

NEUTRON PERSONNEL DOSIMETRY

Neutron Personnel Dosimetry

(44060C and 44100S)

Purpose

This document describes the setup, measurement, and reporting procedures for calibrating neutron personnel protection devices, both active (e.g., remmeter) and passive (e.g., albedo dosimeters). Most calibrations of instruments and dosimeters are performed under Service ID 44060C, while Service ID 44100S is used for non-standard calibrations and special tests.

Scope

This procedure covers the calibration of instruments in neutron fields having intensities and energy spectra similar to those found in nominally occupied areas. The fields are produced by ^{252}Cf sources, either lightly encapsulated (i.e., free in air) or in the center of a 15 cm radius heavy water sphere with a cadmium shell. Fields from AmBe sources (made with ^{241}Am and ^9Be) can be used for special tests. Results are reported in either dose equivalent (i.e., rem or sievert) for passive instruments or dose equivalent rate (rem/hour or sievert/hour) for active instruments. Some instruments report in neutron counts, and the results for those instruments are reported in counts per unit time per dose equivalent rate.

Definitions

Many terms are defined in the text, but some definitions can also be found below:

- ALARA – (As Low As Reasonably Achievable) the guiding principle in radiation safety to minimize radiation exposure
- Albedo dosimeter – measures indirect neutrons scattered by the human body
- ANAB – (ANSI National Accreditation Board) performs independent audits to assure competence and reliability of a laboratory
- AmBe – the alpha emitted by ^{241}Am interacts with ^9Be in the source to create a high-energy neutron
- CCRI(III) – (Consultative Committee of Ionizing Radiation) coordinates international measurement standards, Section III is specifically for neutron-related measurements
- D_2O sphere – the 30 cm diameter stainless steel sphere that is filled with heavy water to moderate neutrons emanating from the ^{252}Cf source deployed within
- Fission chamber – a gas-filled radiation detector with a fissionable material that

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ionizes the gas when hit by a neutron

- Heavy water – a form of water where the hydrogen atoms are replaced by deuterium, a hydrogen isotope containing an extra neutron
- ISO water slab – the international standard for representing the human body, used for calibrating albedo dosimeters
- NBS – (National Bureau of Standards) is the original name of NIST
- NBS-1 – the national primary standard neutron source that serves as a reference for all sources calibrated by NIST
- NIST – (National Institute of Standards and Technology)
- NMI – (National Metrology Institute) is a unique organization authorized by a country that is responsible for establishing, maintaining, and developing measurement standards
- PMMA – (Polymethyl Methacrylate) is a type of acrylic that mimics the radiation absorption and scattering properties of the human torso
- Rem – (Roentgen Equivalent Man) is a legacy unit for measuring the biological effect of ionizing radiation on the human body, replaced by the sievert
- Remmeter – a radiation detection device used to measure absorbed dose rates, typically in rem units
- Ring stand – a custom aluminum ring used to support a 9 in diameter remmeter at the correct height above the moving platform
- Rolling staircase – a movable set of stairs that is more stable for working at heights than a ladder
- Service ID (SKU) 44060C – the SKU for typical instrument calibrations using a bare or moderated ^{252}Cf standardized field
- Service ID (SKU) 44100S – the SKU for any special tests, including instrument calibrations with AmBe
- SKU – (Stock Keeping Unit) is a unique identifier for a particular product or service in the NIST Store
- Sievert – the SI unit used to measure the biological effect of ionizing radiation on the human body, defined as J/kg
- Source holder – a custom aluminum ring with a central tube that holds the bare sources in a reproducible position

Safety

ALARA procedures are observed with guidance from the NIST Gaithersburg Radiation Safety Division under safety evaluation SE-0007. “Distance” and “Shielding” (e.g., being out of the room when the source is raised) are required by SE-0007 except for unusual and limited circumstances. For those circumstances, “Time” (e.g., staying in the vicinity of the source for as little time as possible) is used to limit dose.

Standard laboratory safety procedures are carefully observed. These include using the rolling staircase instead of a traditional ladder for lifting heavy detectors up to the rolling platform, and minimizing contact with cadmium by wearing a lab coat, gloves, and a face mask.

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Equipment

The equipment used for these calibrations is categorized into five broad groups: positioning equipment, neutron sources, neutron-field-moderating equipment, fissionable deposits (in fission chambers), and data-acquisition equipment. To ensure reliable results, all equipment changes are validated by verifying the consistency of measurements before and after the change.

Positioning Equipment

A **rolling cart** on fixed tracks, driven by a stepping motor, is used to modify the distance between the source and the detector. This cart is constructed of small quantities of materials having relatively low neutron scattering cross sections (e.g., aluminum and steel). It is a height such that various types of neutron instruments can be positioned above it without mechanical modification of the cart itself.

Changes in the position of the rolling cart are measured using a **tape measure** permanently attached to the floor of the calibration room (hereby referred to as the “scale”). A steel indicator connected to the bottom of the rolling cart indicates the cart's position to approximately 1 mm. The indicator is read out using a video camera attached to the cart and aimed at the indicator. This information, in combination with the procedure for positioning the instrument on the cart as described in “Positioning of Detector/Phantom” below, allows the absolute distance between the detector and the mechanical location of the source to be set with approximately 1 mm resolution.

The sources are raised and lowered using a **fishing reel and Kevlar® thread**. This allows the person raising and lowering sources to minimize radiation exposure. Mechanical positioning of bare sources is achieved using an aluminum **source holder**, pictured below in Figure 1. A source attached to the Kevlar thread will snugly seat at the bottom of the central aluminum cylinder. The source holder is attached (indirectly) to the steel I-beams holding up the aluminum floor above the calibration range.

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Figure 1: Source positioning apparatus

The height of the most common size remmeter (a 9-inch diameter sphere) above the rolling cart platform is set using a **ring stand** designed and constructed for this purpose. A grooved circular ring, pictured below as both a mechanical drawing and a photograph (Figure 2), holds three 19.05 mm (0.75") diameter ball bearings. The center of a 9-inch diameter remmeter above the bottom of the grooved ring with the ball bearings in position is calculated to be 11.41 cm. Aluminum legs are attached to the ring to position the remmeter above the rolling table platform. The heights of the bare and D₂O-moderated sources above the rolling table platform have been measured to be 31.9 cm and 30.3 cm, respectively.

All distances that impact the calibration are NIST-traceable through GEI International Stainless Steel Ruler Model 2020A, Serial Number C27424 (or equivalent). The markings on this ruler were verified on 2/4/2022 to be correct within 0.0356 mm (0.0014 inches) by an ANAB-accredited laboratory (the cumulative deviation between 5 mm and 915 mm was 0.259 mm). To establish traceability, all other rulers used in these service IDs have been compared against this ruler.

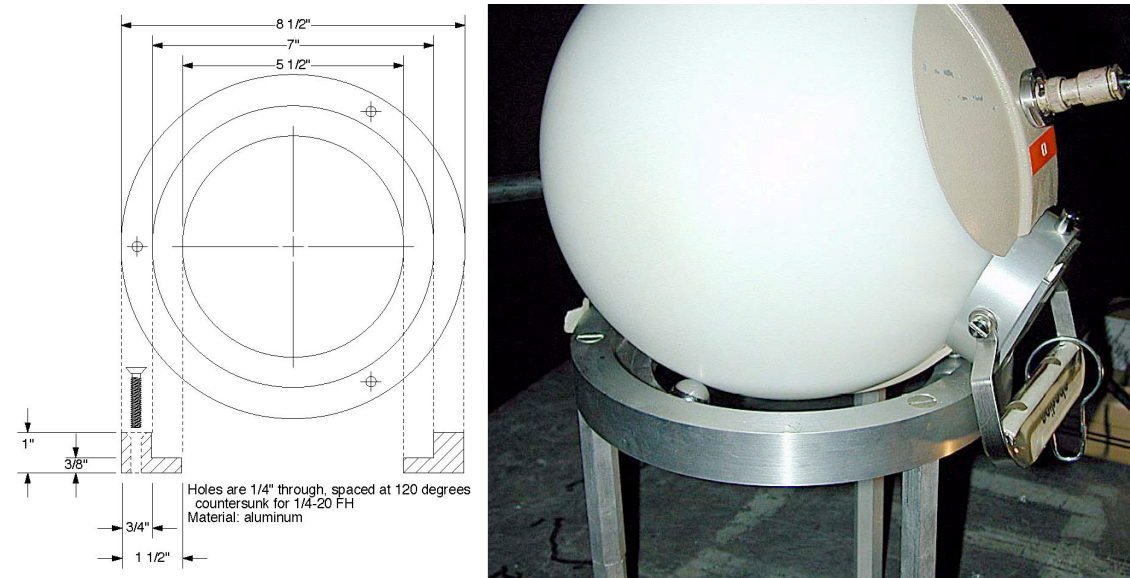
The alignment of the instrument on the rolling cart with respect to the source location is set using a Bosch GLL 3-80 self-leveling laser alignment system. The accuracy of all three planes of the Bosch laser is to be checked annually by following the procedure described in its manual. The uncertainty is to be measured using a NIST-traceable ruler.

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Figure 2a: Mechanical design of the ring stand used to hold 9-inch diameter remmeters. The drawing is as it was submitted to the machine shop and thus has non-SI units.

Figure 2b: Picture of the ring stand used to hold 9-inch diameter remmeters. Note that the readout cable is directed perpendicularly from the source so that neutrons do not stream directly into the detector but are first moderated in polyethylene.



Environmental Effects on Positioning Equipment

Positioning equipment is, in principle, subject to change in size as a function of temperature. Because we measure using a steel measuring tape and an aluminum meter stick, changes in their size could cause us to position the instruments incorrectly. Steel has a thermal expansion coefficient of approximately $15 \times 10^{-6} \text{ K}^{-1}$, while aluminum alloys have a thermal expansion coefficient of $23 \times 10^{-6} \text{ K}^{-1}$. The largest distances used in these calibrations are around 2.5 m, which would require a temperature change of 18 K to equal our current positioning uncertainty for aluminum (an even larger temperature change would be needed to degrade our measurement for steel). The temperature of the calibration range is generally constant within $\pm 5 \text{ K}$, so this is not a significant source of uncertainty.

Neutron Sources

Lightly encapsulated ^{252}Cf neutron sources are essential for calibrations. Characteristics of the sources used in calibrations are in Table 2 in the Procedures section. All sources are swabbed biannually to check for leaks of radioactive material.

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Neutron Field Moderating Equipment

The **D₂O Sphere** is described in Reference 2.

The **PMMA phantom** is specified in ANSI N13.11.

The **ISO water slab phantom** is specified in ISO 29661:2012 and referenced from ISO 8529-3:2023, section 6.3.

Fissionable Deposits

Fissionable deposits (usually ²³⁵U but sometimes ²³⁹Pu or other fissionable isotopes) in NBS/NIST custom fission chambers can be used (almost always under Service ID 44100S) to characterize neutron fields. The deposits used and how to use them, including traceability to NIST, are described in detail in Reference 7. Other fissionable deposits have been calibrated by ratio measurement against one or more deposits described in Reference 7.

Data Acquisition Equipment

Because of the wide variety of instruments we receive, and the need to use their associated electronics as part of the testing procedure, our data acquisition system relies on the use of **video cameras** to read out the instruments. One video camera points at the steel indicator showing the location of the rolling cart, while another points at the readout display of the instrument. Additional cameras show when the source is in position and when it has been safely returned to storage.

Still images of the instrument readout and cart position indicator are acquired from digital video cameras and saved to the internal storage of a **data acquisition computer**. Software on the computer saves the video images at specified time intervals for analysis later. The time at which the image was taken is encoded in the image file name. The accuracy of the hardware/software combination has been tested by recording a calibrated digital stopwatch using the software and verifying that the reported delays from the file name and the time from the watch image were the same within the accuracy of both (1 second over a 20-minute measurement).

Software

Although these calibrations could be performed with only a stopwatch, a video camera, and a lab notebook, the data is acquired, time-stamped, stored, and analyzed using NIST-developed software. This software is stored in a source code versioning system at <https://gitlab.nist.gov/gitlab/dmj2/commonfiles> and is backed up regularly to both an external storage device and the NIST central file servers. Use of the software, including selections from the source code, is described in “Appendix A: Source Flux Calculation & Data Analysis Software,” “Appendix B: Dosimetry Video Data Acquisition Software,” and

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“Appendix C: Video Analysis Software.”

Comments in the source code versioning system will indicate validation of new versions of the software. While the binary parts of the experiments are constantly changing as calculations are made and data entered, the source code itself should be stable. Only validated versions of the code will be used for calibrations.

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Procedures

Device Acceptance Criteria

Upon receipt of customer artifacts (active or passive detectors), shipping containers are inspected for damage. If there is significant damage to the shipping container, the client is contacted as quickly as practicable and guidance is requested. Otherwise, the shipping container is opened and the devices are inspected.

For dosimeters, which are designed to withstand large amounts of physical abuse, the only requirements are that the active elements have not become detached from the protective cover and that the protective cover has not come apart in any way.

For active instruments, all cable connections are tested for mechanical stability and displays are checked for cracks, bent dials, etc. Then the instrument is turned on, in “battery/ display check” mode if available. If the instrument passes this test, it is turned on in the most sensitive setting available. Because the neutron background in the calibration range is very low, a reading above 1 $\mu\text{Sv/h}$ (0.1 mrem/h) is a cause for concern (i.e., it may indicate a malfunctioning instrument) and is discussed with the customer before proceeding with the calibration.

Finally, to save time on alignment and setup for instruments that are not functional on arrival, the instrument may be exposed to a neutron field to verify that it responds. If there is no response to the neutron field, the customer is contacted for instructions on how to proceed (typically, the instrument is returned to the customer for repair).

Determination of Room Return

All calibrations covered in this Procedure are conducted in the sub-basement level of room B-023 in building 245 on the main NIST campus at 100 Bureau Drive in Gaithersburg, Maryland, USA, and the room return characteristics are specific to that facility. Room return is determined and applied as described in *ISO 8529-2:2000*, section 6.3.3, with the addition of a “quartic” term (Q in the formula below) for some source-detector combinations. Equation (19) from that reference, with the inclusion of the quartic term, reads:

$$\frac{M_T(l)}{\Phi F_l(l)(1 + Al)} = R_\Phi(1 + Sl^2 + Ql^4)$$

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where M_T is the value indicated by the instrument, l is the distance from the center of the source to the center of the instrument, Φ is the neutron fluence, F_l is the geometry factor, A is the net air-scatter effect, R_Φ is the fluence response of the instrument, S is the fractional room-scatter contribution, and Q is the additional quartic term. The values of A , S , and Q currently in use are shown in Table 1. Instruments that do not appear in Table 1 can be characterized by fitting uncorrected data to the above functional form; this characterization is usually done within Service ID 44100S. There are instruments that are similar to a 9-inch diameter remmeter but have a slightly different diameter ± 3 cm. The corrections for the 9-inch diameter remmeter are used for these instruments.

Table 1: Room Return and Air Scatter Corrections

Source	Bare		Moderated		
Parameter	A [m^{-1}]	S [m^{-2}]	A [m^{-1}]	S [m^{-2}]	Q [m^{-4}]
3" sphere	1.2 %	33 %	4.5 %	13 %	
Albedo Dosimeter	1.2 %	20 %	3.7 %	5.4 %	
9" Spherical Remmeter	1.2 %	5.3 %	2.6 %	7.35 %	− 0.28 %
Andersson-Braun Remmeter	1.2 %	2.9 %	2.6 %	9.53 %	− 0.51 %
REM500	1.2 %	4 %	1.4 %	4.5 %	
SWENDI	1.2 %	5.3 %	2.6 %	4.4 %	
PRESCILA	1.2 %	9.8 %	1.4 %	14.3 %	−0.73 %

Changes in the arrangement of materials, especially hydrogenous materials, in the calibration range can, in principle, change the room return corrections, though the amount of material moved or introduced would have to be large. The person performing the calibration ensures that no sizeable shift of material has occurred in the room before starting a calibration. Moving any large pieces of material to the edge of the room away from the detector should reduce any effects on room return because scattering from the walls of the room dwarfs any scattering from a movable piece of material. If significant changes to the arrangement of material in and comprising the calibration range should occur, calibrations shall cease until room return corrections can be verified.

Fluence Rate Calculation

The source emission rate is calculated with the algorithms used in Reference 3. Parameters for sources currently in use are shown in Table 2. Source calibrations were done by NIST and are traceable to the NIST reference RaBe neutron source, NBS-1. Sources are periodically recalibrated as resources allow.

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Table 2: Parameters Used for Source Fluence Calculation

Source Name	Source Calibration Date	Calibrated Neutron Emission Rate (s ⁻¹)	Isotopic Calibration Date	Isotopic Percent ²⁵⁰ Cf	Isotopic Percent ²⁵² Cf	Isotopic Percent ²⁵⁴ Cf
NS-118	2/1/94	4.79×10 ⁸	2/14/85	8.16	86.26	0.021
NS-100	9/3/13	1.91×10 ⁶	7/2/75	8.05	87.7	0.028
NS-39	8/17/94	6.08×10 ⁶	12/20/70	10.83	84.82	0.028
Cf-144	2/20/83	1.27×10 ⁷	7/27/70	9.76	84.34	0.017
NS-130	1/10/90	4.42×10 ⁹	2/23/87	8.33	85.08	0.014
NS-108	10/30/86	1.12×10 ⁹	9/26/77	7.736	87.726	0.039
NBS-131	1/10/94	6.87×10 ⁹	9/2/92	9.22	81.99	0.018
NBS-132	7/31/23	1.17×10 ⁷	8/29/96	9.36	80.98	0.01
NBS-133	4/17/24	1.09×10 ¹⁰	6/22/23	14.11	73.74	0
NBS-134	5/23/25	2.07×10 ⁸	6/22/23	14.11	73.74	0

Source fluence rate in cm⁻²s⁻¹ is converted to dose equivalent rate using the conversion factors in Table 1 of Reference 1; these factors are approximately 16 % higher than factors used before June 19, 2009, as documented in the sample report at the end of this procedure.

Because many of the sources have aged beyond the point anticipated by the authors of Reference 3, an additional correction is needed: neutron emission from ²⁴⁸Cm. To calculate this quantity, the initial mass of ²⁵²Cf in the source is determined from information provided by the manufacturer (see Table 3). “Purification Date” is the date when Cf was separated from all other radionuclides, and “Emission Assay Date” is when the mass of ²⁵²Cf in the source on that date was determined. From the initial ²⁵²Cf mass, the current mass of ²⁴⁸Cm is calculated from the decay of the initial quantity using the alpha decay branching ratio of 0.969 (Reference 3). The current mass of ²⁴⁸Cm is multiplied by its spontaneous fission neutron yield of 4.04×10⁴ s⁻¹ mg⁻¹ to calculate the ²⁴⁸Cm contribution to the source emission rate.

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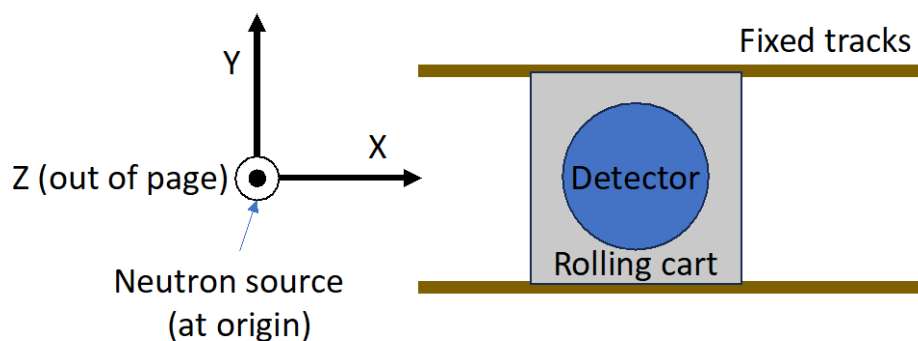
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Table 3: Parameters Used for ^{248}Cm Contribution to Source Emission Rate

Source Name	Purification Date	Emission Assay Date	^{252}Cf Mass on Emission Assay Date (mg)
NS-118	12/13/83	10/22/84	2.317
NS-100	10/25/77	2/13/79	2.646
NS-39	12/17/70	11/7/71	0.929
Cf-144	10/28/70	10/28/70	0.1311
NS-130	1/13/88	4/25/88	3.05
NS-108	10/21/80	3/13/81	2.062
NBS-131	9/2/92	4/7/93	3.641
NBS-132	6/6/96	6/6/96	3.33
NBS-133	9/14/23	12/29/23	5.113
NBS-134	9/13/24	10/29/24	5.02

Positioning of Detector/Phantom

The coordinate system for positioning of the detector/phantom with respect to the source is shown in Figure 3.

Figure 3: Coordinate system used for calibration positioning.

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The vertical distance from the rolling cart platform to the center of the source (Δz) has been measured as discussed in the paragraph discussing the ring stand. The PMMA phantom has a specific platform on which it rests to make its center be at the same height as the moderated source (Δz). 9-inch diameter remmeters have the ring stand to set their position. Other detectors or phantoms are vertically positioned using a lab jack and a NIST-traceable ruler. There are other specialized positioning systems (made from materials with negligible impact on the neutron field) that are used for instruments that are not less common. For these systems, instrument height is always verified with a NIST-traceable ruler.

Once positioned vertically, the transverse alignment of phantoms or detectors with the source (Δy) is done using a laser alignment system. Permanent marks on the walls perpendicular to the tracks along which the rolling cart moves are used to establish an xz-plane parallel to the direction of motion. The laser is then moved so that the plane of laser light passes through the center of the source ($y=0$), whether bare or D_2O -moderated, while remaining parallel to the rolling cart tracks. The detector is then moved perpendicular to the direction of motion (i.e., the y-direction) such that it is bisected by the plane of laser light ($\Delta y=0$). This alignment is done before the distance of the detector from the source (Δx) is set.

The distance of the detector or phantom from the source (Δx) is then iteratively set by moving the rolling cart to approximately the correct position and then measuring the distance between the source position and the surface of the detector. For bare sources, the distance measured is from the bottom center of the central vertical aluminum tube to the detector. For moderated sources, the instrument is moved to be *almost* in contact with the moderating sphere, such that a piece of paper can be moved with a small amount of resistance between the detector and sphere, but the paper will not support its own weight. For calculating the distance from the source center to the detector center, the moderating sphere is assumed to have a radius of 15.26 cm (e.g., a detector with radius 10 cm in near contact with the moderating sphere would have a distance from the source center to the detector center of 25.26 cm) as described in Reference 2.

Establishing Traceability of Stopwatch

The stopwatch used in irradiation of dosimeters should be traceable to standard time. This procedure is followed several times per year (or whenever the stopwatch is used in a calibration, if traceability has not been established within 120 days preceding use) to ensure that traceability has been established.

Approximately 10 seconds before a “memorable time” (e.g., 3:00:00 PM), a network-connected computer’s clock is synchronized using the Network Time Protocol to a NIST internal Internet Time Server. At the “memorable time”, the stopwatch is started, and the time and identifying information for the stopwatch (e.g., serial number or unique ID from a sticker permanently attached to the stopwatch) are recorded in the laboratory notebook. After at least 20 minutes, and approximately 10 seconds before another “memorable time” (e.g., 3:20:00 PM), the computer clock is again synchronized. When the computer clock reaches the “memorable time” the stopwatch is stopped. The elapsed time on the stopwatch and on the NIST Internet Time Server must agree to within one second

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per 20 minutes elapsed, or the stopwatch must be replaced with a traceable stopwatch before starting the calibration.

Experimental Procedure – Dosimeters and Other Passive Devices

For dosimeters, the phantom is positioned as described above in “Positioning of Detector/Phantom.” Strips of weather stripping (~2 mm thick foam, sticky on both sides) are attached to the phantom, and the dosimeters are pressed against the weather stripping so that they will stay in position (being careful not to move the cart or phantom in the process). On occasion, the dosimeters are taped from the front as well, using thin packing tape.

If more than one dosimeter is to be irradiated, the dosimeters are arranged in a circle centered on the phantom’s face, with all dosimeters oriented the same with respect to the center of the circle (e.g., the “top” of the dosimeter is further from the center than the “bottom”). SP 250–12 (Reference 4, page 8) states that the distance from the source to the detector is calculated from the radius of the dosimeter circle; this is no longer done because the position of the active elements within the dosimeter is difficult to determine. Instead, the distance to the center of the circle is used for all dosimeters. The difference in distance is similar in size to the uncertainty of the position of the active elements within the dosimeter if the circle is sufficiently small.

After the dosimeters are positioned and the source is prepared for deployment, the room is scanned to verify that all sources of room return (including personnel) are in appropriate locations before the source is deployed.

As soon as the source visibly clears the top of the storage the stopwatch (Cole-Parmer Model 94410-10 or equivalent) is started. The time that the source reaches the irradiation position is recorded. The source is left in position for the duration of the required time for the requested dose. At that point, the source is lowered quickly and the time at which the source reaches the top of the storage vessel is also recorded.

There are two uncertainties stemming from the inability to instantaneously turn the source on/off: actual irradiation time, and total dose delivered. The uncertainty in the time the source was in position would normally be determined by the accuracy of the stopwatch (<1 s). However, some dose gets delivered during the transition times of raising/lowering the source, so the uncertainty is conservatively set to be the total time the source was being raised and lowered; this is typically a small contribution to the total uncertainty. The total dose reported to the customer is the dose delivered with the source in position plus the estimated dose when the source was in transition. The actual dose rate during transition is changing, so it is estimated to be 50 % of the source-in-position dose rate.

Any dosimeter that falls off the phantom during irradiation is reported as spoiled to the customer. All dosimeters (including unirradiated, irradiated, and control dosimeters) are stored in the same location, which is typically in the office area outside of the low scatter room itself. This location is partly to mitigate any possible effect of heat on dosimeters (the office area temperature is regulated better than the calibration range temperature). Because dosimeters can be sensitive to heat and are sensitive to radiation that could, in principle, be coming from nearby packages, they are shipped to the customer

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overnight with care taken that they will not be in storage at a shipping company's facility over a weekend.

Experimental Procedure – Active Devices

There are two sets of procedures for active devices, depending on whether the device supports “integration” mode or just “ratemeter” mode. If the device can integrate the dose received over a long time period (minutes to hours), higher accuracy can be achieved. Most digital meters can do this.

All devices are set up such that the readout fills as much of the video screen as is practical. Analog meters are set up such that shadows from the indicator needle can be readily distinguished from the indicator itself on saved video images. Only images containing a clean and unambiguous reading of the meter are accepted for analysis; other images are marked in the analysis software as missing data.

After the meter is positioned and the source is prepared for deployment, the room is scanned to verify that all sources of room return (including personnel) are in appropriate locations before the source is deployed.

Special consideration must be taken with devices such as the REM500 that are sensitive to movement. A full minute must be allotted for it to settle after repositioning the moving platform, and the device should be reset remotely after each move.

Ratemeter Mode Devices

Ratemeter mode devices are positioned as described in “Positioning of Detector/Phantom.” A source is raised (or the readout unit is attached to an electronic simulator of detector signals), and the refresh rate of the instrument is observed. Readouts of the video camera are taken, if practicable, at a rate at least three times slower than the refresh rate of the meter (i.e., the delay between images is at least three times longer than the refresh time) to avoid any correlations between readings. Typically, the meter is read out at a rate more than ten times slower than the refresh rate.

At least ten readings (but ideally more) are taken at each dose equivalent rate, so a good estimate of uncertainty can be extracted from the data, even if a few of the images are unreadable due to changes in the readout during the video frame grab.

Integrating Devices

These devices are positioned as described in “Positioning of Detector/Phantom,” the meter is reset, and the source is raised into position as soon as possible (a small amount of time is needed to allow the scientific staff to evacuate the calibration range). The integrated dose is read out through the video camera at a rate such that as many digits change on the display as is practicable. The integrated dose vs. time is fit to a line. The slope of the line is the dose rate and the fit uncertainty is output by the Singular Value Decomposition, Levenberg-Marquardt, or Markov Chain Monte Carlo (MCMC) software

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used to fit the data, as described in Reference 5. The confidence interval is calculated from the fit uncertainty and (except for MCMC fitting) the Student's T distribution. The uncertainty assigned to the dose rate is the confidence interval for the slope of the line at the 95 % confidence level.

Stability Checks

Although these checks are only performed at the request of the customer, the stability of the instrument can be checked by making repeated measurements (either in ratemeter mode or in integration mode) in a fixed neutron field. In ratemeter mode, deviations from a flat line indicate stability issues. In integration mode, any curvature of the line indicates instability. Stability issues at the level of 10 % are common. With some types of instruments, it has been observed that the response will increase asymptotically for a given dose equivalent rate (Reference 9).

Another simple stability check is to move the meter back to a previously measured point and re-measure the calibration factor at that point. This will often reveal the same level of instabilities as the above check.

Procedures for Special Tests under Service ID 44100S

Most calibrations of instruments and dosimeters are performed under Service ID 44060C, but customers frequently have needs for non-standard calibrations. These special tests can be grouped into three broad categories: (1) calibration/irradiation of an artifact for which the room-return characteristics have not previously been measured, (2) calibration/irradiation of an artifact using an unusual field (such as the neutron field produced by an AmBe source), and (3) measuring characteristics of an unknown neutron field using fission chambers (with possible calibration/irradiation after the field has been characterized).

The first of these categories has already been discussed and is documented in Reference 4. Measurements of instrument reading are collected as a function of source-detector distance and fit (using Levenberg-Marquardt, Singular Value Decomposition, or MCMC algorithms) to the functional form in the first formula in the section "Determination of Room Return" to extract the terms used to correct for room return. The corrections are applied to the existing data, and a calibration report that is similar to a standard Service ID 44060C calibration report is provided to the customer.

The second category of special tests is when calibrations/irradiations are performed in one of the standard fields described in the ISO 8529 series of standards, but using a field that is less commonly used at NIST. In this case, the guidance from ISO 8529 (including, particularly, any spectrum-averaged fluence to dose equivalent conversion factor) is used to calculate the field characteristics at the point of test, and the response of the instrument in that calculated field is reported. Measurements of room-return response may be needed, depending on whether an instrument identical or similar to the device under test has previously provided a reliable characterization of room-return parameters.

The third category of special tests is when a not-well-known or unknown neutron field must be characterized. This is often a prerequisite for calibration/irradiation of a

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detector, such as when a cold or thermal neutron beam produced at a reactor must be characterized to allow calibration/irradiation of a detector in the characterized field. This process (including uncertainties) is described in detail in Reference 8 and must be specifically documented in each calibration report.

Quality Assurance Practices

For active detectors, quality assurance is achieved through two different activities. First, there is an internal consistency check in the fact that a given instrument is calibrated at multiple distances, often from multiple sources, which provides calibrations at multiple dose equivalent rates (typically one or two sources, with two to four distances for each source). Although an instrument might perform differently at different dose equivalent rates, most instruments submitted perform similarly at all dose equivalent rates, within statistical uncertainty. Significant non-statistical deviations in calibrations would trigger a check of whether, for instance, a source had become compromised or a clock was not functioning properly. Second, the consistency of calibrations for returning instruments is checked against previous calibration reports if there are sufficient staffing resources and an instrument history to do so.

For both active and passive detectors, the validity of calibration results is periodically verified via round-robin intercomparison measurements with other National Metrology Institutes (NMIs), organized by the Consultative Committee for Ionizing Radiation – Neutron Measurements (CCRI Section III).

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Uncertainty Analysis

The basis for the determination of uncertainties associated with the calibration of neutron personnel dosimetry devices is found in Reference 6. Uncertainties specific to the type of device (active or passive) are discussed above (see “Experimental Procedure - Dosimeters and Other Passive Devices” and “Experimental Procedure - Active Devices”). Our uncertainties (and central values) are periodically verified in measurement comparisons with other National Measurement Institutes, as specified in RPD-QM-II, section 7.7.

Source strength uncertainties are derived from source strength calibrations and the time elapsed from the most recent source calibration to the performance of the calibration measurements. These uncertainties are Type B and are consistent for all measurements using a given source.

Room return correction uncertainties are a fixed fraction of the room return correction and are Type B. See Reference 4 for a discussion of the derivation of this uncertainty. See Table 1 in Appendix D for the fraction of the correction taken to be the uncertainty.

Source-detector distance uncertainties are dominated by the uncertainty in the position of the effective center of the instrument (see Reference 4 for details and Table 1 of Appendix D for the value), but they include a small contribution (1 mm) from uncertainty in the readout of distance on the scale and the measurement of source-detector distance during initial positioning. Because the relationship of dose equivalent rate to source-detector distance goes as the inverse square, this uncertainty must be carefully propagated. This uncertainty is Type B.

Uncertainty in the conversion from neutron fluence rate to dose equivalent rate is described in Reference 4. Numerical values for these uncertainties (bare and moderated ^{252}Cf are different) are given in Table 1 of Appendix D.

Instrument stability, as described at the end of section “Experimental Procedure - Active Devices,” can be measured and reported to the client but is not added to the total uncertainty. This is because the way in which the calibrated instrument is used by the client may eliminate this uncertainty (e.g., if it is used as a field instrument, this uncertainty will probably not manifest itself).

A more thorough discussion of uncertainty is given in “Appendix D: Uncertainty Analysis.” The full uncertainty analysis can be gleaned from the source code selections in “Appendix A: Source Flux Calculation & Data Analysis Software.”

Records

Procedures Specific to Dosimeters and Other Passive Devices

For passive instruments, raw data is recorded in a laboratory notebook. Data are recorded and maintained as specified in RPD-G-06 and section 4.3.4.2 of RPD-QM-II. Paper laboratory notebooks containing these data are kept in building 245, room B021; electronic laboratory notebooks (or equivalent) are edited on a local computer and archived on the NIST central file servers and an external backup drive.

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Procedures Specific to Active Devices

Raw data files (images captured from video) are copied from the data acquisition computer to removable storage as quickly as possible after acquisition and from removable storage to the computer of the staff member performing the analysis. These files may be processed before copying (e.g., cropping the images to remove unneeded backgrounds, file format conversion), but not in a way that will visibly degrade the core image.

A file containing the transcribed video data and derived averages and uncertainties in those averages is generated as part of the analysis. This file is stored in the appropriate folder on the computer of the staff member performing the analysis. See “Appendix C: Video Analysis Software” for more information about this intermediate file.

Filing and Retention

Calculations associated with a calibration, as well as electronic copies/scans of reports and any pertinent data (including electronic laboratory notebooks or equivalent and image files), are kept in organized directories on the NIST central file servers. To be specific, this is the “elwood” file server, and the root for Neutron Physics Group data is `smb://elwood.nist.gov/68_PML/682/internal/682_Shared/CalData/682.03`. Within that root directory, there are subdirectories for each calibration service ID or SKU. Within the SKU directories are subdirectories for each fiscal year in which a calibration was started, and within each fiscal year directory are subdirectories for each calibration. Some calibrations have mixed SKUs, so symbolic links or aliases are used to allow the calibration to be found via either SKU. These directories are identified with the year and month of the calibration (starting date) and the name of the institution submitting the detectors. Calculations and analysis data are stored in Igor Packed Experiment (.pxp) files, which can be easily reloaded into Igor. These files are backed up from the analysis computer within a week of when they are changed and are maintained for at least as long as the valid time of the report as specified on the calibration folder (usually three years).

After all required signatures have been obtained, copies of the final calibration report are stored in the calibration directory, uploaded to the eCommerce system, and sent to the customer.

The RPD Quality Manager shall maintain the original and all past versions of this RPD Procedure.

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References

1. International Organization for Standardization, *Reference neutron radiations-part 1: characteristics and methods of production*. ISO 8529-1 (ISO: Geneva) (2001).
2. R.B. Schwartz and C.M. Eisenhauer, *The Design and Construction of a D₂O-Moderated ²⁵²Cf Source for Calibrating Neutron Personnel Dosimeters Used at Nuclear Power Reactors*, NUREG/CR-1204, January, 1980.
3. *NBS Measurement Services: Neutron Source Strength Calibrations at NBS by the Manganese Sulfate Bath Method*, E. D. McGarry and E. W. Boswell, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-18 (Mar. 1988), Appendix C.
4. *NBS Measurement Services: Neutron Personnel Dosimetry*, R. B. Schwartz, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-12 (July 1987).
5. Igor Pro Manual, available from www.wavemetrics.com with purchase of software.
6. NIST Technical Note 1297, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*.
7. ANL/NDM-118, *Characteristics of the Samples in the FNG Fission Deposit Collection*, J.W. Meadows, Argonne National Laboratory, Argonne, Illinois, 60439 (December 1990)
8. J. A. Grundl, D. M. Gilliam, N. D. Dudey, and R. J. Popek. "Measurement of absolute fission rates." *Nuclear Technology* 25, no. 2 (1975): 237-257.
9. A. V. Mozhayev, R. K. Piper. "Understanding the Radiation Soaking Effect in Neutron Survey Instruments." *Health Phys.* 2022 Jul 1, 123(1): 1-10, DOI:10.1097/HP.0000000000001562.

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Appendix A: Source Flux Calculation & Data Analysis Software

Overview

An Igor experiment file is used to calculate fluence rates, plan experiments, and analyze data (after basic averaging has already been done by the Video Analysis experiment described in “Appendix C: Video Analysis Software”). The experiment and associated code are mirrored onto the NIST central file server elwood in the 68_PML/682/internal/682_Shared/CalData/682.03/CommonFiles/SourceFluxCalc directory after each significant update (such as completion of a calibration).

Usage

Planning

Planning an experiment is done by bringing to the front either the “PlanTable” table or the “PlanTableDosimeter” table (depending on whether the calibration is for an active or passive instrument). Conversion and correction factors are set by entering “convAndCorr = convAndCorr9inMod” (or another appropriate conversion and correction wave, depending on the source and detector) on the command line. The values desired for dose equivalent rate or dose are entered into the appropriate columns (note: all columns requiring user input appear in bold) and “DoPlanCalib” or “DoPlanCalibDosimeter” are selected from the Macros menu, as appropriate.

Planning for Active Instruments

The source chosen for a given rate can be modified to keep the source surface-detector surface distance (D_SS) and background correction (CorrPCT) in reasonable ranges. Ideally, D_SS should be more than 5 cm (10 cm for bare sources), but the only requirement is that D_SS be greater than or equal to zero. Corrections, ideally, should be less than 10 %; they must be less than 40 %.

D_SS, coupled with the knowledge of the relationship between the position of the instrument and the scale reading, allows the user to determine scale positions for each requested dose equivalent rate.

Planning for Dosimeters

Because the distance between the source center and phantom surface is set to be 50 cm, only the irradiation time and source can be adjusted. A source is chosen such that the irradiation time is significantly longer than the raising and lowering time of the source,

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ideally by a factor of 100 or more.

Analysis

For both types of instruments, the tables “AnalysisTable” and “AnalysisTableUncert” are brought to the front of the screen.

Active Instrument Analysis

The actual scale distances and instrument reading are entered into the appropriate (boldface) columns. D_SS is calculated on the command line from the positioning measurements. For data taken using the method specified in “Integrating Devices,” the number of measurements taken during each integration is also entered.

Raw uncertainties are entered into the (boldface) “dReadingAbs” column in the “AnalysisTableUncert” table. “dReading” (in percent) is calculated on the command line from dReadingAbs and Reading.

The macro “CrunchCalibNew” is used to analyze the data and produces a summary of results in the history area. This macro takes one argument, which is 1 for data taken with integrating active devices and 0 for ratemeter devices.

Dosimeter Analysis

For dosimeters, the time during which the source is in position (i.e., subtracting the raising and lowering time) is entered into “TimeUp” and the sum of the raising and lowering time should be entered into “dTimeUp”. After running the “CrunchCalibDosimeter” macro, the user should verify that D_CC is 50 cm and D_SS is appropriate for the source (bare or moderated) in use. The wave “RealDose” will contain the total dose received by the dosimeter corrected for room-return and air scatter backgrounds.

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Source Code

Selections from the source code are presented below for information.

Function/D NActivity(Name, month, day, year)

```
String Name;
variable/d month,day,year
variable index;
variable answer; // create so can stuff info into isoNeuts wave.... -- akt 20150930
WAVE CfActNeutrons = root:cfCalibFolder:CfActNeutrons // -- akt 20150930
WAVE isoNeuts = root:cfCalibFolder:isoNeuts // -- akt 20150930

NVAR cfSourceCalibDate = root:cfCalibFolder:cfSourceCalibDate
NVAR cfSourceCalibVal = root:cfCalibFolder:cfSourceCalibVal
NVAR CfAtomCompCalibDate = root:cfCalibFolder:CfAtomCompCalibDate
WAVE CfActivityACC = root:cfCalibFolder:CfActivityACC
WAVE CfAtomCompCalib = root:cfCalibFolder:CfAtomCompCalib
WAVE sourceAtomComps = root:cfCalibFolder:sourceAtomComps
WAVE sourceCalibDates = root:cfCalibFolder:sourceCalibDates
WAVE sourceCalibFluence = root:cfCalibFolder:sourceCalibFluence
WAVE atomCompDates = root:cfCalibFolder:atomCompDates
WAVE CfNus = root:cfCalibFolder:CfNus
WAVE CfHalfLives = root:cfCalibFolder:CfHalfLives
WAVE CfAlphaSFRatios = root:cfCalibFolder:CfAlphaSFRatios
WAVE CfActivitySC = root:cfCalibFolder:CfActivitySC
WAVE/T sourcenames = root:cfCalibFolder:sourcenames
WAVE mgCf252onAssayDate = root:cfCalibFolder:mgCf252onAssayDate;
WAVE mgCf252EmisAssayDates = root:cfCalibFolder:mgCf252EmisAssayDates;
WAVE mgCf252FinalPurifDates = root:cfCalibFolder:mgCf252FinalPurifDates;
WAVE cm248emissionEstimate = root:cfCalibFolder:cm248emissionEstimate;

// find which source this is in the list -- index then will find all other information about the source
index = FindStringInWave(sourcenames,Name)
if( index < 0)
    return(NaN)
endif

CfAtomCompCalib[] = sourceAtomComps[index][p];
Renorm(CfAtomCompCalib); // make the isotopic composition add up to 100%

cfSourceCalibDate = sourceCalibDates[index];
// the "2^((mgCf252EmisAssayDates-mgCf252FinalPurifDates)/CfHalfLives[1])" term is to correct the Cf back to the purification date
// from the (estimated) Cf on the Assay date (assay date is usually on the source cert)
// the "0.969*(1-2^(-(cfSourceCalibDate-mgCf252FinalPurifDates)/CfHalfLives[1]))" term converts the mgCf252onPurificationDate (the
// result of the first term, and when there was only Cf-252 and no Cm-248) into Cm-248
// the "0.969" is the branching fraction for alpha decay (and hence from Cf-252 to Cm-248)
// 4.04e4 is the specific activity of Cm-248 in neutrons per mg
cm248emissionEstimate = 4.04e4*mgCf252onAssayDate * 2^((mgCf252EmisAssayDates-mgCf252FinalPurifDates)/CfHalfLives[1]);
// cm248emissionEstimate *= 0.969*(1-2^(-(cfSourceCalibDate-mgCf252FinalPurifDates)/CfHalfLives[1])); -- was 20131202
cm248emissionEstimate *= 0.969*(1-2^(-(date2secs(year,month,day)-mgCf252FinalPurifDates)/CfHalfLives[1]));
cfSourceCalibVal = sourceCalibFluence[index]-cm248emissionEstimate[index];
CfAtomCompCalibDate = atomCompDates[index];

// this is on atomic calibration date
CfActivityACC = (ln(2)*CfNus*CfAtomCompCalib/(CfHalfLives*(CfAlphaSFRatios+1)))

// this is on source strength calibration date
CfActivitySC = CfActivityACC*exp(-ln(2)*(CfSourceCalibDate-CfAtomCompCalibDate)/CfHalfLives)
// added 20100614t110055, not yet compatible with quality manual

answer = Activity(month,day,year)+cm248emissionEstimate[index]
isoNeuts = cfActNeutrons;
isoNeuts[3] = cm248emissionEstimate[index];
return(answer)
End
```

Function/D Activity(month, day, year)

```
variable/d day,month,year
make/n=3/o/d cfAct
NVAR CfSourceCalibDate = root:cfCalibFolder:CfSourceCalibDate
NVAR cfSourceCalibVal = root:cfCalibFolder:cfSourceCalibVal
WAVE CfActivitySC = root:cfCalibFolder:CfActivitySC
WAVE CfActNeutrons = root:cfCalibFolder:CfActNeutrons
WAVE CfHalfLives = root:cfCalibFolder:CfHalfLives
CfAct[] = CfActivitySC[p]*exp(-ln(2)*(date2secs(year,month,day)-CfSourceCalibDate)/CfHalfLives[p]);
```

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```

cfAct = CfActivitySC*exp(-ln(2)*(date2secs(year,month,day)-CfSourceCalibDate)/CfHalfLives)

// print sumwave(cfAct), sumwave(cfactivitySC), cfSourceCalibVal
variable answer = cfSourceCalibVal*SumWave(cfAct)/SumWave(cfActivitySC);
CfActNeutrons = cfAct*answer/sumwave(CfAct);
return( answer );
End

Macro CrunchCalibNew(LinAnalysis )
variable LinAnalysis=0;// was the data taken in integral mode and fit to a line? 0: no, 1: yes-- akt 20030709-1515
variable whichSource=-1;
variable WeightedUncert;
String fldrSav= GetDataFolder(1)
SetDataFolder root:InstrCalibAnalysis:
SourceFluence = NActivity(sourceName, mmonth, mday, myear)
D_CC = D_SS - convAndCorr[1]
FFDE = SourceFluence*convAndCorr[0]/(D_CC)^2
CorrPct = convAndCorr[2]*D_SS/100 + convAndCorr[3]*(D_CC/100)^2 + convAndCorr[4]*((D_CC/100)^4 )
// non-point correction, added 8/13/98
CorrPct += 100*convAndCorr[5]/(4*D_CC^2);
RealDose = FFDE*(1 + CorrPct/100)
CalFac = RealDose/Reading
// multiply everything by two here to adhere to new NIST policy -- AKT 8/20/97
//dQ = 2*1.2
// look up source uncertainties in wave
dQ = 2*root:cfCalibFolder:uncert[FindStringInWave(root:cfCalibFolder:sources, sourceName)]*dReadingAbs/dReadingAbs
dCorr = 2*CorrPct/5
// next line is a hack to get index for sourceName in "sourceType" wave -- akt 20220818
dConv = FindStringInWave(root:cfCalibFolder:sourceNames, sourceName); // *dReadingAbs/dReadingAbs why was this here? it's in
the next line... --akt 20151203
dConv = 2*(dReadingAbs/dReadingAbs)*(1 +
(abs(cmpstr(root:cfCalibFolder:sourcetype[dConv], "bare", 0)*cmpstr(root:cfCalibFolder:sourcetype[dConv], "AmBe", 0)))^3)
// 20220818 updated formula above to include support for AmBe, which has uncertainties similar to bare -- AKT 8/18/2022
// change formula for "dDists" to reflect source of uncertainty better; dR/R is 0.5 cm. -- AKT 12/9/98
// "2" in there is because it goes as r^2 -- akt 20021001 1317
dDists = (2*0.5/D_CC)*100
// dCorr *= ( D_SS < 3 ? 9.0 : 1.0)
dTotalCorrelated = sqrt(dQ^2 + dCorr^2 + dConv^2);
if( LinAnalysis ) // if linear analysis, dReading's are k=2 confidence intervals already, propagate-- akt 20031201-1137
    dTotalUncorrelated = sqrt(dDists^2 + dReading^2); // -- akt 20030709-1515
else // otherwise, dReading's are standard deviations of data and need to be turned into confidence intervals -- akt 20031201-1137
    // line below was only choice before; not sure why dReading is where it is -- akt 20030709-1515
    dTotalUncorrelated = StudentT(erf(2/sqrt(2)), NumMeas)*sqrt(dDists^2 + dReading^2)/sqrt(NumMeas);
endif
dTotal = sqrt(dTotalCorrelated^2 + dTotalUncorrelated^2)
print "SourceFluxCalcProc $LastChangedRevision: 4289 $";
if(LinAnalysis == 0) // data taken in ratemeter mode -- akt 20060522
    print "Did you remember to multiply dReading by 200?"
else
    print "Did you remember to multiply dReading by ONLY 100?"
endif
// CalcMeanCalib(dTotalCorrelated, dTotalUncorrelated, 1) calculates the "average" correlated uncertainty -- akt 20021001 1840
// "4*" removed -- akt 20031201 1123 WeightedUncert = sqrt(4*CalcMeanCalib(CalFac, dTotalUncorrelated, 0)^2 +
CalcMeanCalib(dTotalCorrelated, dTotalUncorrelated, 1)^2);
WeightedUncert = sqrt(CalcMeanCalib(CalFac, dTotalUncorrelated, 0)^2 + CalcMeanCalib(dTotalCorrelated, dTotalUncorrelated,
1)^2);
make/o/n=6/t exportVarNames
make/o/n=6 exportVarMins, exportVarMaxs
variable whichExportVar=0;
print "Weighted Average Calibration Factor is ", CalcMeanCalib(CalFac, dTotalUncorrelated, 1), " ± ", WeightedUncert, " %"
// exportVarNames[whichExportVar] = "AverageCalFac"; exportVarMins[whichExportVar] = CalcMeanCalib(CalFac, dTotalUncorrelated,
1); exportVarMaxs[whichExportVar] = WeightedUncert; was -- akt 20110211
exportVarNames[whichExportVar] = "AverageCalFac"; exportVarMins[whichExportVar] = CalcMeanCalib(CalFac, dTotalUncorrelated,
1); exportVarMaxs[whichExportVar] = WeightedUncert*exportVarMins[whichExportVar]/100.;
whichExportVar += 1;
wvestats/q CalFac
print "Statistical Average Calibration Factor is ", V_avg, " ± ", 200*V_sdev/(V_avg*sqrt(V_npnts)), " %"
wvestats/q CorrPct
print "Corrections range from ", V_min, " to ", V_max
exportVarNames[whichExportVar] = "ScatterCorr"; exportVarMins[whichExportVar] = V_min; exportVarMaxs[whichExportVar] =
V_max;
whichExportVar += 1;
wvestats/q dReading
// was -- akt 20060522 print "Type A uncertainties range from ", 2*V_min, " to ", 2*V_max
print "Type A uncertainties range from ", V_min, " to ", V_max
exportVarNames[whichExportVar] = "UncertTypeA"; exportVarMins[whichExportVar] = 2*V_min/2; exportVarMaxs[whichExportVar] =
2*V_max/2; // don't double double uncer, for fit you have k=2, for ratemeter you already multiplied by 2

```

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```

    whichExportVar += 1;
    wavestats/q dQ
    print "Source uncertainties range from ", V_min, " to ", V_max
    exportVarNames[whichExportVar] = "UncertSourceStrength"; exportVarMins[whichExportVar] = V_min;
exportVarMaxs[whichExportVar] = V_max;
    whichExportVar += 1;
    wavestats/q dCorr
    print "Correction uncertainties range from ", V_min, " to ", V_max
    exportVarNames[whichExportVar] = "UncertScatterCorr"; exportVarMins[whichExportVar] = V_min; exportVarMaxs[whichExportVar]
= V_max;
    whichExportVar += 1;
    wavestats/q dDists
    // print "Distance uncertainties range from ", 2*V_min, " to ", 2*V_max
    // exportVarNames[whichExportVar] = "UncertLocation"; exportVarMins[whichExportVar] = 2*V_min; exportVarMaxs[whichExportVar] =
2*V_max;
    // prior lines incorrect -- 0.5 cm *2 /D_CC is k=2 uncertainty
    print "Distance uncertainties range from ", V_min, " to ", V_max
    exportVarNames[whichExportVar] = "UncertLocation"; exportVarMins[whichExportVar] = V_min; exportVarMaxs[whichExportVar] =
V_max;
    whichExportVar += 1;
    print ""
    dTotalAbs = dTotal*CalFac/100 // added by akt 20220908 because I always do it by hand
    SetDataFolder fldrSav
End

```

Macro CrunchCalibDosimeter()

```

variable whichSource=-1;
String fldrSav= GetDataFolder(1)
SetDataFolder root:InstrCalibAnalysis:

SourceFluence = NActivity(sourceName, mmonth, mday, myear)
//D_CC = D_SS - convAndCorr[1]
//D_CC = 50
print "Not setting D_CC today"
D_SS = D_CC + convAndCorr[1]
FFDE = SourceFluence*convAndCorr[0]/(D_CC)^2
CorrPct = convAndCorr[2]*D_SS/100 + convAndCorr[3]*(D_CC/100)^2 + convAndCorr[4]*((D_CC/100)^4 )
RealDose = FFDE*(1 + CorrPct/100)
Reading = RealDose*(TimeUp + 0.5*dTimeUp)/3600
FFDE *= (TimeUp + 0.5*dTimeUp)/3600
CalFac = RealDose/Reading
// multiply everything by two here to adhere to new NIST policy -- AKT 8/20/97
//dQ = 2*1.2
// look up source uncertainties in wave
dQ = 2*root:cfCalibFolder:uncert[FindStringInWave(root:cfCalibFolder:sources, sourceName)]*Reading/Reading
dCorr = 2*(Reading/Reading)*CorrPct/5
dDists = 2*(Reading/Reading)*(1.0/D_CC)*100
dConv = FindStringInWave(root:cfCalibFolder:sourceNames, sourceName)
dConv = 2*(1 + (abs(cmpstr(root:cfCalibFolder:sourcetype[dConv],"bare")))*3)*(Reading/Reading)
dReading = 2*100*dTimeUp/TimeUp;
dTotalCorrelated = sqrt(dQ^2 + dCorr^2 + dConv^2 + dDists^2);
dTotalUncorrelated = sqrt(dReading^2);
dTotal = sqrt(dQ^2 + dCorr^2 + dDists^2 + dReading^2 + dConv^2)
dTotalAbs = dTotal*Reading/100;
print "All uncertainties are k=2"
wavestats/q CorrPct
print "Corrections range from ", V_min, " to ", V_max
wavestats/q dReading
print "Irradiation time uncertainties range from ", V_min, " to ", V_max
wavestats/q dQ
print "Source uncertainties range from ", V_min, " to ", V_max
wavestats/q dCorr
print "Correction uncertainties range from ", V_min, " to ", V_max
wavestats/q dDists
print "Distance uncertainties range from ", V_min, " to ", V_max
print ""
SetDataFolder fldrSav
End

```

Function PlanCalibDosimeter()

```

WAVE SourceFluence = root:InstrCalibAnalysis:SourceFluence
WAVE D_CC = root:InstrCalibAnalysis:D_CC
WAVE CorrPct = root:InstrCalibAnalysis:CorrPct
WAVE D_SS = root:InstrCalibAnalysis:D_SS
WAVE convAndCorr = root:InstrCalibAnalysis:convAndCorr
WAVE RealDose = root:InstrCalibAnalysis:RealDose
WAVE mmonth = root:InstrCalibAnalysis:mmonth
WAVE mday = root:InstrCalibAnalysis:mday

```

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```

WAVE myear = root:InstrCalibAnalysis:myear
WAVE FFDE = root:InstrCalibAnalysis:FFDE
WAVE TimeUp = root:InstrCalibAnalysis:TimeUp
WAVE Reading = root:InstrCalibAnalysis:Reading
WAVE/T sourceName = root:InstrCalibAnalysis:sourceName
Variable i=0
SourceFluence = NActivity(sourceName, mmonth, mday, myear)
// D_CC = 50
print "Not setting D_CC today"
D_SS = D_CC + convAndCorr[1]
FFDE = SourceFluence*convAndCorr[0]/(D_CC)^2
CorrPct = convAndCorr[2]*(D_CC + convAndCorr[1])/100 + convAndCorr[3]*(D_CC/100)^2 + convAndCorr[4]*((D_CC/100)^4 )
CorrPct += 100*convAndCorr[5]/(4*D_CC^2); // non-point correction added 5/28/02
RealDose = FFDE*(1 + CorrPct/100)
TimeUp = 3600*Reading/RealDose
End

Function PlanCalib()
WAVE SourceFluence = root:InstrCalibAnalysis:SourceFluence
WAVE D_CC = root:InstrCalibAnalysis:D_CC
WAVE CorrPct = root:InstrCalibAnalysis:CorrPct
WAVE D_SS = root:InstrCalibAnalysis:D_SS
WAVE convAndCorr = root:InstrCalibAnalysis:convAndCorr
WAVE RealDose = root:InstrCalibAnalysis:RealDose
WAVE mmonth = root:InstrCalibAnalysis:mmonth
WAVE mday = root:InstrCalibAnalysis:mday
WAVE myear = root:InstrCalibAnalysis:myear
WAVE FFDE = root:InstrCalibAnalysis:FFDE
WAVE/T sourceName = root:InstrCalibAnalysis:sourceName
Variable i=0
SourceFluence = NActivity(sourceName, mmonth, mday, myear)
D_CC = sqrt( SourceFluence*convAndCorr[0]/RealDose )
for( i= 0; i< 25; i+=1)
    CorrPct = convAndCorr[2]*(D_CC + convAndCorr[1])/100 + convAndCorr[3]*(D_CC/100)^2 + convAndCorr[4]*((D_CC/100)^4 )
    CorrPct += 100*convAndCorr[5]/(4*D_CC^2); // added - akt 6/8/01
    D_CC = sqrt( SourceFluence*convAndCorr[0]*(1 + CorrPct/100)/RealDose)
endfor
D_SS = D_CC + convAndCorr[1]
FFDE = SourceFluence*convAndCorr[0]/(D_CC)^2
CorrPct = convAndCorr[2]*(D_CC + convAndCorr[1])/100 + convAndCorr[3]*(D_CC/100)^2 + convAndCorr[4]*((D_CC/100)^4 )
CorrPct += 100*convAndCorr[5]/(4*D_CC^2); // non-point correction added 5/29/01
RealDose = FFDE*(1 + CorrPct/100)
End

```

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Appendix B: Dosimetry Video Data Acquisition Software

Overview

This is the code used to acquire data from the video frame grabber. It starts the frame grabber software and takes data as specified on the command line. It is stable (i.e., neither maintenance nor updating is needed) with the current hardware setup. Regardless, any changes are tracked using the git software versioning system on the low scatter data acquisition machine. This software is mirrored onto the NIST central file server, elwood, in the 68_PML/682/internal/682_Shared/CalData/682.03/CommonFiles/LowScatterDataAcq directory, and changes would be promptly mirrored as well.

The variables \$beforeAfterDiff and \$beforeAfterFrac allow data to be taken at precise intervals, but these depend on the system configuration and speed. Because such precision is only occasionally needed, these are not available as command-line options. Validation of these values will be done before any experiment requiring their modification, with the validation procedure and documentation to be entered into the laboratory notebook.

Source Code

Selections from the source code are presented below for information.

```
#!/usr/bin/perl -w
#
# Take a bunch of screen grabs and save them in descriptive file names
#

use Getopt::Long;
use File::Path;
use Cwd 'abs_path';

my $pause = 10;
my $delay = 60;
our $showLongToSleep = $delay;
our $showmany = 10;
my $basename = '100mr';
my $destdir = '.';
my $printhelp = "";
my $printexample = "";
my $timesArray = "";
our @atTimes;

GetOptions( 'pause:i' => \$pause,
            'delay:i' => \$delay,
            'howmany:i' => \$showmany,
            'basename:s' => \$basename,
            'destdir:s' => \$destdir,
            'help|usage' => \$printhelp,
            'example' => \$printexample,
            'timesarray:s' => \$timesArray
```

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```

) or die("unknown option");;

if( $printhelp )
{
    print "DosimDAQ [--pause seconds] [--delay seconds] [--howmany numImages]\n";
    print "    [--basename fileBaseName] [--destdir destination_directory] [--example]\n";
    print "    [--timesarray perlSource]\n";
    exit;
}

if( $printexample )
{
    print "/Users/akt/Documents/LowScatterDataAcq/DosimDAQSS.pl --delay 60 --howmany 12 --destdir ./mod/ --basename 100mr\n";
    print "/Users/akt/Documents/LowScatterDataAcq/DosimDAQSS.pl --timesarray '((30) x 3, (60) x 3, (100) x 3)' --destdir ./mod/ --
basename 100mr\n";
    print '/Users/akt/Documents/LowScatterDataAcq/DosimDAQSS.pl --timesarray \'my @foo = (30) ; foreach (0..21) {push @foo, int
($foo[-1]*1.1);} ; @foo\' --destdir ./mod/ --basename 100mr.\'"\n';
    exit;
}

if( $timesArray )
{
    @atTimes = eval($timesArray);
    # exit;
    # example : --timesarray '((30) x 3, (60) x 3, (100) x 3)'
    # example : --timesarray 'my @foo = (30) ; foreach (0..21) {push @foo, int ($foo[-1]*1.1);} ; @foo'
}
else
{
    @atTimes = eval "((($delay)x$showmany)";
}
my $sum=0;
foreach(@atTimes)
{
    $sum += $_;
}
print join(" ", @atTimes)."\n";
#exit;
print "Total time for measurements approximately $sum seconds\n";
$delay = $atTimes[0];
$showmany = scalar(@atTimes)+1;

if (open PowMgmt,"/private/var/db/SystemConfiguration/com.apple.PowerManagement.xml")
{
    while(<PowMgmt>)
    {
        if( m/.key.Display Sleep Timer.Vkey./ )
        {
            $nextline = <PowMgmt>;
            $nextline =~ m/>([0-9]+)</;
            unless( $1 == 0 )
            {
                print "\007\007\007";
                print "Display sleep may kill DAQ\n";
            }
        }
    }
}

# was system('open /XLR8\ Folder/Interview/InterView\ Capture'); -- akt 20080623t101700
#system('open /Applications/InterView/InterView\ Capture');
system('open /Applications/SecuritySpy.app');
sleep $pause;

#print "(2) $pause, $delay, $showmany, $basename, $destdir\n";
#Showmany--;
# print "Destdir is (1) $destdir\n";
$destdir =~ s/(\/+s*){}g;
$destdir = abs_path($destdir);
# print "Destdir is $destdir\n";
mkpath($destdir, 1, 0755);
die "No files will actually be written, so I'm quittin'\n" unless -d $destdir;

our $beforeAfterDiff = 0; # was 1 -- akt 20121016t1028 was 5 -- akt 20080623t101544
our $beforeAfterFrac = 0; # was -0.48; -- akt 20121016t1028
if(0)
{
    my $showManyFoo = 10;
    $before = time();

```

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```

#print "$before\n";
foreach (1..$howManyFoo)
{
    my $curTime = time();
    system("screencapture $destdir/$basename"._$. "foo.pdf");
    print "$basename"._$. "foo.pdf $curTime\n";
    sleep 5;
}
$after = time();
$beforeAfterDiff = ($after - $before)/$howManyFoo;
$beforeAfterDiff -= 5;
print "beforeAfterDiff $beforeAfterDiff\n";
$beforeAfterFrac = $beforeAfterDiff - int $beforeAfterDiff;
$beforeAfterDiff = int( $beforeAfterDiff);
print "beforeAfterFrac $beforeAfterFrac\n";
$showLongToSleep = $delay - $beforeAfterDiff;
if ($beforeAfterFrac > 0.5)
{
    $beforeAfterDiff += 1;
    $beforeAfterFrac = $beforeAfterFrac-1;
}
print "beforeAfterDiff final $beforeAfterDiff\n";
print "beforeAfterFrac final $beforeAfterFrac\n";
}
our $whichone; $whichone = 1;
my $fracErr = 0;
my $fracFudge = 0;
snapshot();
snapshot();
foreach $delay (@atTimes)
{
    $fracErr += $beforeAfterFrac;
    if (abs($fracErr) > 1)
    {
        $fracFudge = (($fracErr > 0) ? 1 : -1);
        $fracErr -= $fracFudge;
    }
    else
    {
        $fracFudge = 0;
    }
    $showLongToSleep = $delay - $beforeAfterDiff - $fracFudge;
    sleep $showLongToSleep;
    $whichone++;
    snapshot();
}
snapshot();
print "\a\n";
#foreach $whichone (1..$howmany)
#{
#    snapshot();
#    sleep $showLongToSleep unless ($whichone==$howmany)
#}

sub snapshotXLR8
{
    $curTime = time();
    system("screencapture $destdir/$basename"."$curTime.pdf");
    print "$basename"."$curTime.pdf ($whichone of $howmany)";
    print scalar localtime;
    print "\n";
}

sub snapshot
{
    $curTime = time();
    my $script = <<EOS;
tell application "SecuritySpy"
    capture image camera name "detector" as "$destdir/$basename$curTime.jpg"
end tell
EOS
# system("screencapture $destdir/$basename"."$curTime.pdf");
# osascript($script);
# print "DEBUG: $destdir/$basename$curTime.jpg\n";
# print "$basename"."$curTime.pdf ($whichone of $howmany)";
# print scalar localtime;
# print "\n";
#}
sub snapshotruler

```

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```
{
  $curTime = time();
  my $script = <<EOS;
tell application "SecuritySpy"
  capture image camera name "ruler" as "$destdir/Ruler$curTime.jpg"
end tell
EOS
# system("screencapture $destdir/Ruler"."$curTime.pdf");
osascript($script);
#   print "DEBUG: $destdir/Ruler$curTime.jpg\n";
  print "$basename"."$curTime.pdf ($whichone of $howmany)";
  print scalar localtime;
  print "\n";
}

my $script = <<EOS;
tell application "SecuritySpy"
  capture image camera name "detector" as "$destdir/$basename$curTime.jpg"
end tell
EOS
# for OS X 10.6, where Adobe has bad osaxen
sub osascript10p6 { system 'arch', '-i386', 'osascript', map { ('-e', $_) } split(/\n/, $_[0]); }
# for 10.8?
sub osascript { system 'osascript', map { ('-e', $_) } split(/\n/, $_[0]); }
```

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Appendix C: Video Analysis Software

Overview

This is the code used for the initial analysis of raw data.

To start, the number of files is entered into the Macro EnterNumFiles. File names, which contain the encoded date and time of acquisition, are entered into the experiment and converted into date, time, and nominal dose rate by ProcessFileNames. The number of dose rates measured is entered into PrepareToCrunch, which makes an effort to find the starting and stopping values of different dose rates from the nominal dose rates. After confirmation that the starts and stops are correct, the data is analyzed using Crunch or LinAnalyzeAll, depending on whether the data is ratemeter or integration mode, respectively. This produces averages, standard deviations, number of points, etc.

Minor changes are sometimes made to the code (e.g., the “3000” in the call to CarefulUncertNonCounts in LinAnalyzeAll might be changed if a meter with significantly different sensitivity were used).

This software is quite stable (i.e., neither changes nor updates are regularly required). Still, it is (at the same time as the software described in Appendix A) mirrored to the NIST central file server, elwood, in the 68_PML/682/internal/682_Shared/CalData/682.03/CommonFiles/SourceFlucCalc directory, with scripts used by the file mirrored in the 68_PML/682/internal/682_Shared/CalData/682.03/CommonFiles/WaveMetrics directory.

Source Code

Selections from the source code are presented below for information.

```
Macro LinAnalyzeAll()
  duplicate/o measDoses uncertDoses, digits
  make/d/o/n=2 W_coef, W_sigma, W_ParamConfidenceInterval
  digits = 3+((measDoses/(10^floor(log(measDoses))))<2)
  uncertDoses = CarefulUncertNonCounts( measDoses, digits )
  // "3000" on next line comes from cts/mrem for a typical meter
  // 50 cpm/(mrem/hr) is 3000 cts/mrem
  uncertDoses = max(uncertDoses, measDoses / sqrt(measDoses*cpmrem) )
//
//  uncertDoses = sqrt(measDoses);
//  tempcomplex = ()
  avgnomdoses = average(nomdoses,starts,stops);
  averages = real(LinAnalyzeOne(measDoses,tTimes,uncertDoses,starts,stops,0))
  print "returning 95% confidence interval on fit";
  sdevs = imag(LinAnalyzeOne(measDoses,tTimes,uncertDoses,starts,stops,3)) // get confidence interval instead of sdev
  chisqs = real(LinAnalyzeOne(measDoses,tTimes,uncertDoses,starts,stops,2))
  numMeas = real(LinAnalyzeOne(measDoses,tTimes,uncertDoses,starts,stops,4))
  //print "scaling standard deviations by sqrt(chisq/dof)";
  //sdevs *= sqrt(chisqs/(stops-starts+1-2))
//  calFacs = AvgNomDoses/averages
End

Function/C LinAnalyzeOne(doseWave, timeWave, uncertWave, startPt,stopPt,whuh)
  wave doseWave, timeWave, uncertWave;
  variable startPt,stopPt,whuh;
  WAVE/D W_coef
  WAVE/D W_sigma
  WAVE/D W_ParamConfidenceInterval
  CurveFit/Q line measDoses[startPt,stopPt] /X=timeWave /W=uncertWave /I=1 /F={0.950000, 4}
```

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```

// print "Chisq = ",V_chisq;
if( whuh==2 )
    return V_chisq;
elseif ( whuh==4 )
    return V_npnts-V_numNaNs;
elseif (whuh ==3) // return confidence interval instead of standard dev of linear fit
    return (cmplx(W_coef[1],W_ParamConfidenceInterval[1]));
else
    return( cmplx(W_coef[1],W_Sigma[1]) );
endif
End

// from "Video Analysis" macro file -- AKT 3/3/99 13:54

Function Average(awave, startR, stopR)
wave awave; variable startR, stopR;
wavestats/q/r=[startR, stopR] awave
return( V_avg )
end

Function Sdev(awave, startR, stopR)
wave awave; variable startR, stopR;
wavestats/q/r=[startR, stopR] awave
return( V_sdev )
end

Macro EnterNumFiles(numFiles)
    variable numFiles;
    make/o/t/n=(numFiles) fileList;
    make/o/n=(numpts(fileList))/d tTimes,nomDoses,measDoses,chisq
    Edit fileList, tTimes, nomdoses, measDoses;
End

Macro ProcessFileNames()
// use ls *.pict | pbcopy under OS X -- akt 20020819 1535
// variable numFiles = LoadFileNames();
// fileList = IndexedFile(mod, p, "????")
// tTimes = name2timeperl(fileList)
// nomDoses = name2nomDose(fileList)
// ModifyTable width(fileList)=160
// SetScale d 0,0,"dat", tTimes
// ModifyTable format(tTimes)=8,width(tTimes)=126
End

Function/D name2timeperl(aString)
    string aString;
    return str2num(aString[strsearch(aString,"mr",0)+2,strlen(aString)])+date2secs(1970,1,1)- 4*3600
End

Function/D name2time(aString)
    string aString;
    return str2num(aString[strsearch(aString,"mr",0)+2,strlen(aString)])+2*31
End

Function name2nomDose(aString)
    string aString
    return str2num(aString[0,strsearch(aString,"m",0)])
End

Macro PrepareToCrunch(numberDoseRates)
    variable numberDoseRates;
    // added "numMeas" -- akt 20021001 1155
    make/o/n=(numberDoseRates)/d averages, sdevs, AvgNomDoses, starts, stops, calFacs, numMeas //,tempcomplex
// redimension/c tempcomplex
edit starts, stops, AvgNomDoses, averages, sdevs,calFacs
FindStartsStops( nomDoses, starts, stops );
numMeas = stops-starts+1
AvgNomDoses = Average(nomDoses,starts,stops);
averages = NaN;
sdevs = NaN;
calFacs = NaN;
End

Function FindStartsStops(nomDoses, starts, stops )
    wave nomDoses, starts, stops;
    variable i,j;
    starts[0] = 0;stops[numpts(stops)-1]=numpts(nomDoses)-1;

```

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```

for( i=0, j=0; i<numpts(nomDoses); i+=1)
    if( nomDoses[i+1] != nomDoses[i] )
        starts[j+1] = i+1;
        stops[j] = i;
        j+=1;
    endif
endfor
End

Macro Crunch()
    averages = average( measDoses, starts, stops )
    sdevs = sdev( measDoses, starts, stops )
    AvgNomDoses = average( nomDoses, starts, stops )
    numMeas = stops-(starts-1)
    calFacs = AvgNomDoses/averages
End

Macro dCrunch()
    averages = average( dmeasDoses, starts, stops )
    sdevs = sdev( dmeasDoses, starts, stops )
    AvgNomDoses = average( nomDoses, starts, stops )
    calFacs = AvgNomDoses/averages
End

Function/d CarefulUncert(counts,digits)
// given a wave of counts and a number of digits the meter reads, return the real uncertainty in number of counts
// -- akt 2001-11-14 1203
variable counts; variable digits;
return( max(10^(floor(log(counts))-digits+1),sqrt(counts)) );
End

Function/d CarefulUncertNonCounts(reading,digits)
// given a wave of readings and a number of digits the meter reads, return the (minimum) uncertainty in reading
// -- akt 2001-11-14 1203
variable reading; variable digits;
return( 10^(floor(log(reading))-digits+1) );
End

Function/D fit4drift(coeffs, x) : FitFunc
    wave coeffs; variable x;
    variable result;
    // coeffs = {t0, y0, R, f, tau}
    x -= coeffs[0];
    result = coeffs[1] + coeffs[2]*x + coeffs[2]*coeffs[3]*coeffs[4]*exp(-x/coeffs[4]);
    return result;
End

```

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Appendix D: Uncertainty Analysis

Single Calibration Factor

For a single calibration factor, *example* uncertainties are shown below in Table 4.

Table 4: Example Uncertainties

Description	Type A (%, k=2)	Type B (%, k=2)	How Determined (bare)	How Determined (moderated)
Instrument Reading	0.4		Std. Dev. of readings	Same as bare
Source Strength		2.6	Source emission rate uncertainty as reported from the calibration. The uncertainty is doubled if more than two half-lives have elapsed since calibration.	Same as bare
Room Return & Air Scatter correction		1.8	0.4 * Total Correction	Same as bare
Fluence / Dose Equivalent Conversion		2	2 %	8 %
Effective Source-Detector Distance		5.1	0.5 cm*2/ source- detector distance	Same as bare
Quadrature Summation	0.4	6.3		

The expanded uncertainty at an approximate level of confidence of 95 % is also 6.3 %, as the Type B uncertainties dominate the combined uncertainty.

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Full example uncertainty analysis

A detailed example of an uncertainty analysis is given here, using data taken from the sample report in Appendix E. The unit mrem is used here because it is the preferred quantity for customers of this calibration service.

The table below contains “correlated” uncertainties. These are uncertainties where the source of the uncertainty does not vary between measurements, thus the uncertainty cannot be reduced by taking more measurements or averaging over several measurements. The total correlated uncertainty is the combination in quadrature of the other three uncertainty columns: source strength, correction, and fluence to dose equivalent conversion.

Table 5: Correlated Uncertainties

Dose Rate (mrem/h)	Source Strength Uncertainty (%)	Correction Uncertainty (%)	Fluence to Dose Equivalent Conversion Uncertainty (%)	Total Correlated Uncertainty (%)
3.0	2.6	0.92	2	3.41
10.0	2.6	2.24	2	3.97
30	2.6	1.01	2	3.43
100	2.6	1.01	2	3.43
300	2.6	1.0	2	3.43
600	2.6	1.56	2	3.63
899	2.6	2.19	2	3.94

The following table contains “uncorrelated” uncertainties, meaning the sources of these uncertainties vary between measurements, and multiple measurements can reduce the overall uncertainty. For instance, the distance uncertainty is dominated by the shifting of the radioactive material (RAM) within the source capsule, combined with the free rotation when raising the source.

Table 6: Uncorrelated Uncertainties

Dose Rate (mrem/h)	Source-Detector Distance Uncertainty (%)	Uncertainty of Readings (%)	Number of Measurements	Total Uncorrelated Uncertainty (%)
3.0	2.17	3.46	13	2.51
10.0	1.09	1.86	12	1.39
30	1.92	1.06	13	1.34
100	1.91	0.59	13	1.23
300	3.31	0.36	13	2.04
600	4.66	0.28	13	2.86
899	5.66	0.21	13	3.47

The calculation of the Total Uncorrelated Uncertainty is complicated by the fact that data is taken either as a collection of independent dose rates in “ratemeter” mode or as an

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integrated dose. If the measurement is taken in integrated mode, then the data of integrated dose vs. time is fit to a line, and the uncertainty is extracted from the $k=2$ confidence level for the slope of the line; in this case, the uncertainties are combined in quadrature. If the data are taken in ratemeter mode, the reading uncertainties are sample standard deviations of measurements and are combined with distance uncertainties using

$$\sigma_{tot} = t(0.9545, n) \frac{\sqrt{\sigma_{distance}^2 + \sigma_{reading}^2}}{\sqrt{n}}$$

where n is the number of measurements, $t()$ returns the value for the Student T given an integrated two-tail probability ($0.9545 \sim$ the integrated probability for $k=2$) and number of degrees of freedom (i.e., the number of measurements). The sigmas are the uncorrelated uncertainties discussed above. The example data in the table above was taken in ratemeter mode.

The correlated and uncorrelated uncertainties are combined in quadrature to calculate the uncertainty for the calibration factor for a given dose equivalent rate; they are separated only for their effect on the *weighted average* calibration factor.

The calculation of the weighted average calibration factor and its uncertainty is difficult. As mentioned above, the correlated uncertainties are not reduced by making multiple measurements (i.e., at different dose rates). Therefore, the weighted mean of the calibration factor is calculated using only the *uncorrelated* uncertainties. The standard weighted uncorrelated uncertainty (which is smaller than the individual uncorrelated uncertainties because of the multiple measurements) is calculated as well. (*n.b.*: the relative uncertainties given in the table must be converted to absolute uncertainties before performing the calculation).

Combining the weighted uncorrelated uncertainty with the correlated uncertainty is problematic because the correlated uncertainties are not equal for all measurements. To solve this issue, an “average” correlated uncertainty is calculated. It is calculated as a weighted mean of correlated uncertainty for all dose rates, using the *uncorrelated uncertainty* for the weighting (thus, measurements with, for instance, high observed standard deviations will not contribute to the average correlated uncertainty as much as measurements with low observed standard deviations).

The total uncertainty on the weighted mean is, finally, calculated as the addition in quadrature of the weighted uncorrelated uncertainty and the average correlated uncertainty.

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Appendix E: Sample Calibration Report

U. S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

Report of Test

Instrument Submitted by: Full Name
Company/Lab Name
Street Address
City, State Zip

Date(s) of Calibration: Month DD, YYYY and Month DD, YYYY

Report Date: Month DD, YYYY

Calibration Facility: Building 245, Room B023-S
100 Bureau Drive
Gaithersburg, MD, 20899

Instrument Calibrated

Type of Instrument: Make Model

Quantity: 1

Serial Number: Serial Number

Neutron Sources

Spontaneous fission sources composed of ^{252}Cf with the following emission rates were used in this calibration:

Table 1: Source Emission Rates

Source Name	Neutron Emission Rate	Relative Uncertainty
NBS-131	$3.95 \times 10^6 \text{ s}^{-1}$	5.1 %
NS-130	$1.395 \times 10^6 \text{ s}^{-1}$	5.1 %
NBS-132	$1.090 \times 10^7 \text{ s}^{-1}$	2.8 %
NS-100	$7.87 \times 10^5 \text{ s}^{-1}$	5.1 %
AmBe-1963	$1.445 \times 10^7 \text{ s}^{-1}$	3.38 %

Sources NBS-131 and NS-130 were moderated in the NIST 30 cm diameter heavy water sphere. Sources NBS-132 and NS-100 were unmoderated (aka “bare”). The uncertainties in the last column of Table 1 are the combined standard expanded uncertainties ($k=2$), that is, they define intervals around the quoted source emission rates within which the unknown value of the source emission rate lies with a level of confidence of approximately 95 %.

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Methods & Results

The instrument was mounted on a stand and measurements were made at one or more distances from each source to obtain different dose equivalent rates. The results of the irradiation are summarized in Tables 2 and 3 at the end of the report. The first two columns in Tables 2 and 3 list the source and distance combinations used. The third column in Tables 2 and 3 lists the “Free Field Dose Equivalent” (FFDE) rates corresponding to the source-distance combinations used. In this report “Dose Equivalent” refers to “Ambient Dose Equivalent” as defined in ISO 8529-1 (2001) [1]. The FFDE rate is the dose equivalent rate due to neutrons from the source alone, in the absence of backgrounds caused by neutrons scattered into the instrument from the walls, the air in the room, and the source support. The FFDE rates, in mrem/h, are calculated from the formulae:

$$\begin{aligned}\text{FFDE Rate} &= 2.66 \times 10^{-3} Q/r^2 \quad (\text{moderated}) \\ &= 1.10 \times 10^{-2} Q/r^2 \quad (\text{bare})\end{aligned}$$

where Q is the neutron emission rate (s^{-1}) and r (cm) is the distance listed in Tables 2 and 3. The FFDE rate in $\mu\text{Sv/h}$ is ten times the FFDE rate in mrem/h.

The next column in Tables 2 and 3, labeled “Corrected Dose Equivalent,” gives the actual dose equivalent rate received by the instrument. This is the FFDE corrected for the backgrounds mentioned above. The corrections are -0.00 % (moderated sources) and -0.00 % (bare sources), depending upon the distance.

The corrected dose equivalent, divided by the instrument reading, gives the calibration factor listed in the last column of Tables 2 and 3. The calibration factor is thus the number by which the instrument reading should be multiplied to get the true dose equivalent rate in mrem/h. These calibration factors should be multiplied by a factor of ten to get the dose equivalent rate in $\mu\text{Sv/h}$. The value listed for the average is the weighted average of the listed calibration factors.

The last column also gives the combined standard expanded uncertainties ($k=2$) in the calibration factors. These uncertainties define an interval around each quoted calibration factor within which the unknown value of the calibration factor lies with a level of confidence of approximately 95 %. These uncertainties include all Type A uncertainties and Type B uncertainties (*i.e.*, uncertainties determined by other than strictly statistical means) added together in quadrature.

The Type A uncertainties for these data are <-0.00 % to -0.00 % (moderated sources) and <-0.00 % to -0.00 % (bare sources). They are calculated as experimental standard deviations of the mean, which are the observed standard deviations of repeated instrument readings at a fixed FFDE rate divided by the square root of the number of measurements.

The Type B uncertainties include the uncertainty in the source strength (-0.00 % (moderated sources), -0.00 % (bare sources)), the uncertainty in the neutron scatter correction (-0.00 % (moderated sources) and <-0.00 % to -0.00 % (bare sources), depending on the distance from the source), and the uncertainty in the location of the effective center of the source with respect to the center of the instrument (-0.00 % (moderated sources) and -0.00 % (bare sources), depending on the distance from the source).

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Fluctuations in the instrument readings (Type A) are the dominant uncertainty at the lowest dose equivalent rates. The main Type B uncertainties are in the source calibration, the neutron scatter correction, and the distance from the source to the instrument for the highest dose equivalent rates.

The results of this calibration are traceable (1) through source emission rate calibrations to NBS-1, the NIST reference RaBe neutron source, (2) to the internationally standardized bare and moderated ^{252}Cf neutron energy spectra as documented in ISO 8529-1 (2001), (3) the meter, and (4) the second. The results provided in this report relate only to the item or items tested/calibrated that are listed in the "Instrument Calibrated" section. Fluence to dose equivalent conversion coefficients from ICRU 57 [2] / ICRP 74 [3] were used to calculate the spectrum-averaged free-field dose equivalent.

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Date(s) of Irradiation: Month DD, YYYY and Month DD, YYYY
Type of Instrument: Make Model
Quantity: 1
Serial Number: Serial Number

Table 2: Moderated Californium

Source Name	Distance (source center to detector center), cm	Free-Field Ambient Dose Equiv. Rate, mrem/h	Corrected Ambient Dose Equiv. Rate, mrem/h	Instrument Readings, mrem/h	Calibration Factor
NBS-000	-0.00	-0.00	-0.00	-0.00	-0.00 ± -0.00
NBS-000	-0.00	-0.00	-0.00	-0.00	-0.00 ± -0.00
NBS-000	-0.00	-0.00	-0.00	-0.00	-0.00 ± -0.00
NBS-000	-0.00	-0.00	-0.00	-0.00	-0.00 ± -0.00
NS-000	-0.00	-0.00	-0.00	-0.00	-0.00 ± -0.00
				Average	-0.00 ± -0.00
Calculations in this table were performed at higher numerical precision than is displayed, thus it may not be possible to exactly reproduce the results using the values shown.					

Table 3: Bare Californium

Source Name	Distance (source center to detector center), cm	Free-Field Ambient Dose Equiv. Rate, mrem/h	Corrected Ambient Dose Equiv. Rate, mrem/h	Instrument Readings, mrem/h	Calibration Factor
NS-000	-0.00	-0.00	-0.00	-0.00	-0.00 ± -0.00
NS-000	-0.00	-0.00	-0.00	-0.00	-0.00 ± -0.00
NS-000	-0.00	-0.00	-0.00	-0.00	-0.00 ± -0.00
NS-000	-0.00	-0.00	-0.00	-0.00	-0.00 ± -0.00
				Average	-0.00 ± -0.00
Calculations in this table were performed at higher numerical precision than is displayed, thus it may not be possible to exactly reproduce the results using the values shown.					

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Measurements associated with this calibration were:

Performed by Daniel M. Jardin, Physicist
Neutron Physics Group

Reviewed by Shannon F. Hoogerheide, Physicist
Neutron Physics Group

Approved by H. Pieter Mumm, Leader
Neutron Physics Group

Approved by Alan K. Thompson, Chief
Radiation Physics Division
Physical Measurement Laboratory
For the Director, National Institute of Standards & Technology

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Appendix: Calculating Free Field Dose Equivalent

Before July 1, 2009, the formulæ used to convert from source emission rate to free-field ambient dose equivalent in the “Methods & Results” section used spectrum-averaged fluence to ambient dose equivalent conversion coefficients [4] [5] derived from ICRP 21 [6]. Although ICRP 21 was superseded by ICRP 74 [3], regulatory agencies have only recently begun to adopt the newer recommendations [7]. The ICRP 74 conversion coefficients, which were used to calculate all values of dose equivalent presented in this report, are consistent with ISO 8529-1 (2001) [1].

The ICRP 74 fluence to ambient dose equivalent recommendations increase the spectrum-averaged fluence to dose conversion coefficients for both bare and D₂O-moderated ²⁵²Cf by 16 % relative to the values derived from ICRP 21. Thus, to convert ambient dose equivalent values provided in this report to be consistent with older regulations and calibration reports dated earlier than July 1, 2009 (*i.e.*, based on ICRP 21), one must divide each ambient dose equivalent by 1.16.

References

- [1] International Organization for Standardization, “Reference neutron radiations-part 1: characteristics and methods of production.” ISO 8529-1 (ISO: Geneva) (2001).
- [2] ICRP Publication 57, “Radiological Protection of the Worker in Medicine and Dentistry,” Pergamon Press, Oxford (1990).
- [3] ICRP Publication 74, “Conversion Coefficients for use in Radiological Protection against External Radiation,” Pergamon Press, Oxford (1996).
- [4] R. B. Schwartz, “NBS Measurement Services: Neutron Personnel Dosimetry,” National Bureau of Standards (U.S.), Special Publication 250-12 (July 1987).
- [5] R. B. Schwartz and C. M. Eisenhauer, “Procedures for Calibrating Neutron Personnel Dosimeters,” NBS Special Publication 633 (1982).
- [6] ICRP Publication 21, “Data for Protection Against Ionizing Radiation from External Sources,” Pergamon Press, Oxford (1973).
- [7] U.S. Federal Register. “Occupational radiation protection,” Washington, DC: U.S. Government Printing Office; 10 CFR Part 835 (2007)

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