# FACTORS AFFECTING QUALITY FOR BETA DOSE RATE MEASUREMENTS USING ISO 6980 SERIES I REFERENCE SOURCES

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*Abstract* - Atlan-Tech, Inc. has performed several calibrations of ISO 6980 Series 1 reference beta sources over the past two to three years. There were many problems encountered in attempting to compare the results of these calibrations with those from other laboratories, indicating the need for more standardization in the methodology employed for the measurement of the absorbed dose rate from ISO 6980 Series 1 reference beta sources. This document describes some of the problems encountered in attempting to intercompare results of beta dose-rate measurements. It proposes some solutions in an attempt to open a dialogue among facilities using reference beta standards for the purpose of promoting better measurement quality assurance through data intercomparison.

## INTRODUCTION

The intention of this work is to establish a dialogue among individuals conducting beta dose-rate measurements for Series 1 reference beta standards as defined in International Organization for Standardization (ISO) Standard 6980-1984 (ISO 1984). Problems encountered in the course of calibrating reference beta sources at Atlan-Tech will be discussed, along with proposed actions to remedy these problems in the future and to promote standardized methods of performing reference beta measurements in order to ensure comparability of results among calibration laboratories.

Due to the increased number of facilities performing dosimetry irradiations with ISO 6980 Series 1 reference beta sources and the availability of the reference instrumentation used to calibrate these sources, there has been an increase in the number of these facilities that are performing their own calibrations of these sources or are having the calibrations performed by a third party. Over the past two to three years, Atlan-Tech has performed calibrations of several ISO 6980 Series 1 reference beta source sets on behalf of its clients and for the purpose of intercomparison among irradiation

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laboratories. The majority of these sources were the Amersham-Buchler calibration sets, containing $^{147}Pm$, $^{204}Tl$, and $^{90}Sr/Y$. In performing these measurements, we encountered many problems in attempting to compare the results of these measurements with those of other laboratories performing calibrations on the same sources. We also experienced difficulty when we tried to compare data measured for our own sources with that measured by the National Institute of Standards and Technology (NIST).

The problems encountered in calibrating these source sets can be broken down into two main categories: those having to do with limitations of the equipment used in the calibration process, and those having to do with the lack of a standardized method for calculating and reporting beta absorbed dose-rate data. Since the reference class extrapolation chambers used for calibrating beta standards are considered to be an "absolute" instrument, i.e., no calibration factors or intercomparisons with a reference standard are employed, there exists the opportunity for a metrologist to employ several different measurement modalities. This fact can result in problems when it comes to intercomparing results of a beta dose-rate measurement from one laboratory to those from another laboratory for the same source or source type. This document will describe the calibration process employed at Atlan-Tech for determining the absorbed dose rate from reference beta sources, and then discuss some of the problems encountered in trying to ensure the integrity of measured values and propose solutions to these problems.

## METHODS AND MATERIALS

The majority of the beta dose-rate measurements performed by Atlan-Tech were done for Amersham-Buchler beta particle calibration sources installed in the beta secondary standard system. All measurements were performed using the appropriate beam-flattening filters and at the calibration distances recommended by the ISO 6980 standard for each nuclide. The measurement methodology employed follows as closely as possible the methods described in the National Bureau of Standards (NBS) Special Publication 250-21, Calibration of Beta-Particle Radiation Instrumentation and Sources (Pruitt, Soares, and Ehrlich 1988). The methodology employed at Atlan-Tech for beta dose-rate determination will be discussed here only briefly; the NBS Special Publication 250-21 should be consulted for more detailed information.

The reference instrumentation used at Atlan-Tech for beta dose-rate measurement consists of a reference class extrapolation chamber, manufactured by the Pychlau Technical Works (PTW) in Germany, and a Keithley Model 617 electrometer. The original entrance window supplied with the PTW chamber, constructed of graphite-coated polyethylene terephthalate (Mylar) having a nominal density thickness of 2.61 mg $cm^{-2}$, was replaced with an aluminized Mylar window having a density thickness of 1.29 mg $cm^{-2}$. The density thickness of the aluminized Mylar window used on the Atlan-Tech chamber was measured by weighing a 100 $cm^2$ sample of the material on a precision analytical balance. The same sample was then cut to size and installed on the chamber. Therefore, the actual density thickness of the chamber entrance window was known without having to rely upon the accuracy of a nominal value. The bias voltage supplied to the chamber plates is provided by the electrometer's internal voltage supply.

The first step in the calibration process is to establish the desired source/detector geometry. The chamber is placed at a height such that the geometric center of the entrance window coincides with the beam centerline of the source to be calibrated. A laser alignment system that installs directly into the beta secondary standard is employed for this purpose. Once the proper height has been established, the next step is to confirm that the plane of the source disk and the plane of the chamber entrance window are exactly parallel. Once these two conditions have been established, then the chamber is placed at the reference distance from the source and the appropriate beam-flattening filter is installed.

A word should be said here about the fact that the density thickness of the chamber entrance window (1.29 mg $cm^{-2}$ for the Atlan-Tech chamber) is not the same as the dose depth of interest, 7 mg $cm^{-2}$. As the intent of beta dose-rate measurement is to determine the absorbed dose rate to adipose tissue at the 7 mg $cm^{-2}$ depth, one has two options when it comes to performing beta dose-rate measurements with an extrapolation chamber. The metrologist can either place additional filtration over the chamber entrance window to bring the total value to that desired, or the measurements can be performed with the chamber window unmodified and the measurements corrected mathematically for the dose depth of interest. Measurements performed at Atlan-Tech are performed with no additional filtration over the chamber entrance window. Data are collected in this manner so that the measurement threshold (lowest absorbed dose rate the system can measure) of the system is not compromised. The correction of data measured at a dose depth other than that desired to 7 mg $cm^{-2}$ will be discussed later.

After the desired geometry has been established, the next step in the calibration process is to perform the charge collections that will be used to compute the ionization current as a function of chamber plate spacing. Charge collections are performed with the chamber plates at typically six different spacings while maintaining a constant voltage gradient. We have found that a constant voltage gradient of 10V per mm of plate spacing provides a good balance between collection efficiency and low chamber dark currents. Once the chamber plate spacing is set and the bias voltage is applied, the chamber is "pre-irradiated" before any charge collection data is recorded. Pre-irradiation consists of exposing the chamber with the source to be calibrated for an extended period of time while intermittently collecting charge with the electrometer. The purpose of pre-irradiation is to see that any stray charge in the chamber or on the electrometer capacitor are collected so that no erroneous results are produced. Once pre-irradiation has been performed, the source is shielded and the chamber dark current is monitored for several minutes. If the dark current is relatively constant with no spurious behavior, then the system is considered to be stable and charge collections can then be performed. Two sets of charge collection data are taken for each chamber plate spacing employed: one set with the chamber bias voltage at positive polarity and one with negative polarity. The polarity of the bias voltage is not switched until measurements for all plate spacings with either polarity have been completed. This minimizes the pre-irradiation time necessary when changing plate spacing and voltage. The final value for the ionization current measured for each plate spacing represents the average of the absolute values of the currents measured at positive and negative polarity. The data collection feature of the electrometer is employed in order to minimize errors associated with the charge collection process. The temperature, relative humidity, and barometric pressure are recorded with each set of charge collection data.

Once charge collection for all plate spacings has been completed, the individual values for each plate spacing and bias polarity are converted to electric current and averaged. This results in two separate sets of data consisting of positive and negative ionization current versus plate spacing. The absolute values of the positive and negative values are subsequently averaged to yield the raw collected current versus plate spacing for the source being calibrated. After the raw collected current data for each plate spacing has been determined, the next step is to apply corrections to this data so that it may be extrapolated properly.

Several correction factors are applied to the measured ionization current data in order to correct for various factors related to the instrument itself, the calibration geometry, and effects of the environment. These correction factors are specific for the PTW extrapolation chamber and are functions of several different parameters. They are also specific for each nuclide for which dose-rate measurement is being performed. The factors are discussed in detail in NBS SP 250-21 and will only be described briefly here.

The expression for correcting the raw ionization current values measured for each plate spacing is

$$I_c = I \cdot \prod_i c_i \cdot \prod_j k_j \qquad (1)$$

where $I_c$ is the corrected ionization current, I is the raw current, the quantities $c_i$ are correction factors relating to the chamber and source, and the quantities $k_j$ are correction factors relating to environmental conditions (Pruitt, Soares, and Ehrlich 1988). The quantities $c_i$ consist of eight factors, while the quantities $k_j$ number three. The eight factors that make up the quantities $c_i$ represent corrections for entrance window thickness ($c_{foil}$), beam divergence ($c_{div}$), attenuation in the chamber air gap ($c_{atten}$), air density ($c_{t,p}$), chamber backscatter ($c_{back}$), chamber sidescatter ($c_{side}$), ion recombination and diffusion ($c_{recom}$), and photon contribution to the ionization current ($c_{phot}$). The three factors that make up the quantities $k_j$ represent corrections for source decay ($k_{dec}$), variations in the air mass between the source and the chamber ($k_{mass}$), and the contribution of relative humidity to the air mass correction ($k_{hum}$). Each of these correction factors is applied for each value of raw current for each plate spacing employed. Equation (1) is then used to compute values of corrected ionization current versus plate spacing. All of the correction factors are computed by following the methodologies outlined in NBS SP 250-21, with one exception. A method is not given in NBS SP 250-21 for computing values of $c_{foil}$, the correction factor for the thickness of the chamber entrance window. This is an area where we had to go beyond the NBS SP 250-21 document in our efforts to perform consistent dose-rate calculations that were directly comparable to others. The exact method we employ for computing values for $c_{foil}$ will be discussed later. Our practice has been to compute a value for $c_{foil}$ that will convert the current measured for air at a dose depth equivalent to the density thickness of the entrance window to current for air with no window present, i.e., 0 mg cm$^{-2}$ dose depth. This is done for two reasons: 1) because we feel that this is the standard convention for reporting absorbed dose rate for reference beta standards, and 2), it makes it more convenient to convert this value to values for other media and dose depths using stopping power values and application of the $c_{foil}$ factor. Once all of the raw values for ionization current have been corrected, they are then used to compute the extrapolation curve for the source being calibrated.

The absorbed dose rate in air from a beta-particle fluence measured with an extrapolation chamber is computed as

$$\dot{D}_{air} = \frac{W}{e\rho A}\frac{dI}{dx} \qquad (2)$$

where W is the mean energy expanded in air per ion pair (electron) formed expressed in J per electron, e is the elementary unit of charge of 1.60218E-19 C per electron, is the density of air expressed in kg m$^{-3}$, A is the effective area of the chamber collecting electrode expressed in m$^3$, and

$dI\ dx^{-1}$ is the slope of the corrected current versus plate spacing curve expressed in amps per meter. The slope of the corrected current versus plate spacing curve is found by performing a linear regression on the corrected current versus plate spacing data discussed previously. The result from Equation (2) is the absorbed dose rate to air expressed in gray (Gy) per second at a dose depth of 0 mg cm$^{-2}$ ($c_{foil}$ was used to correct for the entrance window thickness).

The final step in the calibration process is to convert this value to a value for the absorbed dose rate to adipose tissue at a dose depth of 7 mg cm$^{-2}$. A value for $c_{foil}$ is computed for the 7 mg cm$^{-2}$ depth for the beta particle spectrum of interest. This value is multiplied by the value for the absorbed dose rate to air from Equation (2). The result is then multiplied by the ratio of the collisional mass stopping power for tissue to air computed for the mean beta energy of the spectrum of interest. The values for the collisional mass stopping power are taken from NBSIR 82-2550, Stopping Powers and Ranges of Electrons and Positrons (Berger, Seltzer 1983).

**DISCUSSION**

As eluded to previously, we have observed several problems with the method used for computing absorbed dose rate from reference beta standards using extrapolation chamber data, as well as problems with making the measurements themselves. The problems we have encountered can be broken down into three subject areas:

1) difficulties with comparing measured values with those from other laboratories

2) lack of published expressions for computing the $c_{foil}$ correction factor

3) problems with low signal-to-noise ratio when attempting to make charge collection measurements with the extrapolation chamber.

The biggest problem we have encountered is that the beta dosimetry data is very difficult to compare due to differences in the methods of calculation. Since the extrapolation chamber is an absolute instrument, there are many factors that are applied to obtain the corrected current. For instance, the W value (energy required in eV to create an ion pair) used can affect the dose-rate calculation significantly. The W values quoted in literature range from 33.7 to 33.97. Currently, 33.97 is considered to be the most acceptable for dry air and 33.85 for moist air. However, it is easy to see how, depending on the judgement of the metrologist, the W may be quite different. This may not seem to be a problem, but, when one tries to intercompare two numbers, it is not immediately obvious whether the W of the original measurement should be changed to reflect current data. For instance, if a metrologist were comparing older NIST data using a W of 33.7 to current data (33.97), there may be a discrepancy in the dose rate of as much as 1% simply because of the difference in this one constant. This kind of situation leads to the broader question of whether the certified dose rate at a given time should be fixed, or whether enough information must be supplied such that the factors applied may be modified as appropriate, given the knowledge of the time.

We propose that all factors applied in the calculation of dose rate must be shown as applied so that during comparison measurements the most recent factors based on current scientific knowledge, may be applied. This would implicitly mean that the dose rate quoted for a source (even a NIST-calibrated one) may be modified as time goes on, based on current scientific data. It also suggests that NIST must promulgate to the scientific community the accepted current values for these factors or other physical quantities.

Physical quantities that this might apply to are eV/ion pair (W), mass stopping power ratios (S), c(div), c(foil), or any other of the twelve factors that apply to dose rate measurement. There needs to be consensus opinion as to the values for these parameters to be used for computing absorbed dose rate from beta sources. We would also like to see a convention adopted for the media and dose depth for which beta dose-rate data are reported. At present, NIST reports absorbed dose to water at a depth of 7 mg $cm^{-2}$, while the Physikalisch-Technische Bundesanstalt (PTB) reports absorbed dose to air at a depth of 0 mg $cm^{-2}$. Our personal preference is the PTB convention of reporting dose rate to air at the 0 mg $cm^{-2}$ depth. This value could then be corrected by application of a standard $c_{foil}$ factor and standard stopping power ratios.

Another problem area we encountered was coming up with a standardized means of computing the $c_{foil}$ correction factor used for converting measured ionization current data for a particular dose depth to values for another depth. There is a set of curves published in SP 250-21 that show the $c_{foil}$ factor for Mylar versus the dose depth, but there are no expressions given for computing these values. We therefore contacted NIST and obtained the following three equations for computing the $c_{foil}$ factor as a function of entrance window thickness (Pruitt 1990). The expression for $^{90}Sr/Y$ is

$$c_{foil} = [1 + (0.0155t) + (2.02E{-}05t^2) + (1.27E{-}07t^3)]e^{-0.01t} \tag{3}$$

where t is the Mylar thickness of interest. This equation is valid for depths up to 130 mg $cm^{-2}$. The expression for the $^{204}Tl$ source is

$$c_{foil} = 1.699e^{-0.026t} - 1.736e^{0.0844t} + 1.037e^{0.1t} \tag{4}$$

This expression is valid for dose depths up to 100 md $cm^{-2}$. The $c_{foil}$ factor for the $^{147}Pm$ source is given by

$$c_{foil} = 0.994e^{-0.219x} + 0.006 \tag{5}$$

This expression is applicable up to a dose depth of 66 mg $cm^{-2}$. Note that the expressions were derived using the Amersham-Buchler beta sources at the ISO 6980 reference distances. We would recommend that these expressions be adopted as the standard means of computing the correction factors used for converting ionization currents measured at a dose depth corresponding to the thickness of the chamber entrance window back to the 0 mg $cm^{-2}$ depth. These expressions should also be employed for converting the absorbed dose-rate value for air at 0 mg $cm^{-2}$ to the value for tissue at 7 mg $cm^{-2}$, along with the appropriate stopping power ratio.

On a related note, we would also like to emphasize the importance of confirming the actual thickness represented by the entrance window of an extrapolation chamber. If an incorrect assumption is made regarding entrance window thickness, then tremendous errors in absorbed dose-rate determination could result. It is our opinion that the entrance window supplied with an extrapolation chamber should either have the thickness certified by a standards laboratory or be replaced with a certified window. It is also a good practice to check the accuracy of the chamber micrometer when a new unit is initially received.

A third problem area we have encountered has been recent attempts at calibrating several Series 1 $^{204}Tl$ sources. Recent batches of sources have been supplied that have activities far below the nominal values specified. This results in a tremendous problem in attempting to calibrate these sources in that the signal (current) being measured is so close to the dark current for the extrapolation chamber, that quality measurements are not possible. It is either impossible to measure the absorbed dose rate from these sources or values are determined that have unacceptably high uncertainty.

The current method of production for these sources is to create the foils and then send them to a different location for incorporation into the source. Upon investigating possible reasons for these "low-output" $^{204}Tl$ sources, we found that sometimes the foils may go unused for long periods of time relative to the half-life of $^{204}Tl$ (3.78 years) before they are incorporated into sources and sold. Therefore, these sources have activities that are far less than the nominal value stated by the vendor and are extremely difficult, if not impossible, to calibrate.

We suggest that some work be done to characterize the sources for absorbed dose rate as a function of source activity. In addition, the end user should require the vendors to supply assay data so there is some idea what the activity of a source is when it is received. Therefore, the end user would have some idea of what the dose rate from a source should be when it is received. If this value is too close to the measurement threshold for the laboratory responsible for performing the calibration of that source, then the metrologist would know that the source was unmeasurable and could not be calibrated. At present, there is no assay data being supplied by the primary vendor for reference beta sources.

In order to have some idea of what the capability of a beta measurement system is, we recommend that anyone performing beta dose-rate measurements determine what we call the measurement threshold for their system. The measurement threshold may be thought of as the lowest absorbed dose rate from a particular source nuclide that may be measured with good statistical confidence. We are in the process of developing the means by which to rigorously determine the measurement threshold for a system based on dark current measurements as a function of plate spacing while maintaining constant voltage gradient. We would welcome any input for other ways of determining this quantity.

One additional problem we have encountered did not have to do with comparing values measured for the absorbed dose rate from a particular beta source, but with comparing response of personnel dosimetry to two different sources of the same isotope. We found that dosimeters irradiated with the Atlan-Tech $^{204}Tl$ source, an Amersham-Buchler source calibrated by NIST, to a known total absorbed dose would give a response approximately 30% higher than the same dosimeters irradiated with another model of $^{204}Tl$ source, also calibrated by NIST. Both sources met the ISO 6980 criteria for $R_{res}/E_{res}$. The difference was that the dosimetry irradiations performed with the Atlan-Tech source were being performed at 30 cm while the irradiations with the other source were being performed at 57 cm. This was the distance used when the source was calibrated by NIST. This 27-cm difference in distance scattered down the electron energy spectrum from the other source to such an extent that the response of TLDs irradiated with this source was some 30% less than those irradiated at the recommended distance of 30 cm. Thus, it would appear that meeting the $R_{res}/E_{res}$ requirements of the ISO 6980 standard does not guarantee equality among different sources. In order to keep the beta spectra as equal as possible, irradiation distances and source construction criteria should also be standardized. It may be necessary in the future to publish standard spectra and transmission data for Series 1 reference beta standards so that spectral purity can be confirmed by a laboratory by acquiring spectra for its Series 1 sources and comparing these to the standards. Criteria may also be set requiring secondary laboratories to meet the transmission fit data of the reference laboratory to within some agreed upon value, or acceptance criteria for spectral composition (energy fluence) would have to be established.

**SUMMARY**

In order to promote intercomparison between laboratories performing beta dose-rate measurement for ISO 6980 Series 1 reference sources, a standardized method of measurement and reporting needs to be adopted. Standardized values of physical constants and ionization current correction factors need to be decided upon and adhered to, and the measurement methodology employed should be that of NBS SP 250-21. Physical parameters of the reference instrument, such as entrance window thickness and micrometer accuracy, should also be confirmed.

In addition, there is the need for a standard reporting convention with respect to the media and dose depth for which beta absorbed dose rates are reported for intercomparison.

Further, there is the need for publication of nominal absorbed dose rate as a function of source activity for Series 1 reference beta sources and for the vendors of these sources to provide assay data with each one. Also, each facility should determine a measurement threshold for their beta measurement system so that decisions can be made as to what kind of calibration uncertainty can be expected as a function of source activity.

Finally, the requirements of ISO 6980 for Series 1 reference sources may need to be expanded in order to further guarantee comparability among laboratories employing these sources in their work.

We would like to propose an open discussion of problems encountered in beta dosimetry. To facilitate this, we are presenting the data in Table 1. Table 1 is a comparison of data from NIST calibrations of Atlan-Tech sources and the sources quoted in SP 250-21, an Atlan-Tech calibration of U.S. Air Force sources, and the PTB calibration of Oak Ridge National Laboratory sources. The important thing to note is that these numbers are significantly different, especially for $^{204}$Tl and $^{147}$Pm. While some of the differences may be linked to foil age due to long shelf times, it cannot be completely dismissed in this fashion. We encourage others to come forth with their ideas and to advocate our comparisons to eliminate some of these problems. Note that if a activity to dose-rate conversion were available and if the vendor had supplied proper assay dates, then it would make the mystery of these differences much easier to find.

## REFERENCES


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## *Table 1 - Comparison of Beta Dose Rates*

**Comparison data for several beta source sets**

| | mg/cm2 | Sr-90 | Tl-204 | Pm-147 |
|---|---|---|---|---|
| Conversion factors for 0 mg/cm2 to 7 mg/cm2 | 7.0 | 1.0345 | 0.9697 | 0.2206 |
| Conversion factors for 7 mg/cm2 to 0 mg/cm2 | 0.0 | 0.9666 | 1.0312 | 4.5333 |
| S-water/S-air | N/A | 1.124 | 1.132 | 1.136 |
| S-air/S-water | N/A | 0.890 | 0.883 | 0.880 |
| S-tissue/S-air | N/A | 1.139 | 1.160 | 1.170 |
| S-air/S-tissue | N/A | 0.878 | 0.862 | 0.855 |

NIST data for AT sources in water @ 7 mg/cm2 — *<<<< Reference data*

| | Date | Dist. (cm) | mCi | MBq | Gy/s | uGy/s | Rad/h | mrem/h |
|---|---|---|---|---|---|---|---|---|
| Sr-90 | 3-Aug-87 | 30 | 50.0 | 185 | 8.71E-05 | 87.100 | 31.356 | 31356.00 |
| Sr-90 | 17-Aug-87 | 30 | 2.0 | 74 | 2.11E-06 | 2.110 | 0.760 | 759.60 |
| Tl-204 | 3-Aug-87 | 30 | 0.5 | 18.5 | 1.82E-07 | 0.182 | 0.066 | 65.52 |
| Pm-147 | 18-Aug-87 | 20 | 14.0 | 518 | 2.53E-08 | 0.025 | 0.009 | 9.11 |

NIST data for AT sources in water @ 0 mg/cm2

| | Date | Dist. (cm) | mCi | MBq | Gy/s | uGy/s | Rad/h | mrem/h |
|---|---|---|---|---|---|---|---|---|
| Sr-90 | 3-Aug-87 | 30 | 50.0 | 185 | 8.42E-05 | 84.193 | 30.310 | 30309.65 |
| Sr-90 | 17-Aug-87 | 30 | 2.0 | 74 | 2.04E-06 | 2.040 | 0.734 | 734.25 |
| Tl-204 | 3-Aug-87 | 30 | 0.5 | 18.5 | 1.88E-07 | 0.188 | 0.068 | 67.57 |
| Pm-147 | 18-Aug-87 | 20 | 14.0 | 518 | 1.15E-07 | 0.115 | 0.041 | 41.29 |

NIST data for AT sources in air @ 0 mg/cm2

| | Date | Dist. (cm) | mCi | MBq | Gy/s | uGy/s | Rad/h | mrem/h |
|---|---|---|---|---|---|---|---|---|
| Sr-90 | 3-Aug-87 | 30 | 50.0 | 185 | 7.49E-05 | 74.905 | 26.966 | 26965.88 |
| Sr-90 | 17-Aug-87 | 30 | 2.0 | 74 | 1.81E-06 | 1.815 | 0.653 | 653.25 |
| Tl-204 | 3-Aug-87 | 30 | 0.5 | 18.5 | 1.66E-07 | 0.166 | 0.060 | 59.69 |
| Pm-147 | 18-Aug-87 | 20 | 14.0 | 518 | 1.01E-07 | 0.101 | 0.036 | 36.35 |

NIST SP-250-21 data in water @ 7 mg/cm2 — *<<<< Reference data*

| | Date | Dist. (cm) | mCi | MBq | Gy/s | uGy/s | Rad/h | mrem/h |
|---|---|---|---|---|---|---|---|---|
| Sr-90 | 1-Jan-83 | 30 | 50.0 | 185 | - | - | - | - |
| Sr-90 | 1-Jan-83 | 30 | 2.0 | 74 | 2.01E-06 | 2.010 | 0.724 | 723.60 |
| Tl-204 | 1-Jan-83 | 30 | 0.5 | 18.5 | 3.30E-07 | 0.330 | 0.119 | 118.80 |
| Pm-147 | 1-Jan-83 | 20 | 14.0 | 518 | 6.00E-08 | 0.060 | 0.022 | 21.60 |

NIST SP-250-21 data in water @ 0 mg/cm2 — *<<<< Reference data*

| | Date | Dist. (cm) | mCi | MBq | Gy/s | uGy/s | Rad/h | mrem/h |
|---|---|---|---|---|---|---|---|---|
| Sr-90 | 1-Jan-83 | 30 | 50.0 | 185 | 7.06E-05 | 70.600 | 25.416 | 25416.00 |
| Sr-90 | 1-Jan-83 | 30 | 2.0 | 74 | 1.93E-06 | 1.930 | 0.695 | 694.80 |
| Tl-204 | 1-Jan-83 | 30 | 0.5 | 18.5 | 3.41E-07 | 0.341 | 0.123 | 122.76 |
| Pm-147 | 1-Jan-83 | 20 | 14.0 | 518 | 2.67E-07 | 0.267 | 0.096 | 96.12 |

NIST SP-250-21 data in air @ 0 mg/cm2

| | Date | Dist. (cm) | mCi | MBq | Gy/s | uGy/s | Rad/h | mrem/h |
|---|---|---|---|---|---|---|---|---|
| Sr-90 | 1-Jan-83 | 30 | 50.0 | 185 | 6.28E-05 | 62.811 | 22.612 | 22612.10 |
| Sr-90 | 1-Jan-83 | 30 | 2.0 | 74 | 1.72E-06 | 1.717 | 0.618 | 618.15 |
| Tl-204 | 1-Jan-83 | 30 | 0.5 | 18.5 | 3.01E-07 | 0.301 | 0.108 | 108.45 |
| Pm-147 | 1-Jan-83 | 20 | 14.0 | 518 | 2.35E-07 | 0.235 | 0.085 | 84.61 |

PTB data for ORNL in air @ 0 mg/cm2 — *<<<< Reference data*

| | Date | Dist. (cm) | mCi | MBq | Gy/s | uGy/s | Rad/h | mrem/h |
|---|---|---|---|---|---|---|---|---|
| Sr-90 | 14-Nov-85 | 30 | 50.0 | 185 | 6.17E-05 | 61.670 | 22.201 | 22201.20 |
| Sr-90 | 30-Sep-85 | 30 | 2.0 | 74 | 1.80E-06 | 1.795 | 0.646 | 646.20 |
| Tl-204 | 1-Oct-85 | 30 | 0.5 | 18.5 | 2.42E-07 | 0.242 | 0.087 | 87.12 |
| Pm-147 | 30-Sep-85 | 20 | 14.0 | 518 | 3.89E-07 | 0.389 | 0.140 | 140.04 |

USAF data in air @ 0 mg/cm2 — *<<<< Reference data*

| | Date | Dist. (cm) | mCi | MBq | Gy/s | uGy/s | Rad/h | mrem/h |
|---|---|---|---|---|---|---|---|---|
| Sr-90 | 8-Aug-90 | 30 | 50.0 | 185 | 7.06E-05 | 70.640 | 25.430 | 25430.40 |
| Sr-90 | 8-Aug-90 | 30 | 2.0 | 74 | 1.87E-06 | 1.865 | 0.671 | 671.40 |
| Tl-204 | 8-Aug-90 | 30 | 0.5 | 18.5 | 4.39E-07 | 0.439 | 0.158 | 158.04 |
| Pm-147 | 8-Aug-90 | 20 | 14.0 | 518 | 6.11E-07 | 0.611 | 0.220 | 219.96 |