Neutron Personnel Dosimetry (44060C)

Purpose

This document describes the setup, measurement, and reporting procedures for calibrations of neutron personnel protection devices, both active (*e.g.,* rem balls) and passive (*e.g.,* albedo dosimeters).

Scope

This procedure covers calibration of instruments in neutron fields having intensities and character similar to that found in nominally occupied areas. The fields available are those produced by californium-252 sources, either lightly encapsulated (so free in air) or in the center of a 15 cm radius heavy water sphere covered with cadmium. 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.

Definitions

This document does not define any new terms.

Equipment

The equipment used for these calibrations has four broad categorizations: positioning equipment, neutron sources, neutron field moderating equipment, and data acquisition equipment.

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 (*i.e.,* aluminum and steel) and 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. A steel indicator connected to the bottom of the rolling cart indicates the position of the cart to approximately 1 mm (the indicator can be read out using a video camera attached to the cart and aimed at the indicator). This information, in combination with the procedure for positioning of the instrument on the cart as described in "Positioning of Detector/Phantom," allows the absolute distance between the detector and the mechanical location of the source to be set to approximately 1 mm resolution.

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The sources are raised and lowered using a ***fishing reel and Kevlar thread***. This allows the person raising and lowering the sources to minimize exposure to radiation.

Mechanical positioning of bare sources is achieved using an aluminum ***source holder*** pictured below in Figure 1. A source attached to the Kevlar thread mentioned above 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.

Figure 1: Source positioning apparatus

The height of the most standard size rem ball above the rolling cart platform is set using a "***ring stand***" specifically designed and constructed for this purpose. A grooved circular ring, pictured below as both a photograph (Figure 2) and as a mechanical drawing (Figure 3), holds three 19.05 mm (0.75") diameter ball bearings. The center of a so-called "9-inch" rem ball 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 rem ball above the rolling table platform. The heights of the bare and D_2O-moderated sources above the rolling table platform have been measured in the past and are 31.9 cm and 30.3 cm, respectively.

All distances which impact the calibration are NIST-traceable through GEI International Stainless Steel Ruler Model 2020A, Serial Number C27424 (or equivalent).

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Figure 2: Ring stand used to hold "9-inch" rem ball

Figure 3: Mechanical design of the rem ball ring stand.

Holes are 1/4" through, spaced at 120 degrees
  countersunk for 1/4-20 FH
Material: aluminum
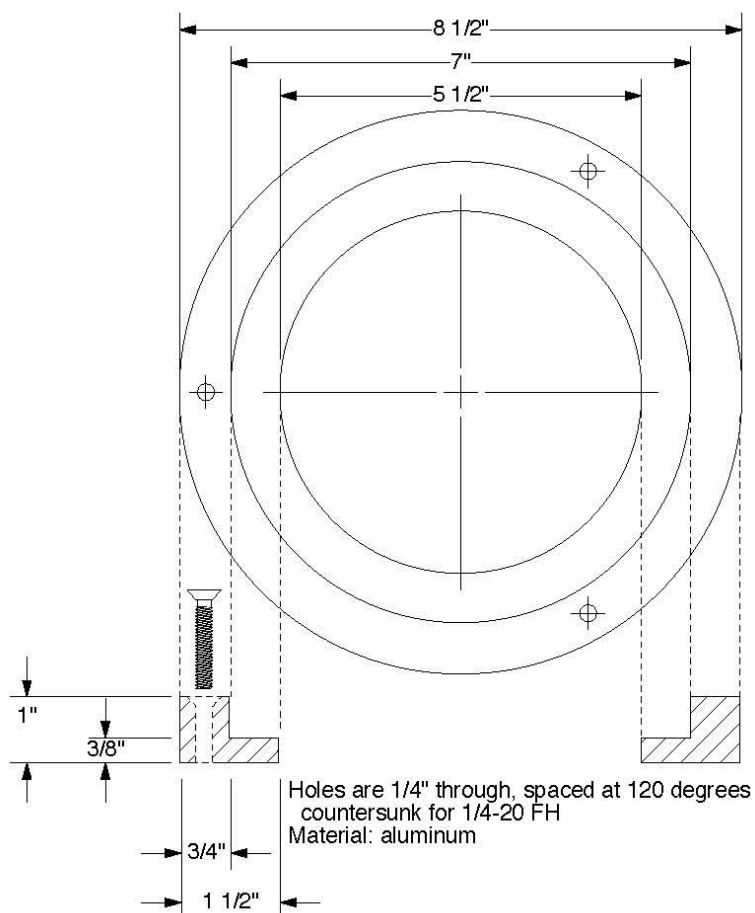
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Environmental effects on positioning equipment

Positioning equipment is, in principle, subject to change of size as a function of temperature. Since 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 15×10^{-6} K^{-1}, while aluminum alloys have a coefficient of 23×10^{-6} K^{-1}. The longest 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 required to degrade our measurement for steel). The temperature of the calibration range is controlled to $\pm$ 5 K, so this is not a significant source of error.

Neutron Sources

Lightly encapsulated californium-252 neutron sources are essential for calibrations. Characteristics of the sources used in calibrations are in Table 2 in the Procedures section.

Neutron Field Moderating Equipment

The *D$_2$O Sphere* is described in Reference 2.

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

The *ISO water slab phantom* is specified in ISO 8529-3:1998, section 6.2.2.

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 is heavily dependent on reading out the instruments using ***video cameras***. These video cameras point to the steel indicator showing the location of the rolling cart and to the readout of the instrument. Additional cameras show when the source is in position, and when it has been safely put back into storage.

Still images of the instrument readout and cart position indicator are acquired from digital video cameras and saved to the hard disk of a ***Macintosh data acquisition computer***. Software on the computer saves the video images at specified time intervals for later readout and analysis. 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 digital stop watch 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, in principle, be performed with a stop watch, video camera, and lab notebook, the data is, in fact, acquired, time stamped, stored, and analyzed using custom software. This software is stored in a source code versioning system on the computer of the person who performs all calibrations and is backed up regularly to an external storage device and to the NIST central file servers. Use of the

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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 "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, all of the source code should be stable. Only validated versions of the code will be used for actual calibrations.

Safety

ALARA procedures are observed with guidance from the NIST Gaithersburg Radiation Safety Division under safety evaluation SE-0031. "Distance" and "shielding" (being out of the room when the source is raised) are required by SE-0031 except for unusual and limited circumstances. For those circumstances, "Time" (staying in the vicinity of the source for as little time as possible) is used to limit dose.

Standard laboratory safety procedures for lifting detectors, minimizing contact with cadmium, etc., are carefully observed.

Procedures

Device Acceptance Criteria

Upon receipt of customer artifacts (active or passive detectors), shipping containers are inspected for damage. If there is significant damage of the shipping container, the client is contacted immediately and guidance 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. Since the neutron background in the calibration range is very low, a reading above $1~\mu Sv~h^{-1}$ ($0.1~mrem~h^{-1}$) is a cause for concern (i.e., it indicates a possibly-malfunctioning instrument), and is discussed with the client before proceeding with the calculation.

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 for 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 for some source-detector combinations. Equation (19) from that reference, with the inclusion of the quartic term, reads:

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$$\frac{M_T(l)}{\Phi F_1(l)(1+Al)} = RF(1 + Sl^2 + Ql^4)$$

The values of S, Q and A currently in use are shown in Table 1.

Changes in the arrangement of materials, especially hydrogenous materials, in the calibration range can change the room return corrections. 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 eliminate any effects on room return since scattering from the wall of the room dwarfs any scattering from a movable piece of material. After significant changes to the arrangement of material in the calibration range calibrations shall cease until room return corrections can be verified.

Table 1: Room Return and Air Scatter Corrections

Device	S (Bare) Quadratic (m^{-2})	A (Bare) Air Scatter (m^{-1})	S (Moderated) Quadratic (m^{-2})	Q (Moderated) Quartic (m^{-4})	A (Moderated) Air Scatter (m^{-1})
3" sphere	33 %	1.2 %	13. %		4.5 %
Albedo Dosimeter	20 %	1.2 %	5.4 %		3.7 %
9" Spherical Remmeter	5.3 %	1.2 %	7.35 %	− 0.28 %	2.6 %
Andersson-Braun Remmeter		1.2 %	9.53 %	− 0.51 %	2.6 %
REM500	4 %	1.2 %	4.5 %		1.4 %

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 Fluence 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	1.123×10^9	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	5/11/98	7.11×10^9	8/29/96	9.36	80.98	0.01

Source fluence rate in $cm^{-2}s^{-1}$ 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 ^{248}Cm. To calculate this quantity, the initial mass of ^{252}Cf in the source is determined from information provided by the manufacturer (see Table 3). "Purification Date" is the date when californium was separated from all other radionuclides, and "Emission Assay Date" is when the mass of ^{252}Cf in the source on that date was determined. From the initial ^{252}Cf mass, the current mass of ^{248}Cm is calculated from the decay of the initial quantity using the alpha decay branching ratio of 0.969 (reference 3). The current mass of ^{248}Cm is multiplied by its spontaneous fission yield of 4.04×10^4 n s^{-1} mg^{-1} to calculate the ^{248}Cm contribution to the source emission rate.

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	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

Positioning of Detector/Phantom

The vertical distance from the rolling cart platform to the center of the source has been previously 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. "9-inch" REM balls have the "ring stand" to set their position. Other detectors or phantoms are usually vertically positioned using a "lab jack" and 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 as common as the "9-inch" REM balls. For these systems instrument height is always checked with a NIST-traceable ruler.

The horizontal position of the detector or phantom *in the direction radially away from the source* is set by moving the rolling cart to approximately the correct position (*e.g.,* such that the scale reads 15.0 cm) 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 (a piece of paper can be moved with a small amount of resistance between the detector and sphere, but will not support its own weight). For calculating the source center – detector center distance, 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 source center – detector center distance of 25.26 cm) as described in reference 2.

The horizontal position of phantoms and detectors *in the direction perpendicular to the axis connecting the center of the source and the center of the detector* is set by aligning the detector/phantom to a mark on the platform of the rolling cart. The mark is checked during each calibration using a laser alignment system.

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 to assure that traceability

Approximately 10 seconds before a "memorable time" (*e.g.,* 3:00:00 PM), the data

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acquisition computer's clock is synchronized using the Network Time Protocol to a NIST Internet Time Server. At the "memorable time", the stopwatch is started and the time recorded in the laboratory notebook. After at least 15 minutes, and approximately 10 seconds before another "memorable time" (*e.g.,* 3:15:00 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 or the stopwatch must be replaced 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 to not 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 (*i.e.,* the "top" of the dosimeter is further from the center than the "bottom"). SP 250–12 (reference 4, page 8) states that the source detector distance is calculated from the source to the circle radius; this is no longer done because the position of the active elements within the dosimeter is difficult to determine, and the change to the distance is similar in size to the uncertainty in the position of the source/position of the dosimeter.

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

As soon as the source 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 until the stopwatch reads the required time for the requested dose. At that point, the source is lowered. The time at which the source reaches the top of the storage system is also recorded. Assuming the same time to raise and lower, and that the dose delivered to the dosimeters during raising and lowering is roughly 50 % of the source-in-position dose, this should yield dosimeters that have the correct dose. Both of these assumptions have associated uncertainties, so the dose reported to the customer is the dose delivered in position plus 50 % of the dose that would have been delivered had the dosimeters been in position during raising and lowering, with uncertainty in the time the source was up being the total time the source was being raised and lowered. Typically this is a small contribution to the total uncertainty.

Any dosimeter that falls off of 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 is partly to mitigate any 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 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 will 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 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 prepared for deployment, the room is scanned to verify that all sources of room return (in particular personnel) are in appropriate locations before the source is deployed.

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 at all possible, at a rate at least three times smaller than the refresh rate of the meter (*i.e.*, a delay between images 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 smaller than the refresh rate.

At least ten readings 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 also positioned as described in "Positioning of Detector/Phantom." The meter is reset and the source is raised into position as soon as possible afterwards (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 possible. The integrated dose *vs.* time is fit to a line. The slope of the line is the dose rate, and the uncertainty assigned to the dose rate is the confidence interval for the slope of the line at the 95 % confidence level. The confidence interval (for the 95 % confidence level) is calculated from the fit uncertainty and the Student's T distribution. The fit uncertainty is output by the Singular Value Decomposition and/or Levenberg-Marquardt software used to fit the data, as described in reference 5.

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, curvature to the line can be observed. Stability issues at the level of 10 % are common. If instability is observed in any given instrument, the sensitivity of the instrument essentially always increases with received dose equivalent, and appears to follow an exponentially asymptotic functional form with either time or dose equivalent.

A less informative 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

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 from multiple sources, which provides calibrations at multiple dose equivalent rates (typically two to three sources, with two to three distances for each source). Although an instrument might perform differently at different dose equivalent rates, most instruments submitted perform the same 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, as resources allow, the consistency of calibrations for returning instruments is checked.

For both active and passive detectors, the RPD participates in appropriate national and international comparisons.

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 4.2.2.2.

Source strength uncertainties are derived from source strength calibrations. 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

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of Appendix D for the value), but includes a small contribution (1 mm) from uncertainty in the readout of distance 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 error 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 (*i.e.,* 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 by hand in a laboratory notebook. Data is 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 B21; electronic laboratory notebooks (or equivalent) are edited on a local computer, and archived on the NIST central file servers.

Procedures Specific to Active Devices

Raw data files (screen dumps) are copied from the data acquisition machine to removable storage as quickly as possible after acquisition, and from removable storage to the desktop computer of the staff member performing analysis. These files may be moderately 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 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 desktop computer of the staff member performing the analysis. See "Appendix C: Video Analysis Software" for more information about this intermediate file.

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 D$_2$O-Moderated ^{252}Cf Source for Calibrating Neutron Personnel Dosimeters Used at Nuclear Power Reactors*, NUREG/CR-1204, January, 1980.

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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*.

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 folders on the NIST central file servers These folders are identified with the year and month of the calibration (starting date), the name of the institution submitting the detectors, and the NIST folder number or eCommerce order number (after the calibration has been completed). These calculations are stored in Igor Text Format (.itf), which can be easily reloaded into Igor for later checks, but are also human readable. These files are backed up at least daily, 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, the original of the report is sent to the customer. A photocopy of the final signed report is placed into the calibration folder to be returned to the calibration office, and an electronic scan of the report is uploaded to the eCommerce system.

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

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 is stored in a SVN server on irdilbert.ncnr.nist.gov at /svn/SourceFluxCalc/trunk/, and is backed up as necessary.

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, ideally by a factor of 100 or more

Analysis

For both types of instruments, the tables "AnalysisTable" and

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"AnalysisTableUncert" are brought to the front of the screen.

Active Instruments

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 one for data taken with integrating active devices, and zero for ratemeter devices.

Dosimeters

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;

    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
    cm248emissionEstimate = 4.04e4*mgCf252onAssayDate * 2^((mgCf252EmisAssayDates-mgCf252FinalPurifDates)/CfHalfLives[1]);
    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

    return(Activity(month,day,year)+cm248emissionEstimate[index])
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]);
    cfAct = CfActivitySC*exp(-ln(2)*(date2secs(year,month,day)-CfSourceCalibDate)/CfHalfLives)

    variable answer = cfSourceCalibVal*SumWave(cfAct)/SumWave(cfActivitySC);
    CfActNeutrons = cfAct*answer/sumwave(cfAct);
```

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```
        return( answer );
End

Macro CrunchCalibNew(LinAnalysis )
        variable LinAnalysis=0;// was the data taken in integral mode and fit to a line? -- 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:tsources, sourceName)]*dReadingAbs/dReadingAbs
        dCorr = 2*CorrPct/5
        dConv = FindStringInWave(root:cfCalibFolder:sourceNames, sourceName)*dReadingAbs/dReadingAbs
        dConv = 2*(dReadingAbs/dReadingAbs)*(1 + (abs(cmpstr(root:cfCalibFolder:sourcetype[dConv],"bare")))*3)
        // 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
        dTotalCorrelated = sqrt(dQ^2 + dCorr^2 + dConv^2);
        if( LinAnalysis ) //  if linear analysis, dReading's are k=2 confidence intervals already, propogate-- 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;
        wavestats/q CalFac
        print "Statistical Average Calibration Factor is ",V_avg, " ± ", 200*V_sdev/(V_avg*sqrt(V_npnts))," %"
        wavestats/q CorrPct
        print "Corrections range from ", V_min, " to ", V_max
        exportVarNames[whichExportVar] = "ScatterCorr"; exportVarMins[whichExportVar] = V_min; exportVarMaxs[whichExportVar] =
V_max;
        whichExportVar += 1;
        wavestats/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 uncerts, for fit you have k=2, for ratemeter you already multiplied by 2
        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;
```

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```
        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 ""
        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:tsources, 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
        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 )
```

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```
            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
```

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 maintained on the irdilbert.ncnr.nist.gov SVN server at /svn/dosimdaq/trunk/DosimDAQ.pl. The code below is from version 3144 of the code in the svn repository; validation of subsequent revisions will be noted in comments when they are committed.

The variables $beforeAfterDiff and $beforeAfterFrac allow data to be taken at precise intervals, but these depend on the system configuration. Since 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

```perl
#!/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 $howLongToSleep = $delay;
our $howmany = 10;
my $basename = '100mr';
my $destdir = '.';
my $printhelp = '';
my $printexample = '';
my $timesArray = '';
our @atTimes;

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

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```perl
    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$howmany)";
    }
print join(",",@atTimes)."\n";
#exit;
$delay = $atTimes[0];
$howmany = scalar(@atTimes)+1;

open PowMgmt,"/private/var/db/SystemConfiguration/com.apple.PowerManagement.xml";
while(<PowMgmt>)
    {
    if( m/.key.Display Sleep Timer.\/key./ )
        {
        $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, $howmany, $basename, $destdir\n";
#$howmany--;
# 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 $howManyFoo = 10;
    $before = time();
    #print "$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 "beforAfterDiff $beforeAfterDiff\n";
    $beforeAfterFrac = $beforeAfterDiff - int $beforeAfterDiff;
    $beforeAfterDiff = int( $beforeAfterDiff);
    print "beforeAfterFrac $beforeAfterFrac\n";
    $howLongToSleep = $delay - $beforeAfterDiff;
    if ($beforeAfterFrac > 0.5)
        {
        $beforeAfterDiff += 1;
        $beforeAfterFrac = $beforeAfterFrac-1;
        }
    print "beforAfterDiff final $beforeAfterDiff\n";
    print "beforeAfterFrac final $beforeAfterFrac\n";
    }
our $whichone; $whichone = 1;
```

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```perl
my $fracErr = 0;
my $fracFudge = 0;
snapshotruler();
snapshot();
foreach $delay (@atTimes)
        {
        $fracErr += $beforeAfterFrac;
        if (abs($fracErr) > 1)
                {
                $fracFudge = (($fracErr > 0) ? 1 : -1);
                $fracErr -= $fracFudge;
                }
        else
                {
                $fracFudge = 0;
                }
        $howLongToSleep = $delay - $beforeAfterDiff - $fracFudge;
        sleep $howLongToSleep;
        $whichone++;
        snapshot();
        }
snapshotruler();
print "\a\a\a\n";
#foreach $whichone (1..$howmany)
#{
#    snapshot();
#    sleep $howLongToSleep unless ($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
{
    $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 initial analysis of raw data.

To start, the number of files is entered into the Macro EnterNumFiles. File names (with 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. 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 also under SVN version control on dilbert.nist.gov at /svn/nDosimetry/VideoAnalyzer.

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}
//     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]) );
```

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```
        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=(numpnts(fileList))/d tTimes,nomDoses,measDoses,chisqs
        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[numpnts(stops)-1]=numpnts(nomDoses)-1;
        for( i=0, j=0; i<numpnts(nomDoses); i+=1)
                if( nomDoses[i+1] != nomDoses[i] )
                        starts[j+1] = i+1;
                        stops[j] = i;
                        j+=1;
                endif
        endfor
End
```

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```
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
```

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	2.6 %	2.4 %
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
Quadratic 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 first table below contains "correlated" uncertainties. These are uncertainties where the source of the uncertainty does not vary between measurements, and 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.

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 next table contains "uncorrelated" uncertainties. The sources of these uncertainties do vary between measurements. For instance, the "distance" uncertainty, which is partially caused by not knowing the position of the radioactive material within the source capsule, is different between sources and, indeed, between different raisings of the source because the sources can rotate freely.

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

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as an 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 ~ the integrated probability for k=2) and number of degrees of freedom (*i.e.,* the number of measurements). The sigma's 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 calculated 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:	Zaphod Beeblebrox
	Ronald Reagan Center for High Energy Physics
	Ref PO # 17025838588
	Receiving - Bldg 100
	Waxahachie, TX 75168

Date(s) of Calibration:	April 22-24, 2013, and May 10, 2013
Report Date:	June 4, 2013

Instrument Calibrated

Type of Instrument:	PKMA Model KM-3
Quantity:	1
Serial Number:	3735928559

Neutron Sources

Californium-252 spontaneous fission sources with the following emission rates were used in this calibration:

Table 1: Source Emission Rates

Source Name	Neutron Emission Rate	Relative Uncertainty
NS-130	8.84×10^7 s^{-1}	2.4 %
NBS-131	3.87×10^8 s^{-1}	2.4 %
NS-100	8.33×10^6 s^{-1}	2.6 %
NS-118	2.79×10^7 s^{-1}	2.6 %

Sources NBS-131, NS-130, and NS-108 were moderated in the NIST 30 cm diameter heavy water sphere. Source NS-118 was unmoderated. The uncertainties in the last column of Table 1 are 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 is believed to lie with a level of confidence of approximately 95 percent.

Methods & Results

In this report "Dose Equivalent" refers to "Ambient Dose Equivalent" as defined in ISO 8529-1 (2001) [1].

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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. The FFDE rate is the dose equivalent rate due to neutrons from the source alone, in the absence of background caused by neutrons scattered into the instrument from the walls, the air in the room, and the source support. The FFDE rates, in mrem/hr, are calculated from the formulæ:

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

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 μSv/h is just 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 range from 4.2 % to 8.6 % (moderated sources) and 2.3 % to 5.6 % (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 factor 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 μSv/h.

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 is believed to lie with a level of confidence of approximately 95 percent. These uncertainties include both Type A uncertainties and Type B uncertainties (*i.e.*, uncertainties determined by other than strictly statistical means).

The Type A uncertainties, for these data, range from <1 % to 6.4 % (moderated sources) and <1 % to 6.9 % (bare sources). They are determined from the uncertainties, for each measurement condition, in the least-squares linear fit values of the slope of integrated dose *vs.* time, expressed as a fraction of the fitted slopes.

The Type B uncertainties include the uncertainty in the source strength (2.4 % to 3.4 % (moderated sources), 2.4 % to 2.6 % (bare sources)), the uncertainty in the neutron scatter correction (1.7 % to 3.5 % (moderated sources) and <1 % to 2.2 % (bare sources), depending on the distance from the source), and the uncertainty in the location of the effective center of the instrument (1 % to 3 % (moderated sources) and 1 % to 6 % (bare sources), depending on the distance from the source).

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 value listed for the mean is the weighted mean of the listed calibration factors.

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 californium neutron energy spectra as documented in ISO 8529-1:2000, (3) the meter, and (4) the second. Fluence to

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dose equivalent conversion coefficients from ICRU 57 / ICRP 74 [2] were used to calculate the spectrum-averaged free-field dose equivalent.

Measurements associated with this calibration were performed by:

For the Director,
National Institute of Standards & Technology

Alan K. Thompson, Physicist
Neutron Physics Group

Lisa R. Karam, Chief
Radiation Physics Division
Physical Measurement Laboratory

Reviewed by Thomas R. Gentile, Physicist
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Date(s) of Irradiation: April 22-24, 2013, and May 10, 2013

Type of Instrument: PKMA Model KM-3

Quantity: 1

Serial Number: 3735928559

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-131	32.6	152	160	162	0.988 ± 0.090
NBS-131	44.9	79.9	83.2	88.6	0.940 ± 0.083
NBS-131	45.8	76.9	80.2	85.5	0.938 ± 0.083
NBS-131	45.8	76.9	80.2	84.3	0.951 ± 0.084
NS-130	31.9	38.1	40.1	41.7	0.961 ± 0.088
NS-130	44.9	19.2	20.0	21.2	0.944 ± 0.095
NS-130	71.5	7.56	7.99	8.29	0.964 ± 0.090
NS-108	40.7	3.82	3.99	4.26	0.937 ± 0.090
				Average	0.943 ± 0.068

Calculations in this table were performed at higher numerical precision than is displayed, and thus it may not be possible to exactly reproduce the results using the values shown.

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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-39	46.0	2.9	3.0	3.2	0.941 ± 0.050
NS-100	91.7	9.5	10.0	10.7	0.937 ± 0.049
NS-100	52.1	29	30	31	0.975 ± 0.042
NS-118	52.3	98	100	101	0.997 ± 0.044
NS-118	30.2	293	300	300	1.003 ± 0.051
NS-118	21.5	578	600	599	1.003 ± 0.066
NS-118	17.7	853	899	886	1.025 ± 0.067
				Average	0.971 ± 0.037

Calculations in this table were performed at higher numerical precision than is displayed, and thus it may not be possible to exactly reproduce the results using the values shown.

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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 [3] [4] derived from ICRP 21 [5]. Although ICRP 21 was superseded by ICRP 74 [2], regulatory agencies have only recently begun to adopt the newer recommendations [6]. 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 D_2O-moderated Cf-252 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 74, "Conversion Coefficients for use in Radiological Protection against External Radiation," Pergamon Press, Oxford (1996).

[3] R. B. Schwartz, "NBS Measurement Services: Neutron Personnel Dosimetry," National Bureau of Standards (U.S.), Special Publication 250-12 (July 1987).

[4] R. B. Schwartz and C. M. Eisenhauer, "Procedures for Calibrating Neutron Personnel Dosimeters," NBS Special Publication 633 (1982).

[5] ICRP Publication 21, "Data for Protection Against Ionizing Radiation from External Sources," Pergamon Press, Oxford (1973).

[6] U.S. Federal Register. "Occupational radiation protection," Washington, DC: U.S. Government Printing Office; 10 CFR Part 835 (2007)

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