Radiation Physics and Chemistry 78 (2009) 457–460

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

The impact of irradiation temperature estimations on the accuracy of dosimetry

M.F. Desrosiers *, T. Ostapenko, J.M. Puhl

Ionizing Radiation Division, Physics Laboratory, National Institute of Standards and Technology, 100 Bureau Dr., Mail Stop 8460, Gaithersburg, MD 20899, USA

ABSTRACT

Quality-control dosimetry is important to the routine operation of a radiation processing facility. For many applications this dosimetry must be traceable to a national primary standard. After irradiation at an industrial facility, National Institute of Standards and Technology (NIST)-supplied transfer dosimeters are certified by measurement and dose interpolation from the NIST calibration curve. However, prior to computing the absorbed dose the dosimeter response must be adjusted for the temperature difference between irradiation temperature for the alanine system calibration and the irradiation temperature for the industrial process. For most industrial applications, the temperature is not controlled and varies during the irradiation process. The alanine dosimeter response has a dependence on irradiation temperature, which is compensated for by applying a correction factor to the dosimeter response to compute the absorbed dose. Moreover, there is no consensus protocol to estimate the irradiation temperature and apply this correction. This work approximates industrial temperature profiles using a ^{60}Co source with a temperature-controlled irradiation chamber, and then compares the relative effectiveness of commonly used industrial methods to correct for irradiation temperature influence on the alanine dosimeter response.

Published by Elsevier Ltd.

1. Introduction

An increase in temperature for the commercial product and associated dosimeter is an unavoidable consequence of high-dose irradiation processing. This temperature increase is also experienced by the dosimeters used in the routine quality-control operations for the process. Since commercial high-dose dosimeters are sensitive to the irradiation temperature, the accuracy of the temperature estimate influences the accuracy and precision of the dosimetry (Nagy et al., 2000; Desrosiers et al., 2006). For accurate dosimetry, the quantity of interest is the average temperature experienced by the dosimeter during irradiation. In practice, the irradiation temperature is difficult to measure for dosimeters exposed in large-scale industrial irradiators. Typically, temperature measurements are limited to the ambient temperature and an estimate of the maximum irradiation temperature that can be obtained from commercial temperature strips placed near the dosimeters.

Routine dosimeter measurements can be made traceable to a national primary standard through transfer dosimetry. The high-dose transfer dosimetry system used by the National Institute of Standards and Technology (NIST) is based on electron paramagnetic resonance (EPR) measurements of the amino acid, alanine. To certify transfer dosimeters irradiated at an industrial facility, the dosimeters are returned to NIST for measurement and the absorbed dose values are calculated from the NIST calibration curve. However, prior to computing the absorbed dose the dosimeter response must be adjusted for the temperature difference between irradiation temperature for the alanine system calibration and the irradiation temperature for the industrial process. The dependence of the alanine dosimeter response to irradiation temperature is well characterized and predictable (Nagy et al., 2000; Desrosiers et al., 2006). However, since the temperature is not controlled in the industrial process and varies during the irradiation process, the average irradiation temperature can be difficult to estimate accurately.

For each transfer dosimetry certification, NIST requests that the client estimate the average irradiation temperature and provide this value upon return of the dosimeters to NIST. Most commonly, a client will report the average temperature by one of three methods: the maximum temperature value read directly from the temperature strip irradiated adjacent to the dosimeter, the average of the starting and maximum temperature, or use this temperature strip value (as $T_{\max}$) along with the starting temperature (as $T_{\min}$) to compute an effective or average temperature through the formula, $T_{\text{effective}} = T_{\min}+2/3(T_{\max}-T_{\min})$, that is recommended by Sharpe and Miller (1999).

* Corresponding author. Tel.: +1 301 975 5639; fax: +1 301 869 7682.
E-mail address: marc.desrosiers@nist.gov (M.F. Desrosiers).

0969-806X/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.radphyschem.2009.04.009

The high-precision temperature-control system that is interfaced with the NIST high-dose gamma-ray sources, along with the high-precision alanine dosimetry system offers a unique opportunity to compare the accuracy of dosimetry resulting from the different methods to estimate the average irradiation temperature. Since the irradiation temperature can be measured throughout the irradiation process in the NIST gamma-ray sources, an accurate average temperature can be determined. Through alanine dosimeter measurements from industrial temperature profiles simulated in the NIST gamma-ray sources, the two methods can be assessed and offer insight to the irradiation processing industry.

2. Experimental

The absorbed doses for this study were delivered by a Gamma cell 220 ^{60}Co irradiator (GC207; Nordion, Canada)[1] with an activity of 703 TBq (19 kCi, serial number GC207), as of June 2006. The calibration scheme for determining the dose rate is described in NIST SP250-45 (Humphreys et al., 1998) with the exception of a modification described by Desrosiers et al. (2008).

The dosimeters were measured within 24–48 h post-irradiation with a Bruker Biospin "e-scan" EPR spectrometer. The EPR response is automatically corrected for dosimeter mass and is normalized to an internal reference standard. The alanine EPR recording parameters for measurements using either the "Pellet High" or the "Pellet Low" e-scan sample inserts were: center field, 347.0 mT; microwave power, 1 or 4 mW; magnetic-field sweep width, 12.0 mT; modulation amplitude, 0.2 or 0.4 mT; time constant, 1.3 s; spectrum scan accumulations, 8 or 32.

A specially designed aluminum holder used previously (Nagy et al., 2000) to achieve thermal equilibrium was used to hold the alanine dosimeters in a fixed geometry. Temperature during the irradiation was controlled by using a high-flow air shower from a TurboJet (FTS Systems) and measured every 60 s with a type-T thermocouple. At the conclusion of the irradiation the dosimeters were immediately transferred to the room-temperature environment.

3. Results and discussion

Eleven temperature profiles from irradiation processing runs in large-scale industrial irradiators were provided to NIST for the purpose of this study. The profiles consisted of analog recordings on chart paper of temperature versus time. From these recordings, temperature and time data were manually interpolated to create a representation of the features of the temperature–time trace. These data were plotted and categorized by the general temperature-time trends they exhibited. Four profiles were selected as representative of the general types of profiles contained in the original set of eleven profiles. Profiles **A** and **I** (Fig. 1) represent temperature profiles that rise slowly over the course of the process with the former having larger, more prominent temperature fluctuations within the profile than the latter. The overall rise in temperature for profiles **F** and **J** occurs earlier in the irradiation process and for these profiles the latter has larger, more prominent temperature fluctuations within the profile than the former.

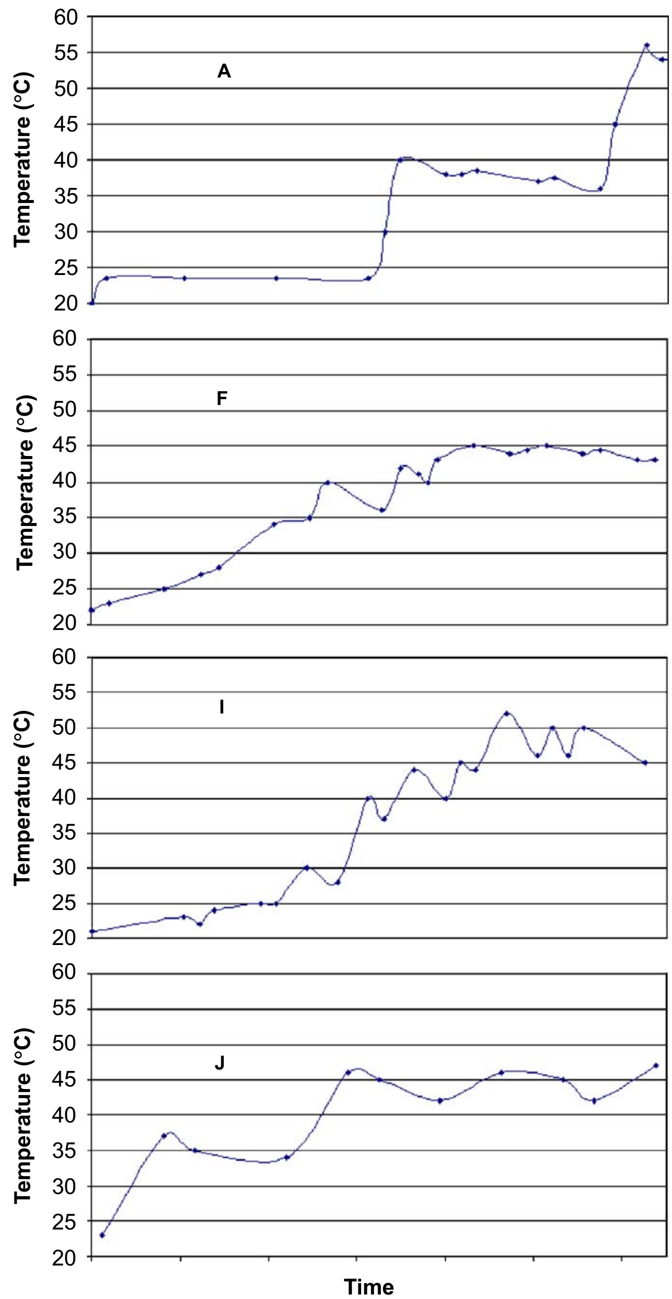

Fig. 1. Temperature-profile trends obtained from industrial process measurements. The time axis has no units since it is dependent on the total absorbed dose for a specific experimental run; typically irradiations were complete within a few hours.

The central feature of the experimental design was to approximate these temperature profiles in the NIST temperature-controlled gamma-ray source. The maximum dose rates for the industrial gamma-ray sources used in the profiles were likely to be different than the NIST gamma-ray source. In fact, even if the industry dose rates were known, the dose rate the product experiences is not constant throughout the process (due to product movement). The industrial profiles represent temperature measurements from detectors traveling through the irradiation process passing near and far from the source at various times during the process (which give rise to the features of the profile). As such, the dose rate varies throughout the process. Therefore, the key features of the profile that were chosen are the general shapes of the profiles and the approximate maximum

[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

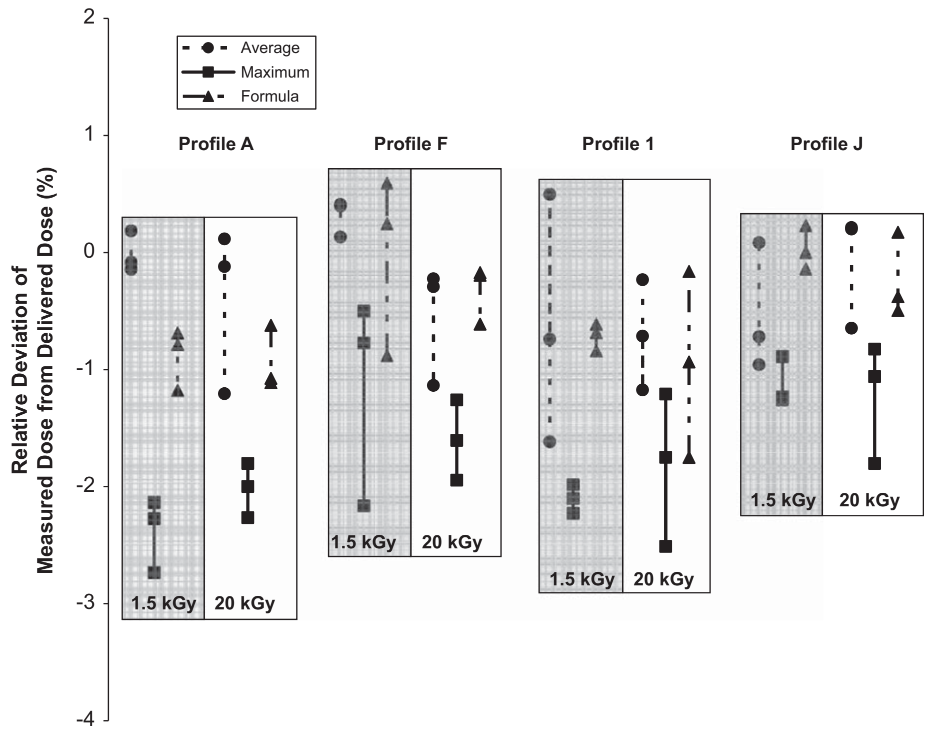

Fig. 2. Plot of the relative difference between the measured absorbed dose (uncertainty of 1%, $k = 1$) and the absorbed dose delivered to the dosimeters. Data are grouped by the temperature profile types and then separated by absorbed dose (1.5 or 20 kGy). The data points represent results from individual profiles that, though similar, are not identical and, therefore, represent the results from single experiments that cannot be averaged. The data are further divided by the method for computing the irradiation temperature: average of the minimum and maximum recorded temperature (circles); the maximum irradiation temperature measured (squares); or the average irradiation temperature determined by the Sharpe–Miller formula (triangles).

temperature. The variability of the manually created temperature profiles may be considered less than ideal, however the process being modeled is an industrial one that will by nature vary itself with product, source loading and environmental conditions, as such these data provide quantifiable insight into the dosimetry system performance. Despite these caveats, this experimental design and implementation may be considered as an acceptable representation of the industrial irradiation process. The advantage of this design is that the laboratory-controlled conditions (fixed time and absorbed dose) allow the assessment temperature effects on the dosimetry through measurement of continuous real-time temperature data and high-quality dosimetry.

For each NIST-generated temperature profile the irradiation temperature is monitored continuously. From these data, an average temperature was computed. Since the thermocouple used to measure the irradiation temperature resides adjacent to but not at each dosimeter location, an additional step was performed to ensure the dosimeter response was representative of the irradiation temperature measured.[2] For each NIST-generated profile an additional irradiation was performed at the same dose and at a constant temperature equivalent to the average temperature computed in the variable temperature industrial simulation. The dosimeter measurements from the variable and constant temperature profiles were compared. If determined to be equivalent, the dosimeter measurements from the variable temperature profile were considered to be valid and the analysis proceeded.

The response of each dosimeter was adjusted relative to the irradiation temperature (24 °C) for the alanine system calibration curve using the temperature coefficient of 0.10%/K and the irradiation temperature for the test dosimeters according to established protocols (ASTM, 2004). The irradiation temperatures were derived from either of three methods: (1) the mean of the pre-irradiation temperature and the peak or maximum irradiation temperature; (2) the peak or maximum irradiation temperature; and (3) the Sharpe–Miller formula (Sharpe and Miller, 1999) that increases the pre-irradiation temperature by two-thirds the temperature rise to compute the average irradiation temperature. To compare the methods employed for temperature corrections the irradiation temperature for the test dosimeters was first computed by each of three methods, then the dosimeter response was adjusted based on this temperature and the absorbed dose was computed by identical procedures to compare the relative results.

The results of the absorbed dose comparisons are shown in Fig. 2. The two dose levels (1.5 and 20 kGy) for each profile are grouped by the profile letter designation. Plotted is the relative deviation from the absorbed dose for each irradiation based on each of the three methods to compute the average irradiation temperature (T_{eff}). The results assess the effectiveness of each method to accurately compute the absorbed dose. The results for profile **A** show that using the maximum temperature ($T_{\max}$) as the T_{eff} will over adjust the dosimeter response by about 2% at each dose level. The Sharpe–Miller formula predicted a T_{eff} higher than the measured T_{eff} that resulted in an over adjustment of the dosimeter response by about 1%. A T_{eff} estimated by the mean of the initial temperature (T_{init}) and $T_{\max}$ proved to be the most accurate for this profile. For profile **F** using the $T_{\max}$ only will over adjust the dosimeter response between 1% and 2% at each dose level. The Sharpe–Miller formula computations of T_{eff} were effectively the same as using the mean of the T_{init} and $T_{\max}$; both were within 1% of the correct dose. Profile **I** gave similar results as

[2] It was previously demonstrated that direct contact between the dosimeter and the thermocouple introduced temperature measurement errors (Nagy et al., 2000).

profile **F**, noting that the T_{eff} determined by the Sharpe–Miller formula and the T_{eff} determined by the mean of the T_{init} and T_{max} were consistent as both methods over adjusted the response by approximately 1%. Profile **J** gave the closest grouping of data between the Sharpe–Miller formula and the T_{eff} determined by the mean of the T_{init} and T_{max}.

4. Conclusions

With the exception of profile **A**, the absorbed dose accuracy based on the Sharpe–Miller formula for determining the T_{eff} and the T_{eff} determined by the mean of the T_{init} and T_{max} was effectively equivalent within the uncertainty of the measurement (1%, $k = 1$). Profile **A** had temperature profile features that were distinctly different from the other three profiles. The irradiation temperature rose in distinct steps that began about halfway through the irradiation process. The temperature rise for profile **I** was also delayed relative to profiles **F** and **J**, but the stepwise temperature changes were absent. Both profiles **F** and **J** featured temperature rises that occurred early in the irradiation process and though similar in accuracy, profile **J** gave the most consistent results among the methods for both doses.

As anticipated, the T_{max} is the least accurate representation of T_{eff} for use in dosimetry calculations. The T_{eff} determined by the mean of the T_{init} and T_{max} was equivalent to the Sharpe–Miller formula with regard to determining a T_{eff} that would lead to the most accurate absorbed dose. In comparing the profiles, it seems that a reduction in performance for the Sharpe–Miller formula occurs when the temperature rise is slow over the course of the irradiation process. This could be attributed to the fundamental difference between these studies and an industrial irradiation process. Here, the absorbed dose rate is constant and in an industrial process the dose rate is variable. At the low points of the temperature profile for the industrial process alanine radicals are produced in smaller yield due to the lower dose rate, whereas at constant dose rate the radical production is the same (aside from the influence of temperature) regardless of the position on the temperature profile. These studies of the irradiation temperature estimation methods are presented to gain insight of the more complex industrial process. Since accurate monitoring of temperature and absorbed dose rate in an industrial irradiation process are not possible, these data offer support for the type B uncertainty that must be estimated for dosimeter temperature corrections in industrial applications.

Acknowledgements

The authors acknowledge the preliminary investigations of guest researcher Amapreet Kaur (Santa Monica College, California) that set the foundation for the work presented here. Ms. Ostapenko performed this work as a guest researcher from Gettysburg College, Pennsylvania. This material is based in part upon the work supported by the National Science Foundation under Grant no. 0453430. Any opinions, findings and conclusions or recommendations expressed in this material do not necessarily reflect the views of the National Science Foundation.

References

American Society for Testing and Materials (ASTM), 2004. Standard Practice for use of the Alanine-EPR Dosimetry System, International Standards Organization & American Society for Testing and Materials, Designation ISO/ASTM 51607: (E).

Desrosiers, M.F., Lin, M., Cooper, S.L., Cui, Y., Chen, K., 2006. A study of the irradiation temperature coefficient for L-alanine and DL-alanine dosimeters. Radiat. Prot. Dosim. 120, 235–237.

Desrosiers, M.F., Puhl, J.M., Cooper, S.L., 2008. An absorbed-dose/dose-rate dependence for the alanine-EPR dosimetry system and its implications in high-dose ionizing radiation metrology. NIST J. Res. 113 (2), 79–95.

Humphreys, J.C., Puhl, J.M., Seltzer, S.M., McLaughlin, W.L., Desrosiers, M.F., Nagy, V.Y., Bensen, D.L., Walker, M.L., 1998. Radiation Processing Dosimetry Calibration Services: Manual of Calibration Procedures, NIST Special Publication 250–45.

Nagy, V.Yu., Puhl, J.M., Desrosiers, M.F., 2000. Advancements in accuracy of the alanine dosimetry system, part 2. The influence of the irradiation temperature. Radiat. Phys. Chem. 57, 1–9.

Sharpe, P., Miller, A., 1999. Guidelines for the Calibration of Dosimeters for use in Radiation Processing, NPL Report CIRM 29.