Radiation-Sensor-Equipped Radio Frequency Identification System*

H. Lee, J. Anderson, B. Craig, H. Tsai, Y. Liu, and J. Shuler[1]

Argonne National Laboratory, Argonne, IL 60439
[1]U.S. Department of Energy, Washington, DC 20585

ABSTRACT

To modernize the management of sensitive nuclear materials, Argonne National Laboratory has developed the ARG-US radio frequency identification (RFID) system for the Packaging Certification Program of the U.S. Department of Energy (DOE), Office of Packaging and Transportation. The system consists of battery-powered RFID tags, a reader network, an application software suite, secured database servers, and storage and transport web applications. The current-generation RFID tags have built-in sensors for seal integrity, temperature, humidity, shock, and battery strength to monitor the state of health of the tagged containers during storage and transportation. Several ARG-US RFID systems, which provide real-time tracking and monitoring capability, have been deployed at selected DOE sites for field testing and application during storage and transportation. To further enhance the system's capability, a radiation sensor module has been added to the ARG-US RFID tag. The potential benefits of the added radiation sensor module for nuclear materials management can be significant: improved situational awareness; enhanced safety, security, and safeguards; and – just as important – reduced radiation exposure for facility personnel. The incorporated sensor module is a modified, compact, personal dosimeter with a wide detection range for gamma radiation: from ≈10 μR/h to 800 R/hr. A multifunctional carrier board has been designed to process data, initiate alarms, manage power, interface tags, and add future sensors. Benchmark testing with a calibrated Cs-137 source has shown that the integrated tags with dosimeters are functioning as designed. The ARG-US software suite has been modified to process and display the dose rate and cumulative dose, as well as an instant alert/alarm when the detected radiation level exceeds the preset threshold. The cumulative dose can be reset to account for multiple segments of storage and transportation campaigns. The added functionalities of area radiation monitoring, process configuration control and supplemental tamper indication with the dosimeter-enabled tags make the ARG-US RFID system even more potent and versatile for nuclear materials management.

INTRODUCTION

The ARG-US RFID system consists of battery-powered RFID tags, a reader network, an application software suite, secured database servers, and storage and transport web applications.[1–3] The current ARG-US RFID tag (MK-II) incorporates five sensors for temperature, humidity, shock, seal integrity, and battery strength. When the system is deployed in the field, the sensor data in the tags are collected autonomously at regular intervals by the

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readers and stored in the control computer and the secured database servers. The polling interval can be adjusted depending on applications – from once every few minutes in transport to once every few hours, or longer, in secured storage. Threshold set points can be selected for each sensor, and the tag will issue an alert/alarm instantaneously whenever any sensor threshold is violated. The tag communicates with the reader via a 433-MHz radio wave, with an effective range of >100 m, and no line-of-sight is required. The MK-II tags have a nearly universal form factor that can be easily modified for attachment to different types of drums, as shown in Figure 1. The front of the tag is a plastic chassis that facilitates radio frequency transmission; the back of the tag is a strong metal enclosure with a flange for drum attachment. The piezoresistive seal integrity sensor is concealed and protected under the attachment flange bolt(s) in these applications.

Figure 1. MK-II tags mounted on several certified Type-B packagings (from left to right: Models 9975, 9977/9978, ES-3100, and DOT 7A).

Figure 2 shows a sample graphical user interface (GUI) screen of the system, called ARG-US OnSite, for monitoring stacked drums in a storage facility. Each symbol represents a drum, with the color indicating the status: green (normal), yellow (warning), and red (alert/alarm). Clicking on a symbol causes the serial and model number of the selected drum to be displayed in the window pane on the right, along with the sensor status and values. (Other drums in the stack can be selected from this pane and the display will change accordingly.) The bottom

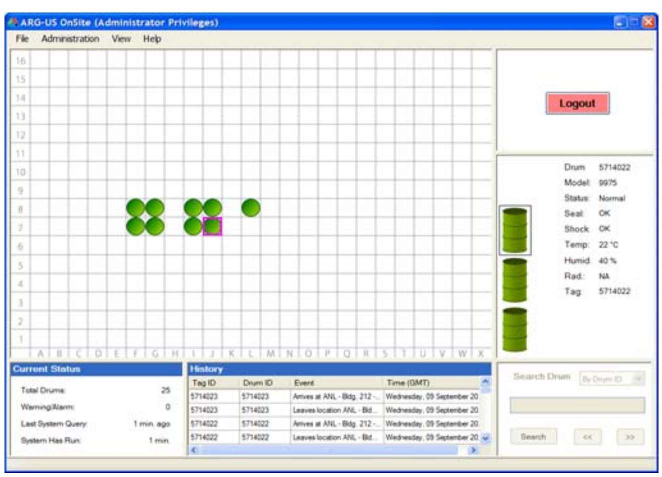


Figure 2. Sample GUI of ARG-US OnSite for a small storage installation. Note that the drums can be stacked as shown in the right window pane.

panes show the current status of drums in storage, historical events, and search functions that can be customized per facility requirements. From submenus of the main GUI (not shown in Figure 2), other pertinent information (e.g., a contents manifest, processing steps, alarm thresholds, auto-collect intervals), as well as detailed sensor history logs, data export, etc. can be entered, viewed, and executed by the user.

With regard to developing the ARG-US RFID system for nuclear materials management, the addition of a radiation sensor to the tag has long been considered an important enhancement or milestone. A radiation sensor, in conjunction with other sensors in the tag, can greatly enhance the overall situational awareness in a facility that has a large number of packages. Readings from radiation-sensor-enabled tags can be used to construct a 2-dimensional or even a 3-dimensional map of the radiation dose field in the facility on a real-time basis. Any significant perturbation of the field would generate an instant alert/alarm to supplement the existing facility measures for safety, safeguards, and security. As a result of having this real-time information on the radiation field in the facility, the need for manned surveillance with handheld devices is greatly reduced, and the universally endorsed principle of protection against radiation (as low as reasonably achievable [ALARA]) is achieved. The knowledge and records on dose and dose rates can also be very useful for process control and aging management for long-term storage, down to the item level of the packages.

An exhaustive search of candidate radiation sensors for tag incorporation was conducted, and a commercially available personnel dosimeter for gamma radiation was selected. The major advantages of a personnel dosimeter over other possible choices are its compactness, reasonable cost, low power consumption, reliability, acceptance by health-physics professionals, and wide dose-rate operating range, matching the range for nuclear materials monitoring. In the incorporation, the dosimeter casing, external display, control buttons, audio/visual alarm provisions, and battery holder were discarded; only the detector components and the electronic core were retained. According to the manufacturer's specifications, the selected dosimeter is sensitive to photonic radiation in an energy range of 50 keV to 6 MeV. The dosimeter also has a wide dynamic measurement range for the dose rate, from ≈10 μR/h to 800 R/h, and a dose from 0.1 mR to 1,000 R.[4]

DESIGN OF DOSIMETER ADDITION

To support the operation of a dosimeter in an ARG-US RFID tag, the following design requirements are considered: (1) ensure secure mounting and easy removal of the dosimeter module if it is not needed, (2) use existing batteries with low power consumption, (3) use versatile communication protocols, and (4) allow room for future expansion of additional sensors.

The next-generation ARG-US RFID tag, code named MK-III, has been designed to meet the above requirements. Figure 3 shows a prototype of the MK-III tag with three main electronic boards: dosimeter carrirer board (left), tag controller board (dubbed mother board with antenna, center), and battery supply and management board (right). The dosimeter carrier board can be slid in and out of its compartment and is held securely by two sets of molded alignment tabs. A 20-pin ribbon cable is used for communication with the tag controller board, and a two-pin header connector wire funishes the power from the battery board. The dosimeter board can be removed easily from the MK-III tag, and the tag would function, after slight modification of the software, just like a MK-II tag.

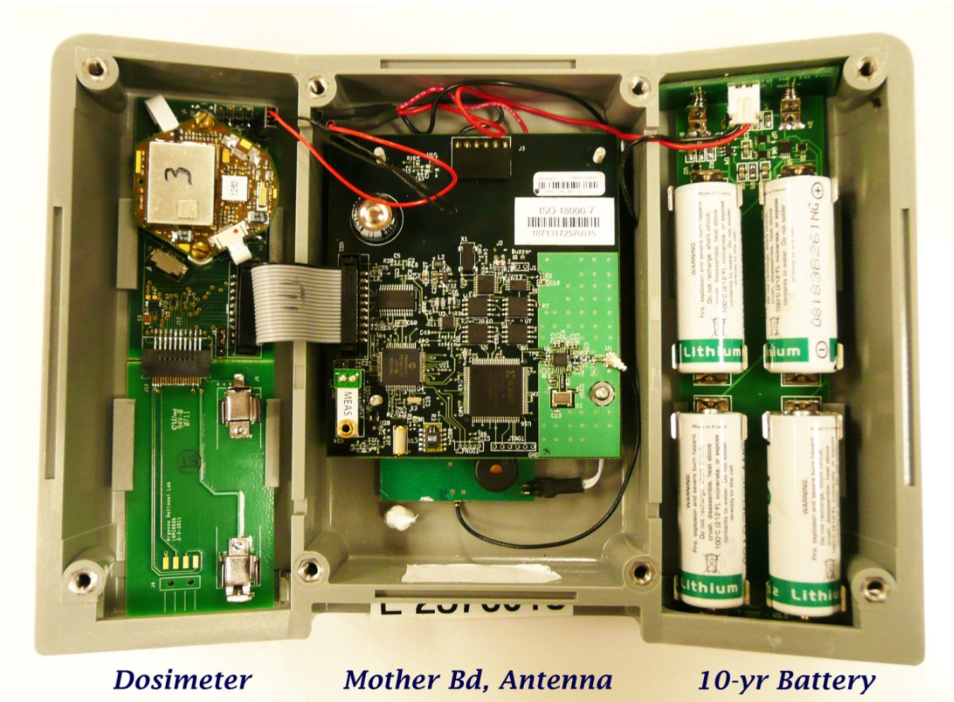


Figure 3. MK-III tag with a dosimeter carrier board incorporated in the left compartment.

Figure 4 is a block diagram of the dosimeter carrier board that shows how the radiation detector (dosimeter) communicates with the tag control unit in the tag controller board via several communication protocols, as follows: (1) A universal asynchronous receiver and transmitter (UART) RS232 protocol is used between the dosimeter and the micro-controller unit (MCU) on the carrier board. (2) A serial peripheral interface (SPI) protocol is used between the MCU and the tag control unit. (3) An ISO 18000-7 RF protocol is used between the tag control unit and the reader (not shown in Figure 4).

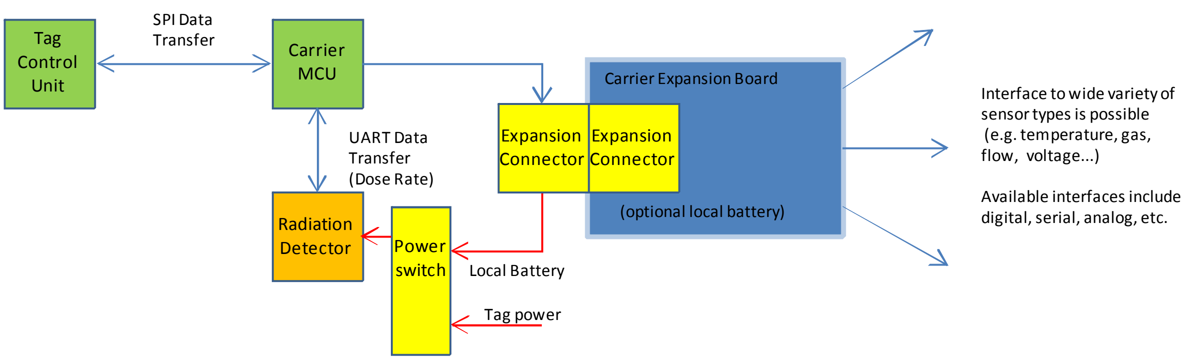


Figure 4. Block diagram of the dosimeter carrier board showing communication between the radiation detector (dosimeter), the MCU on the carrier board, and the tag control unit on the tag controller board.

To meet the requirement for low power consumption, the data from the dosimeter are collected by the MCU on the carrier board. A nonvolatile memory implemented within the MCU allows retention of accumulated dose rate information when the power is off. In the low-power mode of the carrier board, the MCU is programmed to wake up the dosimeter at regular intervals and read the instantaneous dose rate a programmable number of times after each wakeup. The dose rate thus obtained is assumed to stay constant for the entire interval, and the accumulated dose is updated and stored in the nonvolatile memory. With the dosimeter used in this way, the wide dose rate range is extended over an arbitrarily large total dose, because the total dose that can be measured is limited only by the amount of memory allocated to the sum within the MCU program. The data are passed along through the tag to the reader network whenever those values are requested. The requested data are then displayed in the GUI and stored in the database in the control PC and the downstream servers. Alarm events due to the dose rate and the accumulated dose are also stored in the MCU.

The interface between the carrier MCU and the tag MCU is implemented as a block of individual memory locations that are accessible by using a block transfer. Only a small fraction of the available data space is currently used for the dosimeter information. The remaining storage space allows for expansion of additional sensors. As different sensor interfaces are developed for the carrier expansion board, each will be allocated a block of the available memory space such that the ARG-US system may identify what additional sensor(s) are present or absent simply by determining which fields of the memory block are filled or empty. "Check sum" information is provided to ensure overall data validity within the block. To allow for faster operation in cases when only alarm states are required, the first few words of the block will contain all the alarm information; thus, the alarm status may be read first, with an option of reading of the actual sensor values only when the alarm state is present. Integration, scaling, or summation of measurements is performed, when required, within the carrier MCU.

The new modular tag design has several advantages. First, the dosimeter carrier board can be removed easily for any application that does not require radiation detection. The remaining tag unit will still function normally. Moreover, future development of the system (e.g., adding a variety of sensors) can be done on the carrier board. The housekeeping tasks of the additional sensor can also be handled by the carrier board MCU. In essence, the modular design can keep the already crowded tag control unit untouched but still provide enough flexibility for future functional expansion of the RFID tag. The dosimeter carrier itself is made from two small circuit boards joined in the middle by a connector. The "top" half of the carrier board contains all the circuitry required to implement the dosimeter function. A variety of signal types (including digital, serial, and analog) are implemented in the connector to maximize the number and type of possible additional features. The current dosimeter implementation only consumes a small percentage of the code and memory space of the MCU, so further sensor additions are easily supported.

TESTING OF THE INTEGRATED DOSIMETER

Ten prototype dosimeter carrier boards were fabricated. The RS232 communication between the board and the tag controller was bench-tested in a laboratory. The communication signal strength was found to be adequate, and the timing was correct. To verify the integral behavior of the dosimeter-enabled tags, a benchmark gamma ray irradiation test was performed with two fully assembled tags: Tag22 and Tag25. The irradiation source was a Shepherd Cs-137 irradiator at Argonne. The source strength, ≈20 Ci, can produce a peak dose rate of ≈80 R/h at the closest usable distance to the source. The irradiator was last calibrated in February 2009 by using a National Institute of Standards and Technology (NIST)-traceable transfer standard.

The configuration of the setup for the irradiation test is shown in Figure 5. The two tags being tested were placed on a platform above a draw table. The tags were placed side by side, with the distances to the source being equal. The height of the table was such that the vertical center of the tags was at the same height as the Cs_137 source. The intensity of the irradiation, in terms of mR/h, was adjusted by two means: distance to the source and insertion of certified attenuators. An up-to-date table of exposure rates provided by the calibrator facility was used in the test design.

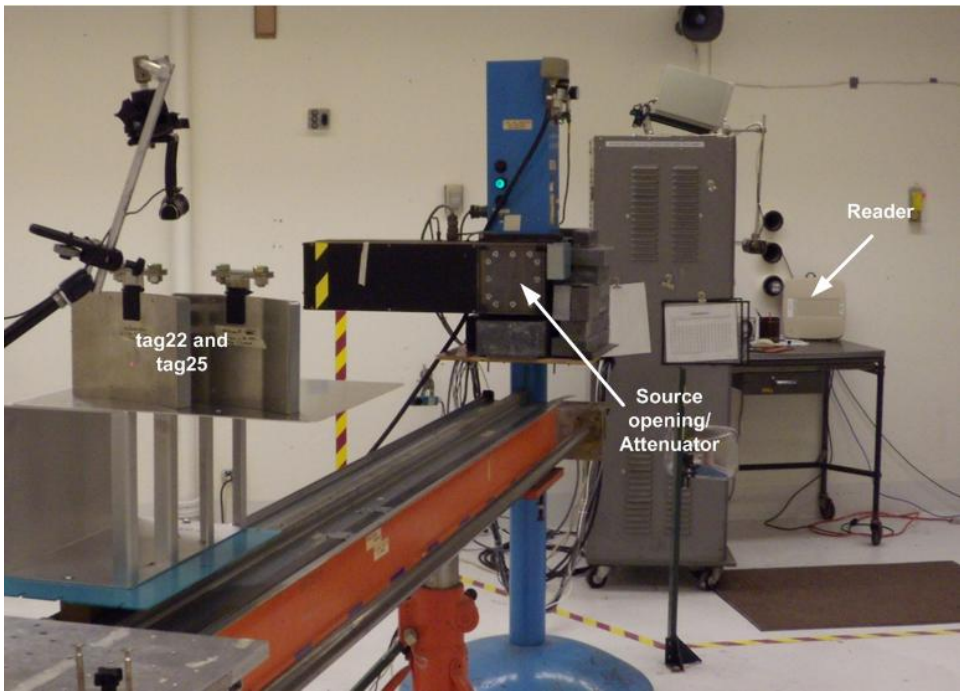
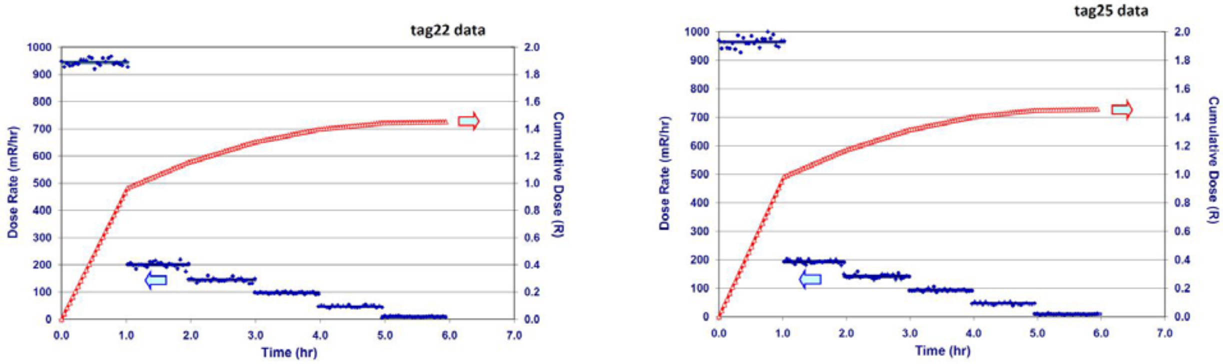


Figure 5. Irradiation testing of two dosimeter-enabled tags, Tags 22 and 25, mounted on a platform at an equal distance from the Shephard Cs-137 source.

Three target-level dose rates were selected for the irradiation test of the dosimeter-enabled tags. The reference dose rate was 200 mR/h (the regulatroy limit on the exterior surface of a Type B transportation package). The other two target dose rates were 10 mR/h (the regulatory limit at 1 m from a Type B transportation package), and 1,000 mR/h (regulatory limit for a Type B transportation package in an exclusive-use shipment). Three intermediate dose rate levels, 50 mR/h, 100 mR/h, 150 mR/h, were also selected to check the dosimeter response. At each selected dose rate level, the irradiation duration was 60 minutes, during which the dosimeter module was instructed to measure and report the instanteneous dose rate (mR/h) and the accumulated dose (mR) at 2-minute intervals to the tag control units. An algorithm was implemented in the carrier MCU to perform dose-rate integration and to verify the linearity of the dosimeter response to the field strength. A longer-duration, 24-h irradiation was conducted at 100 mR/h to validate sustained integration performance.

The results of the irradiation tests showed that at all selected dose rate levels, both the dosimeters and the integrated tags performed as designed. There was no failure of dosimeter/tag communication at any time. Figure 6 shows the data for the 60-minute irradiation tests of Tags 22 and 25 at both target and intermediate dose rate levels. Although the expected



(a) (b)

Figure 6. Results from 60-minute irradiation tests of (a) Tag 22 and (b) Tag 25 at target and intermediate dose-rate levels (from left to right: 1,000, 200, 150, 100, 50, and 10 mR/h). Horizontal straight blue lines are the averaged values of the measured dose rates.

scattering of individual dose-rate readings at 2-minute intervals occurred, all the dose rates averaged over the hour (blue straight lines in the figure) were consistent with the target and intermediate levels of dose rates. Close examination showed that the average dose-rates were slightly (≈4%) below the target values, which was also expected as a result of attenuation caused by the casing of the tag. The cumulative doses of the tags showed the expected downward trends.

Figure 7 shows the tag performance during the 24-h irradiation at 100 mR/h. The cumulative

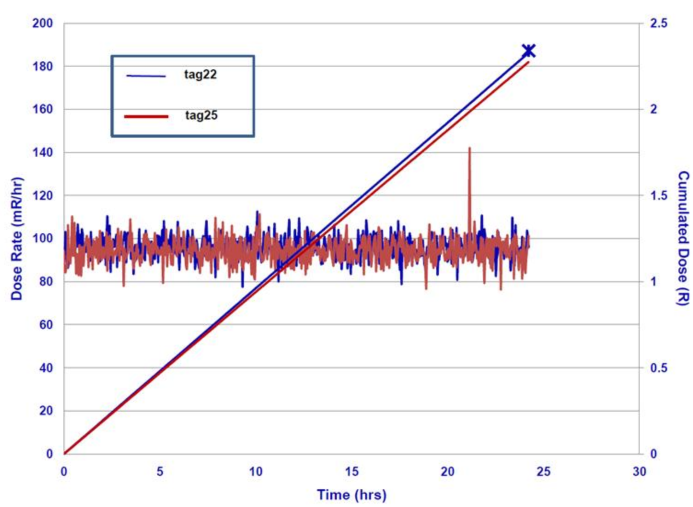


Figure 7. 24-h irradiation test results for Tags 22 and 25 at 100-mR/h. The “blue star” at the end of irradiation is the reading of a certified dosimeter standard.

doses reported by the tags were consistent and slightly lower than those measured by a certified dosimeter standard placed next to the two tags. The dosimeter reading accuracies shown in Figures 6 and 7 were well within the manufacturer specification of ±5%.[4] The results of the Cs-137 irradiation tests indicate that the dosimeter integration was successful.

DISCUSSION

The ability of ARG-US RFID to monitor the physical and environmental conditions of drums containing nuclear materials has been verified in systems deployed at DOE sites and during transportation campaigns.[3] In one such case involving a Category 1 vault, twenty (20) MK-II RFID tags were deployed over a span of six months to monitor temperatures and other environmental parameters as part of the Phase I testing program to verify the long-term performance and reliability of the system in a real storage environment. The aggregate temperature data of the 20 tags collected during the testing are shown in Figure 8. The results show that all tags behaved reliably and consistently, with temperatures in a narrow spread of ≤4°C. This spread is expected because the vault is large and not air-conditioned. The RFID tag-recorded data were corroborated with independent temperature monitoring and testing equipment throughout the period.[5] The overall trend in Figure 8 reflects the ambient temperature change from spring to summer. Other sensory functions of the tags were also verified during the deployment. These included drum-lid closure, humidity, and shock. All functions were found to perform reliably.

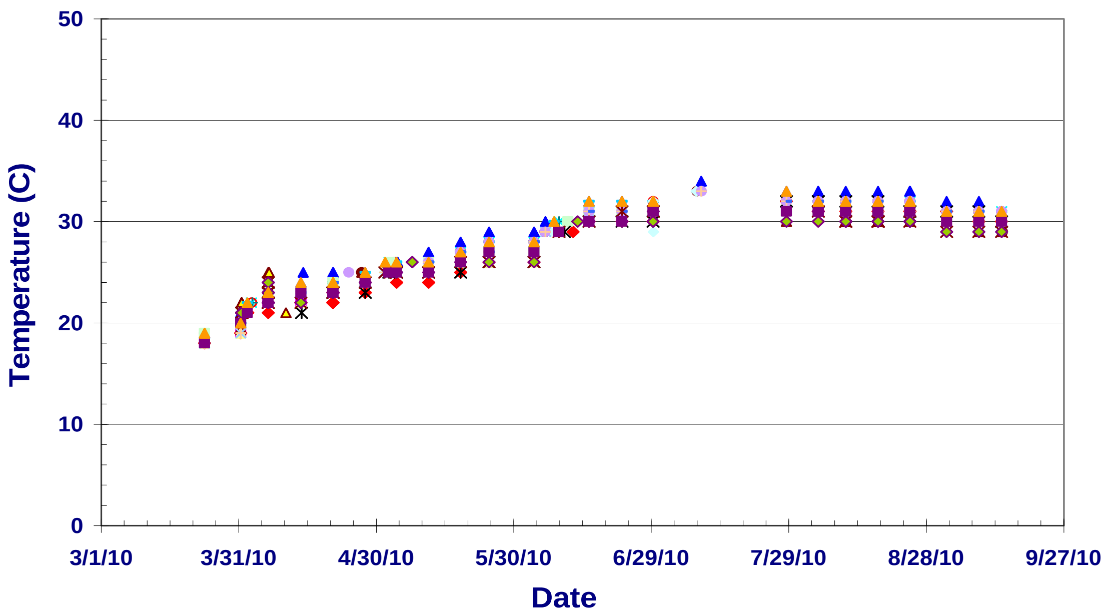


Figure 8. Aggregated temperature data for 20 MK-II tags distributed in a Category 1 vault over a period of ≈6 months. The system was not available during several weeks in July 2010.

Planning has begun for a Phase II testing program in the same Category I vault to deploy dosimeter-enabled MK-III RFID tags and a distributed reader network for remote and continuous real-time monitoring of the state of health of the storage drums and environmental conditions. Production of a small batch of dosimeter-enabled MK-III tags is underway. Fully functional systems are expected to be available before the end of 2011.

SUMMARY

Commercially available gamma dosimeter modules have been successfully incorporated into the ARG-US RFID tags. The performance of the integrated dosimeter has been verified in a range of target dose rates in gamma irradiation tests that used a certified Cs-137 irradiator. The response of the dosimeters was found to be accurate and linear in the range of dose rates that were of interest. The dosimeter-enabled ARG-US RFID tags will provide significant benefits by improving situational awareness – not only with regard to safety, security, and safeguards but also with regard to the ALARA posture in the facilities – and by drastically reducing radiation exposure to facility personnel.

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