact mobile station, such as the one shown in Figure 4, may be more appropriate. In transportation tracking, a reader would be mounted inside the cargo bay or other suitable location.

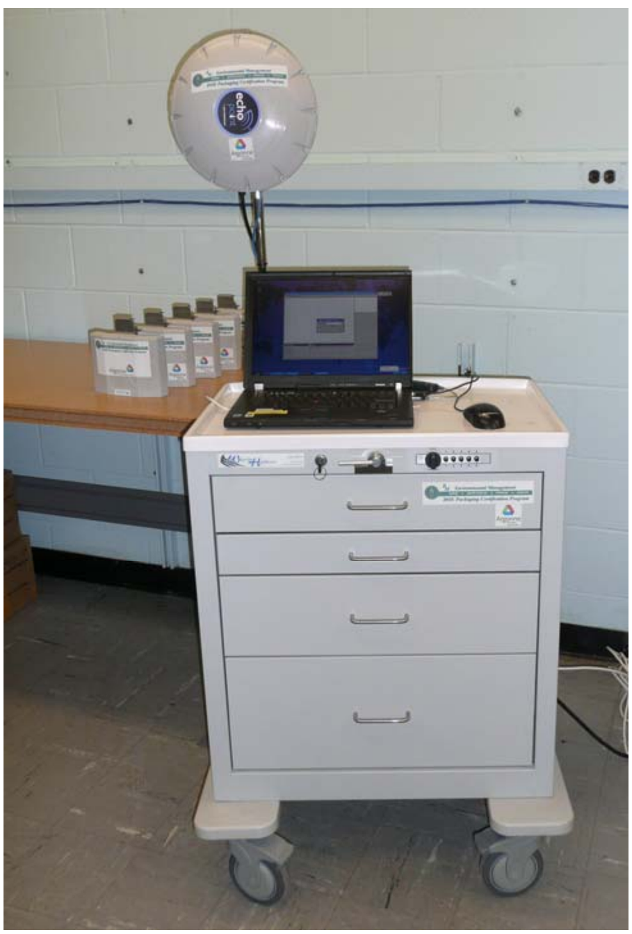

FIGURE 4. A complete RFID monitoring system on a compact, mobile platform

Software Platform

Software is the vital linkage between the technology and the end user and is a key factor for any successful implementation. In the design of ARG-US software, user-friendliness is one of the most important considerations.

The software package consists of a program called ARG-US OnSite, local and central databases, and web applications. ARG-US OnSite, the basic building block, controls the readers via the control computer and provides a graphical user interface (GUI) to operate the hardware. The design philosophy is to present all relevant information in an intuitive way on the console screen so that the user can take control of the information presented. In ARG-US OnSite, a user can enter or retrieve pertinent information easily by using pull-down menus.

A sample GUI screen of ARG-US OnSite for packages in a storage application is shown in Figure 5. Although only a few packages (drums) are displayed in this screenshot, thousands of packages can be monitored in actual operations. The main window with a grid definition depicts a selected zone or room of a facility. Each package represented by a drum symbol occupies an assigned grid location in the main window. As can be seen, stacking of drums can be managed. A green panel approach is adopted so that when the status of a drum becomes abnormal, the symbol would turn to yellow (warning) or red (alarm). By clicking on a drum, the detailed information of the selected drum, including the battery status, is displayed in the window on the right. At the bottom of the GUI screen are panes showing current status, history events, and search functions. The user can instruct the system to automatically collect data of all tags at specified intervals or obtain data from a specific tag at any time.

From sub-menus of the main GUI, there are provisions for the user to enter content manifest and processing histories, adjust alarm thresholds, set auto-collect intervals, view detailed history log, and prepare data for export. The alarm triggering threshold for each sensor can be set per operating conditions. For instance, the thresholds for shock and temperature sensors would be appropriately relaxed before a transportation campaign and reset to the higher sensitivity levels afterwards to detect minute movements or unusual temperature swings in storage.

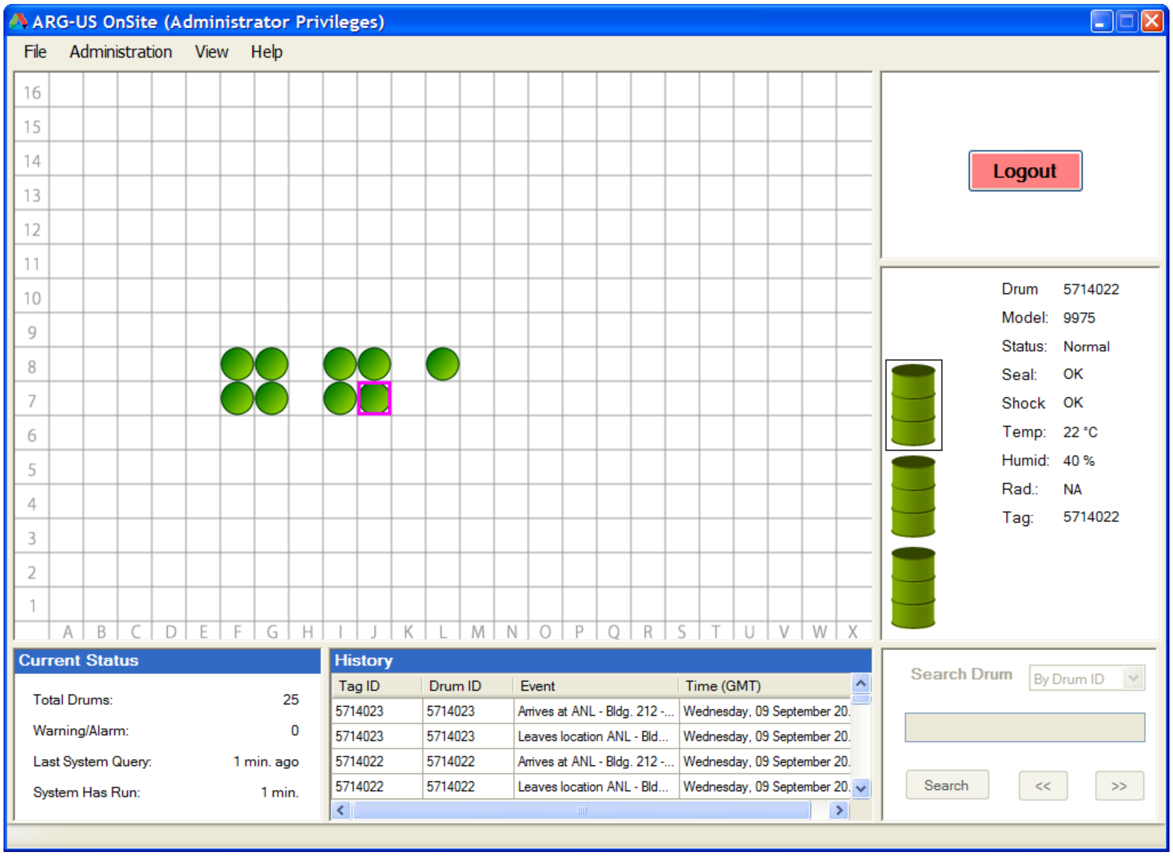

FIGURE 5. Sample screen display of ARG-US OnSite

ARG-US OnSite processes the collected tag data and stores them in a local database. When appropriate, the data may be encrypted, authenticated, and uploaded to a central server as well. With a secure web setup, authorized users can access and retrieve information on the servers thousands of kilometers away in real time. The central database is located in a data/command center that can monitor all tagged package in storage and transportation over the entire life cycle.

By incorporating mapping and GPS, and utilizing mobile communication equipment in the transport vehicle, a subset of the ARG-US system – called ARG-US TransPort – can monitor and track nuclear materials in transport. The webpage of ARG-US TransPort is illustrated in Figure 6. Multiple fleets of vehicles can be tracked. Planned route, route tracking (bread-crumbing), zoom, and spot information are some of the features implemented. Similar to the display functions in ARG-US OnSite, detailed information for an individual package is accessible for the current and past time steps. An important function of the webpage is geographic information system (GIS) reporting – preformatted GIS spatial reports, when called for, can be issued with a single click from the command center. The report provides the first responders and emergency management team with a concise summary of local assets and vulnerabilities and is an important tool in case of a transport incident.

Packages in storage at various sites may be monitored and tracked in similar manner. A specific site would be selected from the map pane, and the facility configuration of the site would be modeled into the webpage. Search functions unique to the site's requirement would be set up. As with ARG-US Transport, remote data access would be done via secure Internet.

A software quality assurance (SQA) program has been established for ARG-US. The SQA program determines the level of activities and documentation necessary for assuring the quality of ARG-US, as well as the practices to be followed in the course of the software developmental effort. The program emphasizes design control, version control, software functionality and reliability tests, user documentation, and document control. Each version of ARG-US will be tested, reviewed, and approved on the basis of the SQA program before it is released. The ARG-US SQA program is governed by subsets of the quality assurance plan of Argonne National Laboratory.

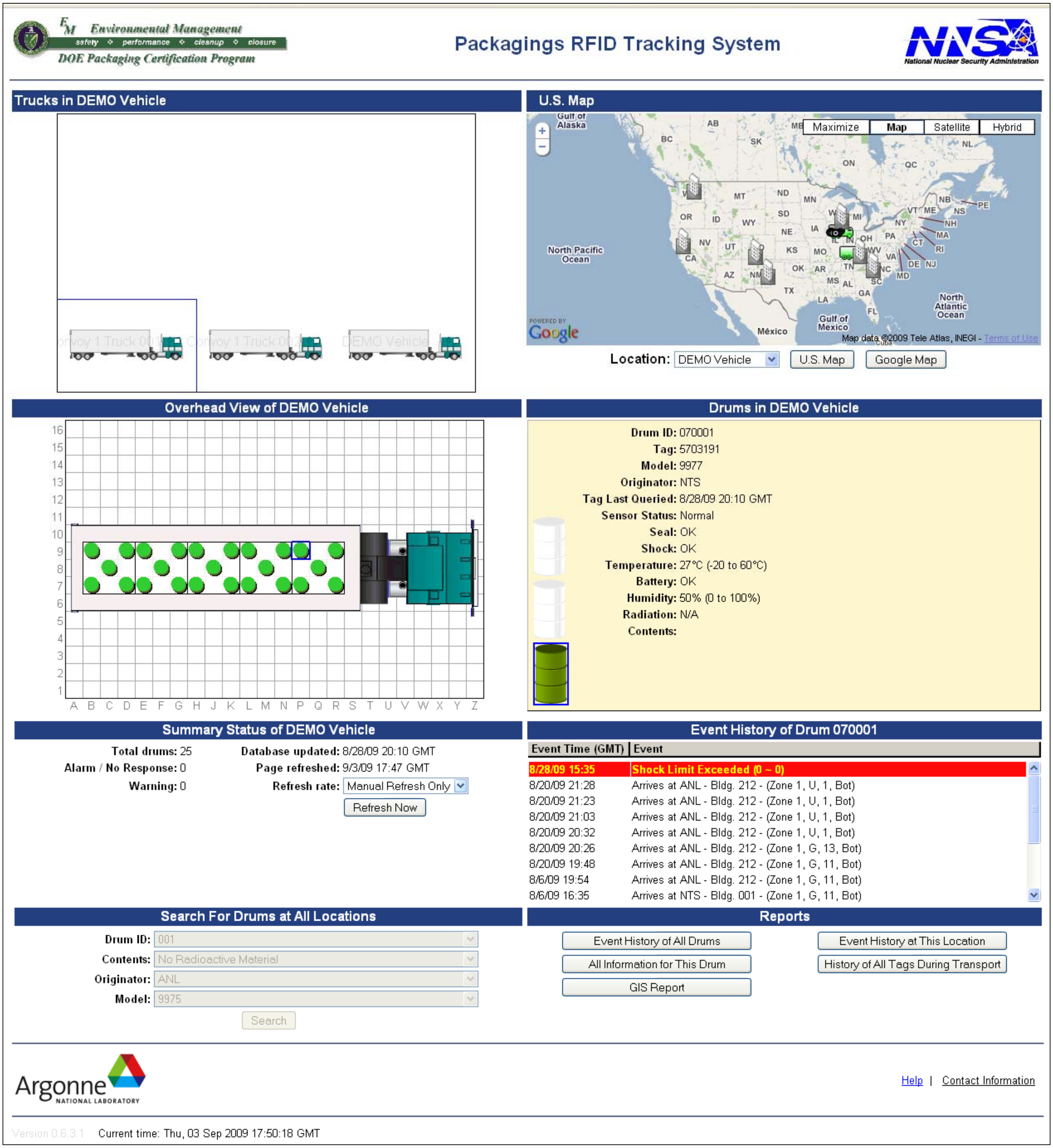

FIGURE 6. Sample screen display of ARG-US TransPort via secure web

PERFORMANCE VERIFICATION

Three road tests have been performed to verify the performance of ARG-US. The first test, dubbed DEMO [13], was carried out in 2008 by using a semi-trailer with 14 clean drums. It covered 2,700 km in 4.5 days. The objective of the DEMO was to test the reliability of the tags and compare side-by-side four candidate vehicle-tracking systems. The second test, dubbed MiniDemo [14], was to verify the result of integration of ARG-US TransPort with the selected tracking system – Qualcomm's OmniTRACS [15]. The third test was an evaluation of "Big Bird," a DOE truck after it was outfitted with ARG-US RFID equipment.

Both the RFID system and the integrated vehicle-tracking features worked well in the three road tests. To verify alarm reaction and notification, staged incidents were conducted during the trips. The system never failed to respond, and equally important, the system never malfunctioned to produce a false alarm. Mock-up GIS spatial query reports were successfully issued according to plans in all three road tests.

Qualcomm's OmniTRACS was selected as the vehicle tracking system for ARG-US TransPort. This decision was a natural one as OmniTRACS is the platform used by TRANSCOM [16], the DOE-EM organization responsible for high-visibility shipments. OmniTRACS exclusively utilizes satellite communication.

When the situation is normal, ARG-US TransPort reports detailed tags status and vehicle position (GPS) data to the Qualcomm satellite at 5-min intervals. If the communication is interrupted as a result of physical obstacles (e.g., tunnels, highway underpass), the unsent data stay in a queue in the vehicle transponder, and the transmission is resumed when satellite communication is restored. The lag between the data sent from the vehicle and the receipt of the data at the command center is typically less than 2 min, which is considered to be excellent in real-life situations. In case of an incident, the alarm takes precedent, and the event and location data are sent immediately. From the command center, notification of the responsible individuals of the alarm is prompt and automatic.

The successful implementation of RFID system in Big Bird, a truck for the DOE's Off-Site Source Recovery Program (OSRP) [17], has a significant practical meaning. With carefully planning, the physical installation went smoothly and was accomplished in less than one day. In the post-installation road test, following the route as depicted in Figure 7, all of the installed features were found to be working properly. The successful incorporation of ARG-US RFID in "Big Bird" bodes well for the conversion of additional transport vehicles to provide them with ARG-US-based item-monitoring capabilities.

FUTURE ACTIVITIES

Several ARG-US RFID systems with Mk-II tags have been delivered to DOE sites and laboratories for field trials. Thus far, the feedback has been excellent. No RF interference with the existing facility equipment, a major implementation concern, has been detected. These field trials, mainly for storage and process applications, are ongoing. Strong institutional support and successful demonstrations described in this paper are instrumental in overcoming the cultural reluctance of accepting this new technology.

The performance of the RFID system installed in the OSRP "Big Bird" will be tracked closely when it performs its assigned duties of collecting unwanted isotope sources from hospitals, universities, industry, and other locations. ARG-US will help to track and monitor the collected sources during the processing and storage phases as well.

TRANSCOM is a DOE-EM organization responsible for the shipment of high-visibility materials and has a mature infrastructure. Integration of ARG-US TransPort with TRANSCOM is under way so that the full capabilities of both systems can be utilized. The integration effort is to be completed in 2010.

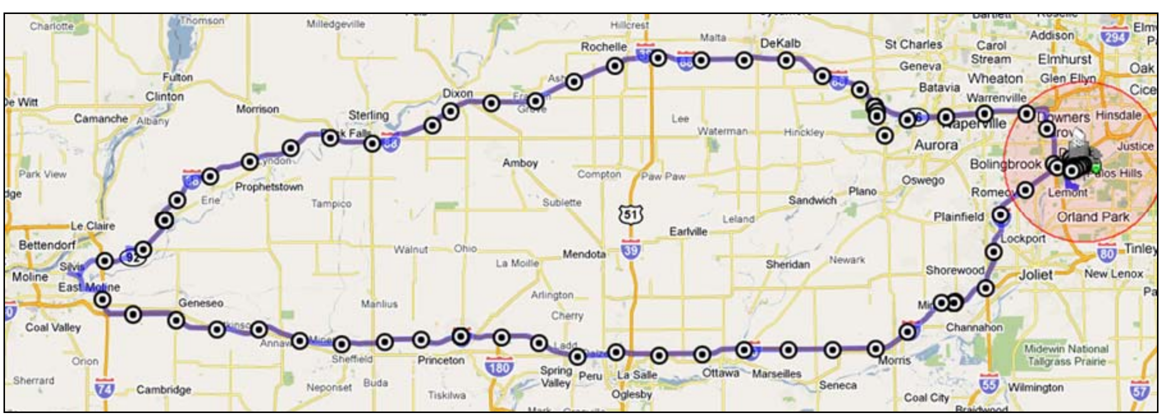

FIGURE 7. Road traveled by the Big Bird in the road test. The total distance is about 500 km. The circular symbols are 5-minute breadcrumbs.

Improving ARG-US component and system performance is a continuing effort. Incorporating dosimeters and specialty sensors, expanding the service envelope, hardening the tag enclosure for greater physical protection, and improving authentication and data security are some of the improvements under development.

CONCLUSIONS

An RFID-based monitoring and tracking system, ARG-US, has been successfully developed by DOE for environmental remediation and radioactive waste management. The tags, with high radiation resistance, full sensor suite, and long-life batteries, can monitor the state of health of packages continuously under challenging conditions. With competent software and secure Internet, the information can be made available to multiple users at near real time, whether the packages are in storage or transport. Deployment of the ARG-US system is taking place in multiple DOE sites and laboratories. The results of deployment thus far have been excellent and should lead to wider acceptance of this technology in the United States, as well as globally.

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