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A RADIOFREQUENCY IDENTIFICATION (RFID) TEMPERATURE-MONITORING SYSTEM FOR EXTENDED MAINTENANCE OF NUCLEAR MATERIALS PACKAGING

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ABSTRACT

A temperature-monitoring system based on radiofrequency identification (RFID) has been developed for extending the maintenance period of the nuclear material packaging for storage and transportation. The system consists of tags, readers, and application software. The tag, equipped with a temperature sensor, is attached to the exterior of a package. The application software enables remote reading, via radio waves, of the temperature from the sensor in the tag. The system reports any temperature violations immediately via e-mail or text message, and/or posts the alarm on a secure website. The system can monitor thousands of packages and record individual temperature histories in a database. The first type of packaging that will benefit from the RFID technology is Model 9977, which has been certified by the U.S. Department of Energy (DOE) to ship and store fissile materials such as plutonium and uranium. The recorded data can be correlated to the temperature of the containment O-ring seals, based on the decay heat load of the contents. Accelerated aging studies of the Viton® GLT O-rings have shown that temperature is one of the key parameters governing the life of the O-ring seals, which maintain the integrity of the containment boundary of the package. Use of the RFID temperature-monitoring system to verify that the surface temperature remains below a certain threshold will make it possible to extend the leak-test period of the package from one year to up to five years. The longer leak-rate testing interval will yield a cost savings of up to $10,000 per package over five years. This work was conducted by Argonne National Laboratory in support of the DOE Packaging Certification Program, Office of Environmental Management, Office of Packaging and Transportation (EM-63).

INTRODUCTION

RFID technology uses radio waves to automatically identify objects and collect data from them. In recent years, this technology is increasingly being used in supply-chain management, healthcare, manufacturing, highway tolling, security, environment protection, and many other applications [1]. An RFID system consists of tags, readers, and application software. A simple tag is made of a microchip with an antenna. Some advanced tags have integrated sensors and memory. The tag is physically attached to the object to be identified; for example, a container, a vehicle, or an animal. The tag communicates with a reader via radio waves. The reader is either connected to or integrated with a computer, on which the application software runs. The software not only controls the communication between the reader and the tag, but it also processes the data from the tag and presents it to the user. Significant advances have been made in microchip and antenna designs that have helped overcome some of the major obstacles for RFID applications: power consumption, radio transmission near conductors, and manufacturing.

Earlier work on applying RFID technology to nuclear materials management for the DOE Packaging Certification Program (PCP) has been reported elsewhere [2]. During the last two years, DOE PCP has tasked Argonne to develop an RFID tracking system for nuclear material packages during storage and transportation. The system development involved hardware modification (e.g., form factor, seal sensor, and batteries), application software development, secured database and web server development, and irradiation experiments. All key elements of the packaging RFID tracking system were tested in a week-long, 1,700-mi demonstration (DEMO) in April 2008 [3, 4]. Both the hardware and software platforms were verified to be stable and meeting the performance requirements. The success of the DEMO has generated considerable interests in the DOE packaging community that led to several RFID system implementation projects at DOE sites. One of the implementation projects, described below, is the development of an RFID temperature monitoring system for the Model 9977 packagings at the Nevada Test Site (NTS).

In June 2008, the Savannah River National Laboratory submitted an addendum application to DOE for the Safety Analysis Report for Packaging (SARP) Model 9977 [5], requesting the addition of new contents and an extension of periodic maintenance beyond the one-year interval to a maximum of five years. The new contents request was based on the need to ship these materials in the Model 9977 packages, which reside at NTS, to other locations to support program missions before returning to NTS. These new contents have been approved. Revision 0 of the DOE CoC USA/9977/B(M)F-96 (DOE-S/T-1) for the Model 9977 package [6], extends the periodic maintenance to a period of two years subject to the use of the RFIDs to track environmental conditions.

MODEL 9977 PACKAGING

The Model 9977 packaging, shown in Figure 1, was designed by the Savannah River National Laboratory to transport nuclear materials [5]. The packaging complies with the regulatory safety requirements set forth in the Code of Federal Regulations, Title 10, Part 71 (10 CFR 71) and the International Atomic Energy Agency (IAEA) Safety Series No. TS-R-1, *Regulations for the Safe Transport of Radioactive Material* [7, 8]. The body of the packaging is a 35-gallon (132.5 liter) drum measuring approximately 36.1 in. (92 cm) in height and 18.35 in. (47 cm) in diameter.

The packaging is designed for transport of uranium and plutonium in solid form inside the containment vessel, which has a nominal inside diameter of 6 in. (15 cm). The containment vessel is a stainless steel pressure vessel built in accordance with Section III, Subsection NB of the American Society for Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, with design conditions of 800 psig (5,600 KPa) at 300°F (149°C). The containment vessel relies on Viton® GLT/GLT-S O-rings to remain *leaktight*. Figure 2 shows the location of the O-rings in the containment vessel. The packaging is designed to meet the American National Standards Institute (ANSI) N14.5 definition of *leaktight* [9], i.e., $\leq 1 \times 10^{-7}$ ref cm^3/sec, under reference air leakage test conditions.

O-ring Temperature

The O-rings are made of Viton® GLT/GLT-S material. Although they have relatively long shelf life, the application-specific life of the O-rings is still to be determined. To ensure that the containment vessel is *leaktight*, a leak-rate test must be performed annually as part of the periodic maintenance, in accordance with Nuclear Regulatory Commission (NRC) Regulatory Guide (RG) 7.4 *Leak Tests on Packages for Shipment of Radioactive Materials* and ANSI N14.5. Savannah River National Laboratory has conducted numerous tests and analyses on the long-term performance of O-rings [10, 11]. The results indicate negligible degradation of the performance of the O-rings, if they are maintained at temperatures below 200°F (93°C). Further analysis [12] showed that if the Model 9977 package is kept in an environment with ambient temperatures below 150°F (65°C), the temperature of the O-rings will be below 200°F (93°C) - as long as the decay heat rate of the contents is limited to 15 W.

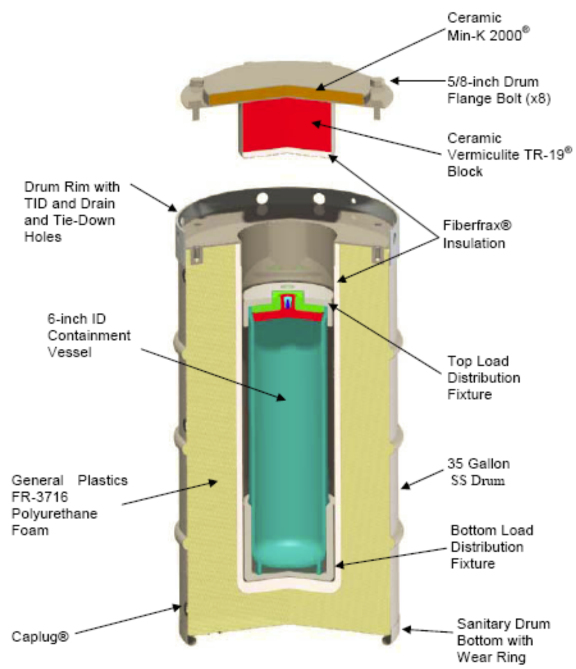

Figure 1. Cut-away view of Model 9977 packaging.

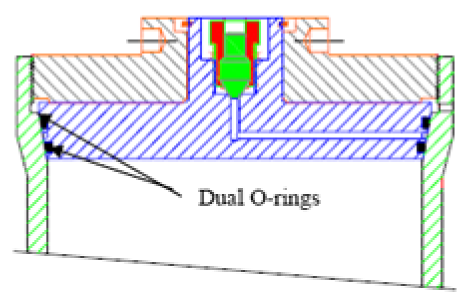

Figure 2. Dual O-rings in a Model 9977 containment vessel.

Extension of Maintenance Period

On the basis of the available data from the O-ring performance tests, DOE has approved the use of the RFID temperature-monitoring system for the Model 9977 package that extends the maintenance period from one year to two years, if the ambient temperature is continuously monitored and verified to be below 150°F (65°C) during the period. Positive findings from the ongoing long-term leak tests on the O-rings can be used to justify extension of the maintenance period further and up to 5 years.

Extension of the maintenance period would result in a reduction in the number of annual leak-rate tests, which currently cost ≈$2,500 per package per test. Extension of the maintenance period to five years could thus reduce the testing costs by $10,000 per package over that period.

RFID TEMERATURE-MONITORING SYSTEM

The RFID temperature-monitoring system for the Model 9977 package, shown in Figure 3, consists of Mk-1 RFID tags, tag reader, and a control computer mounted on a mobile platform that can operate as a stand-alone system, or it can be connected to the local IT network. The application software (ARG-US OnSite) runs on the control computer and manages the data flow between the Mk-1 RFID tags and the reader. The system is capable of monitoring not only ambient temperature, but also other environment parameters, e.g., humidity and shock, and status of seal sensor and batteries.

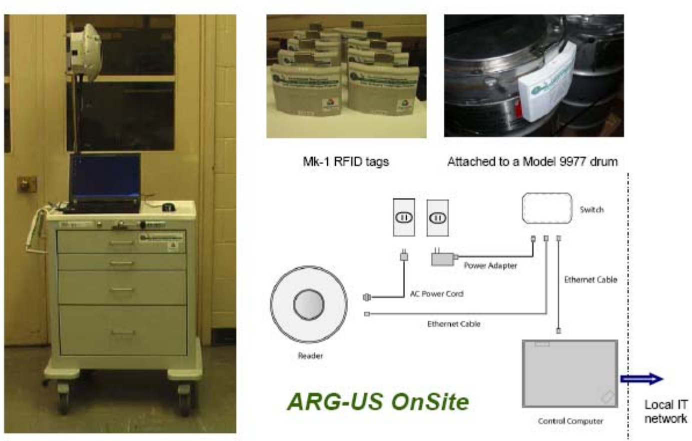

Figure 3. The RFID temperature monitoring system for Model 9977 packages at NTS.

Tag and Reader

The Mk-1 tag is a universal RFID tag that can be attached to a variety of packages, such as Models 9977, 9975, and ES-3100 [3, 4]. The back plate and the seal sensor of the tag are customized to fit each type of package. For Model 9977, the Mk-1 tag uses a single bolt to attach itself to the lid of the package, as shown in Figure 4. The stainless steel back plate and hard plastic cover provide adequate protection against damage under normal conditions of transport.

The Mk-1 tag has temperature, humidity, shock, and seal sensors. The tag also has non-volatile memory that can store the readings from the sensors. Four A-size lithium batteries are installed in the tag to provide up to ten years of battery life, depending on use.

The Mk-1 tag communicates with the RFID reader via radio waves at 433 MHz. The reading range is up to 300 feet (100 m) in line-of-sight. The presence of metal objects and water do not significantly affect the performance of the tag. The RFID reader can be powered by using either AC power or a 12-volt battery. The reader is connected to the computer via Ethernet. A handheld reader (not shown) is also available for mobile use.

Figure 4. Mk-1 RFID tag on Model 9977 package.

Application Software

The application software (ARG-US OnSite) is a key part of the system. The software is installed on the control computer that connects to the reader, enabling the reader to retrieve data from the tag. Users can also use the software to remotely change the settings of the tag (e.g., the alarm threshold for temperature). Figure 5 provides a screenshot of the software. Round labels on the screen represent packages (top-view) with Mk-1 tags attached. The software features a user-friendly graphical user interface, allowing users to easily read or write the tags.

The tags are pre-programmed to report alarms from the sensor to the software instantaneously. The software also automatically queries each tag at a preset interval to ensure the integrity of the tag. The software automatically saves the readings from the tag sensors to a local database in the computer. The information in the database can be easily retrieved and exported.

Besides reading sensors, the software is used in writing user data, such as contents of the package, to the tag memory. The data written to the tag is encrypted by using an Advanced Encryption Standard with a 256-bit key (AES-256). The user data are also saved in the local database to prevent accidental loss of data.

The software has the capability to upload the data stored in the local database to a remote server via the Internet. All the data sent via the Internet is encrypted. The server can show the information associated with each packages on a Web page. Users who have a password can log on to the Web page and get the latest information of the packages. The server can also send emails and text messages to alert users about alarm events.

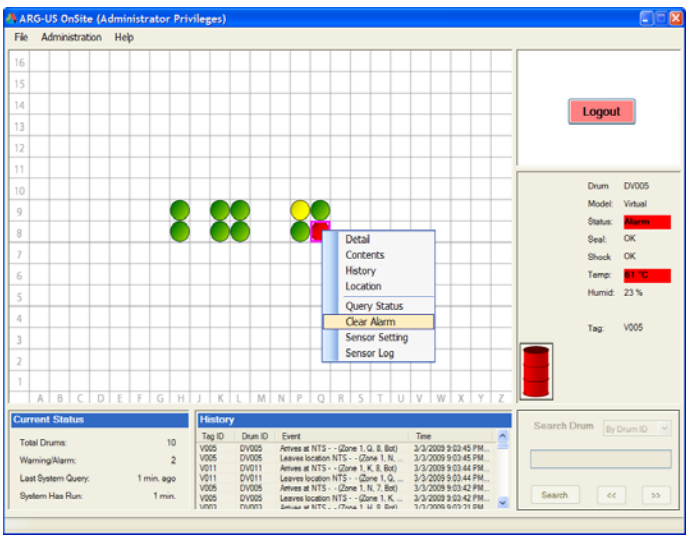

Figure 5. Screenshot of the ARG-US OnSite software.

Quality Category

The RFID tag hardware and application software are considered to be non-"Q" (i.e., not safety-related) based on the graded approach described in 10 CFR 71.105(b), Packaging and Transportation of Radioactive Material, and on the definition of quality categories described in Appendix A of the NRC Regulatory Guide (RG) 7.10, *Establishing Quality Assurance Programs for Packaging Used in Transport of Radioactive Material*.

Relative to the RFID hardware, the quality categories are derived from the safety significance of each item and the consequence of its failure to perform based on the design and performance requirements of the item. Should the failure of an item result in the loss of containment, the loss of shielding, or an unsafe geometry that compromises criticality safety, the item is considered to be an important-to-safety item. 10 CFR Part 71 addresses the regulatory requirements of packaging to ensure that public health and safety are protected. In accordance with 10 CFR Part 71, as long as the failure of an item does not jeopardize the packaging from performing its important-to-safety functions, the item is not considered to be important-to-safety. The NRC Regulatory Guide 7.10, Appendix A, embodies the same philosophy.

In application, the RFID tag is attached to the exterior of the Model 9977 packaging by affixing the tag's sheet-metal top plate under one of the drum's flange bolts. The bolt is original issue and then is retightened to the same torque specifications as the other flange bolts. The drum lid remains closed during transport and storage, and the primary containment vessel inside the drum is never exposed. Thus, from the standpoint of configuration, the packaging is not altered in any way by the attachment of the RFID tag. Failure of the RFID hardware will not result in the loss of primary containment, the loss of shielding, or the loss of subcriticality. Therefore, based on the definition of the graded approach in 10 CFR 71.105(b) and NRC Regulatory Guide 7.10, Appendix A, the RFID hardware is not considered to be an important-to-safety item for the packaging.

The application software, ARG-US OnSite, collects, processes, stores, and presents the RFID tag information. A malfunction of the software may affect some of the above functions but would not impact the containment, shielding, or subcriticality of the packaging in any way. The safety posture of drums with RFID tags is identical to drums without the tags. For this reason, based on the Argonne National Laboratory Decision and Information Sciences (DIS) Division Software Quality Assurance Plan (SQAP), ARG-US OnSite has been classified as Level C software — for medium risk, general service, and mission minor applications. The DIS SQAP is based on the Argonne National Laboratory Quality Assurance Procedures Manual. It references the U.S. Department of Energy Orders on quality assurance (QA) and software QA, the Institute of Electrical and Electronics Engineers and the U.S. Department of Defense standards on software QA, and the verification and validation of the software. All quality requirements for Level-C software, including the SQAP, configuration management, testing, and test documentation/results, have been met for the ARG-US OnSite software.

Quality Assurance

To ensure the quality and reliability of the RFID temperature monitoring system for the Model 9977 packagings at NTS, two quality assurance programs were developed for the hardware and software. The hardware quality assurance program covers the acceptance tests of the hardware, durability tests of the seal sensors, calibration of the temperature sensor, and document control. The software quality assurance program emphasizes design control, version control, software functionality and reliability tests, user documentation, and document control.

Every tag destined for NTS deployment was calibrated against certified thermocouples to ensure the temperature readings are accurate in the design operating range of 32 -150°F (0 - 65°C). Figure 6 shows the calibration results for a batch of ten MK-1 tags.

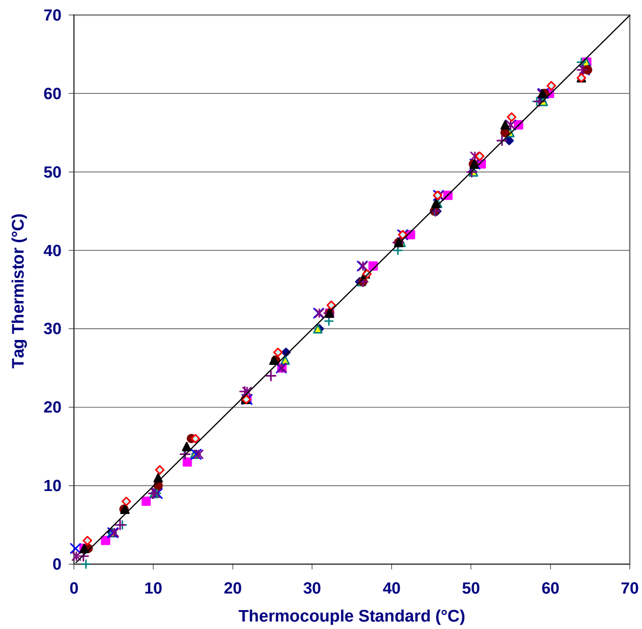

Figure 6. Temperature calibration of Mk-1 tags for NTS.

Application at NTS

There are many possible operating scenarios for the Model 9977 packages at NTS, including handling, storage, transport on site, and off site. The RFID temperature monitoring system (Fig. 3) on a mobile platform is designed to offer maximum flexibility and assure performance and reliability. For on-site applications, the mobile platform and the simple power and Ethernet connections for the reader and the control computer ensures that the Mk-1 tags are always within the optimal range (≈30 m) of the reader. The Mk-1 tags are preprogrammed to sample the ambient temperature every five minutes. If the temperature exceeds 140°F (60°C), the tag will immediately report the condition as an alarm to the reader. The alarm will be shown in the software application. The temperature reading and the time of the alarm will be recorded in the tag memory and the database for future reference. To ensure that the tag is functioning correctly, the reader polls the tag every six hours. The sampling frequency of the tags and the polling interval of the reader can be adjusted, if necessary, based on the facility requirements.

In addition to the temperature sensor, the Mk-1 tag has other sensors for humidity, shock, seal, and battery status. Alarm thresholds are also set for these sensors so that violations are reported automatically. For example, the seal sensor in the Mk-1 tag is attached to one of the lid bolts of the Model 9977 package (Fig. 4), which operates under normal torque load and alarms when the bolt is loosened. The seal sensor of the Mk-1 tag is thus a tamper indicating device for the Model 9977 package against unauthorized opening of the drum. Another example is the shock sensor in the Mk-1 tag that detects movement of the Model 9977 package. Experience of the DEMO [3, 4] indicated that the threshold level of the shock sensors can be adjusted to detect even minute movement of the drums. The performance and reliability of the humidity sensor in the Mk-1 tag, including its alarm features, has also been proven stable and reliable in the DEMO [3, 4].

The Mk-1 tag has four A-size lithium batteries and a battery management board designed for long life application. Operations of the sensors in the Mk-1 tags depend on the battery. If the battery is dead prematurely, or if the Model 9977 is moved outside the range of the reader, the system will report the incident automatically, and the event will also be recorded in the non-volatile memory of the tag.

It should be noted that once the Mk-1 tag is attached to a Model 9977 package, it will stay with that package at NTS. A label affixed to the tag identifies the serial numbers of the tag and the Model 9977. The unique pair allows recording of the events of the Model 9977 package, from normal handling to any alarms detected by the sensors during storage and on-site transport, in the tag's memory that can be interrogated instantly along with the manifest of the contents. Both the sensor data and event histories of the Model 9977 packages are also readily available for query by authorized users and system administrator via the control computer and network interfaces.

Occasionally, a Model 9977 package may be transported to other locations for some time before returning to NTS. Although it is possible to send the mobile platform of reader and control computer with the Model 9977 package, it is not practical, nor economical. Currently one would rely on the Mk-1 tag to record the event of temperature violations away from the NTS. When the Model 9977 package is returned to NTS, the sensor readings and event history stored in the tag memory will be checked to verify that the temperature remains below the limit set for the extended periodic maintenance. Use of a hand-held reader periodically to query the temperature sensor of the Mk-1 tag on the Model 9977 at an off-site location is another option.

Rev. 0 Certificate of Compliance [6] for the Model 9977 package requires the RFID tags be verified to be functional in accordance with the Operating Procedures requirements of the SARP Addendum [5]. If due to a failure of the RFID tag or the temperature recording system that results in a loss of temperature data for a duration ≥72 hours, then the packaging shall have a Nonconformance Report issued against it and be tagged and segregated until the disposition of the Nonconformance Report has been approved by the 9977 Design Authority and Argonne National Laboratory and has been implemented.

Training and Certification

Rev. 0 Certificate of Compliance also requires user of the Certificate to complete the prescribed training to become qualified and be certified for operation of the RFID temperature monitoring system. The training course will be administered by Argonne National Laboratory on behalf of the DOE Headquarters Certifying Official.

A complete documentation package has been prepared for the RFID temperature monitoring system of the Model 9977 packages at NTS [13]. The documentation package includes the acceptance testing procedure and results of the Mk-1 RFID tags, performance test of the single-bolt seal sensor for the Model 9977 packaging, calibration of built-in thermistors in the Mk-1 RFID tags, procedure for installing and removing the Mk-1 RFID tag on Model 9977 drum, user guide for the RFID reader and software, and various software quality assurance documents prepared in accordance with the software quality assurance plan for the ARG-US OnSite system. The documentation package is referenced in Chapter 7 (Operating Procedures), Chapter 8 (Acceptance Tests and Maintenance), and Chapter 9 (Quality Assurance) of the SARP Addendum [5].

DISCUSSION

The RFID temperature monitoring system developed for the Model 9977 packages at NTS can be easily configured for other types of packages, such as Model 9975 and ES-3100, at other sites and for multiple facilities. The cost of the system, i.e., Mk-1 tags, reader and control computer is minor, compared to the cost of packaging and its annual maintenance, not to mention the value of the nuclear materials and other benefits. The sensors and on-board memories in the RFID tags are the key attributes of the system, whereas radio wave acts merely as a carrier of message. Each tag is a sensor node, and these sensor nodes are autonomous data collection devices distributed in a space to sample environmental conditions, e.g., temperature, humidity, shock, seal, motion, at different locations. The nodes are connected by a wireless sensor network (433 MHz), which is connected to another network, i.e., Internet, via a gateway node, for example, the reader and the control computer in the RFID temperature monitoring system.

Because of the success accomplished in the DEMO of the packaging RFID tracking system in 2008 [3, 4], Argonne and DOE PCP were recently invited to join, as members of the Technical Board of Advisors, by the Developers Alliance for Standards Harmonization ISO/IEC 18000 Part 7 (DASH7). The International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 18000 is a global RFID air interface Standard, and Part 7 addresses parameters for air interface communications at 433 MHz. The DASH7 alliance is formed as a cross-industry initiative to expand the use of wireless technology based on the ISO/IEC 18000-7 Standard, with particular emphases on advanced sensor networking, electronic seals, mobile phone integration, test and certification, and interoperability and reliability. As an RFID technology and system developer for the U.S. Department of Energy's Packaging Certification Program, Argonne and DOE PCP plan to participate in the DASH7 activities as member advisors in the Technology and Outreach Working Groups, respectively, while providing perspectives as an end user of the RFID technology for management of nuclear materials. Both DOE and DASH7 should benefit from Argonne's participation.

SUMMARY

An RFID temperature-monitoring system has been developed for extending the maintenance period of the nuclear material packaging for storage and transportation. The first type of packaging that will benefit from the RFID technology is Model 9977, which has been certified by DOE to ship and store fissile plutonium and uranium. The RFID temperature monitoring system on a mobile platform is designed specifically for the Model 9977 packages at NTS to offer maximum flexibility and assure performance and reliability. Similar RFID system can be easily configured for other types of packagings such as Model 9975 and ES-3100 at other sites and for multiple facilities. The cost of the RFID temperature monitoring system is modest, and the potential benefits are enormous: enhanced safety, security and materials accountability; reduced radiation exposure and the need for manned surveillance; real-time access of status and event history data, including continuous environmental conditions monitoring; and overall cost effectiveness.

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