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Functional Evaluation of the DOZA DKG-05D Electronic Dosimeter System

R.K. Piper
R.I. Scherpelz

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Executive Summary

The DOZA DKG-05D electronic personal dosimeter (EPD) was the subject of a limited type-test evaluation in support of Plutonium Production Reactor Agreement (PPRA) Implementation. The primary goal of this evaluation was to provide confidence in the functionality of the dosimeter and identify potential weaknesses in PPRA applications.

The tests were based on IEC-61526, recommendations of the International Electrotechnical Commission pertaining to EPDs. All tests were performed in Pacific Northwest National Laboratory's (PNNL) Radiological Calibrations and Standards Facility in the 318 building.

The first testing category was functional considerations. The tests found that the mechanical characteristics of the DKG-05D support usability. However, user controls are not intuitive and straightforward, and the user instructions were unclear and difficult to follow. The unit functioned in a variety of humidity conditions. In high temperature conditions it performed well. However, in cold conditions the display began to fade, which limits its usefulness below about 5 °C. The vendor claims that the unit functions to -20 °C, and it may be correctly recording doses at that low temperature, but the doses cannot be read in real time.

Testing found that battery life is generally good, operating for 200 hours on a full charge. This is far more than needed for the intended application. Charging the battery, however, had some pitfalls resulting from two charging modes. The high-current mode would be automatically selected if the battery charge fell below a threshold value when inserted in the charger. Otherwise, a low-current mode would be selected. In some cases a battery needing recharging would not get sufficient current to fully charge in a reasonable time period. There were also problems found in the low-battery indication and there was a possibility for data loss in the low-battery condition.

The EPD generally performed well in measuring dose and dose rate. There were some small problems with non-linearity over a range of doses, but these non-linearities were at extremely low and very high doses and would not adversely affect the performance in our intended application.

The testing resulted in the general conclusion that the DOZA DKG-05D is suitable for use in PPRA applications for real-time indication of dose received by a user and for estimation of stay times in radiation zones. It can be used as a supplement to a passive dosimeter, but it should not be used for measuring the user's dose of record.

Acronyms and Abbreviations

ANSI	American National Standards Institute
DOZA	Russian Federation
EPD	electronic personal dosimeter
IEC	International Electrotechnical Commission
PIC	pressurized ionization chamber
PMMA	polymethyl methacrylate
PNNL	Pacific Northwest National Laboratory
PPRA	Plutonium Production Reactor Agreement
SI	International System of Units

1.0 Introduction

The DOZA DKG-05D electronic personal dosimeter (EPD) was the subject of a limited type-test evaluation requested in support of Plutonium Production Reactor Agreement (PPRA) Implementation. The primary goal of this evaluation was to provide confidence in the functionality of the dosimeter and identify potential weaknesses, subsequently allowing proposed users to take suitable actions or use due caution in the application of this dosimeter under field conditions.

The equipment for this test was purchased by Pacific Northwest National Laboratory (PNNL) from the vendor, DOZA (Russian Federation). It included five test units of the DOZA DKG-05D (serial numbers 6171 – 6175), a model US-05 reader/charger, DKG-05D Tools computer software (version: "V4.2.3 Build:14:46:55 Dec 24 20"), and operating manuals for the dosimeter and for the reader/charger[1]. The user manual was originally written in Russian, but was translated to English for this procurement. The labels on the EPDs and reader also were translated to English specifically for this procurement. If this model EPD is acquired for routine use by PPRA, it will be assigned to users at Russian institutions and the manuals and labeling will be in the original Russian.

In preparation for this evaluation, a determination of suitable tests was conducted in consideration of probable field conditions and uses. Once a set of evaluations was determined, tests were prepared and conducted, in most cases using at least two or more of the provided five test units. In the course of performing these evaluations, there were several obstacles, including 1) difficulty in the clear functionality of the dosimeter/computer interface software, 2) understanding the method of battery recharging, and 3) testing facility limitations and functionality. Despite—and perhaps due to—some of these issues, information was obtained that should aid users in their awareness of the dosimeter capabilities and limitations.

All tests were performed in PNNL's Radiological Calibrations and Standards Facility in the 318 building.

1.1 Scenario for Use

The units would be stored, maintained and controlled at Russian institutions under the responsibility of the plant dosimetry staff. PPRA staff would be issued an EPD by the plant staff when entering a radiation zone, and the unit would be collected again upon final exit from the zone for the day. The unit would typically be reset to zero and recharged if necessary after each day's use.

The PPRA staff members would wear their EPDs during all times they were in radiation zones within the plant. Users would be able to observe the display at any time to get a real-time indication of their accumulated exposure at that site. It would be used in conjunction with a passive dosimeter that would serve as the dose of record. It may also be used to control stay times in radiation zones.

The radiation fields would be either photon or mixed neutron-photon fields. If used to determine stay times in a mixed neutron-photon field, the neutron/gamma ratio, previously evaluated by plant staff,

[1] Scientific and Production Company DOZA. Personal Gamma Dosimeter DKG-05D, Operation Manual. Scientific and Production Company DOZA. Reading Device US-05, Operation Manual.

would be used in conjunction with the EPD-displayed gamma dose. Calibrating the unit to a ^{137}Cs source would be appropriate for the gamma component of the radiation field where the EPD is actually worn. The dose rates would typically be low, usually below 100 μSv/h (10 mrem/h). Any entry into areas with dose rates greater than 1 mSv/h (100 mrem/h) would be brief. The total accumulated dose for a plant visit would rarely approach 1 mSv (100 mrem).

1.2 Evaluation Goals

Previously-performed type-tests were considered for this evaluation—both for their insight and as references to specific standards and other guidance with respect to such tests. Noteworthy evaluations in prior years considering dosimeters commonly used in the U.S. were largely a compilation of evaluations referencing various survey instrument and passive dosimetry standards. The most pertinent contemporary type-test guidance appeared to be the International Electrotechnical Commission (IEC) standard 61526 (International Electrotechnical Commission 2005). Most evaluations were derived from this standard—especially those considering the physical aspects of the dosimeter, its usability, and some of the non-radiological evaluations and general conditions of testing. Although the standard was useful in identifying tests and methods for conducting such evaluations, it fell short in clearly identifying analysis protocols for some evaluations.

Radiological evaluations were chosen to cover a range of photon energies potentially experienced in the anticipated practical use of the dosimeter. Evaluated ranges of dose and dose rates likely exceed anticipated conditions of use, but are chosen to provide assurance in coverage under more extreme cases. An evaluation was included to identify the result of potential wearing of the dosimeter in a backward condition—a likely scenario since the clip is placed on the opposite side of the dosimeter compared to most electronic dosimeters used in the U.S.

Specific tests are briefly listed in Table 1. While there are some criteria identified for these evaluations (as identified within the referenced standard[s]), this evaluation does not necessarily seek to judge the dosimeter against these since exceeding such criteria may have little overall potential impact given their likely use. Perceived/anticipated use should be evaluated using the results of this study (and possibly future follow-up evaluations) in determining protocols and/or limitations of use, methods of calibration, and alarm set-points (e.g., to compensate for possible biases with respect to energy dependence, rate dependence, and/or battery limitations).

Table 1. Evaluation Overview

Evaluation	Assessment of…	Reference(s)
Mechanical Characteristics	Size, Mass, Case/Clip, Controls, Alarm Access	IEC 61526
Exterior Markings	Orientation, Reference Point, Controls, etc.	Various
Units of Readout	Dose Equivalent, Identifiable, Readable	IEC 61526
Range of Capabilities	Dose: 1μSv–10 Sv Rate: 1 μSv/h–1 Sv/h	IEC 61526
Zero-Effect	Negligible dose build-up	IEC 61526, ANSI N13.27*
Zeroing	Cannot be casually zeroed	N/A
Instructions	Comprehensible	N/A
Battery	Not easily/accidently removable	IEC 61526
Consistency of Response	Stability of response under various states of battery power	IEC 61526
Memory Protection	Readings/Alarms retained after power loss	ANSI N42.20**
Humidity	Response consistency in 40%–90% RH environments	IEC 61526, Other
Temperature	Response consistency in 5 °C–40 °C environments	IEC 61526
Dose Linearity	Response consistency over the range of 2 μSv to 850 mSv.	IEC 61526
Dose Rate Linearity	Response consistency over the range of 6 μSv/h to 12 mSv/h.	IEC 61526
Photon Energy Dependence	Response consistency at photon energies of 65, 164 and 662 keV.	N/A
Wear Orientation	Effect of wearing dosimeter backward.	N/A

*American National Standards Institute (ANSI). 1997. *American National Standard for Dosimetry—Performance Requirements for Pocket-sized Alarm Dosimeters and Alarm Ratemeters*, Draft ANSI N13.27.

**American National Standards Institute (ANSI). 1995. *American National Standard Performance Criteria for Active Personnel Radiation Monitors*, ANSI N42.20, Institute of Electrical and Electronics Engineers.

2.0 Non-Radiological Evaluations

2.1 Mechanical Characteristics

IEC 61526 prescribes limitations and characteristics for the physical properties of the dosimeter. Such criteria facilitate the effective use and wear of the dosimeter and, if satisfied, would be expected to prevent the inadvertent loss or destruction of the dosimeter during field use.

2.1.1 Evaluation Protocol

The mechanical characteristics are readily measureable from simple observation and physical measurements. Some parameters are provided in the Operation Manual, and observed properties were compared to those statements in addition to the criteria of the IEC standard.

2.1.2 Results

The findings in this area generally were favorable and complied with available criteria. The dosimeter is not overly large and is relatively convenient to use and access. One possible concern would be the dust and moisture resistance via the alarm and infrared access holes on the front of the dosimeter. These were not physically evaluated as part of this testing. In addition, there is mild concern when the unit is unlocked (it may be locked in software) with respect to the use of the controls to inadvertently turn the unit off which zeros the displayed dose reading but not the total dose[2]. Table 2 summarizes the evaluation of size and mass of the dosimeter unit.

Table 2. DOZA DKG-05D Physical Specifications

Parameter	Criteria	Actual	Reference
Length	15 cm	9.7 cm	Instrument Manual/Specifications (confirmed via measurement)
Depth	3 cm	2.4 cm	
Width	8 cm	4.7 cm	
Volume	250 cm^3	108 cm^3	
Mass	200 g	89 g	

The evaluation of the case was limited to the manufacturer's specifications coupled, as necessary, with a subjective assessment. The casing is clearly manufactured using a smooth, rigid plastic. It has only limited recesses in which contamination may collect. These include, primarily, the seam defining the front and rear encasement portions and the area around the display atop the unit. The manufacturer states on Page 5 of the Operation Manual that the material is "shock-resistance" plastic and that the unit is hermetically sealed. Therefore, it is assumed the dosimeter is dust and moisture proof. There are two sets of holes on the front of the dosimeter. One set apparently enables the projection of the audible alarm, while the second set enables the infrared communication of the EPD with the reader unit. It was not determined if these interfaces were completely hermetically sealed as claimed.

[2] The dose value displayed by the unit is reset to zero each time the unit is powered off. This dose is referred to as the "displayed dose." A cumulative dose is stored in the unit's electronic memory and is not reset by powering the unit off; it is only reset by a computer command when the unit is in the charger/reader which is connected to the computer. This long-term dose is called the "total dose" or "accumulated dose."

There are two switches provided on the dosimeter. One controls only the light for the display. The second controls the mode of display and turns the unit off/on via single or combinations of short and long presses. The US-05 reader/charger unit can be used to disable the function of this button. Turning the dosimeter off is not casually performed. It requires a press of several seconds to switch to the alternate mode from which a second brief press of the button is required within a specific time interval.

When the unit is turned on, it displays a 0 (zero) accumulated dose reading. It also retains a total dose that remains until reset using the computer interfaced reader/charger. The unit will briefly display the total dose when a series of button presses is conducted.

With respect to use within anti-contamination clothing or within bags, the dosimeter appears to be relatively well situated. The buttons are easy to press whether in or out of a bag. The recognition of the display through an additional bag may be of more concern, especially if there are concerns about the battery condition, as the identified indication for a weak battery is quite difficult to determine even under ideal conditions.

There is no capability via the dosimeter's external controls to alter the alarm settings. These can only be altered using the computer interfaced US-05 reader/charger, although there were no evident access restrictions using the provided software. It appears that only general computer access limitations (e.g., Windows account) would provide commensurate access restriction limitations. The user may gain access to view the alarm settings by going through the process to view total dose accumulated on the dosimeter. However, this is a bit tedious, and the alarm set points flash only briefly on the EPD display.

2.2 Exterior Markings

Exterior markings must be clear and easily understood by the user.

2.2.1 Evaluation Protocol

The exterior markings are readily identified from simple observation. Descriptions of markings are provided in the Operation Manual and observed properties were compared to those statements.

2.2.2 Results

The markings of the dosimeter are clear and comprehensive. The effective center of the sensitive detector(s) is indicated in two perpendicular axes (from the top and one side). The orientation with respect to the wearer is clearly indicated on the dosimeter's label. The manufacturer, model, and serial numbers also are provided clearly on the unit's label. The control buttons and nominal instructions for their use are provided on the label as well. As these labels are on the body side, it is possible that with long term or frequent use they could wear or possibly become loose. Field users should be aware of proper labeling and markings and decline using dosimeters with severely blemished or missing labels/instructions.

There is one operational subject of concern. The label provides a legend depicting a speaker/alarm icon, which the manual describes as a "list of light and sound signals given at dosimeter operation." It is not clear whether the "speaker" icon refers to the speaker icon on the display (observed flashing with

irregularity on some dosimeter units during testing), or if it is meant to represent an audible signal (coinciding with the red light diode flashing) from the dosimeter when either measurement, alarm signal, low battery, or overload conditions are present. More clarity is needed from the manufacturer regarding the intention of this legend.

2.3 Units of Readout

The units of readout should be clear and consistent.

2.3.1 Evaluation Protocol

The units of readout are observed on the dosimeter's display, within the software interface with the US-05 reader/charger, and within the Operation Manual.

2.3.2 Results

All three resources for identifying the units of measurement (i.e., dosimeter, software, and Operation Manual) describe the output (integrated or rate) in terms of International System of Units (SI) dose equivalent, sievert (Sv). The manual further clarifies the dose equivalent as Hp(10), the personal dose equivalent at a depth of 10 mm in soft tissue. Although this is indicated, the dosimeter output is largely shaped by the method in which it is calibrated. Therefore, the user should be aware of the units identified in applicable calibration reports/certificates current at the time of use.

The dosimeter output makes effective use of three available digits by altering the display to reflect microsievert (μSv), millisievert (mSv), Sv, and equivalent rates (in units per hour). The characters identifying these levels of output are generally distinguishable under routine use. However, if dosimeters are used within plastic bags or under restricted lighting conditions (even though there is a display light feature), the distinction between micro and milli may be difficult to observe with a quick glance.

Readout of dosimeters via the computer interface provides flexible units of SI dose equivalent as necessary given the magnitude of the dose (μSv, mSv, or Sv). Alarm set-points are in terms of Sv. Downloadable history files (which can be translated to spreadsheet form) are all presented in μSv with a fixed decimal format and two digits to the right of the decimal.

2.4 Range Capabilities

The range of values displayed should be appropriate for the intended use.

2.4.1 Evaluation Protocol

The dose equivalent and dose equivalent rate range capabilities are identified in the Operation Manual and were evaluated in comparison to the recommendations of IEC 61526, Parts 6.5 and 6.6. Specifically, the dosimeter should cover a dose equivalent range from 1 μSv to 10 Sv and dose equivalent rate range from 1 μSv h^{-1} to 1 Sv h^{-1}. Furthermore, where multiple detectors are employed, the transition between detectors will be automatic.

2.4.2 Results

The Dosimeter Operation Manual (Page 3) identifies a dose equivalent range of 0.1 μSv to 15 Sv and a dose equivalent rate range of 1 μSv h^{-1} to 10 Sv h^{-1}. The manual (Page 6) identifies two silicon diode detectors as the basis for measurement. This description does not specify at what level the interpretation of the response switches from the "fine" [low range] detector to the "rough" [high range] detector; however, the description implies the switch is automatic. During the course of measurements, there were no indications of dual results or instructions to switch detector modes. Therefore, the assumption of automatic switching is presumed to accurately reflect the function.

2.5 Zero Effect/Background Response

The purpose of the background response test is to verify that the dosimeter does not have an intrinsic signal which contributes to the total dose measurement. The test is performed by placing the dosimeters in an area with a known, low, stable background exposure rate for an eight-hour period. The dose accumulated during the exposure is then compared with the background exposure rate. IEC standard 61526 specifies the manufacturer shall state the zero response (or natural background response). Draft ANSI standard N13.27 places an upper bound of 2 μSv (0.2 mrem) in an eight-hour period (at a nominal background level of 10 μrem/h).

2.5.1 Evaluation Protocol

This test was performed by placing four units in the large environmental chamber in Room 127. Background radiation levels were monitored using a Reuter Stokes pressurized ionization chamber (PIC) placed close to the dosimeters. All dosimeters were zeroed before beginning the test. The test was allowed to run an additional eight hours, from which additional confidence was gained for the response.

2.5.2 Results

The dosimeters were left in the chamber for 16 hours. During that time, the background reading on the PIC averaged 0.071 μSv/h. The total dose recorded by each dosimeter during the 16-hour exposure is detailed in Table 3.

Table 3. Background Response of the DOZA DKG-05D Electronic Dosimeter

Dosimeter Number	Net Response after 8 hrs at Low Background (μSv)	Net Response after 16 hrs at Low Background (μSv)
6171	0.60	1.13
6173	0.53	1.23
6174	0.60	1.11
6175	0.57	1.10
PIC	0.56	1.14

With respect to the IEC 61526 requirement that the manufacturer state the zero response—although it is difficult to ascertain from the Operation Manual if this is satisfied due to the translation and various references to standardized criteria or requirements (e.g., Type I, II, atmosphere, GOST criteria)—there was no explicit statement of zero or intrinsic response due to influences other than radiation energy in Section 1.2 or throughout the document. Therefore, it is assumed that this criterion is not satisfied.

Concerning the ANSI N13.27 (draft) criterion of less than 2 μSv response in eight hours of exposure at normal background conditions, the results in Table 3 demonstrate satisfactory performance. Thus, it is concluded the dosimeters tested would not contribute to an artificial signal that could be translated to a significant dose assigned to a wearer.

2.6 Zeroing

It should not be permitted for the field user to zero a dosimeter during use—either intentionally or inadvertently.

2.6.1 Evaluation Protocol

An examination was made of the operational function of the control buttons and the computer software functionality via interface to the US-05 reader/charger.

2.6.2 Results

It is possible to zero the displayed reading of the dosimeter by simply turning off the dosimeter and subsequently turning the dosimeter back on. This action, however, does not clear the "total dose" being accumulated and stored within the dosimeter memory. The total dose will be retained in the unit and is accessible either via a series of button presses or the reader/charger interfaced to the computer.

In contrast, placing the dosimeter in the US-05 reader/charger and selecting the Reset Total Dose option will wipe out the total accumulated dose immediately and, apparently, without questioning the user. To prevent an inadvertent reset, access control to the computer interface should be maintained.

The dosimeter can be locked prior to issue so the field user cannot turn the unit off and inadvertently delete the displayed integrated dose.

2.7 Instructions

This evaluation addresses the vendor-supplied instructions for the dosimeters.

2.7.1 Evaluation Protocol

The general instructions on the dosimeter, as well as the comprehensive instructions of the Operation Manual, were reviewed for understandability and comprehensive coverage. In addition, the help features of the software interface to the reader/charger system were assessed during use.

2.7.2 Results

All written materials appear to be translated from Russian, as expected. The labeling and instructions on the dosimeter are understandable and logical. The Operation Manual is more complex and often difficult to follow. Aside from simple language issues, terminology is easily misconstrued. In the opinion of multiple reviewers, the manual also is difficult to use from the standpoint of layout (indents, use of numbering and bullet schemes, etc.). The verbiage and detailed translation and some information also appear to be excluded. Through repeated readings and searches, much information can be found. However, there are some key elements missing or perhaps lost in translation.

The software also has definite deficiencies. The help menu is limited, and there is a lack of warnings with regard to certain steps/functions that, if followed, will lead to missed opportunities for recording or downloading data, which was discovered during the testing phase. Functions such as setting and retaining alarm thresholds are not well covered. The software needs to be used cautiously.

2.8 Power

Evaluations reported within this section concern the performance of the dosimeter with respect to supplied power. The issues described in subsections 2.8.1 through 2.8.4 were pre-planned evaluations. Subsection 2.8.5 describes a noteworthy observation concerning the charging of the dosimeter and its potential readiness to perform.

2.8.1 Battery—General

IEC 61526 states the manufacturer will specify the acceptable types of batteries for replacement (if power is supplied by primary [replaceable] batteries) and that batteries may not be removed without the use of a specialized tool (applicable to both primary and secondary [rechargeable] batteries).

The DOZA DKG-05D dosimeter uses permanently installed (i.e., secondary) batteries (identified as "accumulators" in the Operation Manual). There appears to be no method to open the case and make a battery exchange. Similarly, and appropriately, there appears to be no recommendation by the manufacturer pertaining to the type of battery needed for replacement. In fact, the instructions within the manual appear to discount any repairs and indicate replacement in the event of failure (Part 5.2, Page 13).

2.8.2 Battery—24 Hour Response Consistency

The purpose of the 24-hour response consistency test is to verify the dosimeter response does not significantly change as the power level of the battery decreases. The test is performed by placing the dosimeters in an area with a consistent dose rate for a period of 24 hours. The dose or dose rate assessed near the beginning of the 24-hour period will be compared to the dose or dose rate assessed near the end of the 24-hour period. IEC standard 61526 specifies a requirement that the response at the different stages will agree within 10 percent.

2.8.2.1 Evaluation Protocol

This test was performed by placing four EPD units in the large environmental chamber located in Room 127. The EPDs were configured at reference points established at roughly equal distances from a ^{137}Cs test source. Each of the reference points was established to maintain a dose rate of approximately 100 μSv/h. The constancy of radiation conditions (including that potentially induced by the adjacent irradiation facilities) was monitored using a Reuter Stokes PIC placed close to the dosimeters.

Each dosimeter was successively charged for at least a 12-hour period and was shut off while awaiting the remainder of the charging preparation. When all dosimeters were charged, each unit was zeroed and alarms set suitably high such that rate or dose alarms would not be expected to occur during the irradiation process. These levels are indicated in Table 4.

Table 4. Battery Conditions and Alarm Thresholds Prior to Initiation of 24-Hour Response Consistency Evaluation

Dosimeter	**6171**	**6173**	**6174**	**6175**
Voltage (current) (V)	4.054	4.054	4.078	4.196
Mode	Dose	Rate	Dose	Rate
Dose Alarm (mem/h)	400			
Dose Warning (mrem)	400			
Dose Rate Alarm (rem/h)	5			
Dose Rate Alarm Reset (rem/h)	5			
Dose Increase (rem)	100			
Record time (sec)	300			

During the evaluation interval, temperature was to be maintained between 18 °C and 22 °C and humidity between 50 percent and 75 percent. Just prior to commencing exposure, however, the environmental chamber ceased to function, and the test was performed outside of the environmental chamber under normal laboratory ambient conditions. Ambient conditions during the evaluation are provided in Table 5.

Table 5. Ambient Conditions During Evaluation of 24-Hour Response Consistency

Condition	**Unit**	**Beginning of 24-hour Period**	**End of 24-hour Period**	**Difference**
Radiation level	μSv/h	1.111	1.109	-0.001
Temperature	°C	24	24	0
Pressure	mmHg	743.2	744.0	0.8
Humidity	%RH	31	24	-7

Note that the radiation levels shown in Table 5 indicate the ambient dose rates with no source in place.

Dosimeters were placed at the exposure locations, the source loaded into the central position nominally equidistant from each dosimeter, and a timer was initiated. Beginning after a nominal stabilization time of 30 minutes, readings were taken at 30-second intervals for five minutes. Approximately 24 hours later, an additional set of readings were recorded at 30-second intervals for five minutes. The data were summarized and compared to the 10 percent criteria previously cited.

2.8.2.2 Results

Upon the final read sequence at the 24-hour interval, it was quickly realized that EPDs configured in the Dose mode would not yield highly accurate results given the parameters of the evaluation due to incrementing significant figures. Readings of these dosimeters at the onset of the evaluation were nominally 50 to 60 μSv with one digit past the decimal. At the end of 24 hours, the readings were nominally 2900 μSv; however, the EPD units had changed the units of display to mSv with two places past the decimal (e.g., 2.90 mSv). Consequently, readings could not be resolved less than 10 μSv/h, which only incremented once during the 10 readings at 30-second intervals. Thus, the observed results did not give a statistically meaningful average. Nevertheless, the observed results are posted for indication of roughly similar outcomes.

Data from the Dose Rate-configured units was satisfactory. In the case of both EPDs configured in this mode, the readings at the end of the 24-hour period were slightly elevated above the readings at the onset of the evaluation. A data summary is provided in Table 6.

Table 6. 24-Hour Response Consistency of the DOZA DKG-05D Electronic Dosimeter

Dosimeter Number	Display Mode	Mean Response at Beginning of 24-hour Period (μSv/h)	Mean Response at End of 24-hour Period (μSv/h)	% Change
6171	Dose	115	133	15.7
6173	Dose Rate	121	127	5.0
6174	Dose	121	133	9.9
6175	Dose Rate	121	128	5.8

With respect to the IEC 61526 requirement that the reading not change more than 10 percent in 24 hours, it is concluded from the results of the Dose Rate-configured EPDs that the change is well within this criteria. Furthermore, the change appears to be well within the manufacturer's stated accuracy (eight-hour reading instability less than or equal to ±5 percent).

2.8.3 Battery—Response Consistency at Battery Indication/Length of Response

Part 10.2 of IEC 61526 provides requirements that a capability for evaluating battery condition will be available within the detector, it will function to provide a warning battery life is going to end, and at least eight hours of life will remain once that indication is provided under conditions of 100 μSv/h. There is also a stipulation that this occur with one minute of alarming during that eight-hour interval. However, functional use related to conditions of alarms is not being considered. Although this evaluation was

initially scoped separately, it was convenient to simply combine the two evaluations in sequence. The first part is to evaluate the consistency of the response between the point of fresh charge of the battery with the response about the time the warning of impending battery failure occurs. The second part is to evaluate the response approximately eight hours past when the battery warning occurred with the initial response. The test is performed by placing the dosimeters in an area with a consistent dose rate for a period lasting until the dosimeter fails or shuts down due to inadequate battery power. A criterion for the response at the different stages agreeing with the initial response is ±10 percent.

2.8.3.1 Evaluation Protocol

This test was performed by placing four EPD units in the large environmental chamber located in Room 127. The EPDs were configured at reference points established at roughly equal distances from a ^{137}Cs test source. Each of the reference points was established to maintain a dose rate of approximately 100 μSv/h. The constancy of radiation conditions (including that potentially induced by the adjacent irradiation facilities) was monitored using a Reuter Stokes PIC placed close to the dosimeters.

Each dosimeter was successively charged for at least a 12-hour period and was shut off while awaiting the remainder of the charging preparation. When all dosimeters were charged, each unit was zeroed and alarms set suitably high such that rate or dose alarms would not be expected to occur during the irradiation process. These levels are indicated in Table 7.

Table 7. Condition of Dosimeters at the Initiation of Testing for Response Consistency at Battery Indication

Dosimeter	**6171**	**6173**	**6174**	**6175**
Voltage (current) (V)	4.28	4.13	4.11	4.21
Mode	Dose	Rate	Dose	Rate
Dose Alarm (mSv)	110			
Dose Warning (mSv)	43			
Dose Rate Alarm (mSv/h)	1.3			
Dose Rate Alarm Reset (mSv/h)	1.3			
Dose Increase (Sv)	1			
Record time (sec)	1200			

During the evaluation interval, temperature was to be maintained between 18 °C and 22 °C and humidity between 50 percent and 75 percent. The environmental chamber was again non-functional, but the evaluation was configured within the chamber and the door left open to the room environment. The test proceeded under normal laboratory ambient conditions.

Dosimeters were placed at the exposure locations, the source loaded into the central position nominally equidistant from each dosimeter, and a timer was initiated. Beginning after 20 to 30 minutes of stabilization time, successive readings were taken to record the beginning response condition. The dosimeters were exposed until the last of the four test dosimeters shut down due to inadequate battery power.

Video records of the testing were then examined to identify at what point a battery warning was displayed. Readings were collected following the indication of a battery warning and just prior to the

point at which the dosimeters shut themselves down in order to compare the consistency of the response with that at the beginning.

2.8.3.2 Results

From the lesson learned in the 24-hour response consistency evaluation, later readings of the dosimeters set in Dose mode were adjusted for intervals to enable replicate resolution of the dose changes. As such, length of exposures were increased in a way that essentially made the anticipated eight-hour alarm warning evaluation overlap with the evaluation near the end of the battery life.

The dosimeter manual does not provide a clear specification for how long the dosimeter will continue to function after a battery warning. It identifies that a battery warning will occur when the voltage drops to 3.52 V and that the unit would be switched off in a few hours due to low power. It also states that in such cases, a two-second audible alarm would occur every 15 minutes once the battery warning alerts.

All of the dosimeters evaluated in this test functioned within the radiation field for well over 200 hours. Longevity was generally about 11 to 12 days. Video recorded to track the progress of the testing was the only sure way to capture the display of the battery warning. Despite the effort to show a clear view of the display, the recorded video image made it difficult to read the tiny indication of the battery symbol at the bottom left of the display. Of additional concern was the possibility of being out of synchronization between the flashing of the indication(s) and the 30-second interval of the video frame capture. However, a thorough evaluation of the video footage was able to modestly resolve the displayed indications–or lack thereof.

The first noteworthy outcome of this evaluation is the specific icon or symbol on the EPD display that indicates pending failure of the battery is difficult to identify with certainty. The manual specifies a "blinking battery symbol" for this indication. One of the symbols on the display resembles that depicted in Figure 1, which was assumed to be the symbol referenced in the manual. This symbol was observed relatively clearly on one detector roughly eight hours before the shutdown of the detector. For two dosimeters, this symbol was thought to be observed, but not at the same time interval prior to shutdown. For a fourth dosimeter, no clear warning of impending shutdown was observed.

The operator aid/legend affixed to the dosimeter identifies a symbol similar to a "speaker" (see Figure 2) that may flash with regularity to indicate a low battery in addition to, or possibly in lieu of, the battery symbol Figure 1. This symbol was observed at times when a battery warning should have been expected. However, this symbol was observed in other cases as well. In at least one case, it began flashing several days before the eventual battery failure.

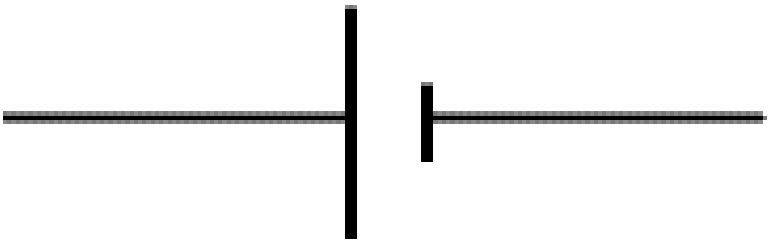

Figure 1. Assumed Blinking Battery Symbol

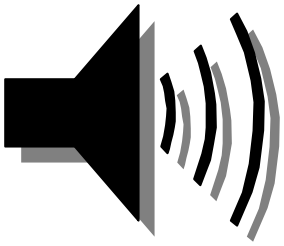

Figure 2. Assumed Low Battery Warning Symbol

For one dosimeter, the red LED light adjacent to the digital display also flashed a warning. That warning appeared to occur approximately every 20 minutes about midway through the interval between the battery warning and the auto shutdown due to low power. However, it appeared to cease approximately 2.5 hours before the shutdown.

A data summary for the response of the dosimeter following the initially observed battery indication is provided in Table 8.

Table 8. Response Consistency of the DOZA DKG-05D Electronic Dosimeter at Battery Warning

Dosimeter Number	Display Mode	Mean Response at Beginning of Test (μSv/h)	Mean Response at Battery Warning (μSv/h)	% Change
6171	Dose	113.8 ± 4.4	115.7 ± 2.0	1.7
6173	Dose Rate	120.3 ± 2.3	125.1 ± 3.5	4.0
6174	Dose	116.4 ± 4.1	119.8 ± 1.7	2.9
6175	Dose Rate	119.5 ± 1.9	126.1 ± 3.1	5.5

A data summary for the response of the dosimeter just prior to shutdown due to low battery is provided in Table 9.

Table 9. Response Consistency of the DOZA DKG-05D Electronic Dosimeter Prior to Shutdown Due to Low Power

Dosimeter Number	Display Mode	Mean Response at Beginning of Test (μSv/h)	Mean Response prior to Shutdown (μSv/h)	% Change
6171	Dose	113.8 ± 4.4	115.7 ± 2.0	1.7
6173	Dose Rate	120.3 ± 2.3	127.6 ± 2.6	6.1
6174	Dose	116.4 ± 4.1	119.8 ± 1.7	2.9
6175	Dose Rate	119.5 ± 1.9	127.3 ± 3.5	6.5

Although recognizing the low battery indication clearly was a problem, the estimated time that each dosimeter continued functioning following a low-battery observation is provided in Table 10.

Table 10. Nominal Time Between Identified Battery Warning and Eventual Shutdown

Dosimeter Number	Nominal Time between Battery Warning/Shutdown
6171	7.76 hours
6173	6.74 hours
6174	None (no indication observed)
6175	5.45 hours

Ambient conditions during the evaluation are provided in Table 11.

Table 11. Ambient Conditions During Evaluation of Response Consistency at Battery Indication

Condition	Unit	Beginning of Test	At Battery Warning	At end of test
Radiation level	μSv/h	1.08	1.07	1.08
Temperature	°C	23	23	23
Humidity	%RH	37	27-38	38-43

The readings of the dosimeters at the time a battery warning indication begins appear to be well within 10 percent of the readings at the initiation of the test. For those dosimeters whose readings just prior to shutdown could be resolved (i.e., dosimeters in the Rate mode), these two responded within 10 percent of the initial readings. A possible trend observed was that dosimeters in the Rate mode tended to deviate more from the initial readings as the battery depleted than the dosimeters in the Dose mode. In general, battery lifetime and consistency of response over that lifetime appears to be acceptable. For those dosimeters that appeared to give a warning—although it must be noted that a clear recognition of this warning was difficult to ascertain from the video record—the length of time the dosimeters continue to function should be sufficient in most cases to recognize the condition and to acquire a replacement.

The difficulty in observing the battery warning and clearly understanding which flashing indicator truly implies a depleting battery condition is of particular concern. Furthermore, the apparent lack of battery indication in one dosimeter suggests it might be possible to continue using a dosimeter that could shutdown without warning during use.

2.8.4 Consistency of Response Following Power Loss

The DOZA DKG-05D dosimeters shutdown automatically to preserve power once the battery voltage drops below a set voltage threshold. There should be confidence that after a dosimeter has performed this function, its reading, alarm settings, and recorded history (if applicable) are still intact. This preservation should be consistent whether the dosimeter is simply turned on manually or is placed into the reader/charger and read out via the computer interface.

2.8.4.1 Evaluation Protocol

This test is a follow-on to the prior testing of response consistency at battery indication/length of response in which dosimeters were exposed until their automatic shutdown occurred due to low battery power. Dosimeters were allowed to sit at least 24 hours post-shutdown. One of each of the dosimeters in the Rate and Dose modes were installed in the US-05 reader/charger system, and the response and settings were evaluated. The history was downloaded. The remaining dosimeters were restarted manually and their readings evaluated.

The dosimeters were then replaced on the irradiation jig and exposed for several more hours. Dosimeters were removed from the jig, and, if possible, the response of all dosimeters was evaluated against initial settings via the US-05 reader/charger and their history files downloaded. The response following the restart was compared to the response at the beginning of the evaluation.

2.8.4.2 Results

The initial parameters for dosimeters included in this evaluation are provided in Table 12.

Table 12. Condition of Dosimeters at the Initiation of Testing for Consistency of Response Following Power Loss

Dosimeter	**6171**	**6173**	**6174**	**6175**
Voltage (current) (V)	4.28	4.13	4.11	4.21
Mode	Dose	Rate	Dose	Rate
Dose Alarm (mSv)	110			
Dose Warning (mSv)	43			
Dose Rate Alarm (mSv/h)	1.3			
Dose Rate Alarm Reset (mSv/h)	1.3			
Dose Increase (Sv)	1			
Record time (sec)	1200			

Dosimeters 6171 (Dose) and 6173 (Dose Rate) were selected to be analyzed using the reader/charger interface. Data and parameters are provided for these two units in Table 13.

Table 13. Readout Condition After Shutdown Due to Low Battery

Dosimeter	6171	6173
Battery Voltage, current (mV)	3390.2	3319.1
Total Dose (Sv)	0.03246	0.03431
Dose (Sv)	0.03246	0.03431
Dose Alarm Threshold (Sv)	1.1E-1*	1.1E-1
Dose Warning Threshold (Sv)	4.3E-2	4.002E-3**
Dose Rate Alarm Threshold (Sv/h)	1.3E-3	1.3E-3
Dose Rate Alarm Reset Threshold (Sv/h)	1.3E-3	1.3E-3
Dose Increase Value (Sv)	1.0	1.0
Dose Increase Value (%)	244	244
Recording Interval (sec)	1200	1200

* Initially this and other alarm/threshold fields were blank, but when the original setting was typed in, the original values in all the fields reappeared.

** Suspect this value was inadvertently entered (mistyped) when dosimeter was set-up prior to evaluation of Response Consistency at Battery Indication.

The response history of both dosimeters 6171 and 6173 was downloaded to file and examined for concurrence with the video records of the exposure.

Dosimeters 6174 and 6175 were powered on manually in order to obtain the current reading; however, neither dosimeter would remain functional long enough to proceed beyond the start-up phase and display a dose reading.

Dosimeters 6171 and 6173 received a short duration charge while readings were collected using the US-05 reader/charger. They were extracted from the reader, at which point their displayed dose was re-zeroed. They were then returned to the exposure jig for additional irradiation. Dosimeter 6171 was still functional more than seven hours later, but unit 6173 had powered down after about half that time. These dosimeters were again placed in the reader and their total dose record and internal parameters identified for consistency with earlier readings. In addition, dosimeters 6174 and 6175 were similarly placed in the reader to obtain their internal parameters, total dose reading, and history files. A summary of the findings are listed in Table 14.

All alarm settings and recording parameters remained as set prior to evaluation of response consistency after battery indication. The two dosimeters that were not placed into the reader had lost their total dose reading. Dosimeter 6174 had no current dose reading, and dosimeter 6175 displayed a current dose of about 5.4 mSv, a reading that did not appear consistent with the original exposure from prior evaluations. Furthermore, there were no history files associated with dosimeters 6174 and 6175. While it is possible that attempting to start up the dosimeters without the reader following the battery failure may have induced a loss of readings, it points to a definite concern regarding the handling of “discharged” dosimeters. It appears that once a battery has discharged to the point that causes the dosimeter to shut down, no attempt should be made to restart the dosimeter, and the dosimeter should be returned to the US-05 charger in order to retain the dose readings that were incurred prior to shutdown.

Table 14. Readout Condition After Shutdown Due to Low Battery

Dosimeter	6171	6173	6174	6175
Battery Voltage, current (mV)	3390.2	3319.1	3627.3	3698.4
Total Dose (Sv)	0.03329	0.03473	0	0
Dose (Sv)	0.0008247	0.0004192	0	0.005412
Dose Alarm Threshold (Sv)	1.1E-1	1.1E-1	1.1E-1	1.1E-1
Dose Warning Threshold (Sv)	4.3E-2	4.002E-3	4.3E-2	4.3E-2
Dose Rate Alarm Threshold (Sv/h)	1.3E-3	1.3E-3	1.3E-3	1.3E-3
Dose Rate Alarm Reset Threshold (Sv/h)	1.3E-3	1.3E-3	1.3E-3	1.3E-3
Dose Increase Value (Sv)	1.0	1.0	1.0	1.0
Dose Increase Value (%)	244	244	244	244
Recording Interval (sec)	1200	1200	1200	1200

2.8.5 Charging Notes

Throughout the evaluations, an attempt was made to prepare dosimeters for testing by inducing a battery charge that placed the dosimeter between roughly half and full battery capacity, depending on the test. In some cases, the specific capacity was difficult to identify from the displayed voltage and/or the software interface to the US-05 reader/charger.

Instructions concerning the charging of the dosimeter are limited, but the Operation Manual provides some characteristics. It identifies the unit has two charging modes. These include a high current charge that is induced when the dosimeter's battery voltage is less than 3.52 V and a low current charge that occurs if the battery voltage is at or above 3.52 V when the dosimeter is placed into the US-05 reader/charger. The charging protocol for a unit below 3.52 V is to charge for a period of 12 hours at the high current. Then, the program switches the current to the low range and maintains the battery until the dosimeter is extracted for use.

It is unknown how long it would take to fully charge a unit that was slightly above the 3.52 V threshold when charged at the low current charge. It is possible that an overnight charge using the low current mode may not fully return the dosimeter to its full capacity.

In one instance, a dosimeter had shutdown after its battery condition dropped below the 3.52 V threshold. After not using the dosimeter for several days and then putting the dosimeter in the charger, its voltage again appeared to be nominally mid-range (e.g., ~3.8–3.9 V), and the low current charge mode was invoked. This dosimeter was allowed to charge for a short duration then placed in a relatively high rate field (nominally 100 mSv/h). The dosimeter quickly shutdown. When placed back into the charger, the low rate charge was again invoked, implying that the voltage was not substantially low enough to invoke the high current charge. The irradiation process was repeated, and, after shutting down a second time, the dosimeter was rushed to the charger. This time, the high current rate was induced.

This behavior appears to imply that even though the battery voltage is low enough to shutdown the dosimeter, given sufficient time, battery capacity could return enough to cause the US-05 firmware to set the low current charge mode. As such, it is difficult to place confidence in the actual readiness of the battery without knowing something of the prior use and of subsequent charge history. Furthermore, given

the inconsistent state of "low battery" indications previously noted, due caution should be used to confirm battery power and capacity is sufficient for the anticipated use of dosimeters.

2.9 Humidity Response

The purpose of the humidity test is to verify that the dosimeter response is stable within the range of 40 percent and 90 percent relative humidity (RH).

2.9.1 Evaluation Protocol

This evaluation was largely derived from the recommendation of Part 10.4 of IEC 61526. The test is performed by placing a test dosimeter within an environmental chamber such that the humidity and temperature can be controlled. A ^{137}Cs source is placed nearby to establish a positive reading on the dosimeter. The temperature is stabilized to a nominal level of 35 °C and 65 percent RH and allowed to remain in the environment for a period of 24 hours. Near the end of the 24-hour period, the response of the dosimeter is recorded to form a baseline. The humidity is then raised to 90 percent and, again, the dosimeter is allowed to remain in the environment for 24 hours. The response is recorded near the end of that interval to form the basis of the dosimeter response (relative to 65 percent RH) at high humidity levels. The humidity is then lowered to 40 percent RH, and the dosimeter is allowed to stabilize for 24 hours. The response is recorded near the end of that interval. This reading forms the basis for response capabilities at relatively low humidity. IEC 61526 identifies an acceptance criteria of 10 percent for the amount of allowed difference between the response at high- and low-humidity levels relative to the reference condition (65 percent RH).

Prior to placing the dosimeter (s/n 6174) within the environmental chamber, the dosimeter was fully charged and audible alarm levels set high enough to prevent activation by the accumulated dose or dose rates anticipated during the test. The dosimeter was used in the Dose Rate mode so that the response could be resolved without concern about loss of significant figures at elevated integrated dose levels.

2.9.2 Results

Readings were collected of the dosimeter reading during the final half hour of exposure within the 65 percent RH environment. This process was repeated for the 90 percent RH and the 40 percent RH environment phases of the evaluation. The mean reading during these three intervals was compared (extremes versus the baseline 65 percent RH condition). The results of this comparison are summarized in Table 15. The measurement timeline is shown in Figure 3.

Table 15. Response of the DOZA DKG-05D Electronic Dosimeter at Varying Relative Humidity Levels

Relative Humidity (%–Nominal)	**Mean Response (± 1σ) During Final 0.5 hr in Environment (μSv/h)**	Change (Relative to Baseline)
90	53.91± 1.35	-0.4%
65 (Baseline)	54.10 ± 1.47	----
40	54.42 ± 0.92	+0.6%

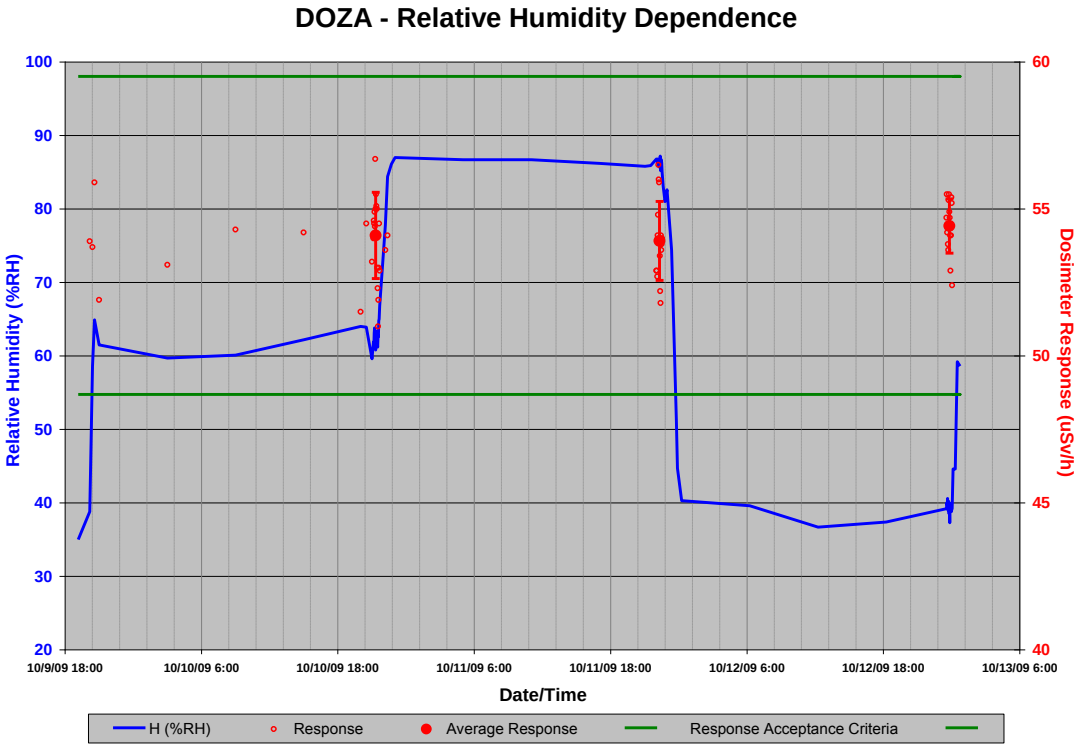

Figure 3. Humidity Dependence Evaluation Sequence

The net difference in response at the high and low relative humidity extremes compared within 1 percent with the baseline reading and well within the specifications defined as acceptable.

2.10 Temperature Dependence

The purpose of the temperature test is to verify that the dosimeter response is stable to within ±15 percent over the range of use stated by the manufacturer per IEC 61526, Part 10.3.2.a. The manufacturer identifies that the range of use is −20 °C to 45 °C.

2.10.1 Evaluation Protocol

The test is performed by placing a test dosimeter within an environmental chamber such that the humidity and temperature can be controlled. A ^{137}Cs source is placed nearby to establish a positive reading on the dosimeter. The temperature is stabilized to a nominal level of 20 °C and allowed to remain in the environment for a period of four hours. Near the end of the four-hour period, the response of the dosimeter is recorded to form a baseline. The temperature is then raised to 45 °C, and the dosimeter is again allowed to remain in the environment for four hours. The response is recorded near the end of that interval to form the basis of the dosimeter response (relative to 20 °C) at high temperature levels. The temperature is then lowered to −20 °C, and the dosimeter is allowed to stabilize for four hours. The response is recorded near the end of that interval. This reading would form the basis for response

capabilities at low temperature. IEC 61526 identifies an acceptance criteria of 15 percent for the amount of allowed difference between the response at high- and low-temperature levels relative to the reference condition (20 °C).

Prior to placing the dosimeter (s/n 6173) within the environmental chamber, the dosimeter was fully charged and audible alarm levels set high enough to prevent activation by the accumulated dose or dose rates anticipated during the test. The dosimeter was used in the Dose Rate mode so the response could be resolved without concern about loss of significant figures at elevated integrated dose levels.

After the initiation of the testing, two unexpected issues induced an alteration to the test protocol. First, the temperature ramp to −20 °C and the subsequent hold at that temperature were both intended to last approximately four hours. However, they actually extended for approximately 40 hours each, indicating that the preprogrammed test plan entered within the environmental chamber controller probably was entered as 40-hour time intervals. In addition, the display of the dosimeter began fading as the temperature dropped to about 10 °C. The fade continued, and the display was almost imperceptible at about 0 °C. The lowest temperature at which 10 measurements could be resolved with good confidence was identified at roughly 3 °C, and readings were taken at that point. Further quantitative readings were not made of the dosimeter response.

2.10.2 Results

The response of the dosimeter was observed to diminish slightly as the temperature increased from nominal ambient conditions to about 45 °C (113 °F). As identified, as the temperature dropped below normal room temperatures, the display faded. Although the function of the dosimeter itself appears to be unaffected, the fading appears to increase with decreasing temperatures until the reading is almost imperceptible at −20 °C (-4 °F). A reading at approximately 3 °C identified a slight increase in the reading. Following the evaluation, the display returned to normal conditions when the temperature reached nominal room temperatures.

The change in reading at 45 °C and 3 °C temperatures were within a several percent of the baseline readings, all well within the ±15 percent tolerance of the standard. The results of this comparison are summarized in Table 16. The measurement timeline is shown in Figure 4.

Table 16. Response of the DOZA DKG-05D Electronic Dosimeter at Varying Relative Humidity Levels

Temperature (°C–Nominal)	**Mean Response (± 1σ) During Final 0.5 hr in Environment (μSv/h)**	Change (Relative to Baseline)
45	62.1 ± 1.1	-1.7%
20 (Baseline)	63.2 ± 1.4	----
3	65.4 ± 1.7	+3.5%

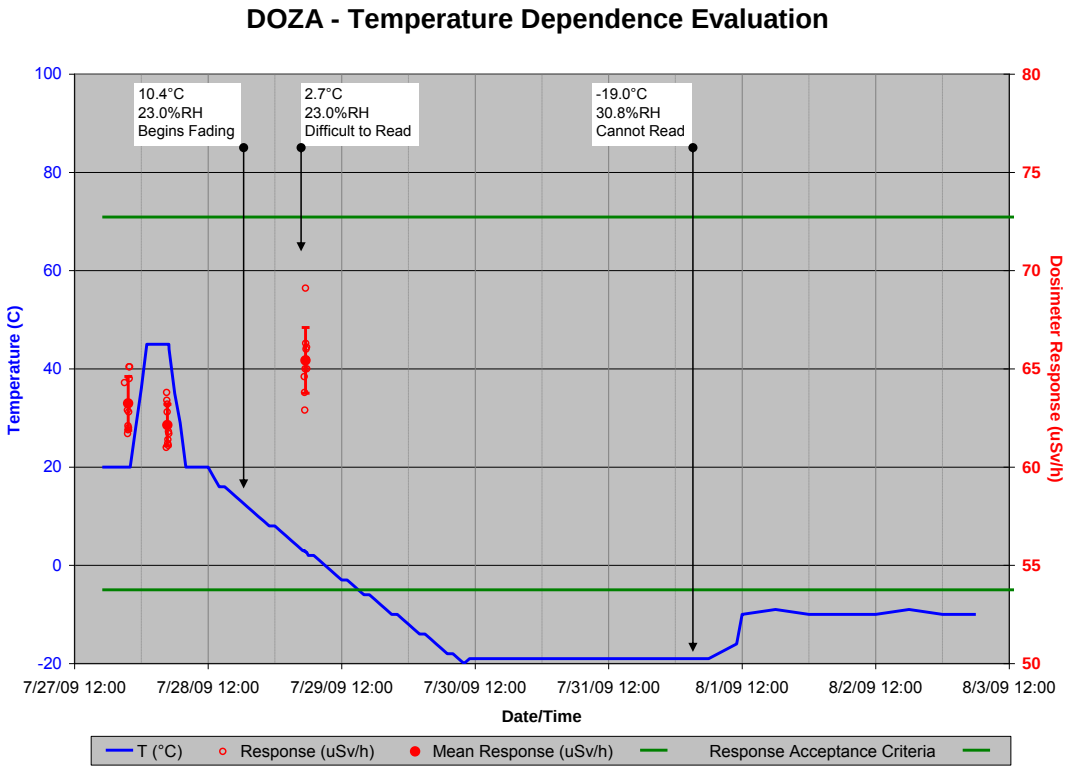

Figure 4. Temperature Dependence Evaluation Sequence

3.0 Radiological Evaluations

3.1 Introduction

Several evaluations were performed to study the general response characteristics of the detector design. These evaluations assessed the linearity of response from low to high doses, the dependence of dose rate, influence of photon energy, and the significance of wear orientation (forward/backward).

Two dosimeters were selected from the available five for each of these evaluations. Two dosimeters were considered advisable for each of these tests in part to provide back-up should one dosimeter fail during the evaluations and to provide corroboration of results. The same two dosimeters were used throughout each individual evaluation to preserve response characteristics. It was not assumed that the five dosimeters provided for testing had been calibrated to respond alike, or that their response characteristics would be necessarily similar. Switching dosimeters midway through an evaluation would have necessitated additional (repeated) irradiations to normalize the response of a replacement dosimeter to the response of the dosimeter being replaced.

Audible alarms quickly deplete the battery capacity. In order to avoid the likelihood that a dosimeter would fail during a test—most likely due to a weakened battery—the total integrated dose and dose rates for each evaluation were estimated and the audible dosimeter alarms established well beyond these levels to avoid inducing such alarms.

3.2 Dose Dependence

An evaluation was made to identify possible response dependence on the total dose delivered (i.e., dose linearity) over the range of 2 μSv to 850 mSv. This evaluation was enabled by performing irradiations of two DOZA units at five different dose rates and geometries. Exposures were performed with the dosimeters placed upon a 30 cm by 30 cm by 15 cm, polymethyl methacrylate (PMMA) phantom with the effective center of the detector placed at the reference distance. To render differences in rate and geometry ineffectual upon the test results, duplicate dose irradiations were performed as the conditions changed, such that each new geometry and rate could be normalized to the prior (and earlier) conditions. The evaluation was performed using ^{137}Cs. The outcome of possible dose dependence is considered to be independent of the photon energy. Therefore, an evaluation of dose dependence with alternate photon energy fields is considered unnecessary for the scope of these evaluations.

IEC 61526 identifies an acceptance criteria of ± 15 percent for the response of the dosimeter across its potential response range, assuming a calibration according to manufacturer's specifications. The manufacturer claims dose accuracy ranges from ± 20 percent at 2 μSv to ± 15 percent at doses above approximately 20 μSv. These values are considered in evaluating the outcome.

The results of the evaluation, depicted in Figure 5, demonstrate an identifiable trend in response as the total delivered dose changes. The results are normalized relative to 0.8 mSv delivered dose, which was assumed to be a likely nominal calibration dose. From these results and, in particular, using 0.8 mSv as a reference dose, a dosimeter's response may range from as low as 30 percent below the true dose to as much as 30 percent above.

Based on this result, the user should know something about how the dosimeter is calibrated. If it is irradiated to a significantly higher or lower dose during the calibration, the relative response will shift accordingly. For instance, if the dosimeters are exposed to a calibration dose of 10 mSv, at which point the units appear to be more responsive, the dosimeters would likely be adjusted downward then potentially under respond by 30 percent to 40 percent at lower doses.

Regardless of the calibration dose, the outcome depicted in Figure 5 demonstrates that the dose linearity for the test dosimeters—calibrated such that they are—is neither compliant with IEC 61526 nor the manufacturer's specification.

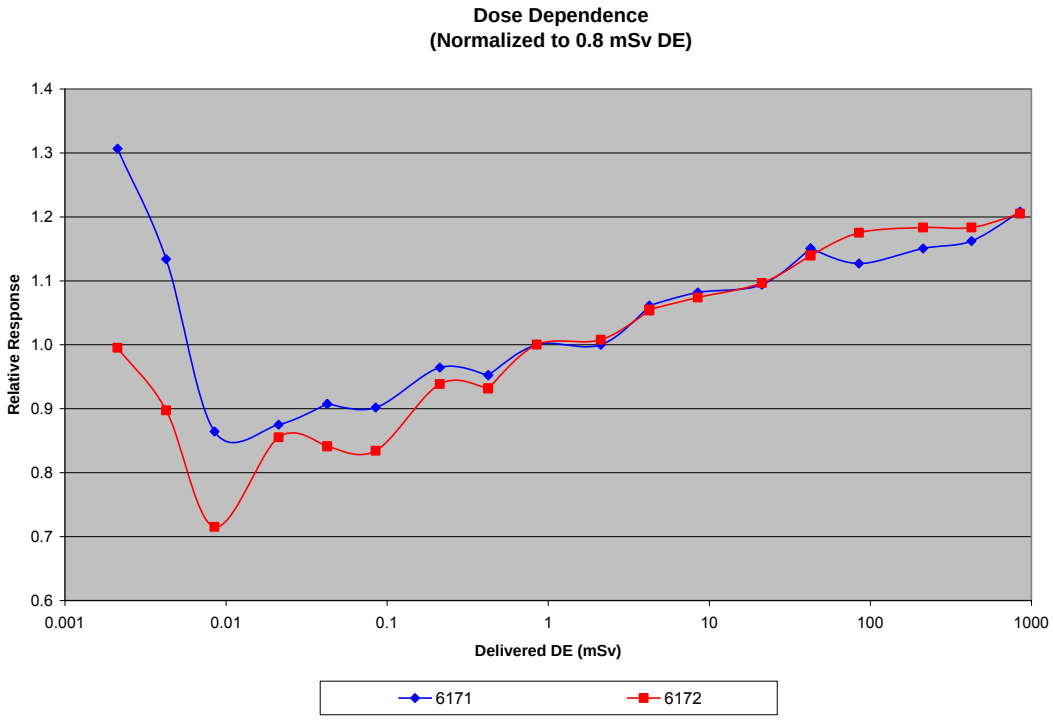

Figure 5. Results of Dose Dependence Testing

3.3 Dose Rate Dependence

Dose rate dependence can be a potential difficulty for electronic dosimeters due to possible detector dead time issues, unless a method to compensate for such limitation is established. The DOZA DKG-05D uses two separate detectors—low range and high range—presumably to enhance the accuracy over a variety of dose rates. The evaluation for rate dependence ranged from approximately 6 μSv/h to13 mSv/h. A protocol for conducting the evaluation was derived from Part 9.4.3 of IEC 61526 and, similar to the dose dependence evaluation, made use of several dose rates and irradiations to multiple dose levels for each rate. Each different dose rate involved adjustments to the exposure geometry and/or selection of an alternate ^{137}Cs source.

Dosimeters were placed on the PMMA phantom and the reference distance measured to the effective center of the dosimeter. Irradiations were conducted at two or more integrated doses for each dose rate.

As dose dependence had already been demonstrated for the DOZA DKG-05D dosimeters, readings at the different dose levels were corrected based upon that earlier data, which also accommodated normalization for geometry differences. The results of this evaluation are provided in Figure 6.

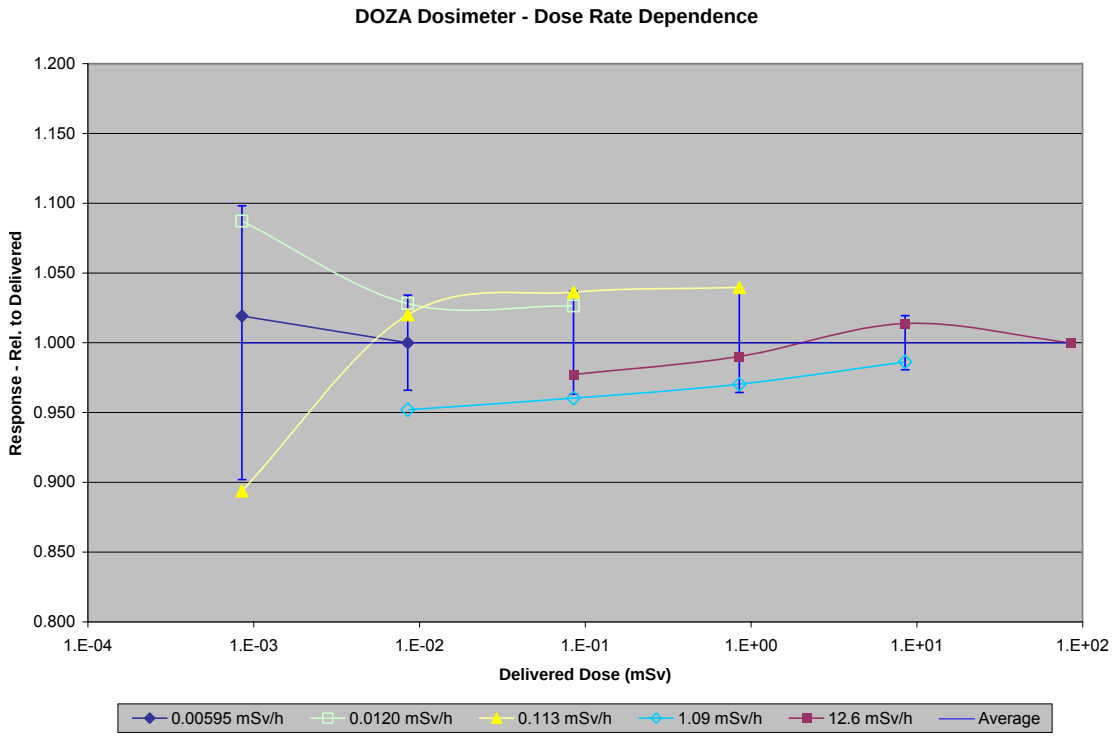

Figure 6. Results for the Evaluation of Dose Rate Dependence

Data in Figure 6 is normalized to the mean response at each total delivered dose in order to identify the spread as a function of the dose rate. From this result, it indicates the distribution of response is well within ± 20 percent, the criteria suggested by IEC 61526. The added deviation at the lowest rate is thought to be most likely due to an especially short exposure time at the 0.113 mSv/h level and, perhaps, the specific display scale in which only two significant figures are displayed for this level. Short exposure times tend to exhibit influences of source transit.

3.4 Photon Energy Dependence

The response of the DOZA DKG-05D to three general photon energy regions, 65 keV, 164 keV, and 662 keV was evaluated using 80 and 200 keV narrow bremsstrahlung spectra X-ray techniques (i.e., NS80 and NS200) and ^{137}Cs, respectively. Exposures were completed on phantom with the reference point measured to the effective center of the detector and incident radiation direct upon the phantom/dosimeter (i.e., perpendicular to the phantom surface). The delivered air kerma, in Gy, was converted to penetrating dose equivalent, Sv, using conversion coefficients provided by ISO 4037-3, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy—Part 3: Calibration of area and personal dosemeters and the measurement of their response as a function of energy and angle of incidence.* Criteria for acceptable

response are taken from IEC 61526 in which the relative response to energies greater than 50 keV shall be within 0.71 to 1.67.

3.4.1 Evaluation Protocol

For this evaluation, it was desired to retain all dose equivalent rates roughly similar to avoid the need for dose rate or integrated dose corrections to the resulting response of the dosimeters. In order to attain such similarities in rate and because of the limitation of the current adjustment on the X-ray machine, it was necessary to conduct X-ray exposures at 200 cm and 300 cm distances. ^{137}Cs exposures were conducted at 100 cm.

Normally, X-ray fields are calibrated and characterized at a distance of 100 cm. Use beyond that distance can lead to alterations in the X-ray spectrum and, in turn, the response efficiency of the calibration standard used to calibrate the field in terms of air-kerma. However, this measurement uses narrow spectra techniques for which the low energy component of the spectrum is relatively limited. As such, the spectrum and air-kerma rate tends to behave marginally similar to a monoenergetic photon field with respect to limited distance alterations. This would be a concern for measurements performed for the purpose of calibration. However, since this evaluation is limited to identifying nominal energy response behavior, the uncertainties induced by this alteration in distance is not viewed as a significant concern.

Dosimeters 6171 and 6172 were mounted upon a 30 cm by 30 cm by 15 cm PMMA phantom with the normal wear orientation (i.e., flat side toward the phantom). Exposures were performed in fields of nominally 1 mSv/h to attain 0.75 mSv (i.e., approximately 75 percent of a decade) integrated dose equivalent. The dosimeters' readings from the display were recorded, and the dosimeters switched off and back on (to zero the reading) prior to exposing to the next energy.

3.4.2 Results

The initial reading of the dosimeters exposed to ^{137}Cs compared to the delivered dose equivalent indicated an over response of approximately 25 percent, raising a concern regarding the specific methodology of calibration. Given this concern, the response generated from the 65 and 164 keV X-ray fields were normalized to ^{137}Cs prior to assess the outcome against the criteria.

Table 17 shows the outcome of the response, indicating that for lower energy concerns, the dosimeter response is within the aforementioned acceptance criteria.

Table 17. Response of the DOZA DKG-05D Electronic Dosimeter with Respect to Photon Energy

Source	Average Energy (keV)	Delivered Dose Eq. (mSv)	Average Response (mSv)	Response Normalized to Dose	Response Normalized to ^{137}Cs
^{137}Cs	**662**	0.745	0.925 ± 0.019	1.24	**1.00**
NS200	**164**	0.701	0.892 ± 0.005	1.27	**1.02**
NS80	**65**	0.701	1.325 ± 0.007	1.89	**1.52**

3.5 Wear Orientation

The evaluation for wear orientation is primarily designed to identify the potential discrepancy induced by inadvertently placing the dosimeter backward on the body (i.e., clip toward the body instead of away).

3.5.1 Evaluation Protocol

This test repeats the above energy response protocol, including acceptance criteria, with the alterations of the dosimeter in a reversed orientation and the normalization of the response to that of the ^{137}Cs response in the "normal" orientation (from the previous testing).

3.5.2 Results

Table 18 shows the outcome of the response in the backward orientation. In this case, the response of the dosimeter to 65 keV photons is nearly double the conventionally true delivered dose equivalent. However, exposure to higher energy photons yields only mildly worse agreement than normal wear orientation.

Table 18. Response of the DOZA DKG-05D Electronic Dosimeter, Worn Backward, with Respect to Photon Energy

Source	Average Energy (keV)	Delivered Dose Eq. (mSv)	Average Response (mSv)	Response Normalized to Dose	Response Normalized to ^{137}Cs*
^{137}Cs	**662**	0.745	0.967 ± 0.023	1.30	**1.05**
NS200	**164**	0.701	0.934 ± 0.006	1.33	**1.07**
NS80	**65**	0.701	1.550 ± 0.057	2.21	**1.78**
* Normalized to ^{137}Cs with dosimeter oriented as per manufacturer's instructions.					

4.0 Conclusions and Recommendations

Based on the results of the tests described in this document, PNNL concludes the DOZA DKG-05D is suitable for use by PPRA monitors for real-time indication of dose received. It recommends the instrument be used as a supplement to another instrument (a passive dosimeter) that provides the dose of record, but it is not suitable for determining the primary dose of record.

4.1.1 Functional Considerations

The mechanical characteristics support usability. The unit has a reasonable size and weight, the display is clear, and two controlling buttons are easy to operate. There is some concern about the ability to read the display if it is used in a plastic bag for contamination control considerations, but the buttons would be easy to operate if the unit were inside a bag.

User controls are not intuitive and straightforward. A casual user would need to learn several sequences of button-pushes for simple operations (switching from dose to dose rate), and more sophisticated operations require careful study of the manual.

The unit should be locked before issuing to a user to prevent inadvertent switching off, which would zero the displayed dose or cause other undesirable resets.

Markings on the EPD are clear and understandable, except for ambiguity about the speaker/alarm icon. The markings on these dosimeters are in English, provided specifically for this procurement. Russian markings would be more difficult to comprehend for non-Russian speaking U.S. staff.

The EPD displays dose and dose rate in SI units. There are three digits for displayed values, and the display automatically scales from μSv to mSv to Sv to make best use of these three digits.

The range of dose and dose rates displayed by the EPD are acceptable for the anticipated application.

The instructions supplied with the evaluation units were unclear and difficult to follow. Part of this problem lies in translation issues, since they were translated into English specifically for this procurement. The Russian plant staff would be reading instructions written in the original Russian. However, there were still logic problems, deficient explanations, and the help menu in the software was especially limited. In order to competently handle the instruments at an administrative level, plant staff may have to rely on substantial trial-and-error experience to supplement the Operations Manual.

The performance of the DKG-05D was acceptable in a variety of humidity and temperature conditions. However, when the temperature drops below approximately 10 °C, the display begins to fade and is unreadable below 3 °C. Thus, the unit should not be used for real-time dose indication when the temperature falls below roughly 5 °C.

4.1.2 Battery

Although battery life was not called out as a specific goal of this testing, experience with the units showed that a full charge would provide more than 200 hours of EPD operation, giving a particularly conservative margin for this application.

The EPDs demonstrated good consistency of response over a 24-hour period, demonstrating that as the battery discharged, its ability to measure dose remained constant. This consistent response also applied to an EPD with a low battery.

The indication for a low battery condition is poorly documented in the Operation Manual and did not appear consistently across the four units tested for the low battery condition. Duration of operation of the EPD after the low battery signal was recognized was not entirely predictable. It would be necessary for the plant staff to keep the units well charged and, at the first sign of a low battery, to change out units promptly. If an EPD goes into shutdown as a result of a low battery, it should be standard practice to read out the unit using the US-05 charger station if the dose reading is needed.

The person responsible for keeping the batteries charged must be cognizant of the two modes of charging, high current charge and low current charge, as well as the charging idiosyncrasies associated with these modes. If the charge of the battery is just above the threshold for choosing the low-capacity mode, it can be difficult to get the battery fully charged.

4.1.3 Dose Measurement

The linearity of dose measurement varied somewhat from standard guidelines and from the claims of the manufacturer, but it should not rule out the use of the DKG-05D as supplemental dosimetry. When exposing the unit to gammas generated by a ^{137}Cs calibration source, the reported dose varied from the expected dose by up to 30 percent at low doses (10 μSv, or 1 mrem) and was high by 20 percent at 1 Sv (100 rem). However, when the unit is used as a real-time indicator or for determining stay times, precise dose estimates are unnecessary at very low doses, and doses above 10 mSv should not be encountered in this application. Also, if necessary, the non-linearity can be reduced by anticipating the nominal range of dose expected during use, then calibrating the unit in a similar region to minimize the non-linearity.

The consistency of dose rate measurement as a function of delivered dose is acceptable, with all tests falling well within the ±20 percent criterion suggested by IEC 61526.

The DKG-05D shows an energy-dependent response when the photon energy varies from 65 keV up to 662 keV, with the lowest energy over-responding by 50 percent relative to the highest energy. This characteristic is not unexpected, however, and falls within the acceptable range specified by IEC-61526.

If the EPD were worn backward by the user, the difference in response would be negligible for higher energy gamma fields (164 to 662 keV). For low energy gammas, there would be a high overresponse—78 percent. Therefore, users should be instructed to wear the unit properly. However, wearing the unit backwards would result in an overly conservative reading and would not degrade safety.

5.0 References

ANSI N13.27. 1997. *American National Standard for Dosimetry – Performance Requirements for Pocket-sized Alarm Dosimeters and Alarm Ratemeters*. American National Standards Institute, New York.

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