

# 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 habitable areas. The fields available are those produced by californium-252 sources, either lightly encapsulated and 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* 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<sub>2</sub>O-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).

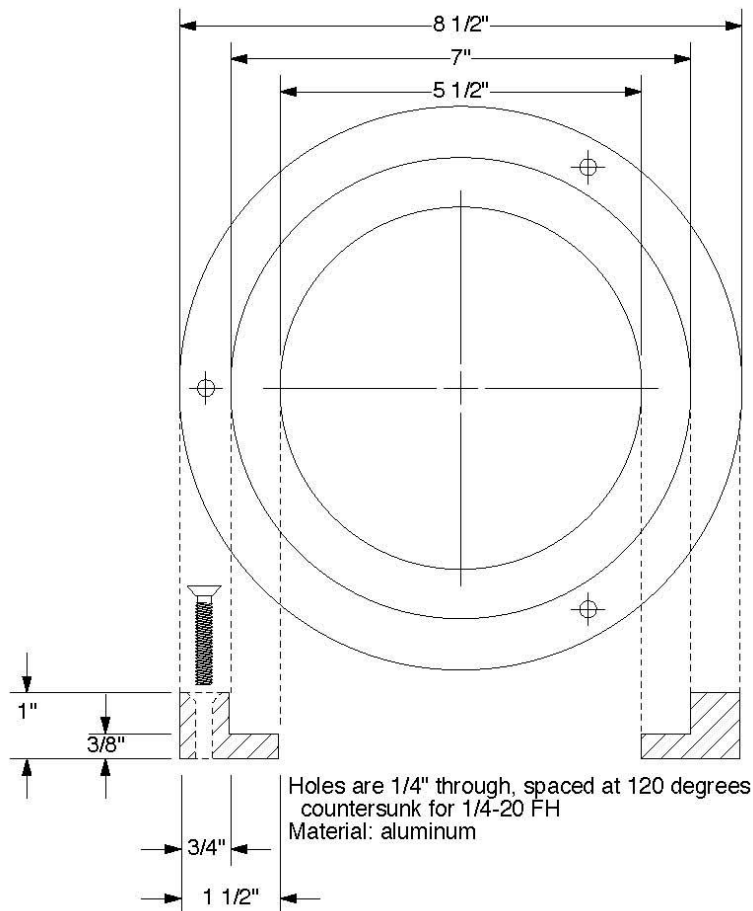
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**Figure 2:** Ring stand used to hold “9-inch” REM ball



**Figure 3:** Mechanical design of the REM ball ring stand.



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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  $15 \times 10^{-6} \text{ K}^{-1}$ , while aluminum alloys have a coefficient of  $23 \times 10^{-6} \text{ K}^{-1}$ . 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 (a larger temperature change would be required to degrade our measurement for steel). The temperature of the calibration range is controlled to  $\pm 5 \text{ K}$ , 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<sub>2</sub>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.

A *USB Video Frame Grabber* is used to save the video images to the hard disk of a *Macintosh data acquisition computer*. Software on the computer saves the video image 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 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 subversion repository on [irdilbert.ncnr.nist.gov](http://irdilbert.ncnr.nist.gov). 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 "Appendix C: Video

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Analysis Software.”

Comments in the subversion repository 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 and validation of new versions will be indicated in the subversion repository comments. Only validated versions of the code will be used for actual calibrations.

## Safety

ALARA procedures are observed with guidance from the NIST Health Physics group. “Distance” and “shielding” (being out of the room when the source is raised) are vastly preferred to “Time” (staying in the vicinity of the source for as little time as possible).

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 requirement is 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 is very low, a reading above 0.1 mremh is a cause for worry, and is discussed with the client.

### Determination of Room Return

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 combination. Equation (19) now reads:

$$\frac{M_T(I)}{\Phi F_1(I)(1 + AI)} = RF(1 + SI^2 + QI^4)$$

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

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calibration range can change the room return corrections. The person performing the calibration ensures and documents 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 room calibrations shall cease until room return corrections can be verified.

**Table 1: Room Return and Air Scatter Corrections**

Device	S (Bare) Quadratic (m <sup>-2</sup> )	A (Bare) Air Scatter (m <sup>-1</sup> )	S (Moderated) Quadratic (m <sup>-2</sup> )	Q (Moderated) Quartic (m <sup>-4</sup> )	A (Moderated) Air Scatter (m <sup>-1</sup> )
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 <sup>-1</sup> )	Isotopic Calibration Date	Isotopic Percent <sup>250</sup> Cf	Isotopic Percent <sup>252</sup> Cf	Isotopic Percent <sup>254</sup> Cf
NS-118	2/1/94	4.79×10 <sup>8</sup>	2/14/85	8.16	86.26	0.021
NS-100	3/9/06	6.79×10 <sup>6</sup>	7/2/75	8.05	87.7	0.028
NS-39	8/17/94	6.08×10 <sup>6</sup>	12/20/70	10.83	84.82	0.028
Cf-144	2/20/83	1.27×10 <sup>7</sup>	7/27/70	9.76	84.34	0.017
NS-130	1/10/90	4.42×10 <sup>9</sup>	2/23/87	8.33	85.08	0.014
NS-108	10/30/86	1.123×10 <sup>9</sup>	9/26/77	7.736	87.726	0.039
NBS-131	1/10/94	6.87×10 <sup>9</sup>	9/2/92	9.22	81.99	0.018
NBS-132	5/11/98	7.11×10 <sup>9</sup>	8/29/96	9.36	80.98	0.01

Source fluence rate in cm<sup>-2</sup>s<sup>-1</sup> 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 is documented in the sample report at the end of this procedure.

### 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 source. “9-inch” REM balls have the “ring stand” to set their position. Any other detectors or phantoms are vertically positioned using a lab jack and 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.

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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.

### **Establishing Traceability of Stopwatch**

The stopwatch used in irradiation of dosimeters should be traceable to standard time to a reasonable approximation. 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 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 ( $\approx$  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 of the same order as the uncertainty in the position of the source/position of the dosimeter.

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

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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 areas temperature is regulated better than the calibration range). Because dosimeters can be sensitive to heat, and are sensitive to radiation, 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; no recently calibrated analog meters have had this feature.

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.

### **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 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 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

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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 there is any instability, 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 IRD 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 comparisons with other National Measurement Institutes, as specified in IRD-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

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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 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  $^{252}\text{Cf}$  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 IRD-G-06 and section 4.3.4.2 of IRD-QM-II. Laboratory notebooks containing these data are kept in building 245, room B21.

### Procedures Specific to Active Devices

Raw data files (screen dumps) are copied from the data acquisition machine to h122113.ncnr.nist.gov as quickly as possible after acquisition. 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 h122113.ncnr.nist.gov. 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).

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2. R.B. Schwartz and C.M. Eisenhauer, *The Design and Construction of a D<sub>2</sub>O-Moderated <sup>252</sup>Cf 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](http://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 of reports and any pertinent data, are kept in folders on [h122113.ncnr.nist.gov](http://h122113.ncnr.nist.gov) in a folder titled "Instrument Calibration Reports." 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 (after it has been received). These calculations are stored in Igor Text Format (.itf), which can be easily reloaded into Igor for later checks, but are also human readable. As with all data on [h122113.ncnr.nist.gov](http://h122113.ncnr.nist.gov), these files are backed up approximately weekly, 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 and copies are placed into the calibration folder to be returned to the calibration office, and to a file folder containing other relevant information to be stored in Building 235, Room B186. These file folders are labeled with the same information as the computer file folders on [h122113.ncnr.nist.gov](http://h122113.ncnr.nist.gov).

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

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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 is stored in a SVN server on [irdilbert.ncnr.nist.gov](http://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.

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For both types of instruments, the tables “AnalysisTable” and “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.

## 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
```

CfAtomCompCalib,sourceAtomComps,sourceCalibDates,sourceCalibFluence,atomCompDates,CfNus,CfActivityACC

```
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
```

```
// find which source this is in the list -- index then will find all other information
about the source index =
```

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## NEUTRON PERSONNEL DOSIMETRY

```

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];
cfSourceCalibVal = sourceCalibFluence[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)

return(Activity(month,day,year)) 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 CfHalfLives = root:cfCalibFolder:CfHalfLives
WAVE cfActivitySC = root:cfCalibFolder:cfActivitySC
CfAct[] = CfActivitySC[p]*exp(-ln(2)*(date2secs(year,month,day)-CfSourceCalibDate)/ CfHalfLives[p]); // print day,
"/",month,"/",year // cfAct = CfActivitySC*exp(-ln(2)*(date2secs(1994,10,18)-CfSourceCalibDate)/CfHalfLives)
cfAct = CfActivitySC*exp(-ln(2)*(date2secs(year,month,day)-CfSourceCalibDate)/ CfHalfLives) // print
sumwave(cfAct), sumwave(cfactivitySC), cfSourceCalibVal
return( cfSourceCalibVal*SumWave(cfAct)/SumWave(cfActivitySC)); End

Macro CrunchCalib()
variable whichSource=-1;
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)]
dCorr = 2*CorrPct/5
// change formula for "dDists" to reflect source of uncertainty better; dR/R is 0.5 cm. -- AKT 12/9/98
dDists = 2*(2*0.5/D_CC)*100
dConv = FindStringInWave(root:cfCalibFolder:sourceNames, sourceName)
dConv = 2*(1 + (abs(cmpstr(root:cfCalibFolder:sourcetype[dConv],"bare")))*3)
dTotal = sqrt(dQ^2 + dCorr^2 + dDists^2 + dReading^2 + dConv^2)
print "Did you remember to multiply dReading by 2?"
print "Weighted Average Calibration Factor is ",CalcMeanCalib(CalFac, dTotal, 1)," ± ",CalcMeanCalib(CalFac,
dTotal, 0)," %"
wavestats/q CalFac

```

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```

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
wvestats/q dReading
print "Type A uncertainties range from ", V_min, " to ", V_max
wvestats/q dQ
print "Source uncertainties range from ", V_min, " to ", V_max
wvestats/q dCorr
print "Correction uncertainties range from ", V_min, " to ", V_max
wvestats/q dDists
print "Distance uncertainties range from ", V_min, " to ", V_max
print ""
SetDataFolder fldrSav 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)]
dCorr = 2*CorrPct/5
dConv = FindStringInWave(root:cfCalibFolder:sourceNames, sourceName)
dConv = 2*(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, 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 revision $Revision: 1.15 $";
print "Did you remember to multiply dReading by ONLY 100?"
// 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;

```

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```

    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
    print "Type A uncertainties range from ", 2*V_min, " to ", 2*V_max
    exportVarNames[whichExportVar] = "UncertTypeA"; exportVarMins[whichExportVar] = 2*V_min;
exportVarMaxs[whichExportVar] = 2*V_max;
    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 ""
    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
    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)] dCorr = 2*CorrPct/5 dDists = 2*(1.0/D_CC)*100 dConv =
FindStringInWave(root:cfCalibFolder:sourceNames, sourceName) dConv = 2*(1 +
(abs(cmpstr(root:cfCalibFolder:sourcetype[dConv],"bare")))*3) dReading = 2*100*dTimeUp/TimeUp; dTotal =
sqrt(dQ^2 + dCorr^2 + dDists^2 + dReading^2 + dConv^2)
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

Macro DoPlanCalib()
PlanCalib()
End

```

Macro

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```

DoPlanCalibDosimeter()
PlanCalibDosimeter()
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 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 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

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

use Getopt::Long;
use File::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
            ) or die("unknown option");;
```

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```

if( $printhehelp )
{
    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 "~/dosimdaq/DosimDAQ.pl --delay 60 --howmany 12 --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)";
}
print join(", ", @atTimes)."\n";
#exit;
$delay = $atTimes[0];
$showmany = 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');
sleep $pause;

#print "(2) $pause, $delay, $showmany, $basename, $destdir\n";
#$showmany--;

```

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## NEUTRON PERSONNEL DOSIMETRY

```

mkpath($destdir, 1, 0755);

our $beforeAfterDiff = 1; # was 5 -- akt 20080623t101544
our $beforeAfterFrac = -0.48;
if(0)
{
  my $showManyFoo = 10;
  $before = time();
  #print "$before\n";
  foreach (1..$showManyFoo)
  {
    my $curTime = time();
    system("screencapture $destdir/$basename"._".foo.pdf");
    print "$basename"._".foo.pdf $curTime\n";
    sleep 5;
  }
  $after = time();
  $beforeAfterDiff = ($after - $before)/$showManyFoo;
  $beforeAfterDiff -= 5;
  print "beforAfterDiff $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 "beforAfterDiff final $beforeAfterDiff\n";
  print "beforeAfterFrac final $beforeAfterFrac\n";
}

our $whichone; $whichone = 1;
my $fracErr = 0;
my $fracFudge = 0;
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();
}
print "\a\a\a\n";
#foreach $whichone (1..$showmany)
#{
#  snapshot();

```

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---

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```
#   sleep $showLongToSleep unless ($whichone==Showmany)
#}

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

---

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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 a valiant 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](http://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
  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*3000) )
  // uncertDoses = sqrt(measDoses);
  // tempcomplex = ()
  avgnomdoses = average(nomdoses, starts, stops);
  averages = real(LinAnalyzeOne(measDoses, tTimes, uncertDoses, starts, stops, 0))
  sdevs = imag(LinAnalyzeOne(measDoses, tTimes, uncertDoses, starts, stops, 1))
  chisqs = real(LinAnalyzeOne(measDoses, tTimes, uncertDoses, starts, stops, 2))
  //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
```

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```
// CurveFit/Q line measDoses[startPt,stopPt] /X=timeWave /W=uncertWave /I=1
/M=dosemask / F={0.95,4}
CurveFit/Q line measDoses[startPt,stopPt] /X=timeWave /W=uncertWave /I=1
/F={0.95,4}
//CurveFit line measDoses[0,38] /X=tTimes /M=dosemask /D /R /F={0.950000, 4}
// print "W_ParamConfidenceInterval[1] = ",W_ParamConfidenceInterval[1];
if( whuh==2 )
return (cmlpx(V_chisq,W_sigma[1]));
else
return( cmlpx(W_coef[1],W_ParamConfidenceInterval[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,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
```

```
// apparently broken under OSX -- akt 20020819 1534
Function LoadFileNames()
NewPath /o/m="Select directory of video images" mod
string fubar;
fubar = IndexedFile( mod, -1, "????")
if( strlen(fubar)==0 )
abort
endif
variable numFiles = NumInList( fubar, ";");
make/o/n=(numFiles)/t fileList
return numFiles;
End
```

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

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

```
Function name2nomDose(aString)
string aString
return str2num(aString[0,search(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 = NaN;
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;
    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 )
    calFacs = AvgNomDoses/averages
End
```

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

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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 1.

**Table 1: 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.

## 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 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 2: Correlated Uncertainties**

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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 3: 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 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

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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 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:* Zaphod Beeblebrox  
Ronald Reagan Center for High Energy Physics  
Ref PO # 17025838588  
Receiving - Bldg 100  
Waxahachie, TX 75168

*Date(s) of Calibration:* May 1, 2010  
*Report Date:* May 6, 2010

### 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:

#### Source Emission Rates

Source Name	Emission Rate	Uncertainty
NS-108	$1.07 \times 10^7$ n/s	2.4 %
NS-130	$8.84 \times 10^7$ n/s	2.4 %
NBS-131	$3.87 \times 10^8$ n/s	2.4 %
NS-39	$6.49 \times 10^5$ n/s	2.6 %
NS-100	$8.33 \times 10^6$ n/s	2.6 %
NS-118	$2.79 \times 10^7$ n/s	2.6 %

Sources NS-130, NS-108 and NBS-131 were moderated in the NIST 30 cm diameter heavy water sphere. Sources NS-39, NS-100, and NS-118 were used "bare". The uncertainties in the last column 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

The instrument was mounted on a stand and measurements were made at various distances from one or another of the sources to obtain different dose equivalent rates. The first two columns in the table below list the source and distance combinations used.

The third column in the table below 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

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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 rate, in mrem/h, are calculated from the formula:

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

where  $Q$  is the source emission rate (n/s) and  $r$  (cm) is the distance listed in the table. The FFDE rate in  $\mu\text{Sv/h}$  is just ten times the FFDE rate in mrem/h.

The next column in the table 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 actual dose, divided by the instrument reading, gives the calibration factor listed in the last column of the table. 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  $\mu\text{Sv/h}$ .

The last column also gives the combined standard expanded uncertainties ( $k=2$ ) in the calibration factors. 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 6.35 % (moderated sources) and <1 % to 6.9 % (bare sources) and are the observed standard deviations of repeated instrument readings at a fixed Free Field Dose Rate. The Type B uncertainties include: the uncertainty in the source strength (2.4 % to 3.4 % moderated, 2.4 % to 2.6 % bare), uncertainty on 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, neutron scatter correction, and in 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 ambient dose equivalent conversion coefficients from ICRU 57 / ICRP 74 [1] 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

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Alan K. Thompson  
Physicist

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Lisa Karam, Chief  
Ionizing Radiation Division

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M. Arif, Leader  
Neutron Interactions and Dosimetry Group

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*Date(s) of Irradiation:* May 1, 2010  
*Type of Instrument:* PKMA Model KM-3  
*Quantity:* 1  
*Serial Number:* 3735928559

**Moderated Californium**

Source Name	Distance (D) (center to center) cm	Free-Field Dose equiv. Rate, mrem/h	Corrected Dose equiv. Rate, mrem/h	Instrument Readings, mrem/h	Calibration Factor
NS-108	94.6	2.8	3.0	4.4	0.68 ± 10 %
NS-108	50.8	9.6	10.0	13.1	0.76 ± 9 %
NS-130	85.4	28	30	41	0.73 ± 9 %
NS-130	46.1	96	100	135	0.74 ± 9 %
NBS-131	55.7	287	300	404	0.74 ± 9 %
NBS-131	39.4	573	599	792	0.76 ± 9 %
				Average	0.74 ± 8.7 %

**Bare Californium**

Source Name	Distance (D) (center to center) cm	Free-Field Dose equiv. Rate, mrem/h	Corrected Dose equiv. Rate, mrem/h	Instrument Readings, mrem/h	Calibration Factor
NS-39	46.0	2.9	3.0	3.2	0.94 ± 5 %
NS-100	91.7	9.5	10.0	10.7	0.93 ± 5 %
NS-100	52.1	29	30	31	0.97 ± 4 %
NS-118	52.3	98	100	101	0.99 ± 4 %
NS-118	30.2	293	300	300	1.00 ± 5 %
NS-118	21.5	578	600	599	1.00 ± 6 %
NS-118	17.7	853	899	886	1.02 ± 7 %
				Average	0.97 ± 3.7 %

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## Appendix: Calculating Free Field Dose Equivalent

Before July 1, 2009, the formulae used to convert from source emission rate to free-field dose equivalent in the “Methods & Results” section used spectrum-averaged fluence to ambient dose equivalent conversion factors [2] [3] derived from ICRP 21 [4]. Although ICRP 21 was superseded by ICRP 74 [1], regulatory agencies have only recently begun to adopt the newer recommendations [5]. The new conversion factors are also consistent with ISO 8529-1 (2001) [6].

The ICRP 74 fluence to ambient dose equivalent recommendations increase the spectrum-averaged fluence to dose conversion coefficients for both bare and D<sub>2</sub>O-moderated CF-252 by 16% relative to the values derived from ICRP 21. Thus, to convert 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 dose equivalent by 1.16.

## References

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

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