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Characterization of the Neutron Fields in the Lawrence Livermore National Laboratory (LLNL) Radiation Calibration Laboratory Low Scatter Calibration Facility

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1. Introduction

In June 2007, the Department of Energy (DOE) revised its rule on *Occupational Radiation Protection*, Part 10 CFR 835 [1]. A significant aspect of the revision was the adoption of the recommendations outlined in International Commission on Radiological Protection (ICRP) Report 60 (ICRP-60) [2], including new radiation weighting factors for neutrons, updated internal dosimetric models, and dose terms consistent with the newer ICRP recommendations. ICRP-60 uses the quantities defined by the International Commission on Radiation Units and Measurements (ICRU) for personnel and area monitoring [3,4,5] including the ambient dose equivalent H*(d). A Joint Task Group of ICRU and ICRP has developed various fluence-to-dose conversion coefficients which are published in ICRP-74 [6] for both protection and operational quantities.

In February 2008, Lawrence Livermore National Laboratory (LLNL) replaced its old pneumatic transport neutron irradiation system in the Radiation Calibration Laboratory (RCL) Low Scatter Calibration Facility (B255, Room 183A) with a Hopewell Designs irradiator model N40. The exposure tube for the Hopewell system is located close to, but not in exactly the same position as the exposure tube for the pneumatic system. Additionally, the sources for the Hopewell system are stored in Room 183A where, prior to the change, they were stored in a separate room (Room 183C). The new source configuration and revision of the 10 CFR 835 radiation weighting factors necessitate a re-evaluation of the neutron dose rates in B255 Room 183A.

This report deals only with the changes in the operational quantities ambient dose equivalent and ambient dose rate equivalent for neutrons as a result of the implementation of the revised 10 CFR 835. In the report, the terms ‘neutron dose’ and ‘neutron dose rate’ will be used for convenience for ambient neutron dose equivalent and ambient neutron dose rate equivalent unless otherwise stated.

2. Executive Summary

The issuance of Part 10 CFR 835 (2007) with revised radiation weighting factors and the installation of a new Hopewell N40 irradiator necessitated a re-characterization of the neutron fields in RCL’s Low Scatter Calibration Facility (B255, Room 183A).

The emission rates of the RCL’s two ^{252}Cf calibration sources were re-evaluated and the updated emission rates are provided in Appendix A. The neutron dose rates from the new Hopewell N40 irradiator configuration were evaluated using three different instruments:

- A Rotating neutron spectrometer (ROSPEC), which utilizes 6 detectors to measure the neutron energy and spectrum unfolding software to calculate the neutron dose. ROSPEC system provides the most accurate dose results in any neutron spectrum in the energy range from thermal to 5 MeV.
- SWENDI-II, a high-efficiency wide-range dose rate meter with ^{3}He detector in a 9” diameter polyethylene moderating cylinder loaded with tungsten power.

- NRD standard neutron dose rate meter (rem ball) with BF_3 detector in a 9-in.-diameter cadmium loaded polyethylene sphere.

The ROSPEC software utilizes both the 'old' (1996) and the revised 10 CFR 835 (2007) fluence-to-dose conversion factors, so a comparison of the dose rates can be made. The 'old' neutron fluence-to-dose conversion factors were based on the National Council for Radiation Protection Report No 38 (NCRP-38) [7]; the 'new' factors are based on ICRP Report No 74 (ICRP-74) [6]. The neutron fluence-to-dose conversion factors for both NCRP-38 and NCRP-74 are provided in Appendix C.

The measurement methodology and the experimental set up, as well as the calibration of the instruments are discussed in detail in sections 4, 5 and 6. ROSPEC measured neutron spectra and neutron dose rates, SWENDI-II and NRD measured dose rates at different distances from both bare and D_2O moderated ^{252}Cf sources and in different directions are presented in section 7 and in Appendices D and E. The neutron spectra and dose rates calculated by the MCNPX Monte Carlo radiation transport code using the 'old' (1996) and the revised 10 CFR 835 (2007) radiation weighting factors are presented in section 8, in Appendix F, and in reference [19].

Discussion of the neutron spectra in the Low Scatter Calibration Facility from both bare and D_2O moderated ^{252}Cf sources is provided in section 9, sub-section 9.1. Discussion of the neutron dose rates at various distances from both bare and D_2O moderated ^{252}Cf sources, and in various directions is provided in section 9, sub-section 9.2. A comparison and discussion of the dose rates measured by ROSPEC, SWENDI-II and NRD and those calculated by MCNPX is provided also in sub-section 9.2. The agreement between the measured dose rates is very good (i.e., within 10%). The MCNPX calculated dose rates were higher than all measured dose rates by 10–17%. The measured dose rates and the free field dose equivalent rates are compared in sub-section 9.2, as well as the neutron fluence-to-dose conversion factors derived from the old and the revised 10 CFR 835.

The recommended ambient neutron dose equivalent rates (H*10)), the personal neutron dose equivalent rates (Hp(10,0)), and the estimated overall uncertainties are provided in section 10. The ambient dose equivalent rates in the RCL Low Scatter Calibration Facility (Room 183A) will increase by (15–18)% for bare ^{252}Cf and 15.5% for D_2O moderated ^{252}Cf when the revised 10 CFR 835 radiation weighting factors are implemented. The personal dose equivalent rates will be higher than the ambient dose equivalent dose rates by 3.7% for bare ^{252}Cf and by 4.2% for D_2O moderated ^{252}Cf.

3. RCL Neutron Calibration Sources Characteristics

Two ^{252}Cf sources are currently used in the RCL's Low Scatter Calibration Facility. They are referred as the Large and Small ^{252}Cf sources with their evaluated activity given in Table 1.

Table 1. RCL's ^{252}Cf sources

Isotope	Alias	Designation	Evaluated neutron emission on 3/10/2008 n/s	Calibration uncertainty
^{252}Cf	Large	NSD-133	6.84E+08	3%
^{252}Cf	Small	NS-120	1.13E+07	3%

The data used to derive the above source emission rates is provided in Appendix A. Although the two ^{252}Cf sources differ in yield, they are similar in physical size and encapsulation. Thus they should produce the same neutron spectrum per source neutron.

Seven moderators are available to be used with these sources to modify the neutron energy spectra produced by the bare ^{252}Cf sources: heavy water (D_2O) with thicknesses 5, 10, and 15 cm and polyethylene with thicknesses 2, 5, 10 and 15 cm. A 1 mm cadmium (Cd) shield covers the 15 cm thick heavy water moderator (D_2O sphere). This conforms with National Institute of Standards and Technology (NIST) recommendation to use this configuration as a standard for calibrating instruments for use at nuclear power plants and is also widely used throughout the DOE complex. The sphere with a 15 cm D_2O moderator is often referred in the literature as 30 cm. in diameter D_2O sphere (or 15 cm radius D_2O sphere). The moderated spectra and dose measurements presented in this report were conducted exclusively with the ^{252}Cf sources moderated by 15 cm thick heavy water (D_2O) spherical assembly covered with 1 mm cadmium. The concentration of the heavy water (D_2O) in our moderating sphere was 99.98%.

Although the 15 cm thick D_2O spherical moderator is considered a national [9] and international [10] standard for ^{252}Cf moderated spectra, the design and the construction of such spheres varies among the calibration laboratories in the U.S. and the world (see Appendix B). The most significant difference is the opening in the sphere for the insertion of the ^{252}Cf source. For example,

- LLNL's sphere has a 36.5 cm diameter (18.25 cm radius) with an opening along the diameter for inserting the pneumatic transport tube that carries the ^{252}Cf source. The opening is 20.5 cm deep with 6.5 cm diameter (3.25 cm radius). This makes the sphere's effective thickness (D_2O thickness) equal to 15 cm (18.25 cm – 3.25 cm = 15 cm). Note that the D_2O moderator is 3.25 cm from the center of the ^{252}Cf source.
- The NIST D_2O sphere has a 30.0 cm internal diameter with a 1.19 cm diameter opening (stainless steel tube) for the ^{252}Cf source. The tube containing the NIST ^{252}Cf source traverses the entire sphere and it is filled with D_2O.

Schematic drawings of LLNL and NIST 15 cm D_2O spheres are presented in Appendix B. According to NIST [11], there may be no two D_2O spheres among the calibration laboratories that are absolutely identical in design and materials. The difference in the 15 cm D_2O spheres may cause larger discrepancies in the neutron dose rates from D_2O moderated ^{252}Cf sources than from bare (free-in-air) ^{252}Cf sources. Larger discrepancies in measured neutron dose rates from D_2O moderated ^{252}Cf source than from a bare ^{252}Cf have been noted before at LLNL and Pacific Northwest National Laboratory (PNNL) [12].

4. Methodology

A high resolution neutron spectrometer (ROSPEC) was used to measure the neutron spectra and neutron dose rates at various source-to-detector distances and locations in Room 183A in the neutron energy range of thermal to 4.5 MeV for both bare ^{252}Cf and D_2O moderated ^{252}Cf sources. Dose rate measurements were also performed using a Thermo Scientific SWENDI-II neutron rem meter calibrated at LANL. Both ROSPEC and SWENDI-II were loaned from Los Alamos National Laboratory (LANL) to LLNL to characterize the neutron fields. These instruments were previously used to successfully characterize the neutron fields at LANL, Brookhaven National Laboratory (BNL) [16], Pacific Northwest National Laboratory (PNNL) [17] and Savanah River Site (SRS) [18] calibration facilities. Neutron dose rate measurements were also performed with Thermo Scientific NRD neutron rem meter calibrated by NIST. A detailed and realistic model of the RCL's Low Scatter Calibration Facility was developed by the LANL team using facility drawings and on-site measurements. The LANL team performed Monte Carlo calculations of the neutron fluence and spectra, and neutron dose rates in Room 183A with MCNPX code [13]. Because ROSPEC measurements and MCNPX calculations use neutron spectroscopic information to derive the neutron dose, they can be used with different fluence-to-dose conversion factors. This methodology provides a convenient way to assess the change in the neutron dose and dose rates as a result of implementation of 10 CFR 835 (2007).

5. Equipment

5.1 ROSPEC

ROSPEC (ROtating SPECtrometer) is a neutron spectrometer designed to measure neutron energy spectra and to provide accurate neutron dose rate data. The instrument is manufactured by Bubble Technologies Industries (BTI) of Chalk River, Canada. ROSPEC is a fairly compact (16" in diameter and 23.75" high) device weighing about 50 lbs; however, it is not a field instrument for everyday use. ROSPEC consists of six gas-filled proportional counters and is shown in Figure 1.

ROSPEC is the only commercially available instrument that can fairly accurately measure the neutron doses and dose rates from various neutron fields in the energy range of thermal to 4.5 MeV by applying energy dependent fluence-to-dose conversion factors. Various conversion factors based on different recommendations (e.g., NCRP-38, ICRP-26, ICRP-74, etc.) can be used with the same neutron spectrum measurement, which provides a convenient way to compare the impact of different dosimetric models or regulatory revisions to the measured doses and dose rates.

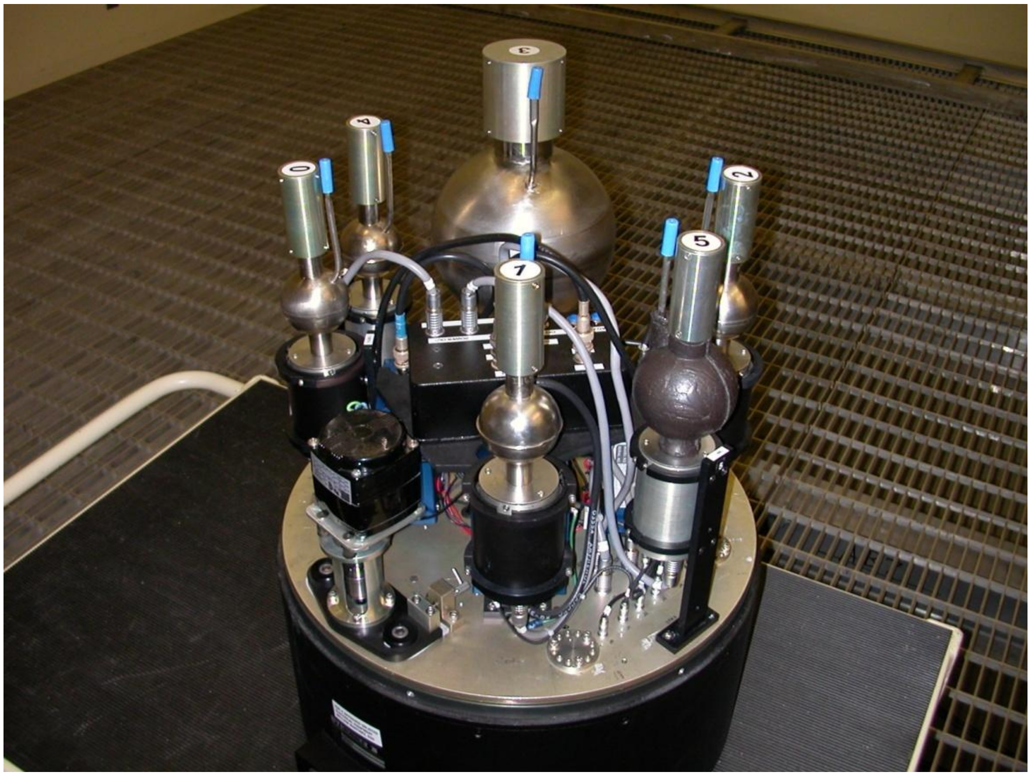


Figure 1. ROSPEC.

Four of the ROSPEC counters measure the neutron energy by measuring the energy from recoiling protons in the gas (H_2 or P10). The other two counters are filled with ^{3}He and use the (n,p) reaction to measure the neutron energy. Each of the counters is dedicated to a particular neutron energy range. The six counters cover the range from thermal to 4.5 MeV. The 5-10 MeV region is covered by a generic fission spectra supplied with ROSPEC. The six neutron counters are mounted on a 30 cm diameter circular rotating platform which constrains each of the counters to follow the same circular orbit. This allows each of the counters to sample the same average neutron field so that spatial variation of the field is averaged. Table 2 details the parameters for the ROSPEC counters.

Table 2. ROSPEC counter parameters

Counter #	**Name**	**Diameter (inches)**	**Gas**	**Pressure (atm)**	**Range (MeV)**
0	SP2-1	2	H_2	0.75	0.05-0.25
1	SP2-4	2	H_2	4.0	0.15-0.70
2	SP2-10	2	H_2	10.0	0.40-1.50
3	SP6	6	P10	5.0	1.20-4.50
4		2	^{3}He	0.08	$<1\times10^{-6}$
5		2	^{3}He	0.5	1×10^{-6}-1×10^{-2}

After the measurement is completed and the pulse height spectra are stored in the computer, a software program is used to calculate (unfold or extract) the neutron spectra from pulse height spectra (the recoil proton and nuclear reaction products spectra) from each of the counters. The unfolded six spectra are normalized and combined into one neutron spectrum with the neutron fluence being arranged in approximately 57 energy bins. The neutron spectrum together with fluence-to-dose conversion factors (derived from NCRP-38 and ICRP-74) are used to determine the dosimetric quantities (kerma, dose equivalent (NCRP-38), ambient dose equivalent (ICRP-74) and personal dose equivalent (ICRP-74)). The fluence and dose data are displayed for the thermal ($E_n < 1$ eV), epi-thermal (1 eV < E_n < 50keV) and fast (50 keV < E_n < 4.5 MeV) regions.

The obtained neutron spectrum is used to calculate the following dosimetric quantities: kerma, total dose equivalent (H), ambient dose equivalent (H*(10)) and personal dose equivalent (Hp(10,0)).

- H is the dose equivalent for neutrons as defined in NCRP-38.
- H*(10) is the ambient dose equivalent as defined in ICRP-74 at a point in a radiation field that would be produced by the corresponding expanded and aligned neutron field in the ICRU sphere at a depth of 10 mm on the radius opposing the direction of the aligned field.
- Hp(10,0) is the personal dose equivalent as defined in ICRP-74 in soft tissue at 10 mm below a specified point on the body at 0 degree between the incident unidirectional neutron field and the direction normal to the surface (in atero-posterior geometry).

The software linearly interpolates the data to determine the appropriate conversion factors at each energy bin mid-point. Kerma is calculated based on the data of Caswell et al [14] using the analytical expression given by Cross and Ing [15]. The energy dependence of the NCRP-38 dose equivalent factors is determined by interpolation of the data given in NCRP-38. The conversion factors for ambient dose equivalent (H*10) and personal dose equivalent (Hp(10,0)) are taken from the data listed in ICRP-74. A best fit curve is created through the fluence-to-dose conversion factors and the appropriate conversion factors at each energy bin mid-point were obtained from the curve. The energy bins and the fluence-to-dose conversion factors needed at these energies to calculate the kerma and dose equivalent (using both NCRP-38 and ICRP-74 conversion factors) are given in Table C-1 in Appendix C. The neutron dose as defined in 10 CFR 835 (2007) is consistent with the ICRP recommendations.

5.1.1 ROSPEC calibration

We used ROSPEC, serial number 01002, which was loaned from LANL's Health Physics Measurements Group. This ROSPEC was re-calibrated by LANL with metrology-grade mono-energetic neutron fields at Physikalisch-Technische Bundesanstalt (PBT) in Germany, the National Physical Laboratory (NPL) in UK, and thermal column data collected at the GKSS facility outside Hamburg, Germany. The ROSPEC was last calibrated at LANL on February 26, 2008 and was used at LLNL within one year of the calibration. The calibration procedure and the results are described in more detail in reference [16-20].

The ROSPEC only requires an energy calibration. The presumption is that if the neutron energy spectrum is correctly measured then the derived dose must also be correct, since the operation is a simple multiplication of the energy (fluence) distribution by the corresponding fluence-to-dose conversion factors. Each year LANL verifies the ROSPEC calibration in the following manner. LANL measures the neutron spectrum from a NIST traceable ^{252}Cf source and compares it against an MCNP calculated ^{252}Cf spectrum with parameters taken from the international standard ISO 8529 for ^{252}Cf [10] to account for any shifts or deviations in the measured neutron energy distribution from the NIST traceable ^{252}Cf source. Additionally, the strength and the dose rates measured by ROSPEC are compared with the decay corrected dose rates from the NIST traceable ^{252}Cf source.

ROSPEC has been also tested satisfactorily at NIST. The first performance test was at the time when ROSPEC consisted of the four original counters, so no assessment was made below 100 keV. ROSPEC was tested in four of the NIST standard fields: bare ^{252}Cf, and ^{252}Cf moderated by D_2O, H_2O and Fe [21]. The authors stated that ROSPEC "gave good differential energy spectral information and very accurate values for the integral quantities fluence, kerma and dose equivalent". A later ROSPEC performance test at NIST [22] included the 6 counter version that we used at LLNL. This version covers energies down to thermal neutron energies. The authors essentially echoed the findings of the previous test at NIST. The principle author of the last NIST testing provided [23] the following dose comparison with the NIST neutron calibration fields since this information was not included in the paper: for bare ^{252}Cf – 5%, for D_2O moderated ^{252}Cf – 3%.

At LLNL we verified ROSPEC calibration with an NRD rem meter calibrated by NIST with bare ^{252}Cf and D_2O moderated ^{252}Cf sources. We measured the dose rates with both instruments at five distances from a bare ^{252}Cf source and at six distances from a D_2O moderated ^{252}Cf source. Excellent agreement was achieved for bare ^{252}Cf (97.6% - 98.9%) and for D_2O moderated ^{252}Cf (90.6% - 95.5%). The larger difference for D_2O moderated ^{252}Cf is due to the fact that LLNL's D_2O sphere is slightly larger than the NIST D_2O sphere (see Appendix B). The results are presented in Table 3 below.

Table 3. Comparison of the dose rates measured by ROSPEC and NRD calibrated by NIST

Bare ^{252}Cf			
Distance (m)	**NRD-NIST (mrem/hr)**	**ROSPEC (mrem/h)**	**Ratio NRD-NIST/ ROSPEC**
1.5	--	--	--
2.0	203.9	207.9	98.1%
2.5	143.4	145.9	98.3%
3.0	109.8	112.5	97.6%
3.5	89.5	90.5	98.9%
4.0	75.5	76.8	98.3%

D_2O Moderated ^{252}Cf			
Distance (m)	**NRD-NIST (mrem/hr)**	**ROSPEC (mrem/h)**	**Ratio NRD-NIST/ ROSPEC**
1.5	76.9	84.25	91.3%
2.0	48.2	51.99	92.7%
2.5	34.3	37.84	90.6%
3.0	27.3	29.02	94.2%
3.5	22.2	23.97	92.7%
4.0	19.5	20.37	95.5%

5.2 SWENDI-II neutron rem meter

SWENDI-II is a high-efficiency, wide-energy commercial neutron dose rate meter consisting of ^{3}He detector in a 9” diameter high density polyethylene moderating cylinder and E600 survey meter, both manufactured by Thermo Scientific (formerly Eberline). The SWENDI-II neutron rem meter is shown in Figure 2. The polyethylene moderator is loaded with tungsten to extend its response to energies higher than 10 MeV. The high purity of the ^{3}He gas allows it to be used as a proportional counting gas as well as a media for neutron interaction. The manufacturer claims that this rem meter has a response which closely follows the theoretical dose for neutrons over the energy range from 0.025 eV (thermal) to about 10 MeV. The instrument we used has the following serial numbers: SWENDI-II # 102, E600 # 00956.

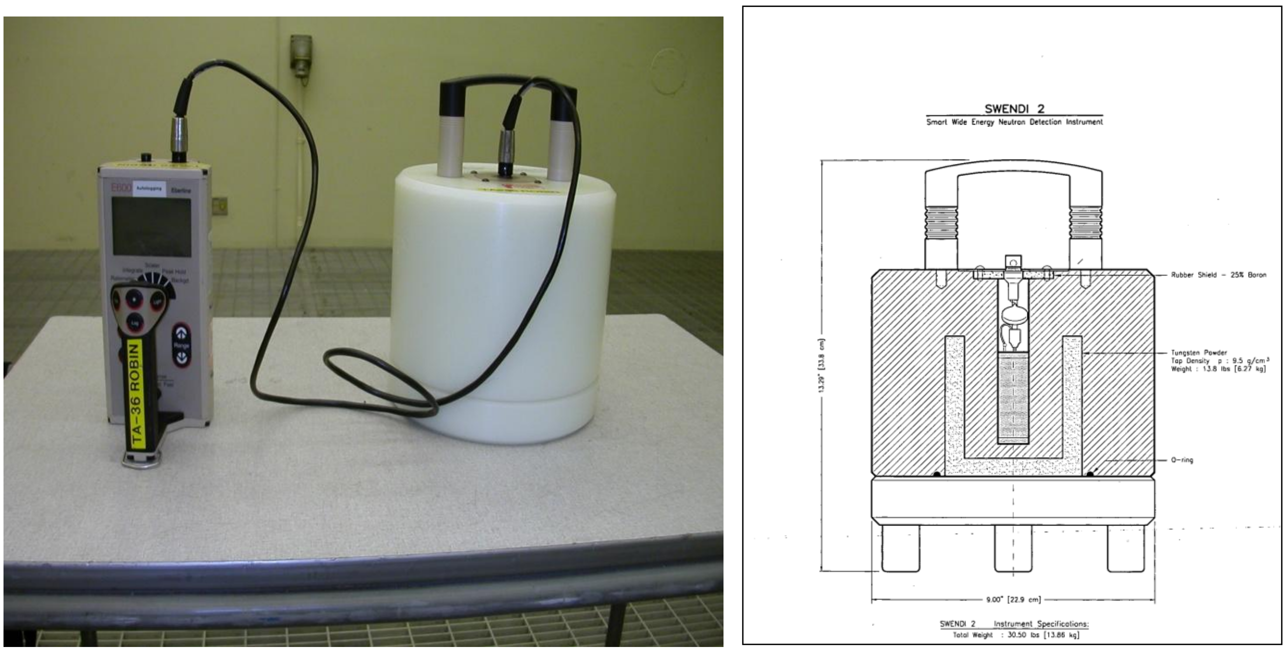


Figure 2. SWENDI-II neutron rem meter.

5.2.1 SWENDI-II calibration

SWENDI-II was calibrated at LANL radiation calibration facility on 11/13/2007 for both bare and 30 cm diameter D_2O moderated ^{252}Cf sources and was used all LLNL within 1 year of the calibration. The calibration factors used were determined by LANL for fluence-to-dose conversion factors derived from NCRP-38 and were equal to 518.8 cpm/(mrem/hr) for a bare (free in air) ^{252}Cf source and 644.3 cpm/(mrem/hr) for D_2O moderated ^{252}Cf source.

5.3 NRD neutron rem meter

The standard neutron rem meter was a commercial instrument from Thermo Scientific, model NRD consisting of a BF_3 detector in a 9” diameter cadmium loaded polyethylene sphere connected to an E600 meter from Thermo Scientific (Eberline). The BF_3 detector allows for excellent gamma rejection. The manufacturer claims that this rem meter closely follows the theoretical dose from neutrons over the energy range from 0.025 eV to about 10 MeV [24,25]. The manufacturer supplied neutron energy response curve in the NRD rem meter manual shows that the NRD response agrees well with the theoretical dose curve (supposedly NCRP-38) at energies below 0.1 eV and between 0.3 – 3 MeV. However, in the 0.1 eV– 300 keV energy region the NRD over-responds by as much as 10 times. The neutron rem meter is shown in Figure 3.

Figure 3. NRD neutron rem meter.

5.3.1 NRD calibration

The Thermo NRD rem ball (serial number 725627) and the Thermo E600 meter (serial number 2442) were calibrated on February 20, 2008 by the National Institute for Science and Technology (NIST) (NIST Test Folder Number 276407-08, Service ID Number 44060C) and used at LLNL within 1 year of its calibration. The NRD rem meter was calibrated with two bare ^{252}Cf sources and three ^{252}Cf sources moderated by the NIST 30 cm diameter D_2O water (heavy water) sphere using the NCRP-38 neutron fluence-to-dose conversion factors. The distances from the bare ^{252}Cf were from 18 cm to 108 cm and the delivered dose was from 4 mrem to 400 mrem. The distances from the D_2O moderated ^{252}Cf sources were in the 30-100 cm range and the delivered dose was from 4 to 450 mrem. The averaged calibration factors provided by NIST are 0.94±6% for bare ^{252}Cf and 0.69±8.7% for D_2O moderated ^{252}Cf source [26]. The LLNL NRD remball readings should be multiplied by these factors to get the true dose equivalent rate.

6. Experimental Set Up

RCL's Low Scatter Calibration Facility (Building 255, Room 183A) has 61-cm- (2-ft-) thick concrete walls and dimensions 12.2 m x 9.1 m and 6 m height (see Figures 4, 5, and 6). A suspended aluminum grating floor 2 m above the concrete floor serves as the main surface for positioning the detection equipment and the objects to be exposed in the radiation field. The calibration sources are stored in a shielded housing on the bottom concrete floor below the aluminum grid when not in use. The Hopewell N40 irradiation system positions the ^{252}Cf sources for exposure in the center of Room 183A at a height of 1 m above the aluminum grating floor and at 3 m above the concrete floor. The ROSPEC, SWENDI-II and NRD detector centers were positioned at the same height above the aluminum grating floor as the ^{252}Cf source (1 m) and in one horizontal plane with the ^{252}Cf source to eliminate effects of source anisotropy (see Figures 7, 8, and 9). The source-to-detector distance was measured from the source (or center of the moderating spheres for D_2O moderated source) to the center of the detector (or center of the rotating disc with the 6 detectors for ROSPEC). Direction is determined from the ^{252}Cf source towards the location of the counting instrument (ROSPEC, SWENDI-II, or NRD).

Measurements were conducted in three directions: North (along a line perpendicular to the North wall), East (along a line perpendicular to the East wall), and Northeast (from the source towards the NE corner of the room). We would have preferred to make the spectroscopic measurements with ROSPEC at distances starting at 0.5 m from the source; however, saturation in the detector electronics prevents such attempts: the buffer that stores and transfers the counts from the six detectors produces excessive dead time for count rates greater than 1000 counts per second, which corresponds to measurements at distances less than 2.5 m for the larger ^{252}Cf source. To circumvent this problem when the total count rates from the six ROSPEC detectors were high and the dead time affected the results, we measured the neutron spectrum in a two-step process—measurement with some of the detectors disconnected (e.g., #3 disconnected), followed by a measurement with the previously disconnected detectors and one additional detector (e.g., #3 and #4). The pulse height spectra (recoiled proton and nuclear reaction products spectra) from all detectors were combined and normalized by the counting time or the counts in the common detector. The combined spectra were then unfolded with the software program to obtain the neutron spectra. Measurements with ROSPEC were not attempted for distances less than 1 m because the rotating disk with the detectors comes so close to the ^{252}Cf source that the source-to-detector distance was not well defined, or for the case of moderating spheres was not possible at all.

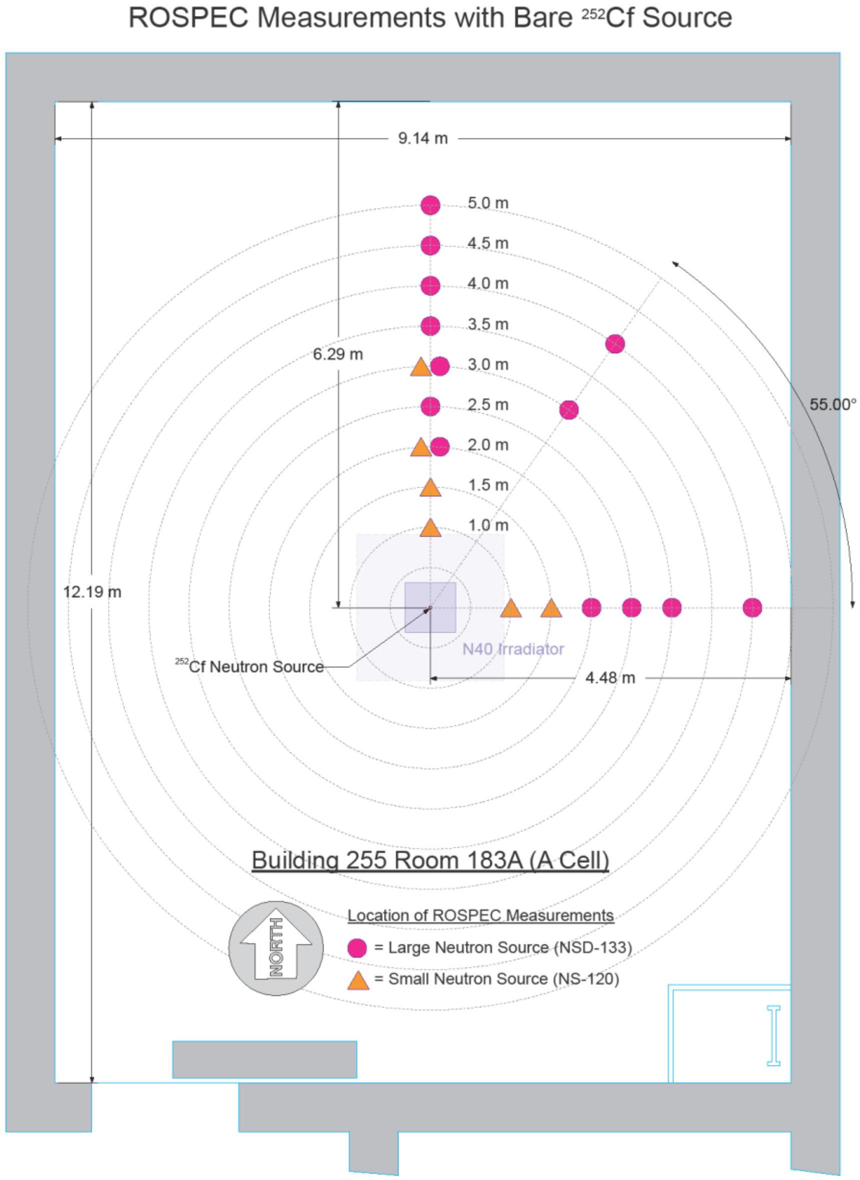


Figure 4. ROSPEC measurement locations with bare ^{252}Cf in Room 183A.

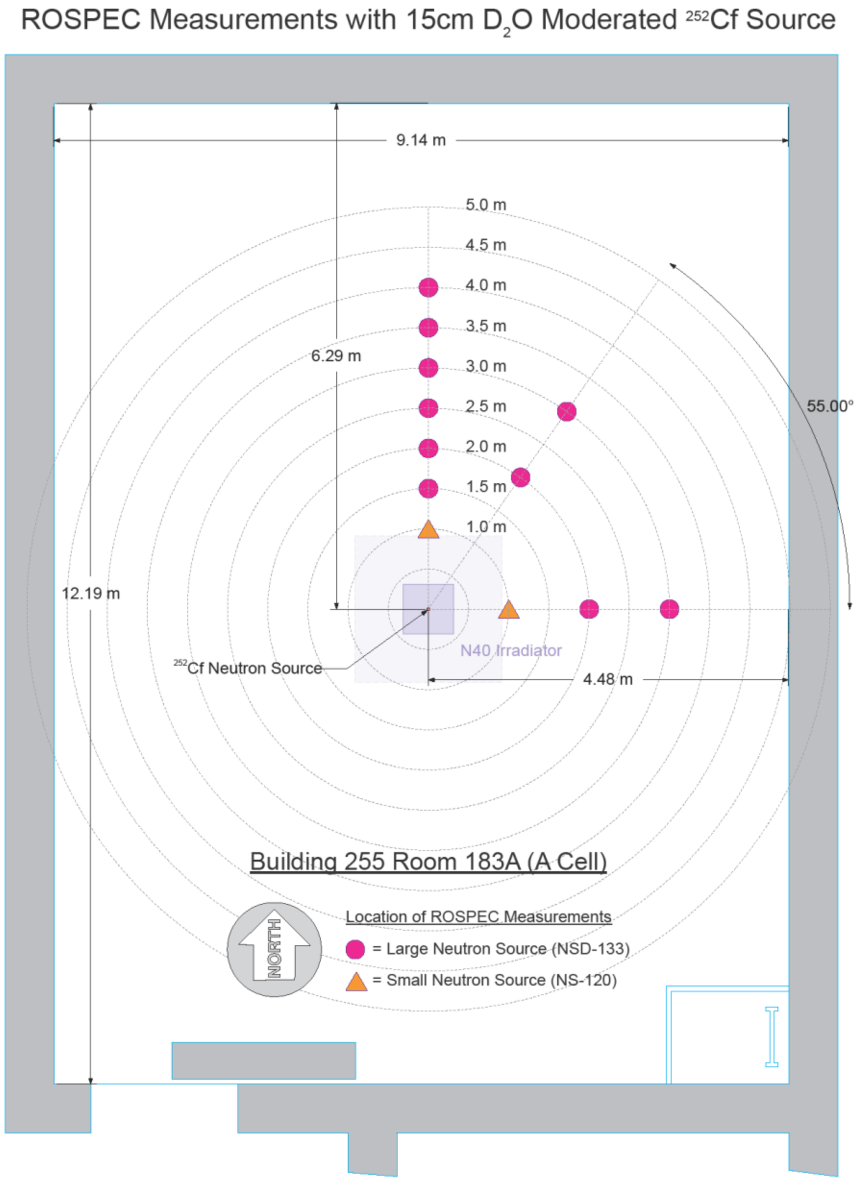


Figure 5. ROSPEC measurement locations with D_2O moderated ^{252}Cf in Room 183A.

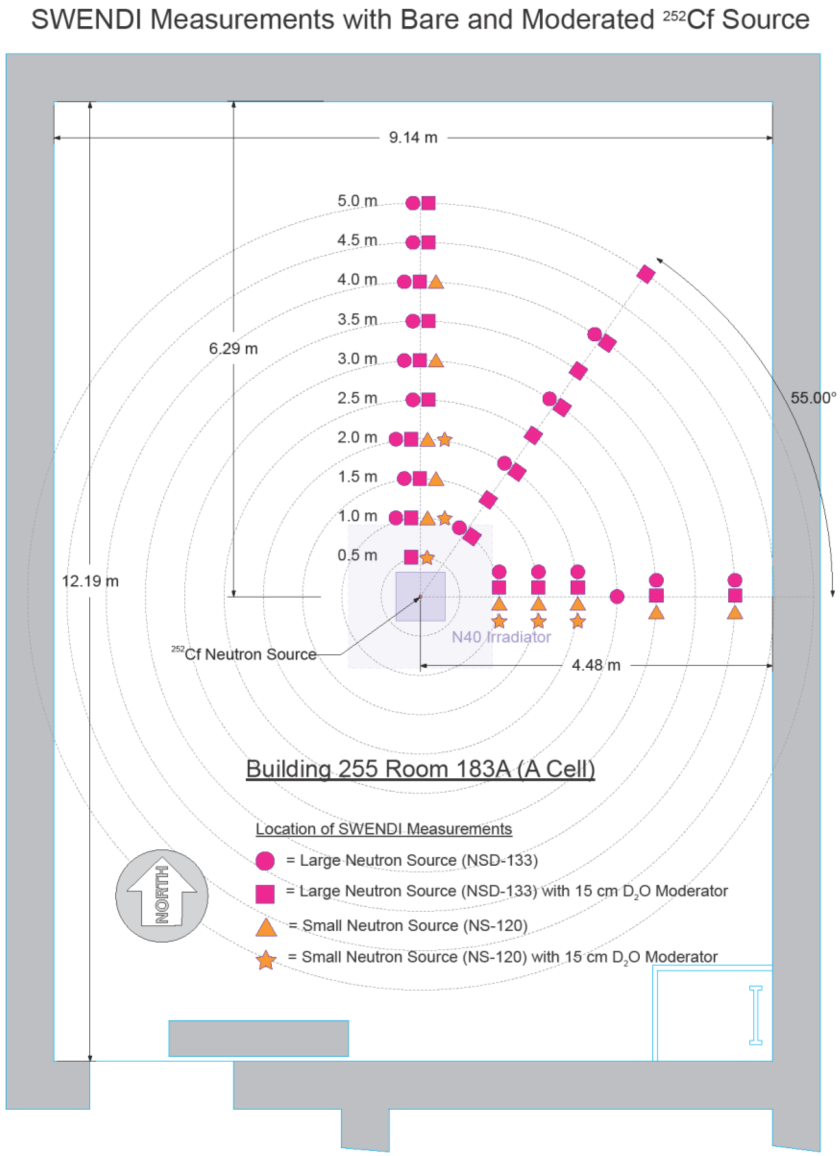


Figure 6. SWENDI-II measurement locations with bare and D_2O moderated ^{252}Cf.

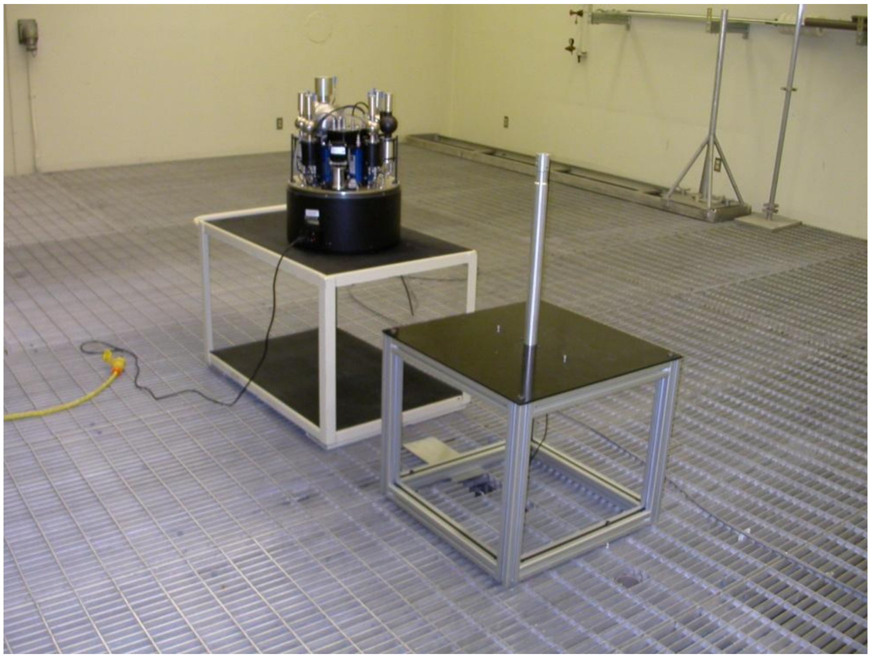


Figure 7. Neutron spectra and dose rates measurement from bare ^{252}Cf source.

The ^{252}Cf source is at the top end of the pneumatic tube during exposure. When not in use the ^{252}Cf sources are stored in a shielded compartment 2 m below the aluminum grating floor.

Figure 8. Neutron spectra and dose rates measurements from a D_2O moderated ^{252}Cf source.

Figure 9. Neutron spectra and dose rates measurements with ROSPEC and SWENDI-II (dose rates only) with D_2O moderated ^{252}Cf source.

7. Measurement Results

7.1 Background

The two ^{252}Cf sources were stored in a shielded compartment 2 m below the grating floor when they were not used. These sources produced negligible neutron background (less than 0.04 mrem/hr at the measurement locations) which was therefore not subtracted from the measurement data.

7.2 ROSPEC measurements

The ROSPEC dose rate and spectra measurements were taken from March 10 to April 2, 2008 with a few more measurements taken in May 2008. The instrument was not powered down during the entire period of March measurements, with the only stops of collection time for moving the instrument to a new location or installing the moderating D_2O sphere. This minimized any potential drift in the detector and processing electronics (pre amplifiers, amplifiers, MCA, buffers, etc.) from occurring. The locations of the ROSPEC neutron spectra and dose rate measurements in RCL are presented in Figure 4 (for bare ^{252}Cf source) and in Figure 5 (for D_2O moderated ^{252}Cf source). ROSPEC dose rate and spectra measurements were also performed at certain locations in LLNL and are published as a separate report [27].

7.2.1 ROSPEC neutron spectra measurements

The high resolution neutron spectra and detailed fluence and dosimetric data measured with ROSPEC for various distances from the ^{252}Cf sources are presented in Appendix D. The neutron spectra are presented in graphical form in Figures D-n (n=1,2,…,30) with n being the Figure's number corresponding to a particular location and particular neutron source. Since the energy spans over 9 decades, the results are presented, as it is customary, in logarithmic scale and in lethargy units. The top graphs in each figure represent the measured spectra from thermal to 10 MeV neutrons and are normalized per one source neutron. The bottom graphs show more details of the same neutron spectra in the 50 keV to 4.5 MeV region. The 50 keV to 4.5 MeV spectra are not normalized per one source neutron. The fluence and dosimetric data for each of the measured spectra are presented in Tables D-n (n=1,2,…,30) in Appendix D.

7.2.2 ROSPEC neutron dose rates measurements

The dose rates measured with ROSPEC from the two ^{252}Cf sources are presented in Table E-1 in Appendix E. The dose rates are calculated from the measured spectral fluence using the appropriate fluence-to-dose conversion factors. The locations of the ROSPEC measurements are presented in Figure 4 for bare ^{252}Cf source and in Figure 5 for D_2O moderated ^{252}Cf source. For each location three dose rates are given: dose equivalent rate based on the fluence-to-dose conversion factors derived from NCRP-38 (NCRP-38) , ambient dose equivalent rate based on the fluence-to-dose conversion factors from ICRP-74 (Ambient ICRP-74) and personal dose equivalent rate based on the fluence-to-dose conversion factors from ICRP-74 for personal dose in atero-posterior geometry (Personal ICRP-74). All dose rates are given in mrem/hr, the source to detector distance is in meters, and the direction is as viewed from the source. Dose equivalent rates measured with ROSPEC and calculated with NCRP-38 conversion factors are given also in Table E-4 in Appendix E for comparison with the SWENDI-II measurements.

7.3 SWENDI-II dose rates measurements

The locations of the dose rates from both Cf sources measured with SWENDI-II are presented in Figure 6. The dose rates were measured from March 10 to March 12, 2008 and are presented in Table E-2 in Appendix E. They are not decay corrected to one single date because the corrections would be negligible. The dose rates were determined from the average neutron count rate multiplied with the appropriate calibration coefficient (see section 5.2.1 SWENDI-II calibration). The count rates were averaged over a sufficient time to achieve statistical error of less than 1%. For the bare Cf source the counting times were 1-2 minutes for the Large source and 3-5 minutes for the Small source. For the D_2O moderated Cf source the counting times were 1-10 minutes for the Large source and 10-20 minutes for the Small source. SWENDI-II's calibration factors for bare and 15 cm D_2O moderated ^{252}Cf are based on NCRP-38 fluence-to-dose conversion factors.

7.4 NRD dose rates measurements

The neutron dose rates were measured with a NIST-calibrated NRD neutron rem meter at five distances from a bare ^{252}Cf source and at six distances from a D_2O moderated ^{252}Cf source in August 2008. Calibration factors of 0.94 for bare ^{252}Cf and 0.69 for D_2O moderated ^{252}Cf were applied in accordance with the NIST Calibration Report [26]. The measured neutron dose rates are presented in Table E-3 in Appendix E. The measurements were conducted only in the North direction because: the North wall was furthest from the source; we had the most complete set of data from the other instruments in North direction; and, we have decided to use primarily this direction for instrument calibration. The neutron dose rates were measured from the Large ^{252}Cf source and were decay corrected for comparison with ROSPEC and SWENDI-II measurements. Comparison of the measured neutron dose rates by NRD, ROSPEC and SWENDI-II is provided in Table 11 in section 9.2.5.

8. Monte Carlo Calculations of the Neutron Spectra and Dose Rates

A team from the Health Physics Measurement Group, RP-2 from Los Alamos National Laboratory conducted Monte Carlo simulations using Los Alamos MCNPX™ code [19]. MCNPX™ code is the latest version of the well-known MCNP code with improvements in the higher energies that are outside of the energies of interest to this characterization effort. The LANL team developed a detailed and realistic model of LLNL's Low Scatter Calibration Facility (B255 Room 183A) using available facility and equipment drawings and on-site measurements. The neutron spectra and dose rates were calculated at 50 cm intervals from 0.5 m to 5 m in the North, Northeast and East directions for both bare and D_2O moderated, large and small, ^{252}Cf sources. The calculated spectra compare well with those measured with ROSPEC as evidenced in Figure 10 for a bare ^{252}Cf and in Figure 11 for D_2O moderated ^{252}Cf source [19].

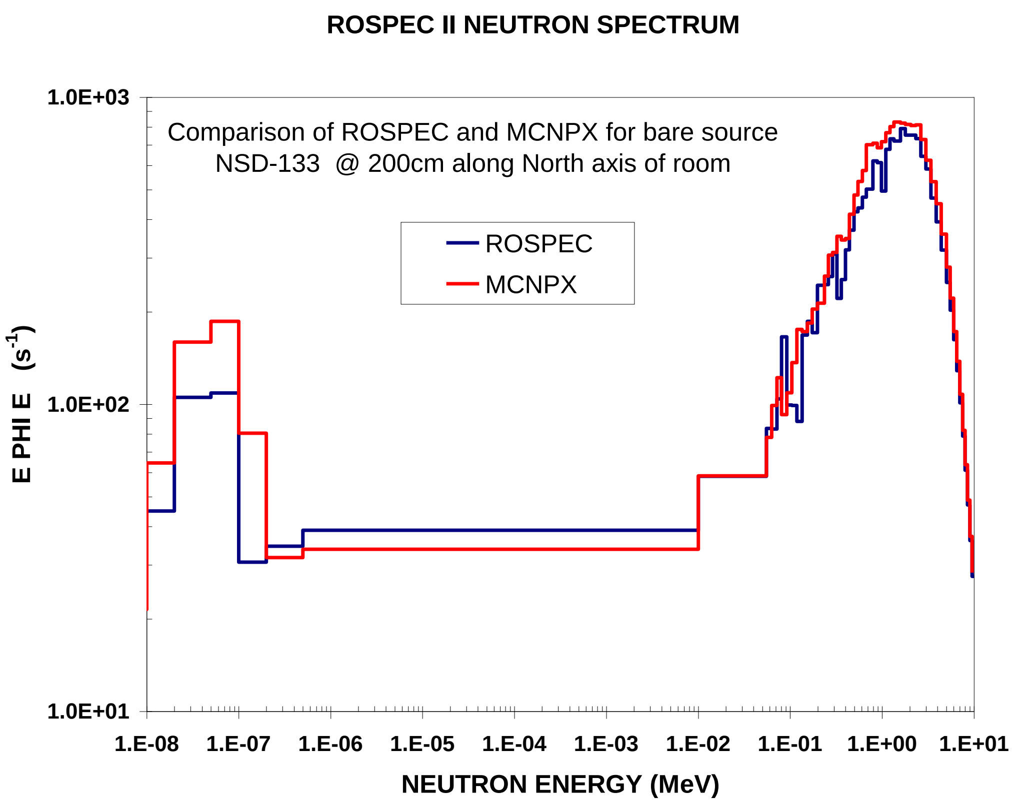


Figure 10. Absolute comparison of ROSPEC and MCNPX spectra for bare ^{252}Cf.

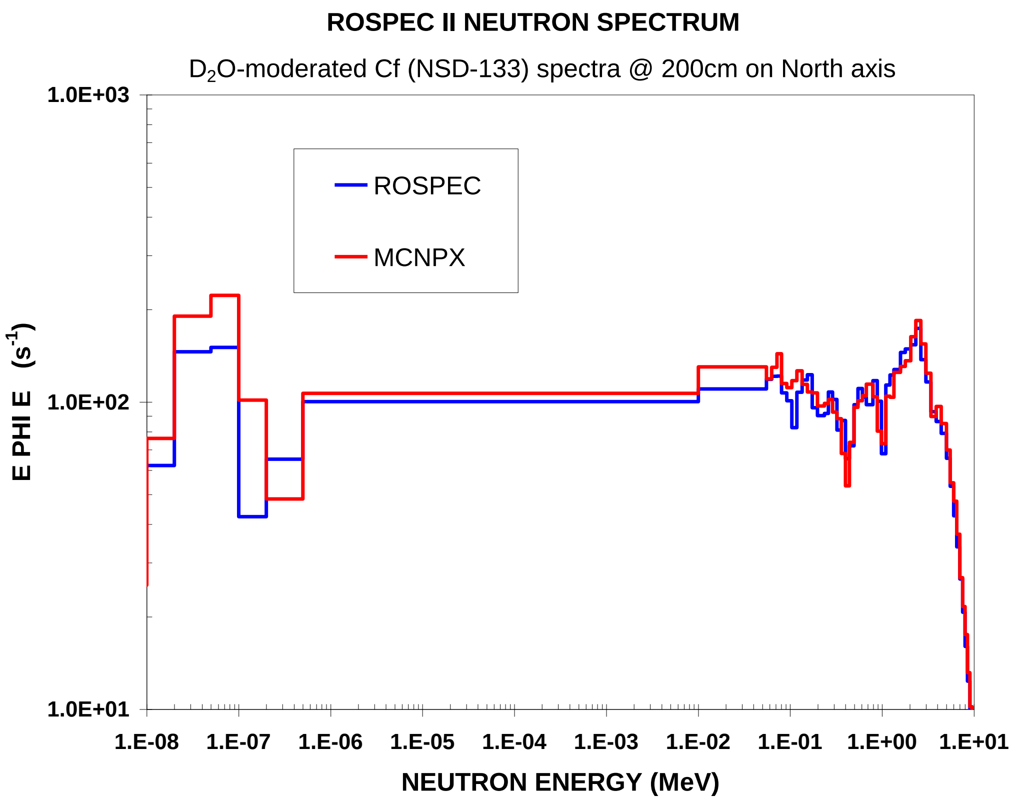


Figure 11. Absolute comparison of ROSPEC and MCNPX spectra for D_2O moderated ^{252}Cf.

The neutron fluence spectral data were then used to calculate the dose equivalent rates using both NCRP-38 and ICRP-74 dose conversion coefficients [19]. A summary of the calculated neutron dose equivalent rates at various distances in the North, East and Northeast directions is presented in Appendix F.

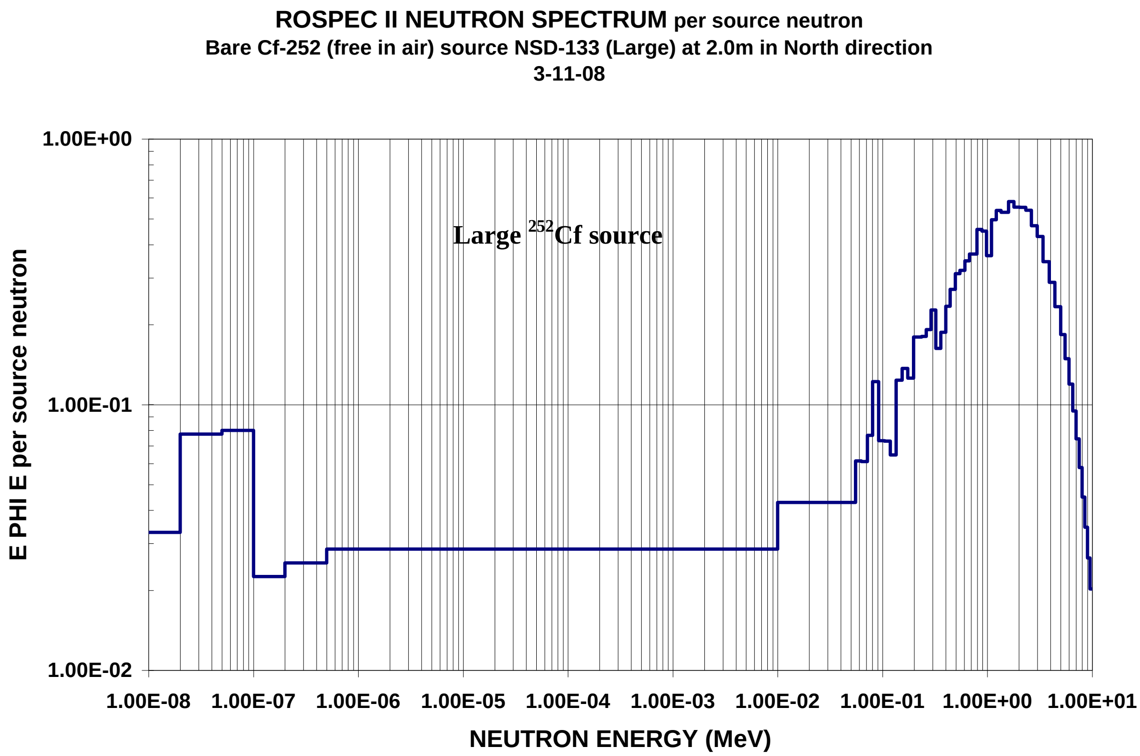
9. Discussion

9.1 Neutron spectra

On all ROSPEC plots of the neutron spectra distribution the vertical axis is in lethargy units. The lethargy is equal to phi(E)/[ln(E2/E1)], where phi(E) is the neutron fluence (in neutrons per cm^2) in a given energy bin and E2 and E1 are the upper and lower bin boundary energies. E PHI E on the plots is a shorthand for lethargy because it often is approximated with E*phi(E)/deltaE. A more detailed explanation of the axis of the energy distribution plots is provided in Appendix D.

9.1.1 Spectra from the Large and the Small ^{252}Cf sources

There is no noticeable difference between the neutron spectra from the bare (free in air) Large and the Small ^{252}Cf sources, when measured at the same location as shown in Figure 12, 2 m from the source in the North direction. The same is true for other locations where it was possible to measure the spectra from the two sources, indicating the inner encapsulation of the ^{252}Cf sources and the "rabbit" containers are similar for both sources and do not significantly contribute to differences in the spectra and the corresponding dose rates.



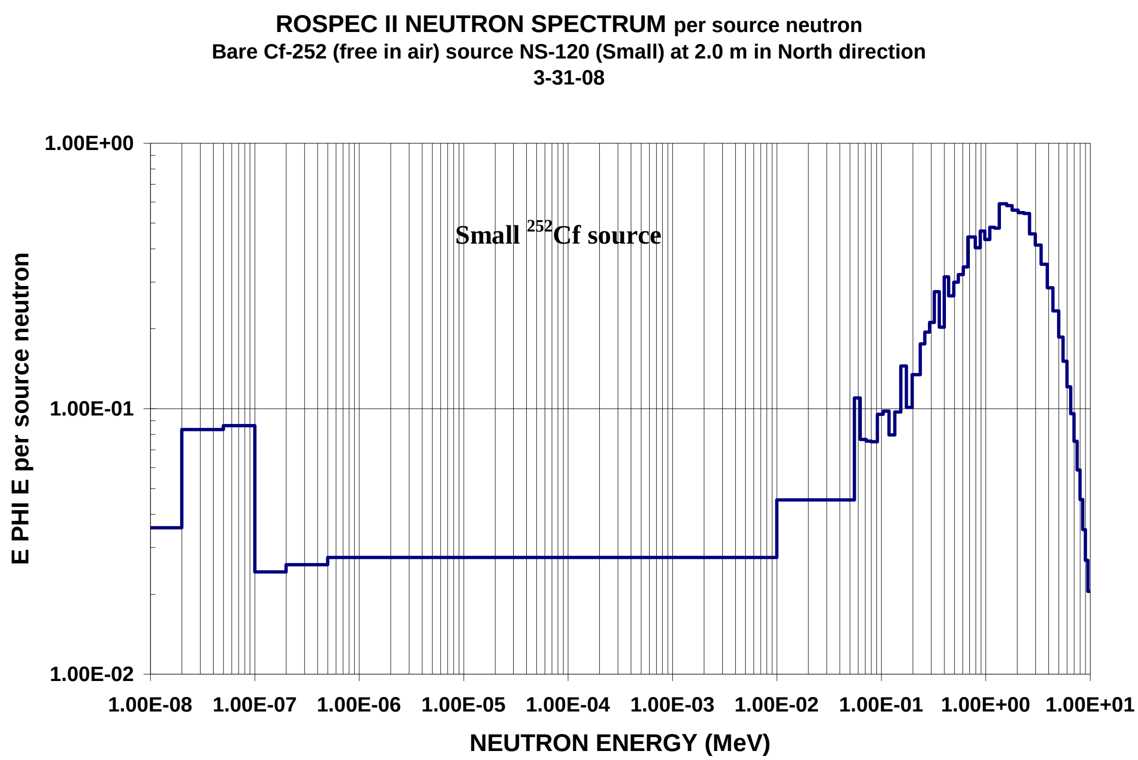


Figure 12. Spectra from (top) large and (bottom) small bare ^{252}Cf sources at 2.0 m.

9.1.2. Spectra at various distances from the ^{252}Cf source

The comparison of the measured neutron spectra from a bare (free in air) ^{252}Cf source at different distances from the source provides information on the contribution of the scattered neutrons from the concrete walls, basement floor and ceiling. Figure 13 shows the spectra from a bare ^{252}Cf source at distances from 1.0 m to 5.0 m from the source. It is evident that the fast neutrons peak around 1 MeV decreases with the distance (away from the source towards the wall). At the same time, the contribution of the epithermal and thermal neutrons increases with the distance (when getting closer to the wall). At very close distance to the source (e.g., 1.0 m) the contribution of the fast neutrons (~1 MeV) is approximately 80-90 times more than the contribution of the thermal and epithermal neutrons to the flux. At distances closer to the wall the relative contribution of the scattered neutrons from the wall increases more than 10 times and the ratio of the fast to thermal and epi-thermal neutrons in the flux drops to a factor of only 8-9.

The change in the shape of the neutron spectra from a D_2O moderated ^{252}Cf source at various distances from the source is different from the changes for a bare ^{252}Cf source (Figure 14). The peak at around 1 MeV is significantly less pronounced and does not change much with the distance from the source (1.0–4.0 m). The contribution of the epi-thermal and thermal neutrons to the total fluence is much closer to the contribution of the fast neutrons. The increase of the thermal and epi-thermal neutrons scattered from the wall with the distance from the source is much less relative to a bare ^{252}Cf source.

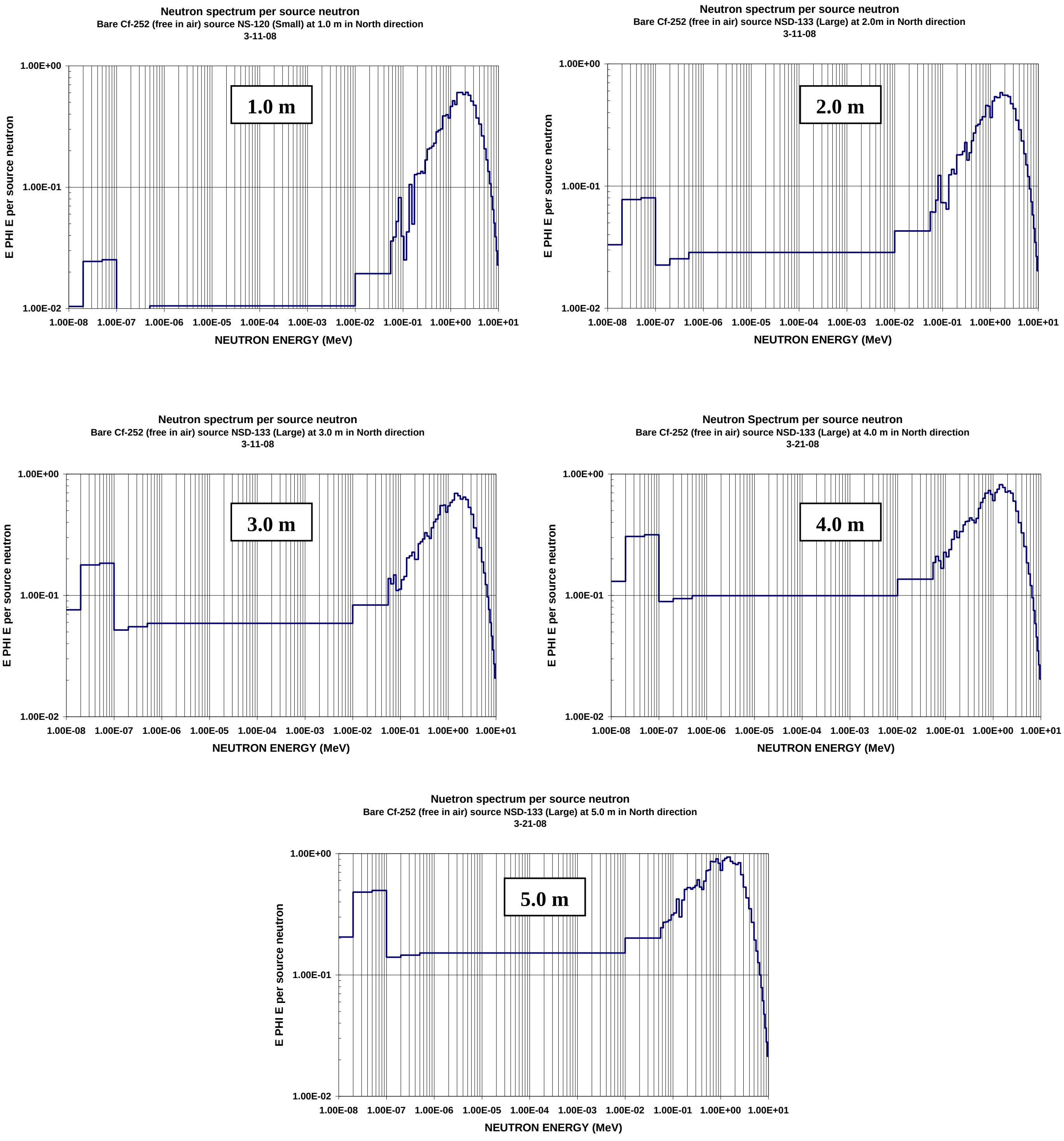


Figure 13. Neutron spectra at different distances (1.0–5.0 m) from a bare ^{252}Cf source in North direction.

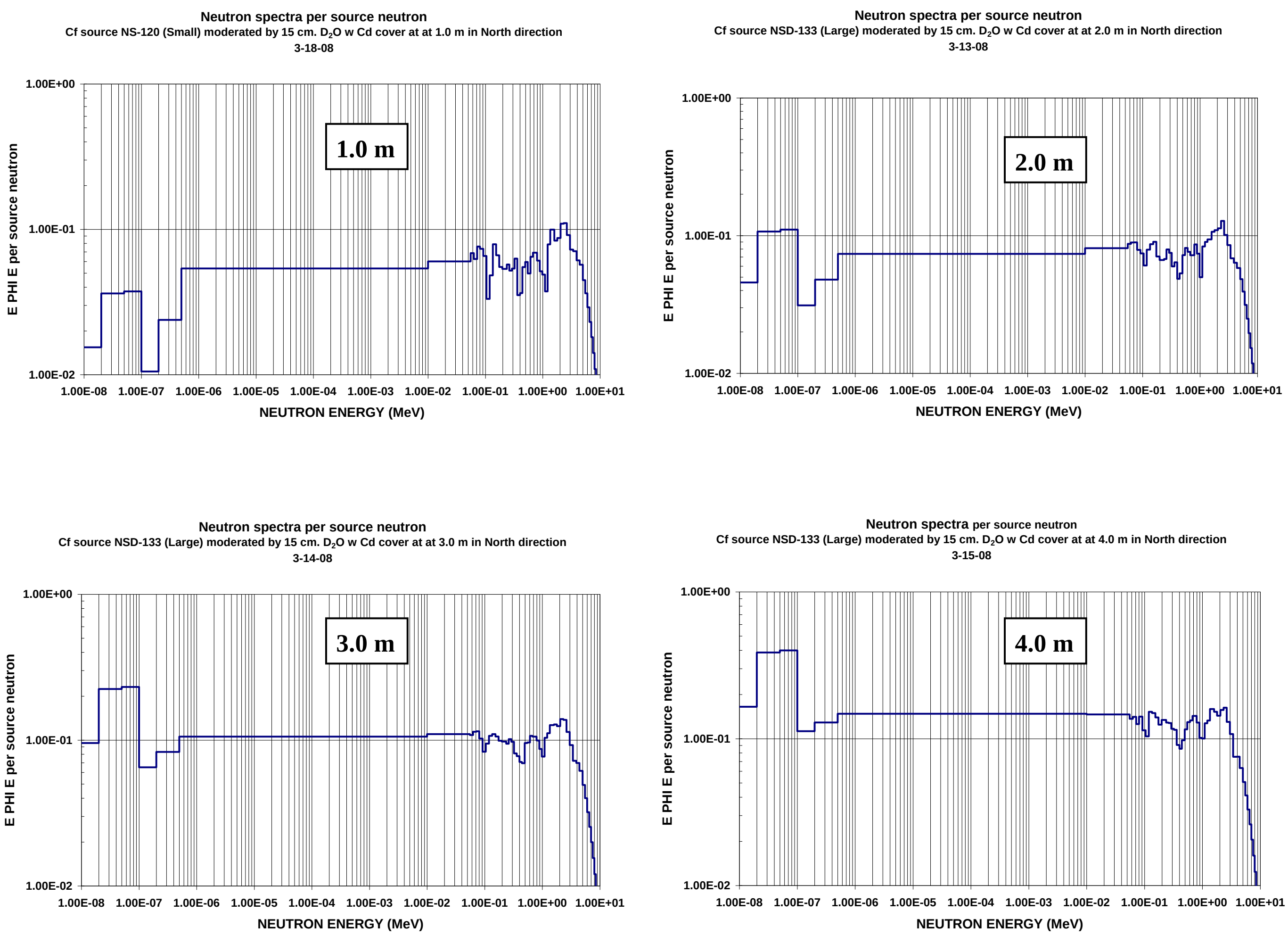
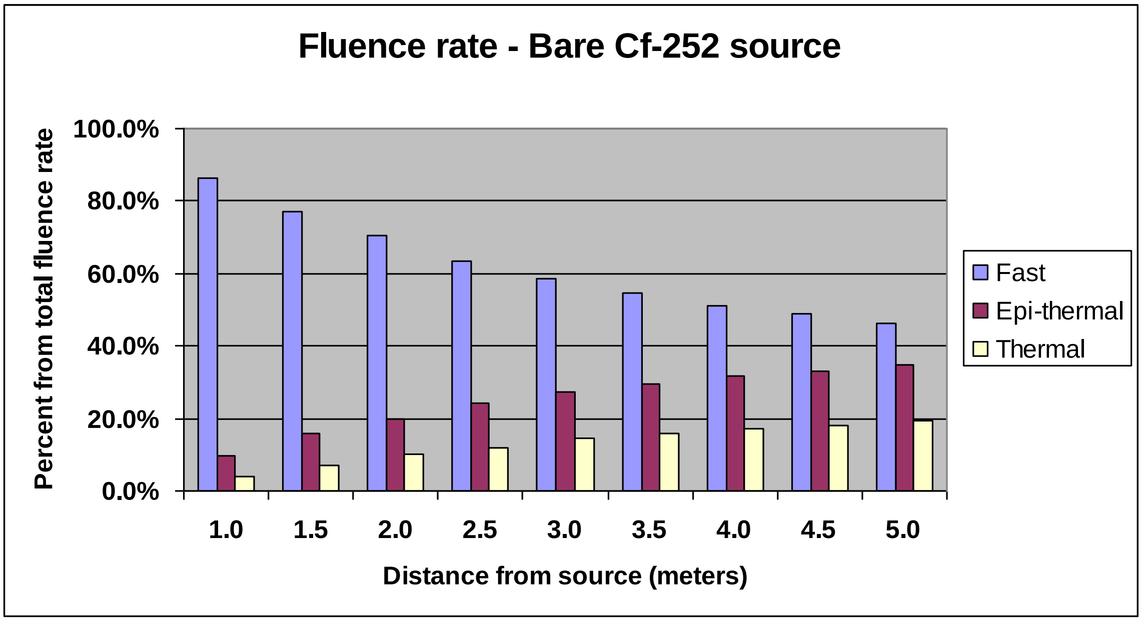


Figure 14. Neutron spectra at different distances (1.0–4.0 m) from a D_2O moderated ^{252}Cf source in North direction.

The relative contribution of the fast, thermal and epi-thermal neutrons to the neutron dose rates from a bare ^{252}Cf source is different from their contribution to the total fluence because the radiation weighting factors (or quality factors in the old 10CFR835) are higher for fast neutrons than for thermal and epi-thermal neutrons. See Table 4 and Figure 15.



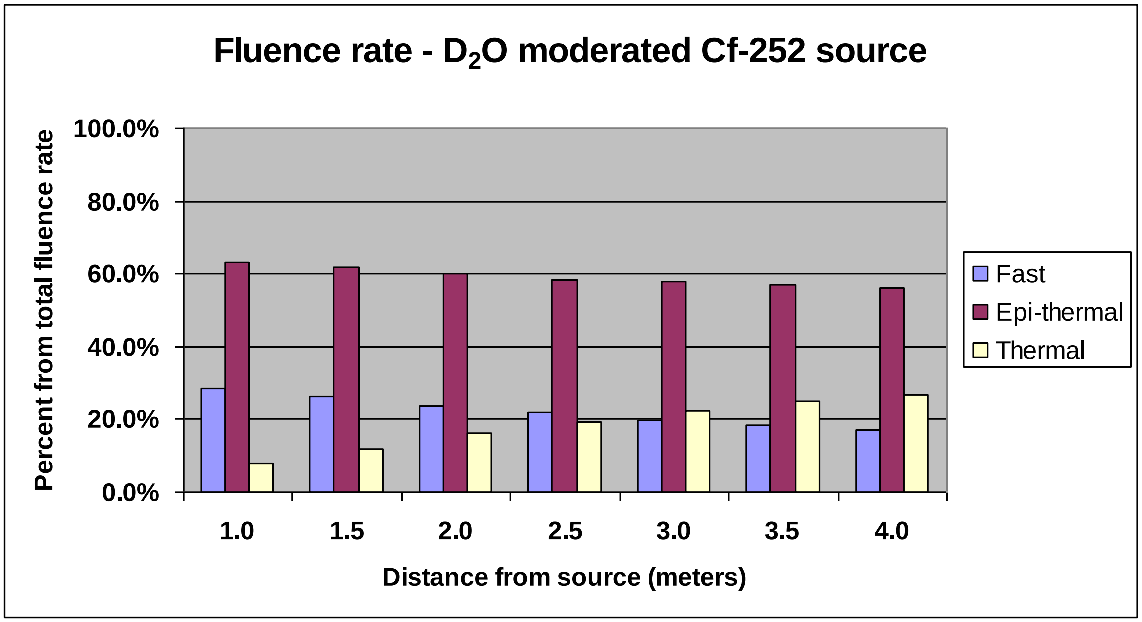


Figure 15. Contribution of different neutron energies to the total fluence at various distances from the ^{252}Cf source measured by ROSPEC.

Table 4. Contribution of fast, epi-thermal and thermal neutrons to the total fluence and dose from a bare ^{252}Cf source measured by ROSPEC

Distance from the Source	1.0 m		3.0 m		5.0 m	
Neutron energy	Fraction of total fluence rate	Fraction of total dose rate	Fraction of total fluence rate	Fraction of total dose rate	Fraction of total fluence rate	Fraction of total dose rate
Fast (50 keV – 4.5 MeV)	86.3%	99.2%	58.5%	97.6%	46.0%	95.9%
Epi-thermal (1 eV – 50 keV)	9.8%	0.05%	27.4%	1.7%	34.7%	2.8%
Thermal (< 1 eV)	3.8%	0.01%	14.3%	0.7%	19.2%	1.3%

9.1.3 Spectra from bare and D_2O moderated ^{252}Cf sources

Side-by-side comparison of the neutron spectra from bare and D_2O moderated ^{252}Cf sources is shown in Figure 16 for 2.0, 3.0, and 4.0 m from the source. The plots of the spectral distribution are normalized per one neutron from the ^{252}Cf source for easier comparison between the spectra. The relative contribution of thermal and epi-thermal neutrons increases with the distance from the ^{252}Cf source, although the magnitude of the change is less pronounced for the D_2O moderated spectra. The decrease of the fast neutron contribution with the approach of the wall is also more pronounced for the bare ^{252}Cf source. With the detector moving closer to the wall, a bare ^{252}Cf source has more fast neutrons than a moderated ^{252}Cf source that can be scattered from the wall, lose energy and be recorded in the thermal and epi-thermal region.

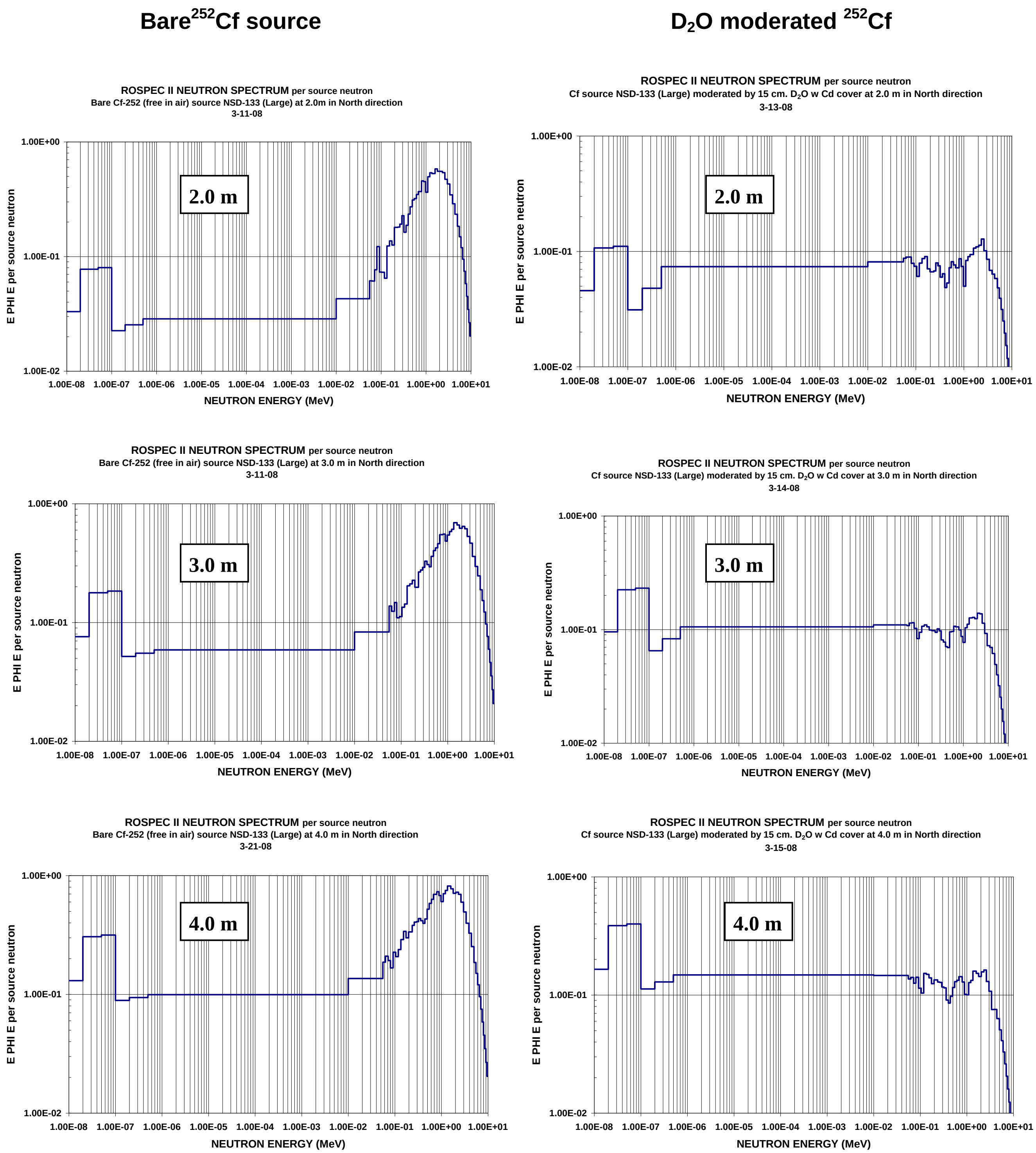


Figure 16. Neutron spectra from (left column) bare and (right column) D_2O moderated ^{252}Cf sources.

9.1.4 Spectra in various directions from the ^{252}Cf sources

There is no noticeable difference in the neutron spectra at the same distance from the source but in different directions with an exception for distances closer to the East wall as it is evidenced in the example in Table 5 below and in Figure 17.

Table 5. Neutron fluence from bare and D_2O moderated ^{252}Cf sources

Distance from source	2.0 m from a Bare ^{252}Cf source		3.0 m from D_2O moderated ^{252}Cf source	
Direction	**NORTH**	**EAST**	**NORTH**	**EAST**
Neutron energy	**Fraction of total fluence rate**	**Fraction of total fluence rate**	**Fraction of total fluence rate**	**Fraction of total fluence rate**
50 keV - 4.5 MeV	70.0%	70.3%	19.9%	19.8%
Epi-thermal region	20.4%	20.3%	57.9%	57.7%
Thermal region	9.5%	9.5%	22.5%	22.7%
Total	100.0%	100.0%	100.0%	100.0%

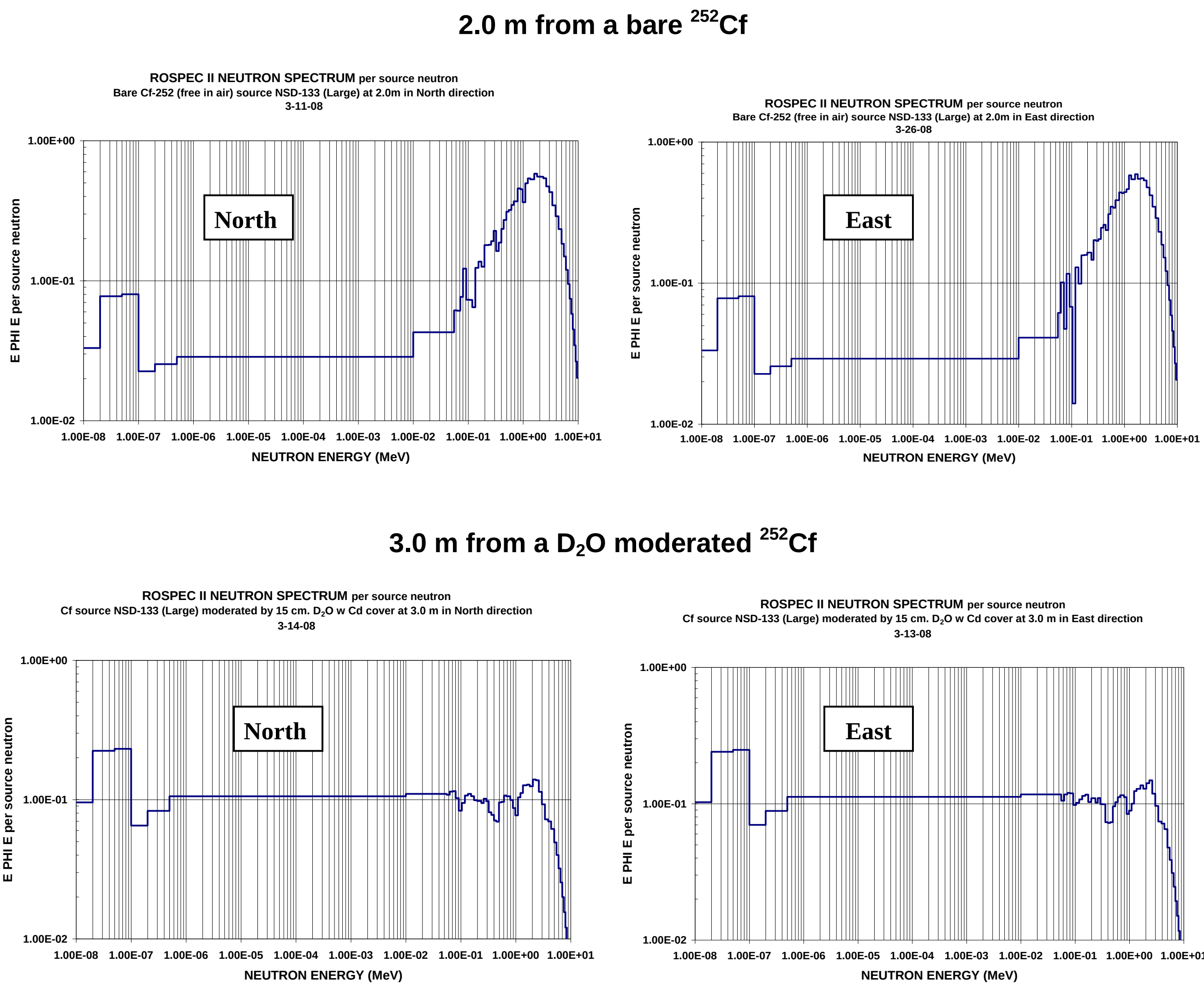


Figure 17. Neutron spectra in North and East direction.

9.2 Neutron dose rates

9.2.1 Dose rates from the Large and the Small ^{252}Cf sources

Table 6 shows that the measured dose rates from the Large and Small ^{252}Cf source are equally proportional for all locations both for bare and moderated ^{252}Cf sources. This is the expected result because the dose rate ratio of the Large and Small ^{252}Cf sources is equal to the ratio of the emission rates of these two sources. The dose rates were measured independently by the ROSPEC and SWENDI instruments. This data provides additional confidence in the integrity of the measurement results.

Table 6. Dose rates from the Large and Small ^{252}Cf sources in the North Direction

Bare Cf: ROSPEC measurements

Distance (m)	NSD-133 Large ^{252}Cf source		NS-120 Small ^{252}Cf source		Dose rate ratio - Large/Small ^{252}Cf	
	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	NCRP-38	Ambient ICRP-74
2.0	207.9	241.6	3.55	4.12	58.6	58.6
3.0	112.5	131.6	1.82	2.13	61.8	61.8

Averaged dose rate ratio = 60.2

Bare Cf: SWENDI-II measurements

Distance (m)	NSD-133 Large ^{252}Cf source	NS-120 Small ^{252}Cf source	Dose rate ratio - Large/Small ^{252}Cf
	Dose rate (mrem/hr)	Dose rate (mrem/hr)	
1.0	723.70	11.90	60.8
1.5	351.20	5.80	60.6
2.0	214.90	3.60	59.7
3.0	119.00	2.00	59.5

Averaged dose rate ratio = 60.1

D_2O moderated Cf: SWENDI-II measurements

Distance (m)	NSD-133 Large ^{252}Cf source	NS-120 Small ^{252}Cf source	Dose rate ratio - Large/Small ^{252}Cf
	Dose rate (mrem/hr)	Dose rate (mrem/hr)	
0.5	657.8	11	59.8
1.0	175.7	2.92	60.2
2.0	55.8	0.9	62.0

Average dose rate ratio = 60.7

9.2.2 Dose rates at various distances from the ^{252}Cf sources

The measured dose rates from bare ^{252}Cf gradually decrease with the distance from the source, however, they do not follow the inverse square law (see Tables E-1 and E-2 in Appendix E). The same is true for the measured dose rates from a D_2O moderated ^{252}Cf source. Contributions from neutrons scattered from the walls account for the higher fluence and dose rates closer to the walls (compared with those calculated by the inverse square law). LANL Monte Carlo calculations for Room 183A confirm that the dose rates do not comply with the inverse square law for both bare ^{252}Cf (see Figure 18 and [19]) and for D_2O moderated ^{252}Cf sources (see Figure 19 and [19]). This fact makes it preferable to calibrate neutron instruments closer to the source in order to use a calibration spectrum closer to that of the source alone and to avoid non-linear effects.

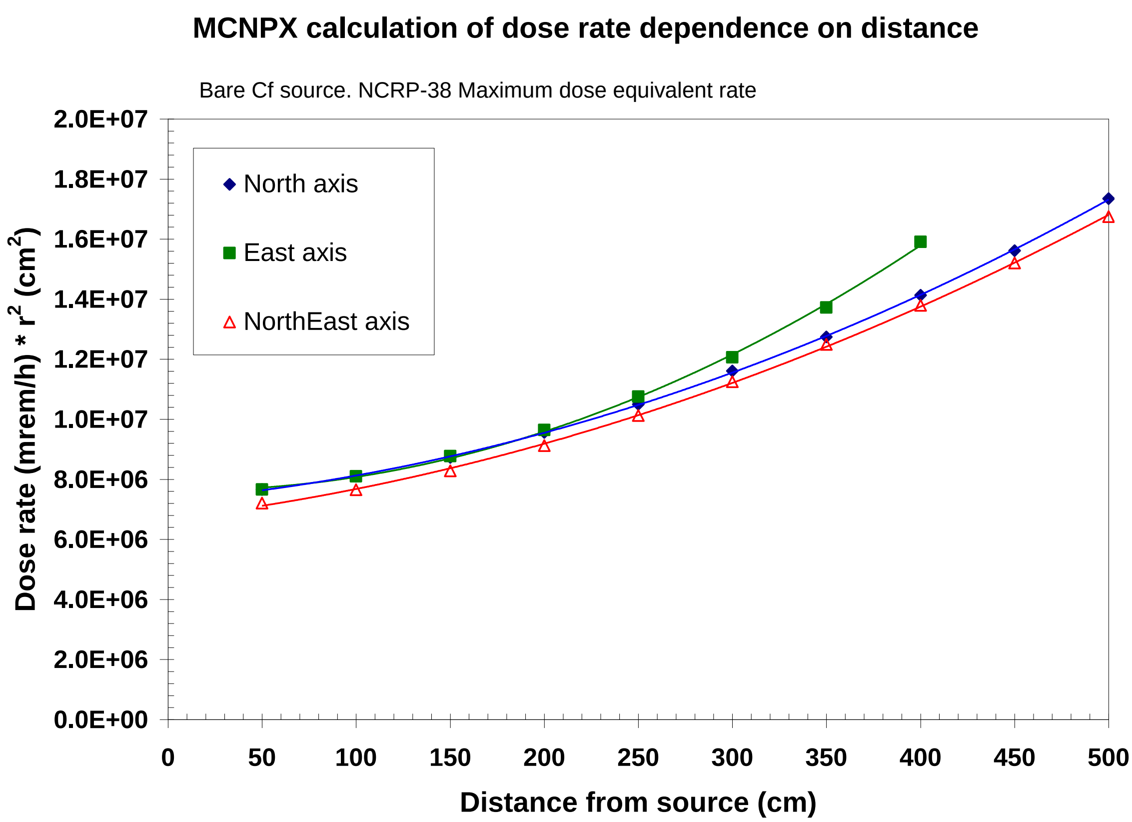


Figure 18. MCNPX calculated dose rate dependence on distance for bare ^{252}Cf.

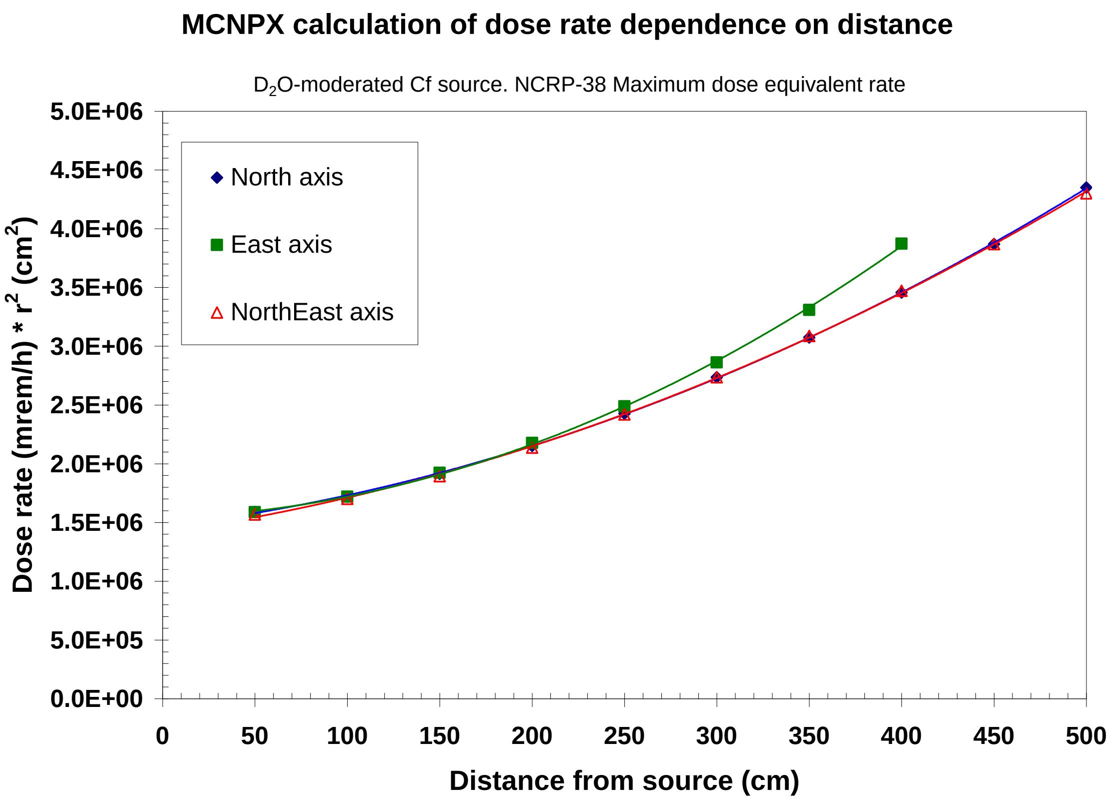


Figure 19. MCNPX calculated dose rate dependence on distance for D_2O moderated ^{252}Cf.

9.2.3 Dose rates from bare and D_2O moderated ^{252}Cf sources

The measured and calculated dose rate data suggest that the dose rates from bare ^{252}Cf and D_2O moderated ^{252}Cf do not change with the distance in the same fashion. The ratio of the dose rates from bare ^{252}Cf and D_2O moderated ^{252}Cf decreases with the distance from the source (see Table 7 and Figure 20) due to the relative change of the neutron fluence (direct plus scattered neutrons) and the energy of the neutrons with the distance.

Table 7. Ratio of the dose rates from bare ^{252}Cf and D_2O moderated ^{252}Cf sources in the North direction

Dose Rate Ratio of Bare ^{252}Cf/Moderated ^{252}Cf				
Distance (m)	**ROSPEC**	**SWENDI**	**NRD-NIST**	**MCNPX**
0.5	--	--	4.79	4.82
1.0	--	4.12	4.43	4.71
1.5	--	4.00	4.38	4.56
2.0	4.00	3.85	4.23	4.44
2.5	3.86	3.80	4.17	4.33
3.0	3.88	3.75	4.03	4.24
3.5	3.78	3.73	4.03	4.14
4.0	3.77	3.66	3.87	4.09
4.5	--	3.65	--	4.04
5.0	--	3.63	--	3.99

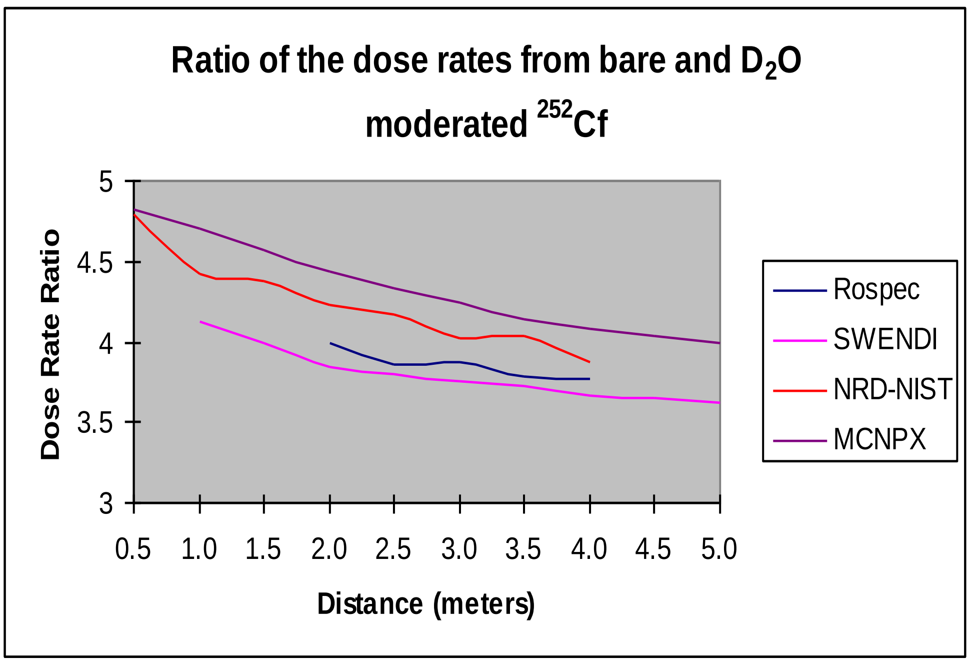


Figure 20. Ratio of the dose rates from bare ^{252}Cf and D_2O moderated ^{252}Cf sources in the North direction.

9.2.4 Dose rates in various directions from the ^{252}Cf sources

The dose rates measured by ROSPEC at the same source-to-detector distances but in different directions (e.g., North, East, Northeast) agree well as seen from Tables 8 and 9. The dose rates measured in East direction are higher by 1-5% than those for North and Northeast direction for all distances but 4.0 m for bare ^{252}Cf source and 1.5 m for D_2O moderated ^{252}Cf source. This effect may be due to the relatively higher number of scattered neutrons from the wall in East direction since the scattering East concrete wall is closer to the detector than the corresponding scattering walls in the other two directions at the same distance from the source. Lower number of counts and poorer statistics may be responsible for the observed difference for the Small D_2O moderated ^{252}Cf source in East direction. The same overall good agreement between the dose rates in different directions holds both for dose rates obtained using the NCRP-38 and ICRP-74 fluence-to-dose conversion coefficients.

Figures 18 and 19 provide a visual indication of the wall's effect in different directions. The difference in dose rates from different directions becomes evident at distances larger than the half-way distance between the source and the wall. Although the differences are very small, it is preferable to use one particular direction for the calibration of all instruments of a given type.

Table 8. Comparison of measured dose rates with ROSPEC using NCRP-38 conversion factors in different directions

Source: Bare ^{252}Cf, Large Source (NSD-133)

Distance (m)	ROSPEC (mrem/hr) [NCRP 38]			Difference (%)		
	North	East	Northeast	N vs E	N vs NE	E vs NE
2.0	207.9	210.4	--	-1.2%	--	--
2.5	145.9	150.4	--	-3.1%	--	--
3.0	112.5	117.5	113.52	-4.4%	-0.9%	3.4%
3.5	90.61	--	--	--	--	--
4.0	76.83	85.1	77.03	-10.8%	-0.3%	
4.5	67.39	--	--	--	--	--
5.0	59.72	--	--	--	--	--

Source: Bare ^{252}Cf, Small Source (NS-120)

Distance (m)	ROSPEC (mrem/hr) [NCRP 38]			Difference (%)		
	North	East	Northeast	N vs E	N vs NE	E vs NE
1.0	12.3	12.33	--	-0.2%	--	--
1.5	5.43	5.823	--	-7.2%	--	--
2.0	3.54	--	--	--	--	--
3.0	1.82	--	--	--	--	--

Source: D_2O moderated ^{252}Cf, Large Source (NSD-133)

Distance (m)	ROSPEC (mrem/hr) [NCRP 38]			Difference (%)		
	North	East	Northeast	N vs E	N vs NE	E vs NE
1.5	84.25	--	--	--	--	--
2.0	51.99	53.97	52.54	-3.8%	-1.1%	2.6%
2.5	37.84	--	--	--	--	--
3.0	29.02	30.4	29.72	-4.8%	-2.4%	2.2%
3.5	23.97	--	--	--	--	--
4.0	20.37	--	--	--	--	--

Source: D_2O moderated ^{252}Cf, Small Source (NS-120)

Distance (m)	ROSPEC (mrem/hr) [NCRP 38]			Difference (%)		
	North	East	Northeast	N vs E	N vs NE	E vs NE
1.0	2.89	2.92	--	-1.0%	--	--

Table 9. Comparison of measured dose rates with ROSPEC using ICRP-74 conversion factors in different directions

Source: Bare ^{252}Cf, Large Source (NSD-133)

Distance (m)	ROSPEC (mrem/hr) [ICRP 74]			Difference (%)		
	North	East	Northeast	N vs E	N vs NE	E vs NE
2.0	241.60	244.7	--	-1.3%	--	--
2.5	170.20	175.52	--	-3.1%	--	--
3.0	131.58	137.45	132.81	-4.5%	-0.9%	3.4%
3.5	106.25	--	--	--	--	--
4.0	90.32	100.22	90.55	-11.0%	-0.3%	9.6%
4.5	79.36	--	--	--	--	--
5.0	70.52	--	--	--	--	--

Source: Bare ^{252}Cf, Small Source (NS-120)

Distance (m)	ROSPEC (mrem/hr) [ICRP 74]			Difference (%)		
	North	East	Northeast	N vs E	N vs NE	E vs NE
1.0	14.29	14.26	--	0.2%	--	--
1.5	6.47	6.76	--	-4.4%	--	--
2.0	4.12	--	--	--	--	--
3.0	2.13	--	--	--	--	--

Source: D_2O moderated ^{252}Cf, Large Source (NSD-133)

Distance (m)	ROSPEC (mrem/hr) [ICRP 74]			Difference (%)		
	North	East	Northeast	N vs E	N vs NE	E vs NE
1.5	97.29	--	--	--	--	--
2.0	60.09	61.03	60.76	-1.6%	-1.1%	0.4%
2.5	43.80	--	--	--	--	--
3.0	33.57	35.26	34.39	-5.0%	-2.4%	2.5%
3.5	27.71	--	--	--	--	--
4.0	23.56	--	--	--	--	--

Source: D_2O moderated ^{252}Cf, Small Source (NS-120)

Distance (m)	ROSPEC (mrem/hr) [ICRP 74]			Difference (%)		
	North	East	Northeast	N vs E	N vs NE	E vs NE
1.0	3.34	3.37	--	-1.0%	--	--

9.2.5 Dose rate comparison between ROSPEC, SWENDI, NRD and MCNPX

The dose rates measured by ROSPEC using NCRP-38 derived fluence-to-dose conversion factors and SWENDI-II in different directions and for different source-to-detector distances are compared in Table 10.

The dose rates measured by ROSPEC, SWENDI-II, and NIST-calibrated NRD instruments and MCNPX calculated dose rates for both bare ^{252}Cf and D_2O moderated ^{252}Cf in the North direction are presented in Table 11. For easy comparison with NRD and SWENDI-II results, the ROSPEC and MCNPX dose rates in Table 11 are derived using NCRP-38 fluence-to-dose conversion factors. ROSPEC dose rates are between the dose rates from SWENDI-II and NRD. They are lower than the SWENDI dose rates, but they are higher than the dose rates from the NRD-NIST. The calculated dose rates are higher than ROSPEC, SWENDI-II and NRD-NIST for bare ^{252}Cf and higher than ROSPEC and NRD-NIST dose rates for D_2O moderated ^{252}Cf. This may imply that by fine tuning the MCNPX modeling of the scattering conditions in B255 Room 183A, the agreement between the calculated and measured dose rates may be improved.

In the last three columns of Table 11 the measured and calculated dose rates in North direction are compared to the dose rates measured by the NIST-calibrated NRD. The agreement between the ROSPEC and NRD-NIST dose rates is excellent; the agreement between SWENDI-II and NRD-NIST is very good and the agreement between the MCNPX calculated and NRD-NIST dose rates is also good. There is a tendency of a relative increase of SWENDI-II's dose rates versus ROSPEC dose rates with increasing the distance from the source (i.e. coming closer to the walls). This may be a result of the different detector response function of the two instruments. ROSPEC is a spectroscopic instrument and the contribution of each measured neutron energy to the total neutron dose is properly accounted for. SWENDI-II, not being a spectroscopic instrument, responds mainly to (i.e. having higher efficiency) for moderated and thermal neutrons. This tendency is evident for both non-moderated and D_2O moderated spectra. The fact that the dose rates determined by different types of instruments and calculations are so close, can serve as indication for the relative uncertainties of the evaluated true dose rates.

Table 10. Comparison between dose rates measured by ROSPEC and SWENDI using NCRP-38 conversion factors

Source: Bare ^{252}Cf, Large Source (NSD-133)

Distance	NORTH			EAST			NORTHEAST		
(m)	ROSPEC	SWENDI	Difference	ROSPEC	SWENDI	Difference	ROSPEC	SWENDI	Difference
1.0	--	723.7	--	--	741.7	--	--	753.3	--
1.5	--	351.2	-	--	346.5	--	--	--	--
2.0	207.9	214.9	-3.4%	--	218.4	--	--	216	--
2.5	145.9	153.3	-5.1%	150.4	158	-5.1%	--	--	--
3.0	112.5	119	-5.8%	117.5	122.7	-4.4%	113.52	121.7	-7.2%
3.5	90.61	98.4	-8.6%	--					
4.0	76.83	83.8	-9.1%	85.1	93.9	-10.3%	77.03	84.9	-10.2%
4.5	67.39	74.1	-10.0%	--	--	--	--	--	--
5.0	59.72	67.1	-12.4%	--	--	--	--	--	--

Source: D_2O moderated ^{252}Cf, Large Source (NSD-133)

Distance	NORTH			EAST			NORTHEAST		
(m)	ROSPEC	SWENDI	Difference	ROSPEC	SWENDI	Difference	ROSPEC	SWENDI	Difference
0.5	--	657.8	--	--	--	--	--	--	--
1.0	--	175.7	--	--	173.9	--	--	180.2	--
1.5	84.25	87.9	-4.3%		85.6	--	--	88.2	--
2.0	51.99	55.8	-7.3%	53.97	55	-1.9%	52.54	56.1	-6.8%
2.5	37.8	40.3	-6.6%	--	--	--	--	39.2	--
3.0	29.02	31.7	-9.2%	30.4	32.9	-8.2%	29.72	32.5	-9.4%
3.5	23.97	26.4	-10.1%	--	--	--	--	26.8	--
4.0	20.37	22.9	-12.4%	--	25.6	--	--	23.3	--
4.5	--	20.3	--	--	--	--	--	--	--
5.0	--	18.5	--	--	--	--	--	18.5	--

Source: Bare ^{252}Cf, Small Source (NS-120)

Distance	NORTH			EAST		
(m)	ROSPEC	SWENDI	Difference	ROSPEC	SWENDI	Difference
1.0	12.3	11.9	3.3%	12.33	11.9	3.5%
1.5	5.57	5.8	-4.1%	5.823	5.67	2.6%
2.0	3.54	3.6	-1.6%	--	3.6	--
2.5	--	--	--	--	--	--
3.0	1.82	2.0	-9.9%	--	2.1	--
3.5	--	--	--	--	--	--
4.0	--	1.4	--	--	1.53	--

Source: D_2O moderated ^{252}Cf, Small Source (NS-120)

Distance	NORTH			EAST		
(m)	ROSPEC	SWENDI	Difference	ROSPEC	SWENDI	Difference
0.5	--	11	--	--	--	--
1.0	2.89	2.92	-1.0%	2.92	2.9	0.7%
1.5	--	--	--	--	1.4	--
2.0	--	0.9	--	--	0.9	--

Table 11. Comparison of the dose rates measured by ROSPEC, SWENDI-II, NRD-NIST and MCNPX calculated in the NORTH direction

Source: Bare ^{252}Cf, Large Source (NSD-133)

Distance North (m)	ROSPEC NCRP-38 (mrem/hr)	SWENDI (mrem/hr)	NRD-NIST (mrem/hr)	MCNPX (mrem/hr)	Ratio ROSPEC - NRD-NIST	Ratio SWENDI - NRD-NIST	Ratio MCNPX - NRD-NIST
0.5	--	--	2756	3063	--	--	111.1%
1.0	--	723.7	699.0	810	--	103.5%	115.9%
1.5	--	351.2	337.0	388	--	104.2%	115.1%
2.0	207.9	214.9	204.0	239	101.9%	105.3%	117.2%
2.5	145.9	153.3	143.0	168	102.0%	107.2%	117.5%
3.0	112.5	119.0	110.0	129	102.3%	108.2%	117.3%
3.5	90.61	98.4	89.5	104	101.2%	109.9%	116.2%
4.0	76.83	83.8	75.5	88.3	101.8%	111.0%	117.0%
4.5	67.39	74.1	--	77.1	--	--	--
5.0	59.72	67.1	--	69.4	--	--	--

Source: D_2O moderated ^{252}Cf, Large Source (NSD-133)

Distance North (m)	ROSPEC NCRP-38 (mrem/hr)	SWENDI (mrem/hr)	NRD-NIST (mrem/hr)	MCNPX (mrem/hr)	Ratio ROSPEC - NRD-NIST	Ratio SWENDI - NRD-NIST	Ratio MCNPX - NRD-NIST
0.5	--	657.8	575.7	636	--	114.3%	110.5%
1.0	--	175.7	157.9	172	--	111.3%	108.9%
1.5	84.25	87.9	76.9	85	109.6%	114.3%	110.5%
2.0	51.99	55.8	48.2	53.8	107.9%	115.8%	111.6%
2.5	37.8	40.3	34.3	38.8	110.2%	117.5%	113.1%
3.0	29.02	31.7	27.3	30.4	106.3%	116.1%	111.4%
3.5	23.97	26.4	22.2	25.1	108.0%	118.9%	113.1%
4.0	20.37	22.9	19.5	21.6	104.5%	117.4%	110.8%
4.5	--	20.3	--	19.1	--	--	--
5.0	--	18.5	--	17.4	--	--	--

9.2.6 Comparison of measured dose rates and free field dose equivalent rates

The "Free Field Dose Equivalent" (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 detection instrument (e.g., ROSPEC, SWENDI or NRD) from the walls, air in the room, source support and in our case, the aluminum grade floor and the background from the sources in the shielded N40 irradiator. The FFDE rates, in mrem/hr, are calculated from the formulae [3]:

$$\text{FFDE rate} = 9.54 \times 10^{-3} Q/r^2 \text{ (bare } ^{252}\text{Cf)}$$

$$\text{FFDE rate} = 2.30 \times 10^{-3} Q/r^2 \text{ (moderated } ^{252}\text{Cf)}$$

Where Q is the source emission rate (n/s) and r (cm) is the distance from the ^{252}Cf source. The conversion factors used in the above formulae follow NCRP-38 and were calculated from the fluence-to-dose-equivalent conversion factors in ICRP-21.

A comparison between the FFDE and the measured dose at any given location in the B255 R183A can serve as a measure of the relative contribution of the neutrons scattered from the walls, ceiling, floor, air in the room, and any other structures in the calibration room. Figure 21 shows the ratio of the measured dose equivalent rate to FFDE rate for bare and D_2O-moderated Cf spectra in North direction in Room 183A. At distances over 4 m from the source, the contribution of the scattered neutrons to the measured dose equivalent rate is more than the contribution directly from the source. The contribution of the scattered neutrons for a D_2O moderated source is a little higher than for a bare ^{252}Cf source. Table 12 provides the ratio of the measured dose equivalent rate for a bare ^{252}Cf source to FFDE rate in North, East and Northeast direction (where available). The contribution of the scattered neutrons in East direction is higher by up to 10% compared to North direction depending on the distance to the wall.

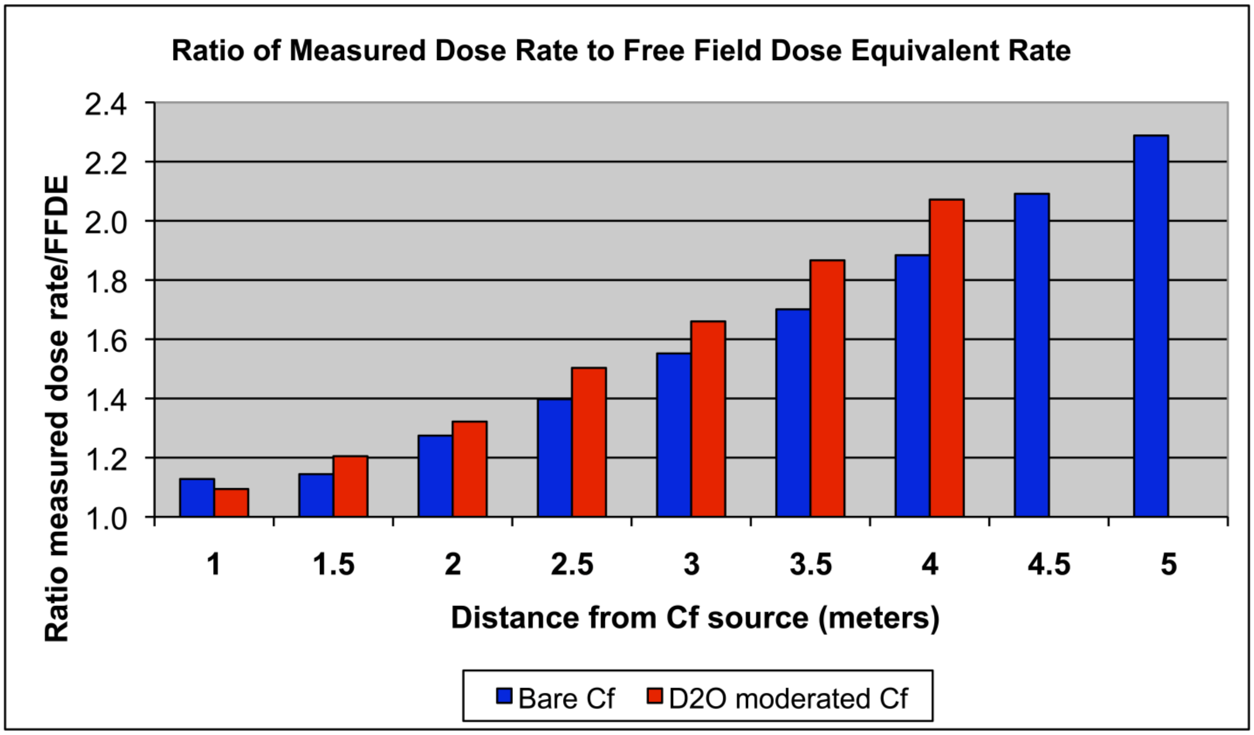


Figure 21. Ratio of measured dose rate to free field dose equivalent rate.

Table 12. Ratio of the measured by ROSPEC dose rates to Free Field Dose Equivalent (FFDE) rates

Source: Bare ^{252}Cf, Large Source (NSD-133)

Distance (m)	FFDE mrem/hr	NORTH	EAST	NORTHEAST
2.0	163.1	127.4%	129.0%	--
2.5	104.4	139.7%	144.0%	--
3.0	72.5	155.2%	162.0%	156.6%
3.5	53.3	170.1%	--	--
4.0	40.8	188.4%	208.6%	188.9%
4.5	32.2	209.1%	--	--
5.0	26.1	228.8%	--	--

Source: D_2O moderated ^{252}Cf, Large Source (NSD-133)

Distance (m)	FFDE mrem/hr	NORTH	EAST	NORTHEAST
1.5	69.92	120.5%	--	--
2.0	39.33	132.2%	134.1%	133.6%
2.5	25.17	150.3%	--	0.0%
3.0	17.48	166.0%	174.2%	170.0%
3.5	12.84	186.6%	--	--
4.0	9.83	207.2%	--	--

Source Bare ^{252}Cf, Small Source (NS-120)

Distance (m)	FFDE mrem/hr	NORTH	EAST
1.0	10.95	112.8%	112.6%
1.5	4.87	114.4%	119.6%
2.0	2.74	129.5%	--
2.5	1.75	--	--
3.0	1.22	149.6%	--

Source D2O moderated ^{252}Cf, Small Source (NS-120)

Distance (m)	FFDE mrem/hr	NORTH	EAST
1.0	2.64	109.4%	110.5%

9.2.7 Comparison between NCRP-38 and ICRP-74 fluence-to-dose conversion factors

ICRP Publication 15 states: “An alternative approach to the determination of the dose equivalent by the use of quality factors and an assessment of absorbed dose is to convert the particle [neutron] fluence incident upon the body directly by the use of conversion factors.” The significant improvements in the mathematical models, transport codes and physical databases used to determine the necessary absorbed dose (and dose related) distributions warranted the revision of the fluence-to-dose conversion coefficients. The ratio of the ICRP-74 and NCRP-38 derived fluence-to-dose conversion factors is presented in Figure 22. The energy scale in the graph is neither linear nor logarithmic. The energy points reflect the published conversion coefficient data for neutron energies from thermal to 20 MeV. For monoenergetic neutrons the difference between the dose (or dose rates) determined by ICRP-74 and NCRP-38 conversion factors may reach ±30%, however, for a broad spectrum this difference will be lower. Figure 22 provides a rough estimate of the energy regions where ICRP-74 determined doses (or dose rates) will be higher than those determined by NCRP-38: namely a portion of the thermal region, entire epi-thermal and intermediate region to fast neutrons up to approximately 3 MeV. These energy regions are where the neutron doses (or dose rates) determined in accordance with 10 CFR 835 (2007) will be higher than the neutron doses (or dose rates) determined in accordance with 10 CFR 835 (1996). From the conversion coefficient comparison, it is expected that ICRP-74 determined dose (or dose rates) from a bare ^{252}Cf will be higher than those determined by NCRP-38, which is confirmed by the ROSPEC measurements and the MCNPX calculations.

The neutron dose equivalent rates determined using the ICRP-74 fluence-to-dose conversion factors in Room 183A are higher by 15-18% than the dose rates determined using the NCRP-38 derived conversion factors for a bare ^{252}Cf source depending on the distance from the source. For most of the ^{252}Cf energies of interest (0.03 MeV – 4.5 MeV, thermal and epi-thermal) the ICRP-74 conversion factors are larger than the NCRP-38 factors as indicated in Figure 22. At larger distances from the source and thus closer to the scattering wall, the contribution of the scattered thermal and epi-thermal neutrons are higher, as was shown earlier. This fact may explain the increase of the ratio seen in Figure 23.

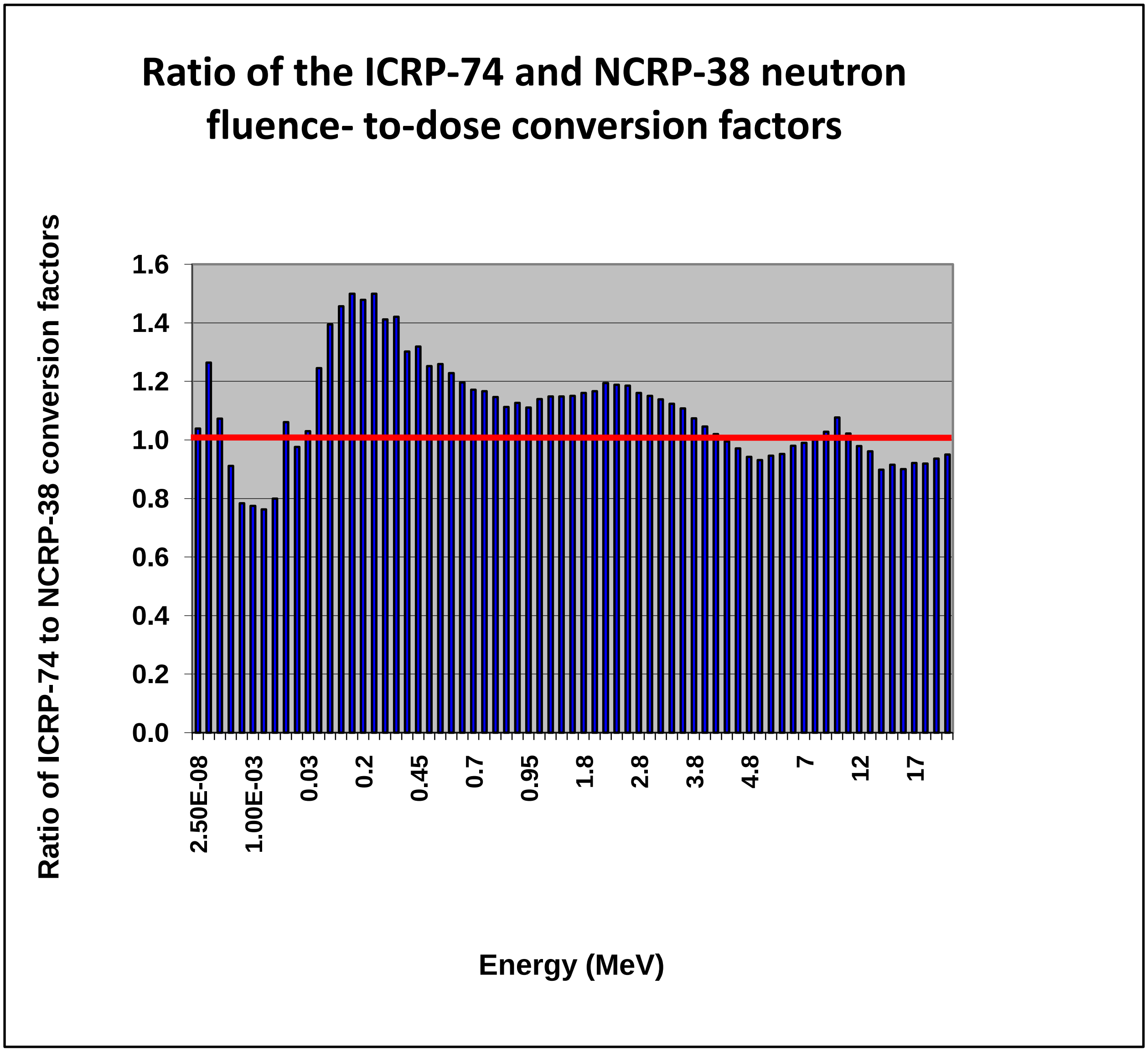


Figure 22. Ratio of the ICRP-74 and NCRP-38 neutron fluence-to-dose conversion factors.

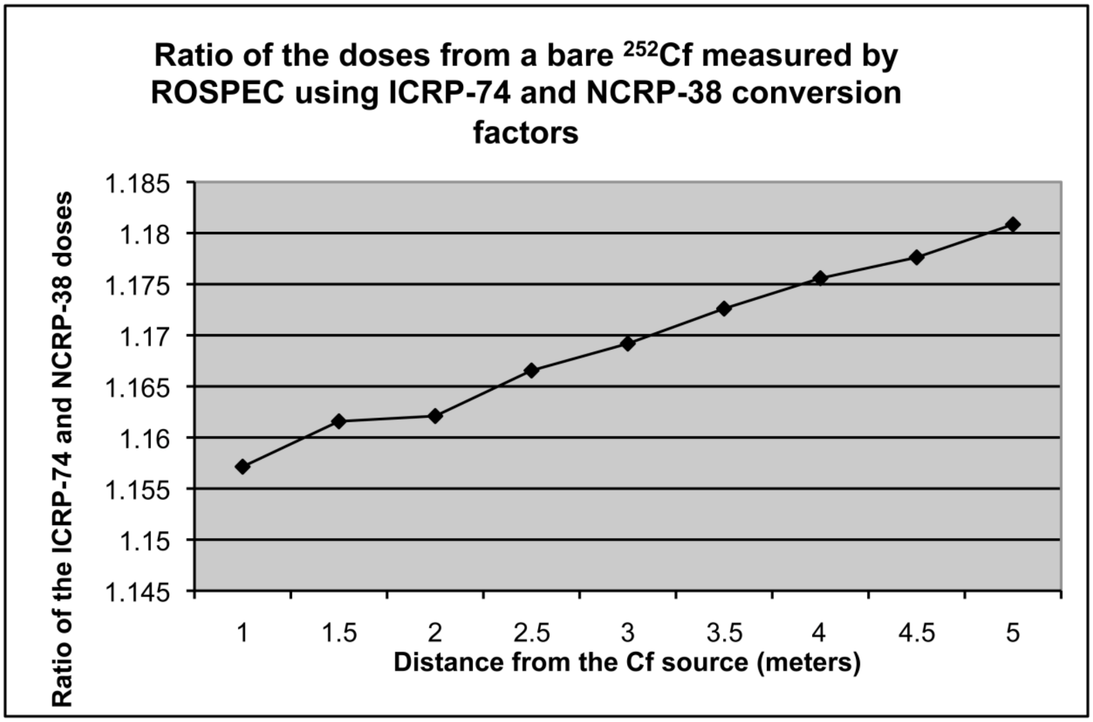


Figure 23. Comparison of the measured dose rates using ICRP-74 and NCRP-38 neutron fluence-to-dose conversion factors.

10. Recommendations

10.1 Use of the LLNL Low-Scatter Calibration Facility

1. Use the neutron dose rates measured by the spectroscopic ROSPEC instrument in B255, R183A for the calibration spectrum for the Hopewell N40 irradiator because:
   a) The ROSPEC instrument is calibrated in state-of-the-art laboratories with wide range of monoenergetic neutrons (especially in the more sensitive to dose fast neutron region), thus providing the most accurate dosimetric data based on the entire detailed neutron spectrum of the ^{252}Cf sources.
   b) ROSPEC dose rates are between the dose rates measured by SWENDI-II and NIST calibrated NRD.
   c) The same ROSPEC system used at LLNL was also used to characterize the neutron calibration facilities for a number of DOE national laboratories (LANL, BNL, PNNL, SRS, SNL) which provides better consistency and common ground for intercomparison among the calibration of instruments and dosimeters in the DOE complex.
   d) ROSPEC measurements provide consistent dose rates for calibration of neutron dosimeters in terms of the ICRP-74 personal dose equivalent.

2. Use the B255, R183A NORTH direction for calibration because:
   a) The distance in North direction is the longest from the ^{252}Cf sources and, therefore, the wall scattering effects are less pronounced.
   b) The North direction is better characterized; more measurements are performed in this direction.
   c) The need to simultaneously calibrate many instruments (requiring the use of more directions) is very rare. If a need to calibrate in positions other than in North direction arises, correction factors may be deduced from our measurements.
   d) If a rail track for precise and possibly automated positioning of instruments and objects is installed (as planned) it is cost-effective to install one rail track rather than two or more tracks.
3. Use distances up to 2.5 m from the ^{252}Cf source where the differences between North, East and Northeast directions are within the typical measurement uncertainty.

10.2 Recommended neutron dose rates for the Hopewell N40 Irradiator

Table 13 lists the recommended neutron dose rates as of March 10, 2008 for use in the Hopewell N40 irradiator. As stated earlier although these dose rates were measured in the North direction, they can be applied for all directions from the source because the differences between the neutron dose rates in different directions are small enough, especially for distances not exceeding 2.5 m from the source. Dose rates for distances greater than 2.5 m are given for completeness and if used their limitations should be fully understood.

- Column 1 provides the distance in meters in the North direction from the center of ^{252}Cf source (center of the D_2O sphere) to the point where the dose rate is evaluated.
- Column 2 (“NCRP-38”) provides the neutron dose rate in mrem/hr as defined in 10 CFR 835 (1996) using fluence-to-dose conversion factors derived from NCRP-38.
- Column 3 (“Ambient ICRP-74”) provides the ambient dose equivalent rate in mrem/hr as defined in 10 CFR 835 (2007) and derived using the ICRP-74 fluence-to-dose conversion factors for 10 mm depth in the ICRU sphere.
- Column 4 (“Personal ICRP-74”) provides the personal dose equivalent rate as defined in the revised 10 CFR 835 and derived using the ICRP-74 fluence-to-dose conversion factors for 10 mm depth in soft tissue and 0 degree angle between the incident neutrons direction and the perpendicular to the surface of the tissue (i.e. monodirectional neutron beam with frontal incidence). The values in this column may be used for personal dosimeter calibrations. ICRU Report 47 suggests that, for the purposes of dosimeter calibration under reference conditions (e.g., monodirectional neutron beam with frontal incidence) the dose equivalent in a 30 x 30 x 15 cm slab of ICRU tissue-equivalent material provides an adequate approximation to the backscatter of the human body so that Hp(10) may be estimated.
- Column 5 provides the ratio of the ambient dose equivalent rates (per ICRP-74 and the revised 10CFR835) to the old dose rates (per NCRP-38 and old 10CFR835),
- Column 6 provides the ratio of the personal dose equivalent rates (per ICRP-74 and revised 10CFR835) to the old dose rates (per NCRP-38 and old 10CFR835),
- Column 7 provides the ratio of personal dose equivalent rates to the ambient dose equivalent rates (per ICRP-74 and the revised 10CFR835).

These ratios indicate that the ambient dose rates in the Low Scatter Calibration Room will increase by (15.5 – 18)% for neutron dose rate instruments used for area monitoring when the revised 10 CFR 835 is implemented. The dose rates for personal dosimeters (TLDs, CR-39) will be approximately 4% higher than the ambient dose equivalent rates due to the backscatter from the phantom or the human body.

Table 13. Recommended dose equivalent rates as of March 10, 2008

Source: Bare ^{252}Cf, Large Source (NSD-133)

Distance NORTH (m)	Dose Rate (mrem/h)			Ratio		
	NCRP-38	Ambient ICRP-74	Personal ICRP-74	ICRP-74 Ambient/ NCRP-38	ICRP-74 Personal/ NCRP-38	ICRP-74 Personal/ Ambient
0.5	2809.7	3245.2	3365.3	1.155	1.198	1.037
1.0	712.7	824.6	855.0	1.157	1.200	1.037
1.5	343.1	398.7	413.3	1.162	1.205	1.037
2.0	207.9	241.6	250.5	1.162	1.205	1.037
2.5	145.9	170.2	176.4	1.167	1.209	1.037
3.0	112.5	131.6	136.3	1.169	1.211	1.036
3.5	90.6	106.3	110.1	1.173	1.215	1.036
4.0	76.8	90.3	93.6	1.176	1.218	1.036
4.5	67.4	79.4	82.2	1.178	1.220	1.036
5.0	59.7	70.5	73.1	1.181	1.223	1.036

Source: D_2O moderated ^{252}Cf, Large Source (NSD-133)

Distance NORTH (m)	Dose Rate (mrem/h)			Ratio		
	NCRP-38	Ambient ICRP-74	Personal ICRP-74	ICRP-74 Ambient/ NCRP-38	ICRP-74 Personal/ NCRP-38	ICRP-74 Personal/ Ambient
0.5	621.8	718.0	747.6	1.155	1.202	1.041
1.0	170.5	196.9	227.4	1.155	1.334	1.155
1.5	84.2	97.3	101.3	1.155	1.202	1.041
2.0	52.0	60.1	62.6	1.156	1.204	1.042
2.5	37.8	43.8	45.6	1.158	1.206	1.042
3.0	29.0	33.6	35.0	1.157	1.205	1.042
3.5	24.0	27.7	28.9	1.156	1.205	1.043
4.0	20.4	23.6	24.6	1.157	1.206	1.043

Source: Bare ^{252}Cf, Small Source (NS-120)

Distance NORTH (m)	Dose Rate (mrem/h)			Ratio		
	NCRP-38	Ambient ICRP-74	Personal ICRP-74	ICRP-74 Ambient/ NCRP-38	ICRP-74 Personal/ NCRP-38	ICRP-74 Personal/ Ambient
1.0	12.35	14.29	14.82	1.157	1.200	1.037
1.5	5.57	6.47	6.70	1.162	1.203	1.036
2.0	3.55	4.12	4.27	1.163	1.205	1.036
2.5	--	--	--	--	--	--
3.0	1.82	2.13	2.20	1.170	1.209	1.033

Source: D_2O moderated ^{252}Cf, Small Source (NS-120)

Distance NORTH (m)	Dose Rate (mrem/h)			Ratio		
	NCRP-38	Ambient ICRP-74	Personal ICRP-74	ICRP-74 Ambient/ NCRP-38	ICRP-74 Personal/ NCRP-38	ICRP-74 Personal/ Ambient
1.0	2.89	3.34	3.47	1.155	1.202	1.041

10.2 Estimate of the uncertainty for the recommended dose rates

Two approaches are used to estimate the uncertainty in the recommended dose rates. In the first approach an evaluation of the different components that contribute to the overall uncertainty is used. The second approach is based on the comparison between the different techniques used to measure the dose rates.

NIST provided "standard expanded uncertainties in the calibration factors" to be applied for the NRD rem meter. According to NIST report, NRD meter's uncertainty for bare ^{252}Cf is 6–8% and the uncertainty for D_2O moderated ^{252}Cf is 9% [26].

The statistical uncertainty for SWENDI's measurement was in the range of 0.1–1.5%. The uncertainty of the source-to-detector distance contributed less than 1% to the overall uncertainty, while uncertainties associated with the calibration for the entire energy scale and how well the instrument response function matches the dose equivalent curve may vary from 20% to even 200% for certain energies. We assume that the average SWENDI uncertainty for bare and D_2O moderated ^{252}Cf would be in the range of 30–50%.

The standard version of the ROSPEC unfolding code does not calculate statistical uncertainties in the fluence or in the dose. Based on past LANL experience, the overall uncertainty is almost always dominated by systematic biases in the unfolding process and, in particular, the inherent uncertainty in the proton recoil response functions. Based on past measurements, where the majority of the dose is delivered between 50 keV and 5 MeV, LANL estimates the systematic uncertainty to be 10% at 95% confidence level.

Uncertainty in the various directions of measurement:	
Distances not exceeding 2.5 m (maximum)	–5.0%
Distances 3.0 m and more from the source	–10.0%
Uncertainty of the source-to-detector distance (maximum)	–1.0%
Uncertainty in fluence-to-dose conversion factors	–1.0%
Uncertainty in the effective center of the ^{252}Cf source:	
Bare ^{252}Cf measurements	–0.1%
D_2O moderated ^{252}Cf measurements	–1.0%
Uncertainty of SWENDI-II and NRD response function matching the dose equivalent curve for bare and D_2O moderated ^{252}Cf sources	–30–50%
Uncertainty of ROSPEC neutron spectra unfolding process	–10%
Uncertainty in the location of the effective center of instrument:	
Bare ^{252}Cf measurements	–1.7%
D_2O moderated ^{252}Cf measurements	–1.7%

The evaluation of the ROSPEC uncertainty dose rate measurements heavily depends on the 10% overall assessment of the uncertainty by LANL. Taking into account the various sources of uncertainties for ROSPEC dose rate measurements yields:

Bare ^{252}Cf

Distances not exceeding 2.5 m from the source	– (10.2–12.5)%
Distances up to 4.5 m from the source	– (11.1–14.9)%

D_2O moderated ^{252}Cf

Distances not exceeding 2.5 m from the source	– (10.6–11.0)%
Distances up to 4.5 m from the source	– (11.3–12.0)%

This approach yields overall uncertainty for

ROSPEC	– 10–15%
SWENDI	– 30–50%

The differences between the recommended dose rates (based on ROSPEC values) and the dose rates measured by the other instruments may be used as another approach for the estimation of the overall uncertainty in the recommended dose rates. Monte Carlo radiation transport calculations (e.g., MCNPX) are very accurate, however the accuracy of the obtained results depends on how well the actual configuration is modeled. MCNPX calculated dose rates seem to have a systematic positive bias towards all measured values and, therefore, they are not used in evaluation of the uncertainty. Table 14 provides the ratios of the SWENDI, NRD-NIST and MCNPX dose rates to ROSPEC dose rates.

Table 14. Dose rates and dose rates ratios of ROSPEC, SWENDI, NRD-NIST measurements and MCNPX calculations

Source: Bare ^{252}Cf, Large Source (NSD-133)

Distance NORTH (m)	Dose Rate (mrem/h)				Ratio		
	ROSPEC NCRP-38	SWENDI	NRD-NIST	MCNPX	SWENDI /ROSPEC	NRD-NIST/ ROSPEC	MCNPX/ ROSPEC
0.5	--	--	2756.3	3063	--	--	--
1.0	--	723.7	699.2	810	--	--	--
1.5	--	351.2	336.6	388	--	--	--
2.0	207.9	214.9	203.9	239	103.4%	98.1%	115.0%
2.5	145.9	153.3	143.4	168	105.1%	98.3%	115.1%
3.0	112.5	119.0	109.8	129	105.8%	97.6%	114.7%
3.5	90.61	98.4	89.5	104	108.6%	98.8%	114.8%
4.0	76.83	83.8	75.5	88.3	109.1%	98.3%	114.9%
4.5	67.39	74.1	--	77.1	110.0%	--	114.4%
5.0	59.72	67.1	--	69.4	112.4%	--	116.2%

Source: D_2O moderated ^{252}Cf, Large Source (NSD-133)

Distance NORTH (m)	Dose Rate (mrem/h)				Ratio		
	ROSPEC NCRP-38	SWENDI	NRD-NIST	MCNPX)	SWENDI /ROSPEC	NRD-NIST/ ROSPEC	MCNPX/ ROSPEC
0.5	--	657.8	575.7	636	--	--	--
1.0	--	175.7	157.9	172	--	--	--
1.5	84.25	87.9	76.9	85	104.3%	91.3%	100.9%
2.0	51.99	55.8	48.2	53.8	107.3%	92.7%	103.5%
2.5	37.8	40.3	34.3	38.8	106.6%	90.7%	102.6%
3.0	29.02	31.7	27.3	30.4	109.2%	94.1%	104.8%
3.5	23.97	26.4	22.2	25.1	110.1%	92.6%	104.7%
4.0	20.37	22.9	19.5	21.6	112.4%	95.7%	106.0%
4.5	--	20.3	--	19.1	--	--	--
5.0	--	18.5	--	17.4	--	--	--

From Table 14 it can be concluded that the recommended (ROSPEC) dose rates differ from those measured by SWENDI-II and NRD as follows:

Bare ^{252}Cf	
Distances not exceeding 2.5 m from the source	– (–1.9% +5%)
Distances up to 4.5 m from the source	– (–2.5% +10%)
D_2O moderated ^{252}Cf	
Distances not exceeding 2.5 m from the source	– (–8.7% +7.3%)
Distances up to 4.5 m from the source	– (–9.3% +12.4%)

Thus, we may assume that the overall uncertainty is:

Bare ^{252}Cf	
Distances not exceeding 2.5 m from the source	±5%
Distances up to 4.5 m from the source	±10%
D_2O moderated ^{252}Cf	
Distances not exceeding 2.5 m from the source	±8.7%
Distances up to 4.5 m from the source	±12.5%

Combining both methods for estimating the uncertainty, we may assume that the uncertainty in the recommended dose rates for source-to-detector distances up to 2.5 m do not exceed 12.5%. These are the distances at which all neutron dose rate meters are calibrated at RCL.

11. Conclusion

Characterization of the RCL Low Scatter Calibration Room (B255 R183A) was performed using three different types of neutron dose rate meters: spectroscopic ROSPEC, wide energy range SWENDI, NRD calibrated by NIST, and by Monte Carlo calculations. All of the methods provided very close results, which provides confidence in the recommended dose rates. The measured dose rates are also very close to the values from the recently replaced ('old') pneumatic irradiation system, despite that the position of the old and the new sources was not exactly the same. The comparison between the neutron dose rates from the 'old' pneumatic system and the new Hopewell system is provided in Table G-1 in Appendix G. The methodology and the instruments used to characterize RCL neutron fields are consistent with those used to characterize the calibration neutron fields at several DOE national laboratories. This provides a higher consistency in the neutron fields used for calibration of radiation protection instruments throughout the DOE complex. Although it is recommended to use the North direction and source-to-detector distances not exceeding 2.5 m for routine calibrations, extensive data are provided along with estimation of the uncertainties for other directions and distances.

The ambient dose equivalent rates at the RCL Low Scatter Calibration Room (B255 R183A) will increase by 15.5–18% for bare ^{252}Cf and 15.5% for D_2O moderated ^{252}Cf when the 10 CFR 835 (2007) radiation weighting factors are implemented. The personal dose equivalent rates will be higher than the ambient dose equivalent dose rates by 3.7% for bare ^{252}Cf and by 4.2% for D_2O moderated ^{252}Cf.

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APPENDIX A
RCL's ^{252}Cf Neutron Source Data

The RCL's ^{252}Cf sources were manufactured and calibrated by ORNL's Chemical Technology Division. Their activity (or emission rate) was stated in the letters transferring the source to LLNL and is provided in Table A-1.

Table A-1. Data from ORNL letters transferring the ^{252}Cf sources to LLNL

Isotope	Designation	Alias	Original Calibration Date	Original Neutron Emission Rate or Mass	Calibration Uncertainty
^{252}Cf	NSD-133	Large	6/21/2000	5.20E+09 n/s	3%
^{252}Cf	NS-120	Small	3/31/1985	1.682 mg	3%

The calculated emission rates on the reference date of 3/10/2008 are as follows:

Large ^{252}Cf source: 6.84E+8 n/s

Small ^{252}Cf source: 9.39E+6 n/s

References and constants used for calculation of the emission rate of the ^{252}Cf sources:

^{252}Cf (NSD-133, Large)

- Letter dated September 21, 2000 from ORNL's P.A. Balo to Curtis Graham
- ^{252}Cf content on 6/21/2000 = 2243.52 microgram (listed in the 9/21/2000 letter)
- ^{252}Cf fluence on 6/21/2000 = 5.1981E+9 n/s (listed in the 9/21/2000 letter)
- Derived mass to fluence coefficient from the above data = 2.316939E+6 (n/s)/microgram
- ^{252}Cf half life ($T_{1/2}$) = 2.638 years (ICRP-38)
- ^{252}Cf fluence on 3/10/2008 = 6.84E+8 n/s

^{252}Cf (NS-120, Small)

- Letter dated April 1, 1985 from ORNL's J. B. Knauer, Chemical technology Division to Curtis Graham
- ^{252}Cf content on 3/31/1985 = 1.682 mg
- Mass to fluence conversion coefficient = 2.3169E+6 (n/s)/microgram (derived from ORNL 6/21/2000 letter to Curtis Graham)
- Fluence on 3/31/85 = 3.8971E+9 n/s
- ^{252}Cf half life ($T_{1/2}$) = 2.638 years (ICRP-38)

- ^{252}Cf fluence on 3/10/2008 = 9.39E+6 n/s

The ratio of the calculated emission rates of the Large and Small ^{252}Cf sources is equal to 72.9, as determined from the ORNL source certificate data (RLarge/Small = (6.84E+08)/(9.39E+06)= 72.9). Previous calibration experience and discussions with Curtis Graham indicated that the calculated emission rates may be off by 8-10%. The current measurements with SWENDI-II neutron rem meter at nine distances between 1.0 and 5.0 m yielded an average ratio of the emission rates of the Large and Small ^{252}Cf sources equal to 60.4. Similar value of the ratio (60.2) was obtained by independent measurement with ROSPEC neutron spectroscopic and dosimetric system (see Table A-2).

Table A-2. Ratio of activities of the Large and Small ^{252}Cf sources

Averaged measured activity ratio of the Large and the Small ^{252}Cf sources with SWENDI remmeter	60.4
Averaged measured fluence ratio of the Large and the Small ^{252}Cf sources with ROSPEC	60.2
Average of the ratios measured with SWENDI and ROSPEC	60.3

The difference between the calculated and measured activity ratios is large enough that cannot be explained by measurement uncertainty. We place a higher confidence on the Large ^{252}Cf source certificate data since it was more recent and its activity better matches ROSPEC measurements. We assume that the Large ^{252}Cf source emission rate on 3/10/2008 is equal to 6.84E+08 n/s based on the ORNL source certificate and that the emission rate of the Small ^{252}Cf source on 3/10/2008 is equal to 1.13E+07 n/s based on the averaged measured emission rate ratio of the two ^{252}Cf sources. Minor contributions of ^{250}Cf isotope ($T_{1/2}$ = 13.08 yrs) into the californium source are always present and they may be responsible for such difference between decay calculated and measured source emission rates. Decay calculations based solely on ^{252}Cf may underestimate the activity of the californium source since ^{250}Cf has a longer half life then ^{252}Cf. It was reported [8] that the initial ^{250}Cf /^{252}Cf atomic ratio is typically in the range of 0.17 to 0.24. Based on these values, the actual neutron yield after 23 years would be 10-13% greater than that calculated based on the decay of ^{252}Cf alone.

The evaluated emission rates of the RCL's ^{252}Cf sources that were used in this report are provided in Table A-3.

Table A-3. Evaluated emission rates of RCL ^{252}Cf calibration sources

Isotope	Designation	Alias	Reference Date	Evaluated Neutron Emission on Reference Date
^{252}Cf	NSD-133	Large	3/10/2008	6.84E+08 n/s
^{252}Cf	NS-120	Small	3/10/2008	1.13E+07 n/s

APPENDIX B

LLNL and NIST D_2O Moderating Spheres

The neutron moderators used at LLNL were originally designed with a 65 mm diameter opening to fit the source tube of the older pneumatic source transport system ("Wabbit"). LLNL's 30 cm D_2O sphere is covered by a thin 1mm aluminum shell with a 1 mm thick cadmium (Cd) layer on the inside surface. The Cd layer consists of small cadmium sheet sectors which are glued to the aluminum shell. The Cd/aluminum shell tightly wraps over RCL's D_2O moderating sphere.

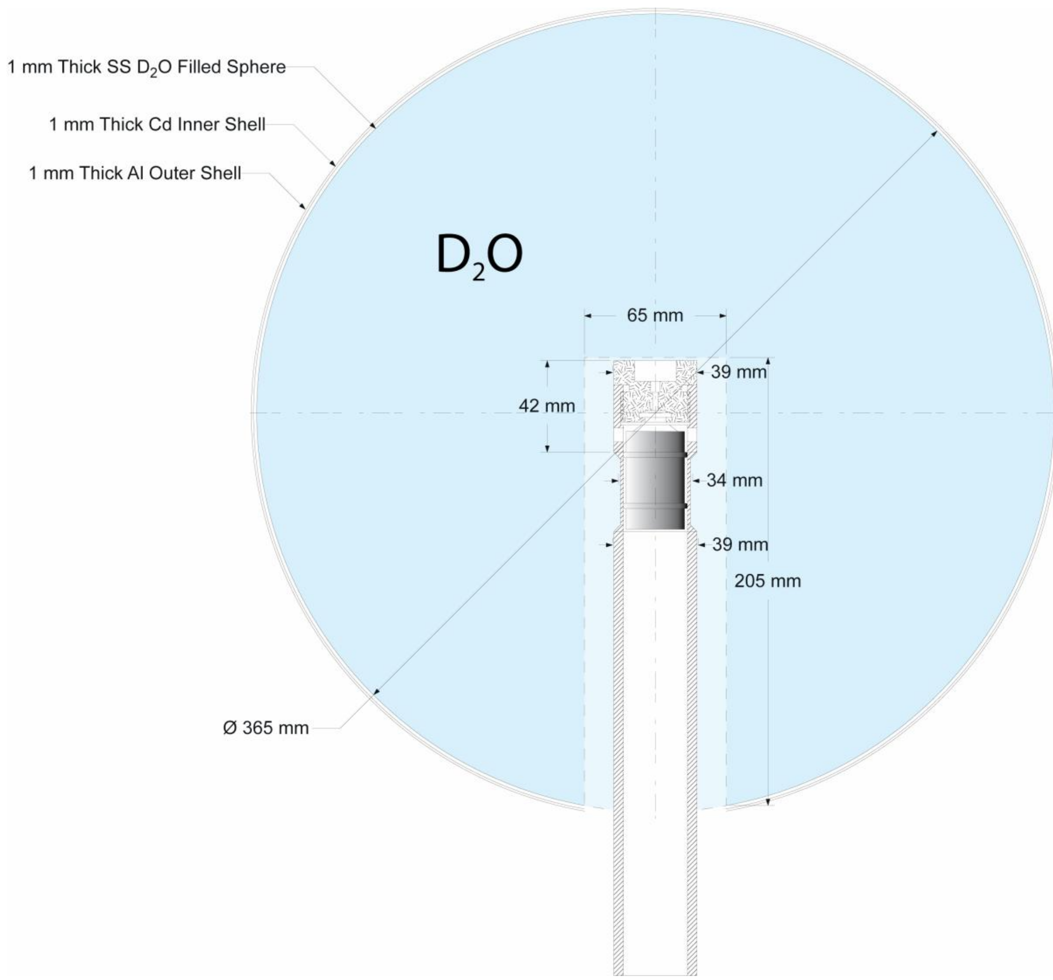


Figure B-1. LLNL 30 cm diameter D_2O moderating sphere.

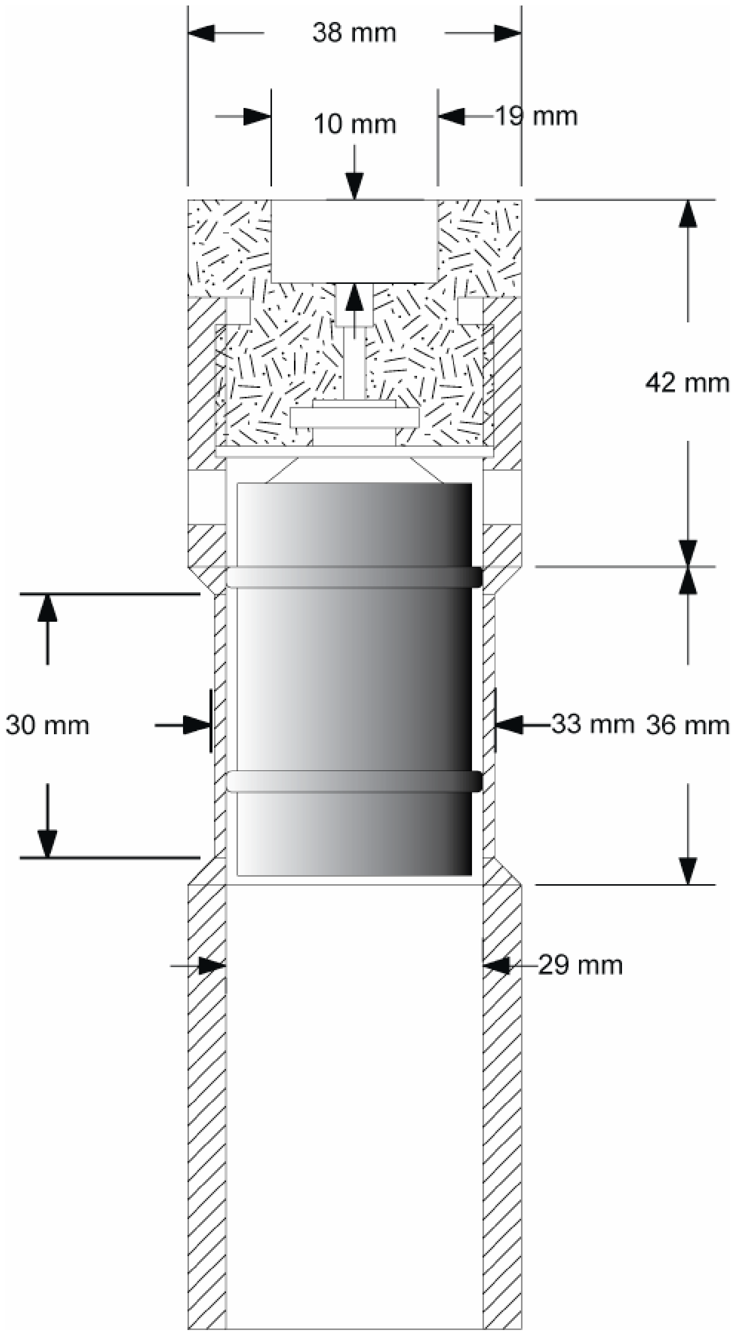


Figure B-2. Diagram of Hopewell N40 irradiator's source tube with the 'rabbit' (pneumatic transport source container) in RCL's Room 183A.

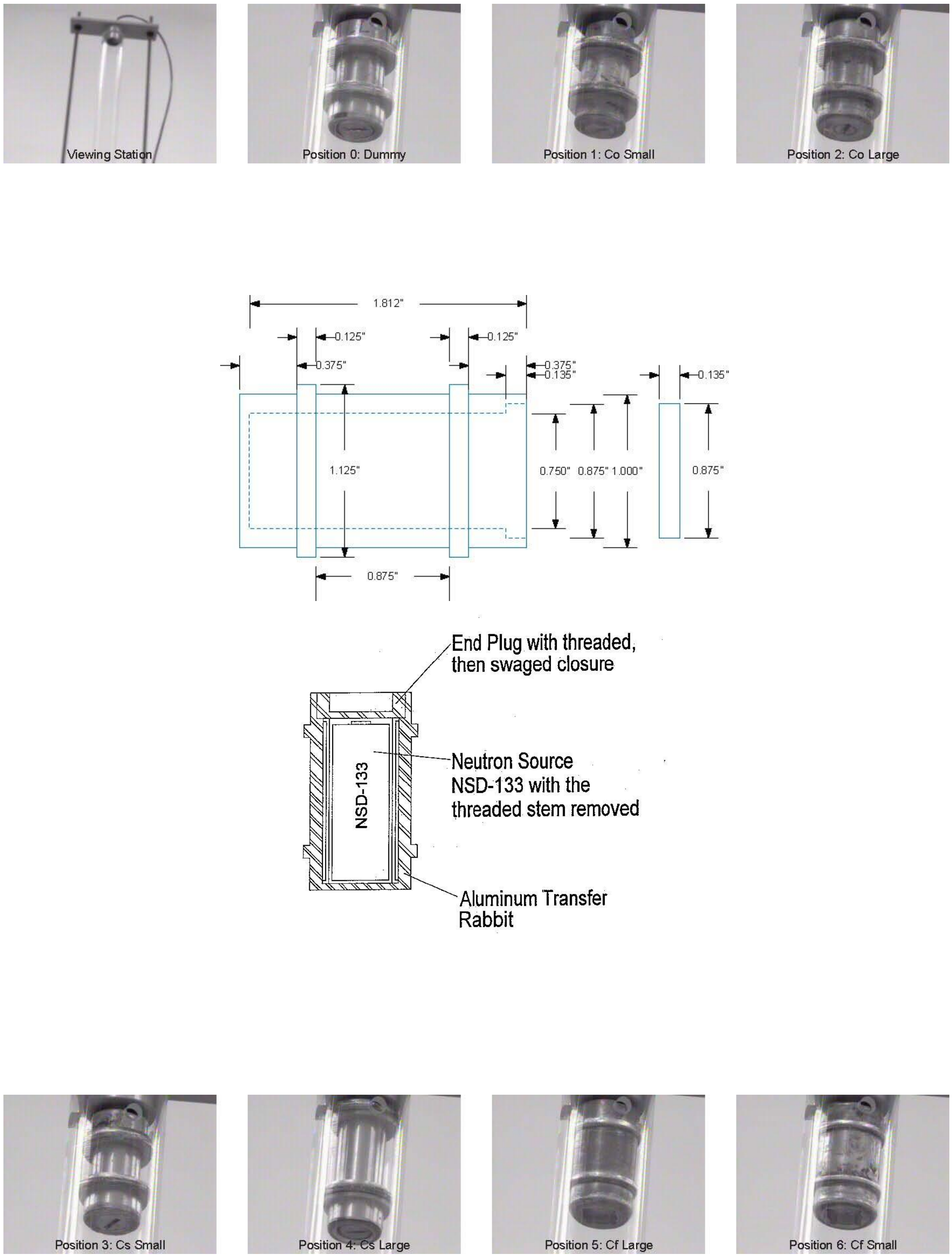


Figure B-3. RCL's pneumatic transport system source containers (rabbits).

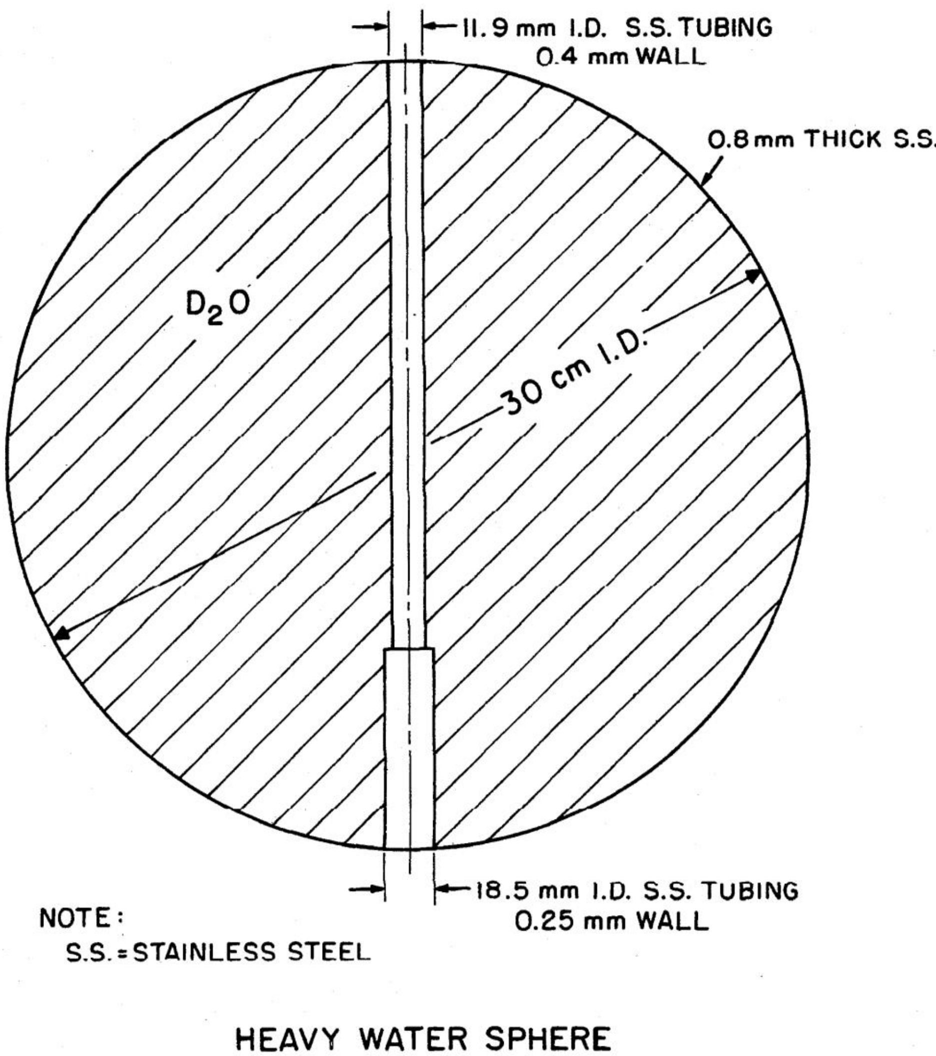


Figure B-4. NIST 30 cm diameter D_2O moderating sphere.

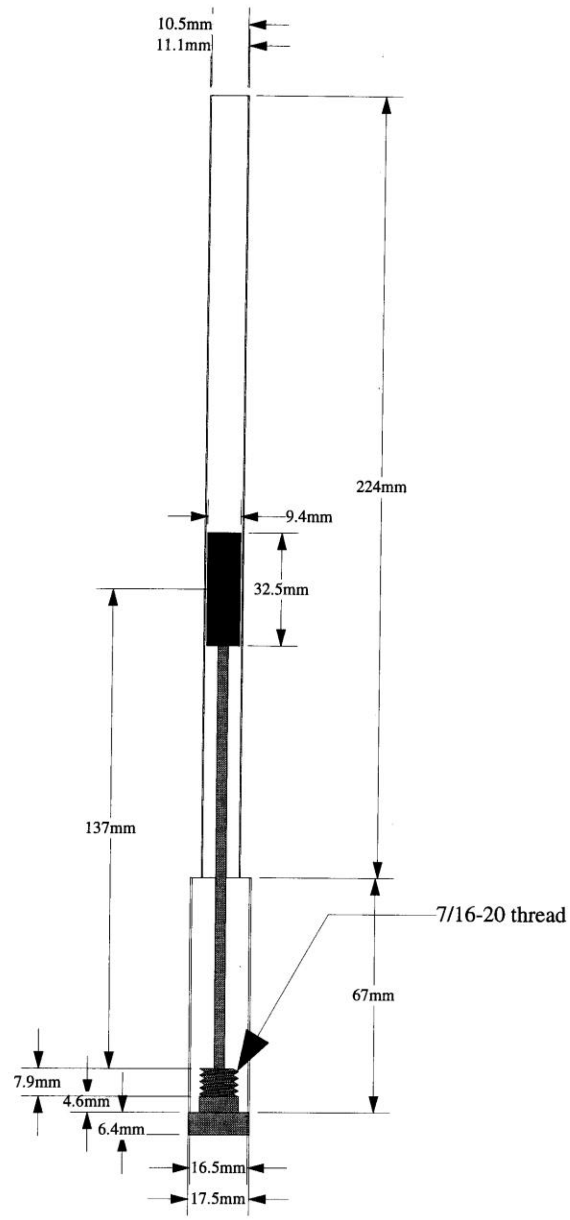


Figure B-5. NIST ^{252}Cf source capsule and stem for the D_2O moderating sphere.

APPENDIX C

Fluence-to-Dose Conversion Factors

Table B below contains the fluence-to-dose conversion factors used in the software program to calculate the dosimetric values from the neutron spectra obtained by ROSPEC.

KERMA – is the quotient of dE by dm, where dE is the sum of the initial kinetic energies of all the charged ionizing particles liberated by the neutrons in a volume element of mass dm.

H (NCRP-38) – is the neutron dose as defined in the “old” 10CFR835 using quality factors and fluence-to-dose conversion factors derived from NCRP-38.

H*(10) – the ambient dose equivalent as defined in ICRP-74 at a point in a radiation field is the dose equivalent that would be produced by the corresponding expanded and aligned neutron field in the ICRU sphere at a depth of 10 mm on the radius opposing the direction of the aligned field.

Hp(10,0) – is the personal dose equivalent as defined in ICRP-74 in soft tissue at 10 mm below a specified point on the body at 0 degree between the incident unidirectional neutron field and the direction normal to the surface (in atero-posterior geometry).

Note: anthropomorphic phantoms of various parts of the body are not yet specified by ICRU with the exception of the human trunk. For the purposes of dosimeter calibration, phantoms have been specified that are taken as surrogates of the human torso. These specified tissue-equivalent phantoms are the ICRU-equivalent sphere (30 cm diameter) and the 30cm x 30cm x 15cm ICRU slab (ICRU Report 47).

Table C-1. Fluence-to-dose conversion factors

En (MeV)	KERMA (nrad/n/cm^2)	H NCRP-38 (nrem/n/cm^2)	H*(10) ICRP-74 (pSv/n/cm^2)	Hp(10,0) ICRP-74 (pSv/n/cm^2)
2.50E-08	0.02	1.02	10.6	11.4
1.00E-07	0.01	1.02	12.9	12.6
1.00E-06	0.003	1.24	13.3	14.4
1.00E-05	0.001	1.24	11.3	13.2
1.00E-04	0.001	1.20	9.4	10.3
0.001	0.011	1.02	7.9	8.78
0.002	0.02	1.01	7.7	8.72
0.005	0.05	1.00	8.0	9.36
0.01	0.10	0.99	10.5	11.2
0.02	0.18	1.70	16.6	17.1
0.03	0.29	2.30	23.7	24.9
0.05	0.41	3.30	41.1	39.0
0.07	0.51	4.30	60.0	59.0
0.10	0.64	6.04	88.0	90.6
0.15	0.82	8.80	132.0	139.0
0.20	0.97	11.50	170.0	180.0
0.25	1.10	14.00	210.0	213.0
0.30	1.22	16.50	233.0	246.0
0.35	1.33	19.00	270.0	268.3
0.40	1.49	21.50	280.0	290.5
0.45	1.65	23.50	310.0	312.8
0.50	1.61	25.72	322.0	335.0
0.55	1.68	27.00	340.0	347.8
0.60	1.76	28.50	350.0	360.5
0.65	1.83	30.50	365.0	373.3
0.70	1.90	32.00	375.0	386.0
0.75	1.97	33.00	385.0	393.0
0.80	2.03	34.00	390.0	400.0
0.85	2.09	35.50	395.0	407.0
0.90	2.16	35.50	400.0	414.0
0.95	2.33	36.00	400.0	418.0
1.00	2.51	36.50	416.0	422.0
1.20	2.46	37.00	425.0	433.0
1.40	2.64	37.00	425.0	435.3
1.60	2.80	36.50	420.0	437.5
1.80	2.95	36.20	420.0	439.8

En (MeV)	KERMA (nrad/n/cm^2)	H NCRP-38 (nrem/n/cm^2)	H*(10) ICRP-74 (pSv/n/cm^2)	Hp(10,0) ICRP-74 (pSv/n/cm^2)
2.00	3.09	36.00	420.0	442.0
2.20	3.22	35.00	418.0	439.8
2.40	3.34	35.00	416.0	437.6
2.60	3.45	35.00	415.0	435.4
2.80	3.56	35.50	412.0	433.2
3.00	3.69	35.80	412.0	431.0
3.20	3.86	36.00	410.0	429.2
3.40	4.07	36.50	410.0	427.4
3.60	4.23	37.00	410.0	425.6
3.80	4.24	38.00	408.0	423.8
4.00	4.20	39.00	408.0	422.0
4.20	4.20	40.00	408.0	421.6
4.40	4.25	41.00	408.0	421.2
4.60	4.31	42.00	408.0	420.8
4.80	4.38	43.00	405.0	420.4
5.00	4.45	43.48	405.0	420.0
5.50	4.60	42.50	402.0	421.5
6.00	4.75	42.00	400.0	423.0
6.50	4.89	41.00	402.0	427.5
7.00	5.01	40.90	405.0	432.0
8.00	5.25	40.85	409.0	445.0
9.00	5.46	40.85	420.0	461.0
10.00	5.65	40.85	440.0	480.0
11.00	5.82	45.00	460.0	498.5
12.00	5.99	49.00	480.0	517.0
13.00	6.14	52.00	500.0	533.5
14.00	6.29	57.87	520.0	550.0
15.00	6.36	59.00	540.0	564.0
16.00	6.41	60.00	540.0	576.0
17.00	6.47	61.00	562.0	585.5
18.00	6.52	62.00	570.0	595.0
19.00	6.57	62.50	585.0	597.5
20.00	6.62	63.13	600.0	600.0

APPENDIX D

Plots of Measured Neutron Energy Spectra and Tables of Fluence and Dosimetric Data

For each location and ^{252}Cf source the ROSPEC data is presented in a figure with 2 plots of the neutron energy distribution and a corresponding table with the fluence and dosimetric data.

Plots

The neutron energy range in the upper plot of each figure is from thermal to 4.5 MeV neutrons. It is normalized per one source neutron. The lower plot is not normalized per one source neutron. Its energy range is from 50 keV to 4.5 MeV. The representation of the neutron spectra in the figures is standard in the field of neutron physics and radiation protection from neutrons. Neutron energy E, times the fluence rate energy distribution dϕ/dE, is plotted on the vertical axis against neutron energy E on the horizontal axis. Energy E is in MeV units and is plotted on a logarithmic scale. It is conceptually simpler to plot just dϕ/dE on the vertical axis, however, that typically requires a log-log plot for neutrons covering many orders of magnitude on both axes, making details difficult to see. The large range of neutron dϕ/dE stems from its characteristic 1/E dependence when the neutrons slow down in a scattering media. On all ROSPEC neutron energy plots the vertical axis is in lethargy units; the lethargy = phi(E)/[ln(E2/E1)], where phi(E) is the neutron fluence in a given energy bin (in neutrons per cm^2) and E2 and E1 are the upper and lower bin boundary energies. E PHI E on the plots is a shorthand for lethargy because lethargy is often approximated with E*phi(E)/deltaE (i.e. E*dϕ/dE). “ROSPEC II” in the title of each plot indicates version 2 of the ROSPEC software that uses data from 6 detectors.

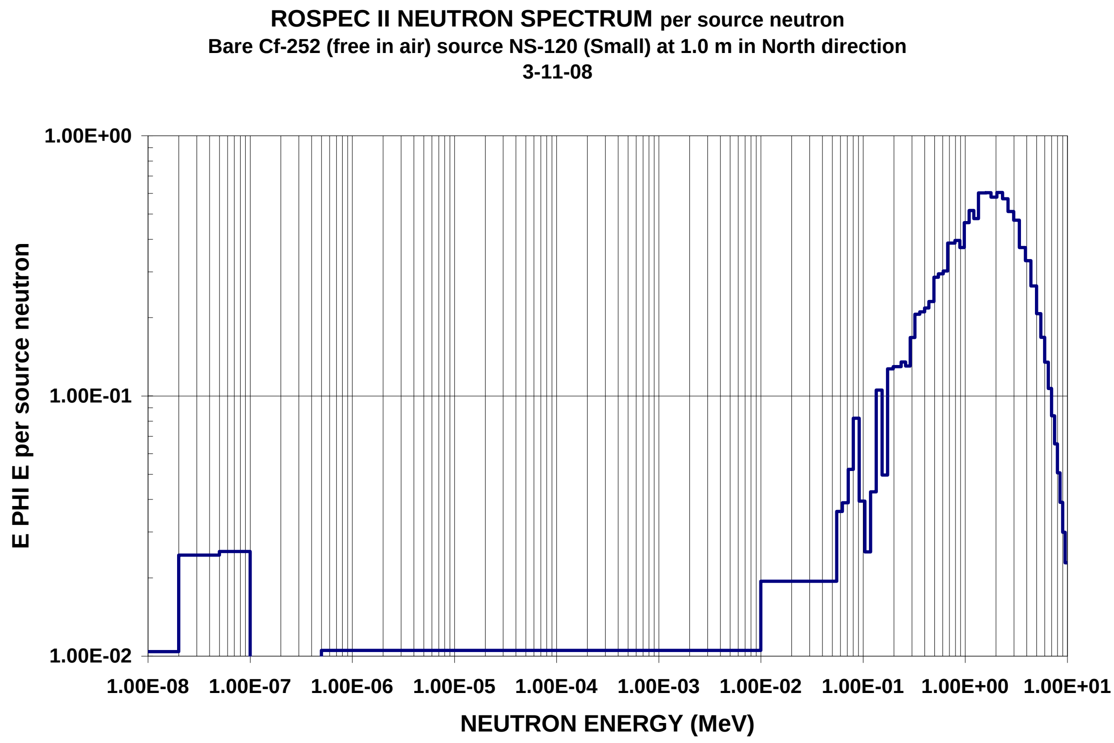
Detailed neutron spectra plots in the upper plots are in the energy region from thermal to 4.5 MeV and are normalized per one neutron in the following fashion. After the spectra from the six detectors are combined, the number of neutrons in each energy bin of the combined spectra is divided by the total number of neutrons in the combined spectra. Such presentation allows for better visual comparison of spectra taken for different periods of time and from sources with different activities.

The neutron spectra in the lower plots are not normalized to one source neutron and, therefore, provide indication on the relative strength of the neutron fields at these locations. These plots provide more details in the energy region of 50 keV-4.5 MeV for the same the neutron spectra.

Tables

The integral neutron fluence (in neutrons per cm^2) and neutron fluence rates (in neutrons per cm^2 per second) measured with ROSPEC are presented in the corresponding Tables D-n (n=1,2,…30). The fluence and fluence rates are also presented for the fast neutron region (50 keV-4.5 MeV), epithermal region (1 eV - 50keV) and thermal region (< 1 eV). The dose rates are calculated from the measured spectral fluence using the fluence-to-dose conversion factors listed in Appendix C. For each location three integrated dose and dose rates are given:

dose equivalent rate based on the fluence-to-dose conversion factors derived from NCRP-38 (H NCRP-38), ambient dose equivalent rate based on the fluence-to-dose conversion factors from ICRP-74 (H*(10) ICRP-74) and personal dose equivalent rate based on the fluence-to-dose conversion factors from ICRP-74 for personal dose in atero-posterior geometry (Hp(10,0) ICRP-74). Additionally dosimetric data are presented in the tables for the three neutron energy regions: 50 keV - 4.5 MeV, epithermal, and thermal.



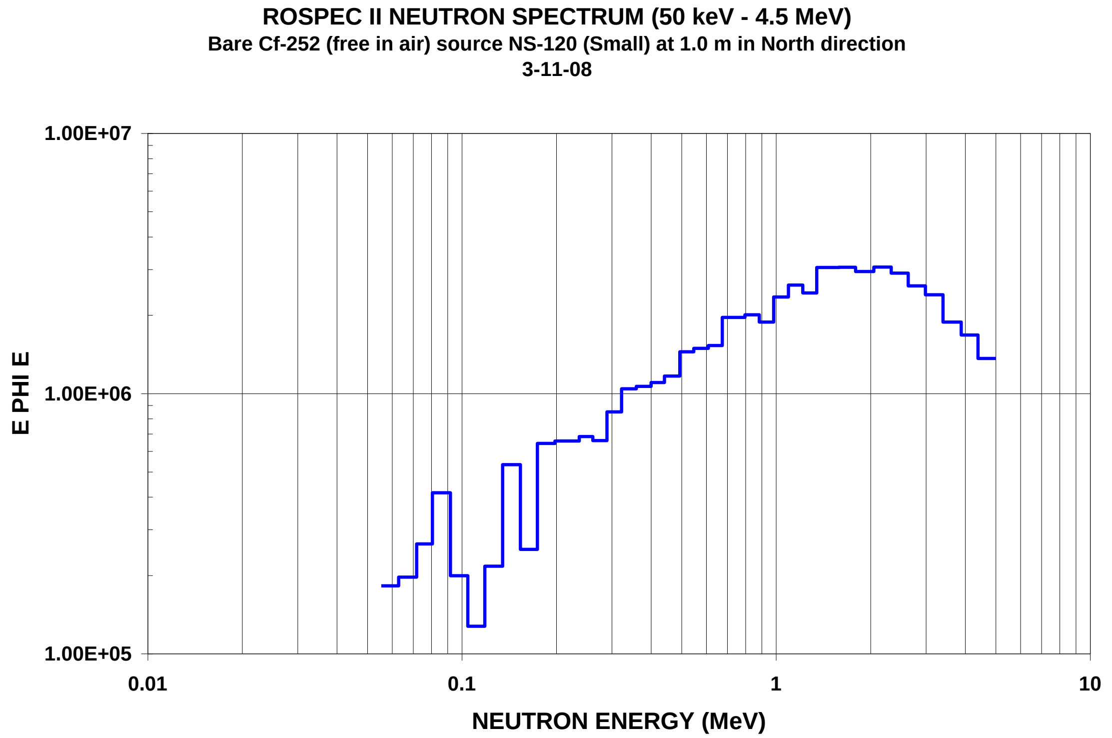


Figure D-1. Neutron spectra from bare ^{252}Cf (free in air) source NS-120 (Small) at 1.0 m in North direction.

Table D-1. Neutron fluence and dose from bare ^{252}Cf (free in air) source NS-120 (Small) at 1.0 m in North direction

Date: 3-11-08
Exposure time = 63,718 sec.

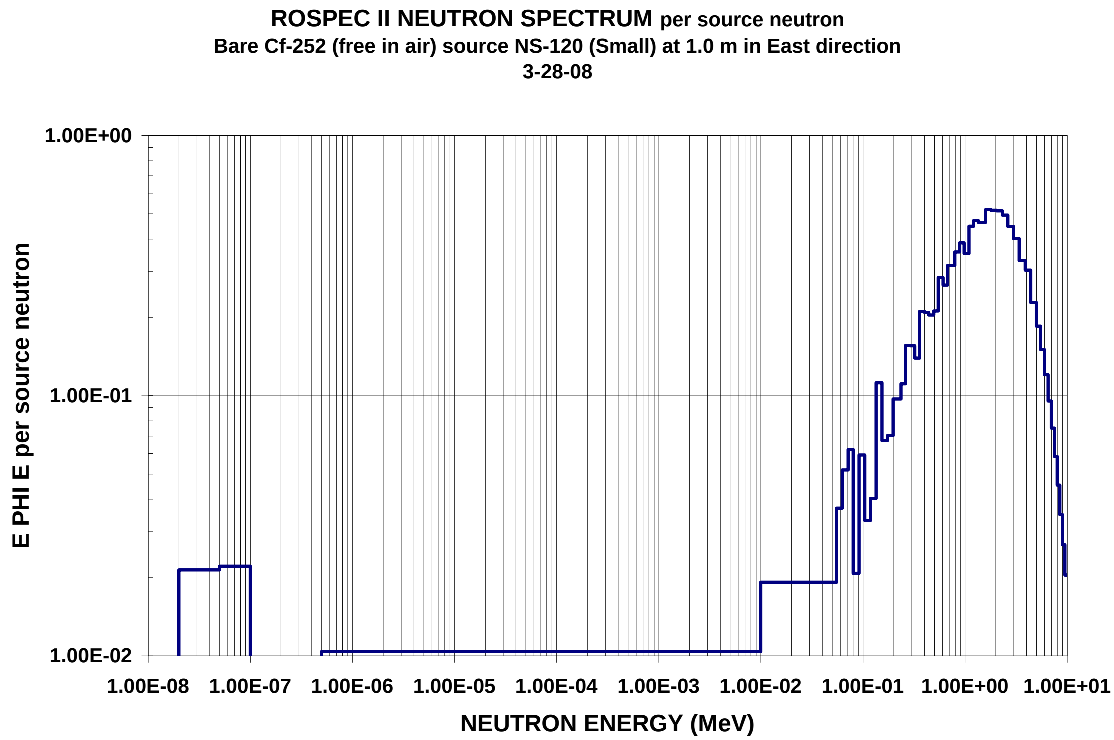
INTEGRATED FLUENCE = 7.8391E+06 FLUENCE RATE = 1.2303E+02

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.8053E-02 rads	1.0200E+00 mrads/hr
H NCRP-38	= 2.1862E-01 rem	1.2352E+01 mrem/hr
H*(10) ICRP-74	= 2.5298E-03 Sv	1.4293E+02 μSv/hr
Hp(10,0) ICRP-74	= 2.6225E-03 Sv	1.4817E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	6.47E+06	1.01E+02
Epi-thermal region:	7.36E+05	1.15E+01
Thermal region:	2.81E+05	4.42E+00
TOTAL:	7.48E+06	1.17E+02

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.68E-02	2.05E-01	2.39E-03	9.48E-01	1.16E+01	1.35E+02
Epi-thermal region:	4.99E-05	1.00E-03	9.65E-06	2.82E-03	5.67E-02	5.45E-01
Thermal region:	5.63E-06	2.87E-04	2.98E-06	3.18E-04	1.62E-02	1.69E-01
TOTAL:	1.68E-02	2.06E-01	2.40E-03	9.51E-01	1.17E+01	1.36E+02



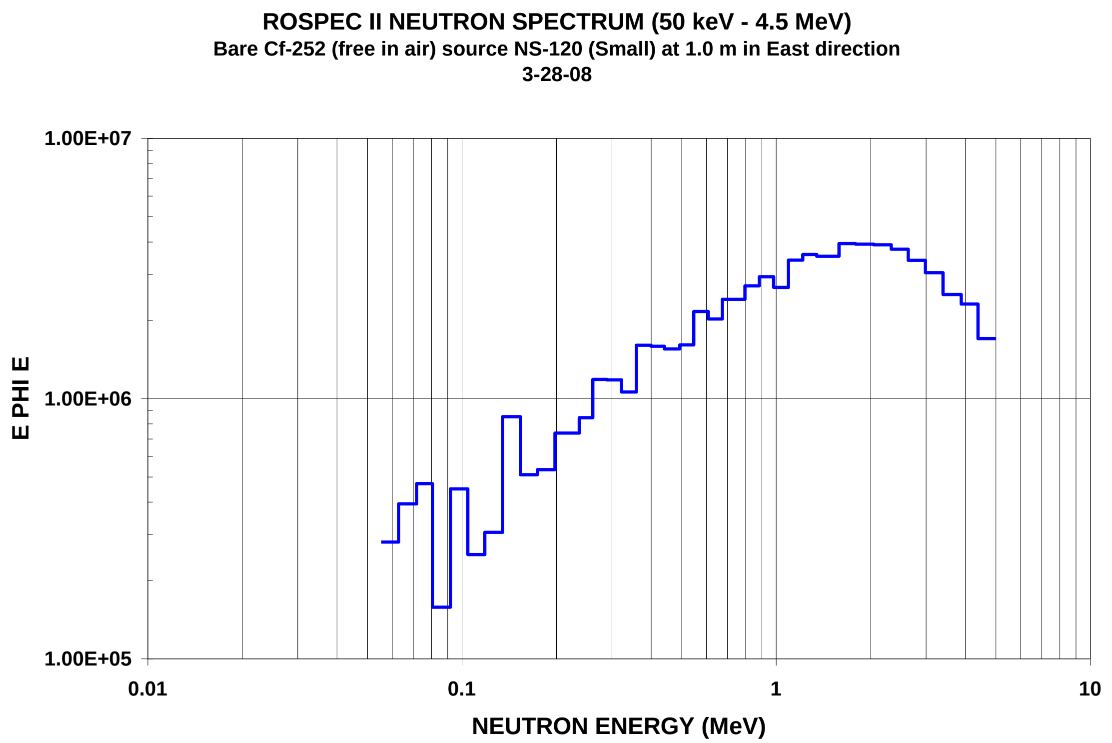


Figure D-2. Neutron spectra from bare ^{252}Cf (free in air) source NS-120 (Small) at 1.0 m in East direction.

Table D-2. Neutron fluence and dose from bare ^{252}Cf (free in air) source NS-120 (Small) at 1.0 m in East direction

Date: 3-28-08
Exposure time = 83,200 sec.

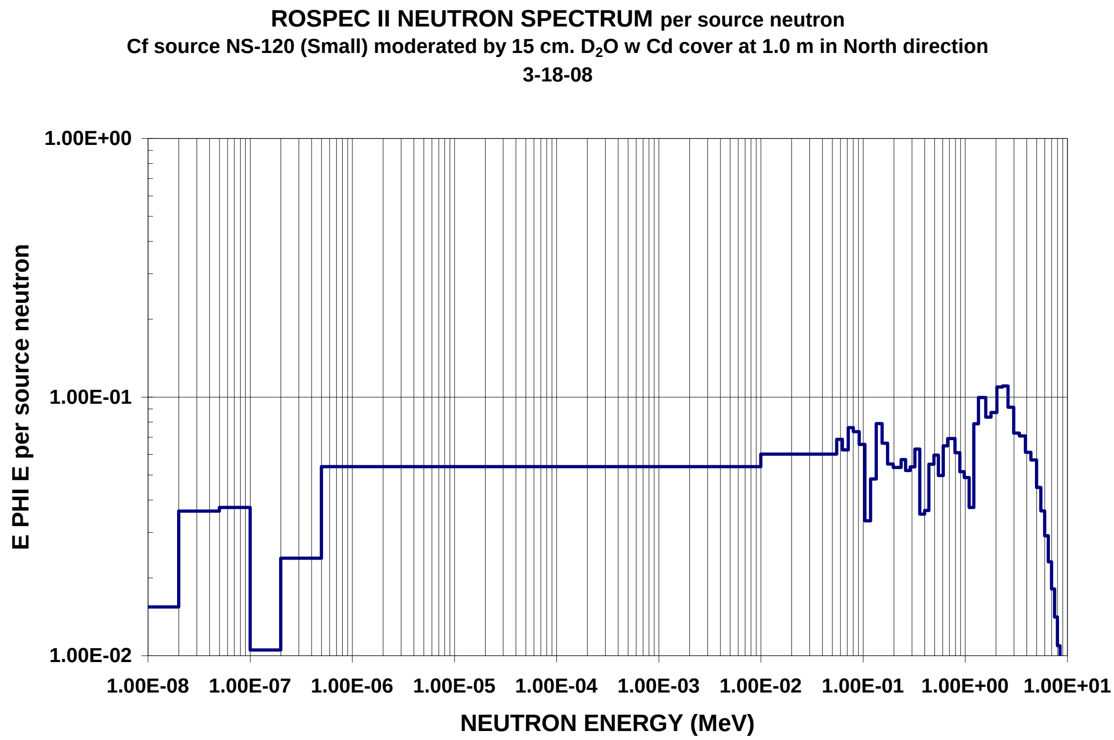
INTEGRATED FLUENCE = 1.0373E+07 FLUENCE RATE = 1.2467E+02

	INTEGRATED DOSE	DOSE RATE
KERMA	= 2.3558E-02 rads	1.0194E+00 mrads/hr
H NCRP-38	= 2.8498E-01 rem	1.2331E+01 mrem/hr
H*(10) ICRP-74	= 3.2966E-03 Sv	1.4264E+02 μSv/hr
Hp(10,0) ICRP-74	= 3.4173E-03 Sv	1.4786E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	8.43E+06	1.01E+02
Epi-thermal region:	1.09E+06	1.31E+01
Thermal region:	3.70E+05	4.44E+00
TOTAL:	9.89E+06	1.19E+02

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	2.18E-02	2.66E-01	3.11E-03	9.42E-01	1.15E+01	1.34E+02
Epi-thermal region:	7.40E-05	1.48E-03	1.43E-05	3.20E-03	6.42E-02	6.17E-01
Thermal region:	7.39E-06	3.77E-04	3.92E-06	3.20E-04	1.63E-02	1.70E-01
TOTAL:	2.19E-02	2.68E-01	3.12E-03	9.46E-01	1.16E+01	1.35E+02



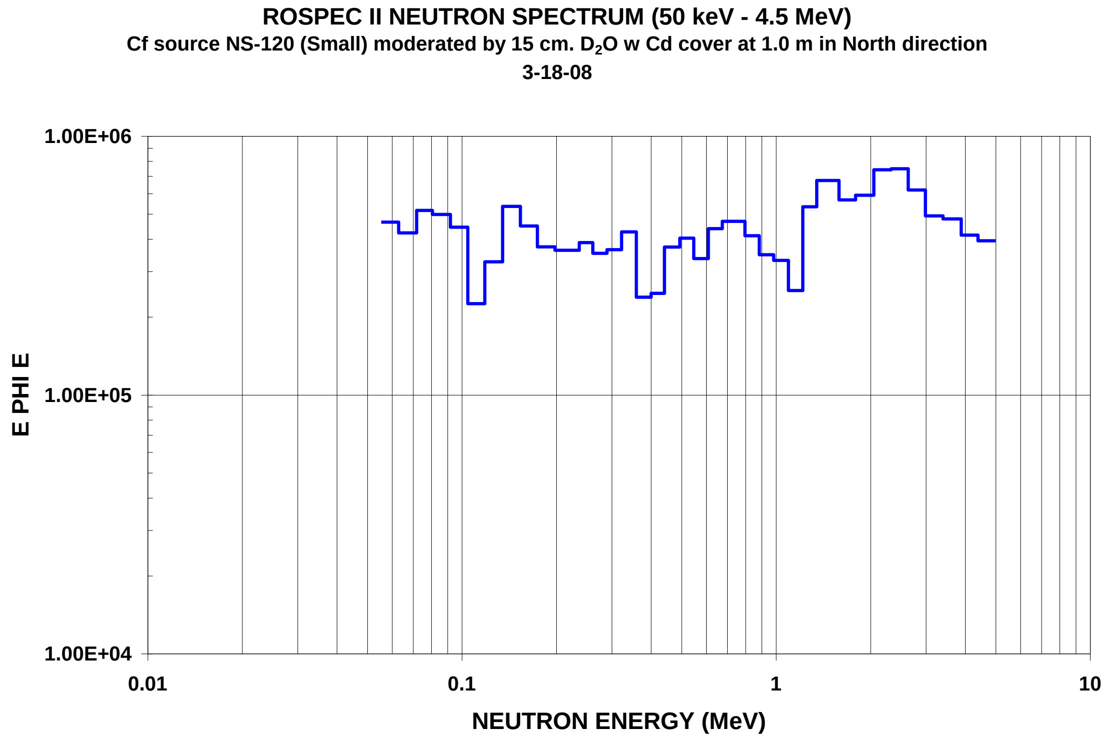


Figure D-3. Neutron spectra from ^{252}Cf source NS-120 (Small) moderated by 15 cm. D_2O with Cd cover at 1.0 m in North direction

Table D-3. Neutron fluence and dose from ^{252}Cf source NS-120 (Small) moderated by 15 cm. D_2O with Cd cover at 1.0 m in North direction

Date: 3-18-08
Exposure time = 74,230 sec

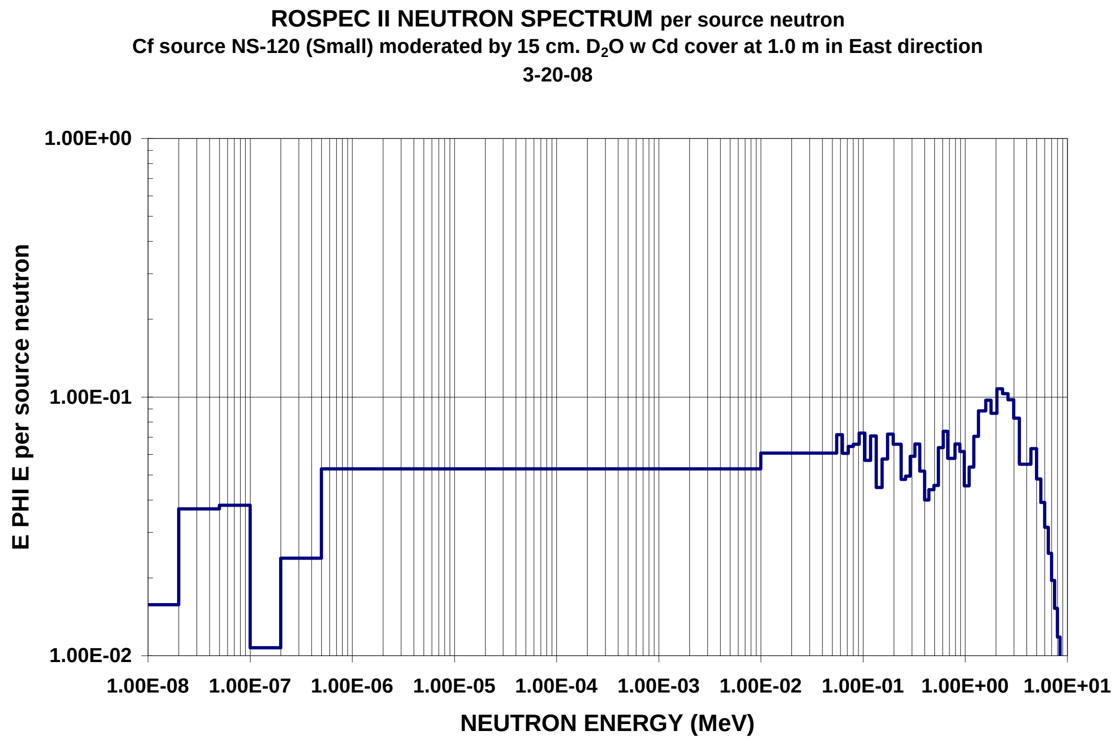
INTEGRATED FLUENCE = 7.1275E+06 FLUENCE RATE = 9.6019E+01

INTEGRATED DOSE		DOSE RATE
KERMA	= 4.7821E-03 rads	2.3192E-01 mrads/hr
H	NCRP-38 = 5.9576E-02 rem	2.8893E+00 mrem/hr
H*(10)	ICRP-74 = 6.8813E-04 Sv	3.3373E+01 μSv/hr
Hp(10,0)	ICRP-74 = 7.1636E-04 Sv	3.4742E+01 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	2.01E+06	2.71E+01
Epi-thermal region:	4.46E+06	6.00E+01
Thermal region:	5.58E+05	7.52E+00
TOTAL:	7.03E+06	9.47E+01

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	4.18E-03	4.98E-02	5.95E-04	2.03E-01	2.42E+00	2.89E+01
Epi-thermal region:	2.27E-04	5.77E-03	5.38E-05	1.10E-02	2.80E-01	2.61E+00
Thermal region:	1.12E-05	5.70E-04	5.92E-06	5.42E-04	2.76E-02	2.87E-01
TOTAL:	4.41E-03	5.62E-02	6.55E-04	2.14E-01	2.72E+00	3.18E+01



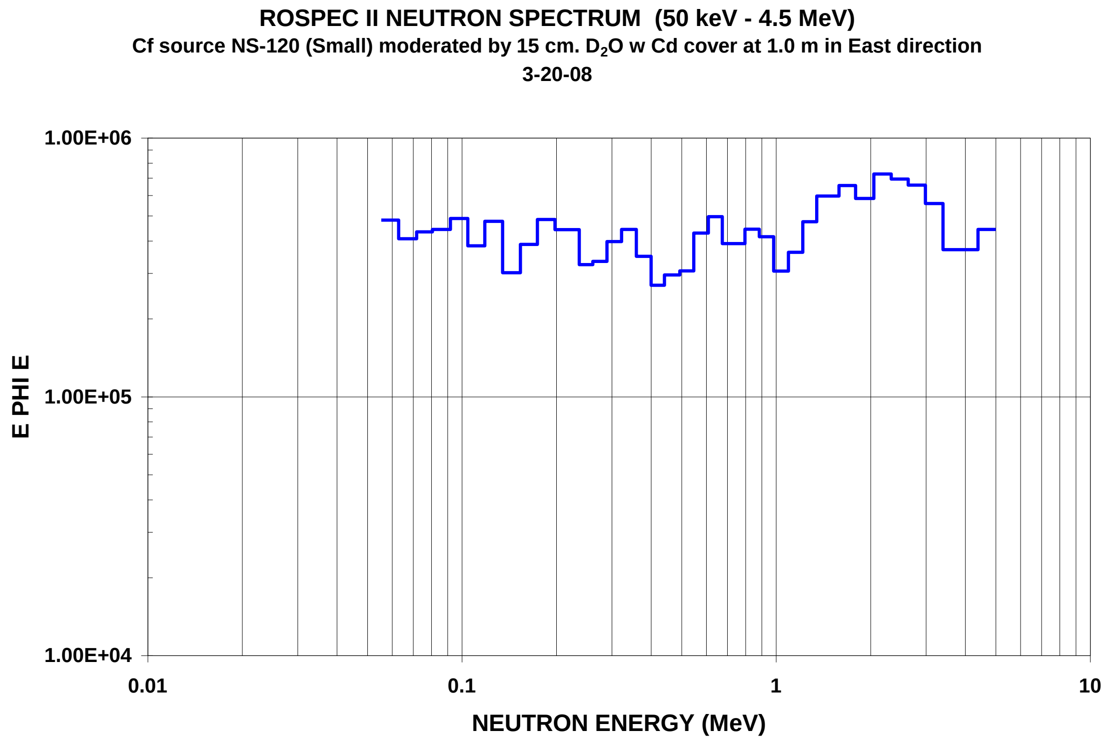


Figure D-4. Neutron spectra from ^{252}Cf source NS-120 (Small) moderated by 15 cm. D_2O with Cd cover at 1.0 m in East direction.

Table D-4. Neutron fluence and dose from ^{252}Cf source NS-120 (Small) moderated by 15 cm. D_2O with Cd cover at 1.0 m in East direction

Date: 3-20-08
Exposure time = 73,800 sec

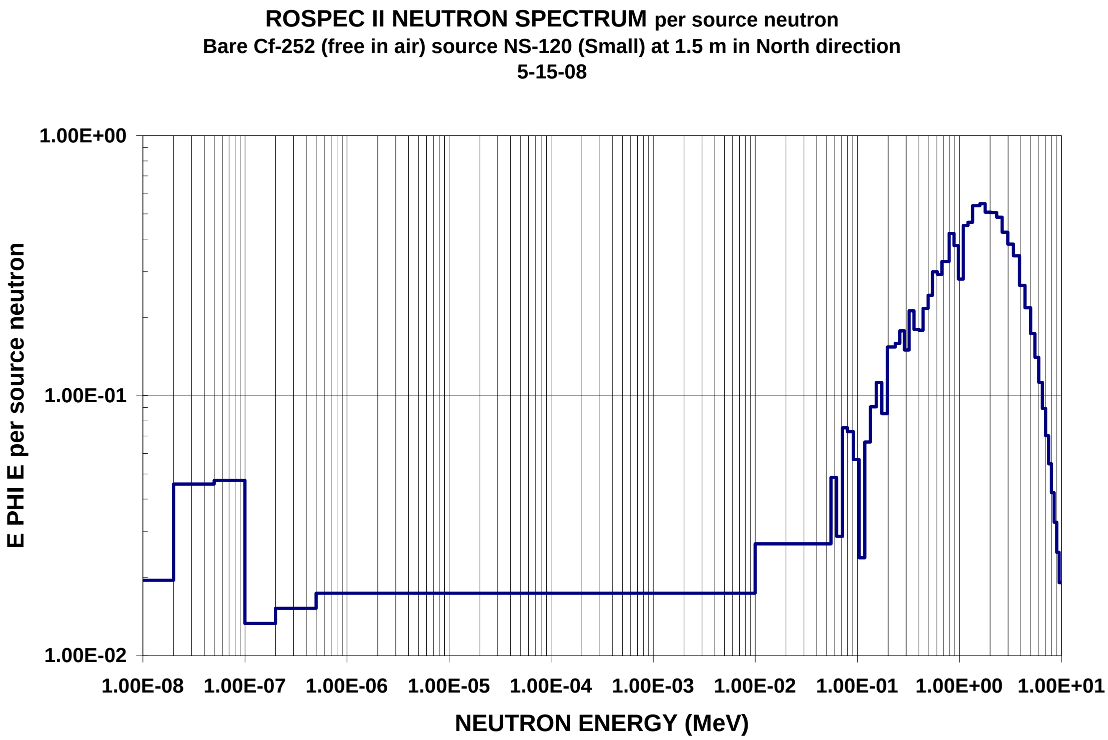
INTEGRATED FLUENCE = 7.0692E+06 FLUENCE RATE = 9.5789E+01

	INTEGRATED DOSE	DOSE RATE
KERMA	= 4.8053E-03 rads	2.3441E-01 mrads/hr
H NCRP-38	= 5.9805E-02 rem	2.9173E+00 mrem/hr
H*(10) ICRP-74	= 6.9117E-04 Sv	3.3715E+01 μSv/hr
Hp(10,0) ICRP-74	= 7.1951E-04 Sv	3.5098E+01 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	2.02E+06	2.74E+01
Epi-thermal region:	4.37E+06	5.92E+01
Thermal region:	5.66E+05	7.67E+00
TOTAL:	6.96E+06	9.43E+01

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	4.17E-03	4.99E-02	5.97E-04	2.03E-01	2.43E+00	2.91E+01
Epi-thermal region:	2.27E-04	5.68E-03	5.30E-05	1.11E-02	2.77E-01	2.59E+00
Thermal region:	1.13E-05	5.77E-04	6.00E-06	5.52E-04	2.82E-02	2.93E-01
TOTAL:	4.41E-03	5.62E-02	6.56E-04	2.15E-01	2.74E+00	3.20



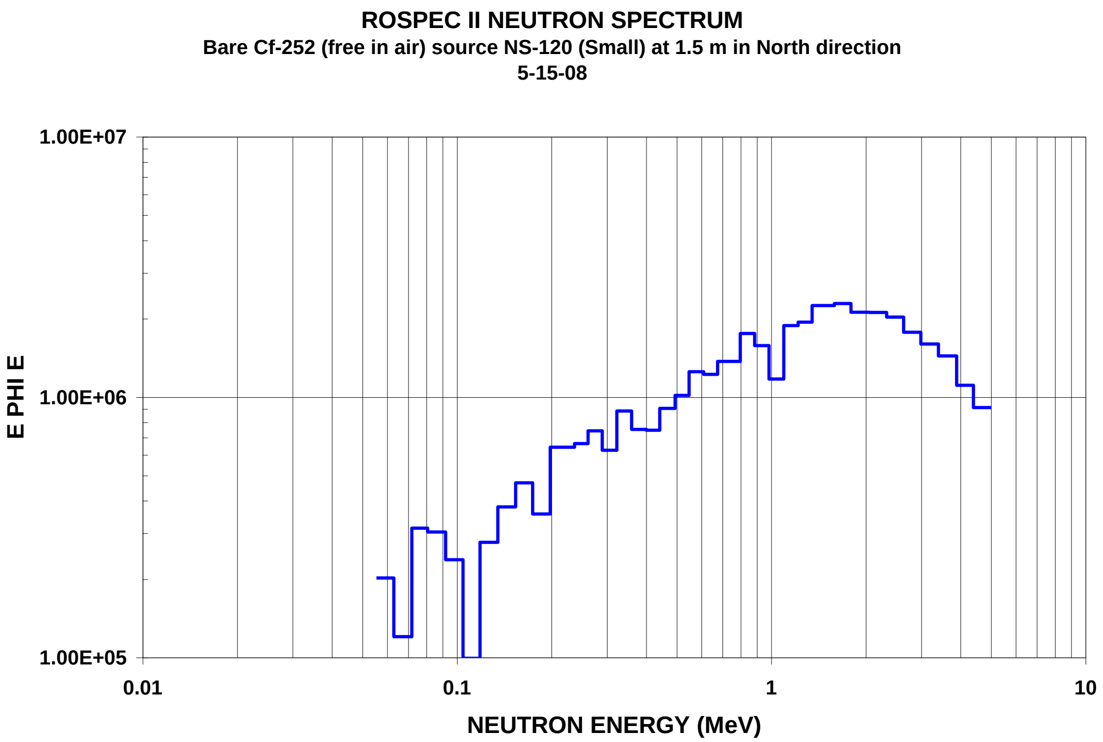


Figure D-5. Neutron spectra from bare ^{252}Cf (free in air) source NS-120 (Small) at 1.5 m in North direction.

Table D-5. Neutron fluence and dose from bare ^{252}Cf (free in air) source NS-120 (Small) at 1.5 m in North direction

Date: 5-15-08
Exposure time = 103,100 sec

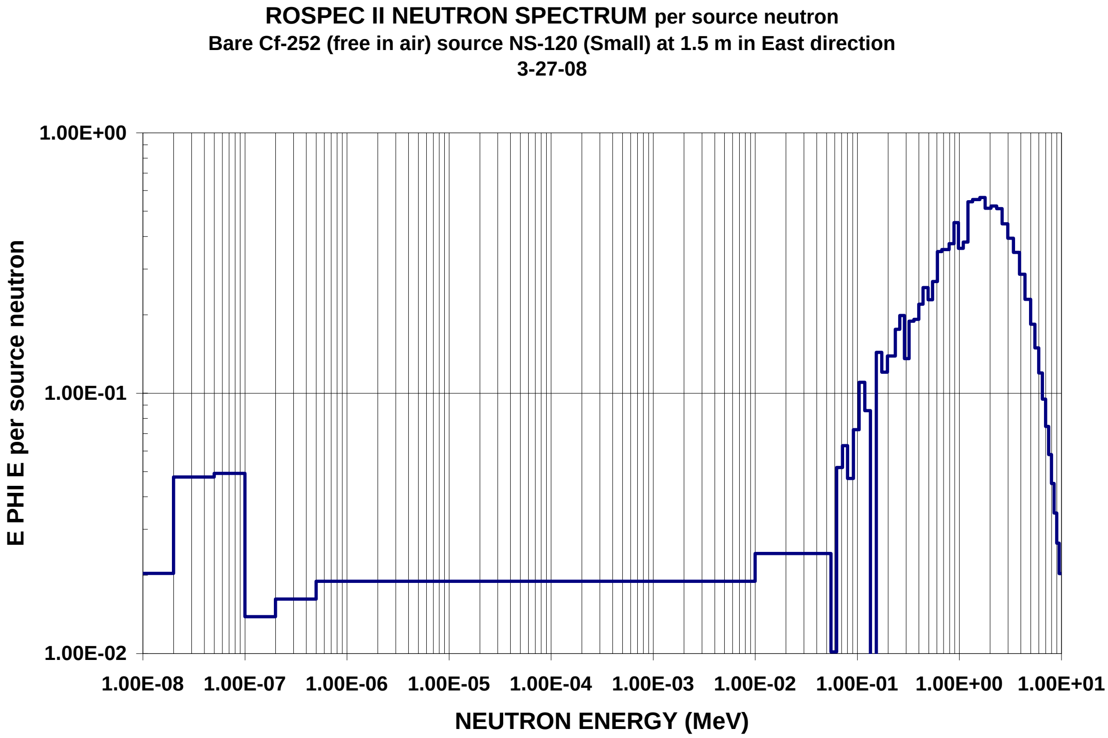
INTEGRATED FLUENCE = 6.4805E+06 FLUENCE RATE = 6.2857E+01

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.3054E-02 rads	4.5581E-01 mrads/hr
H NCRP-38	= 1.5956E-01 rem	5.5714E+00 mrem/hr
H*(10) ICRP-74	= 1.8523E-03 Sv	6.4678E+01 μSv/hr
Hp(10,0) ICRP-74	= 1.9199E-03 Sv	6.7040E+01 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	4.83E+06	4.68E+01
Epi-thermal region:	9.72E+05	9.42E+00
Thermal region:	4.35E+05	4.22E+00
TOTAL:	6.23E+06	6.05E+01

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.22E-02	1.49E-01	1.75E-03	4.24E-01	5.22E+00	6.11E+01
Epi-thermal region:	5.89E-05	1.30E-03	1.24E-05	2.06E-03	4.53E-02	4.31E-01
Thermal region:	8.70E-06	4.44E-04	4.61E-06	3.04E-04	1.55E-02	1.61E-01
TOTAL:	1.22E-02	1.51E-01	1.77E-03	4.27E-01	5.28E+00	6.17E+01



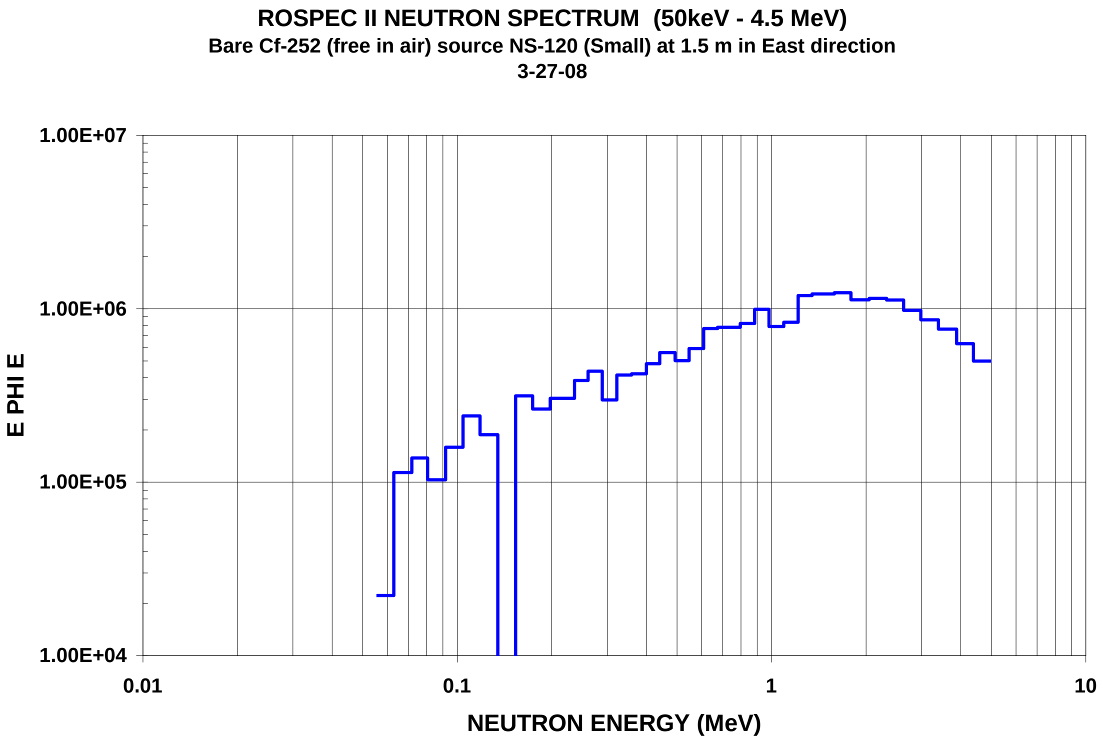


Figure D-6. Neutron spectra from bare ^{252}Cf (free in air) source NS-120 (Small) at 1.5 m in East direction.

Table D-6. Neutron fluence and dose from bare ^{252}Cf (free in air) source NS-120 (Small) at 1.5 m in East direction

Date: 3-27-08
Exposure time = 54,000 sec

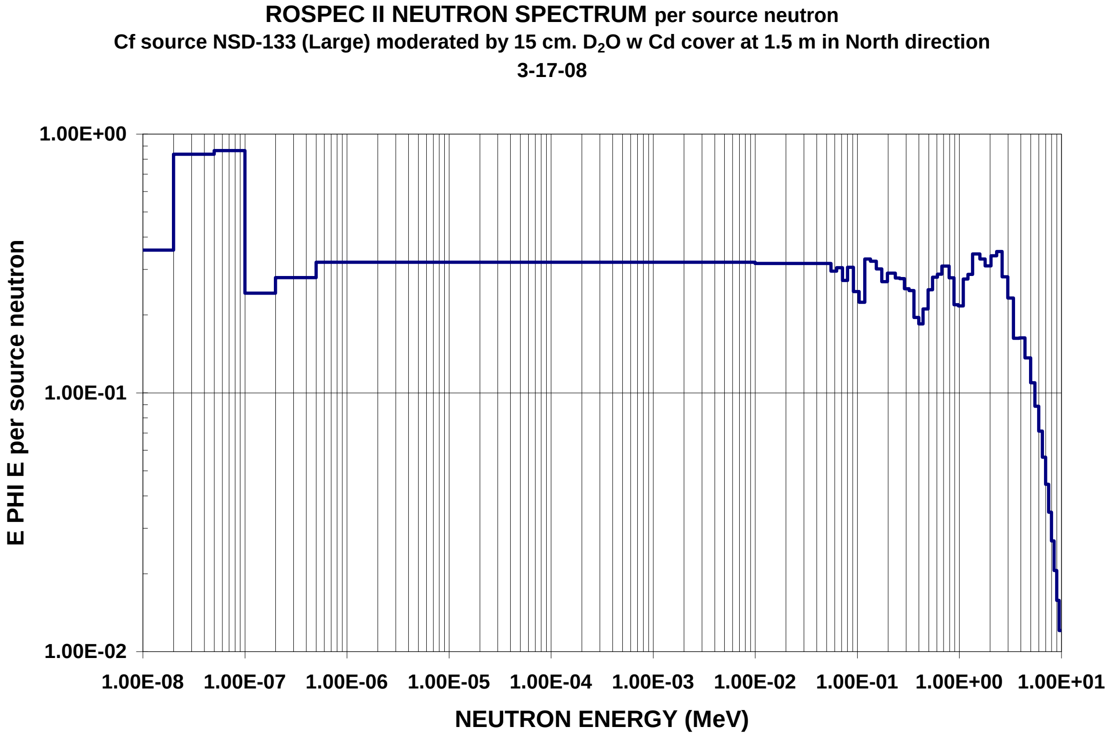
INTEGRATED FLUENCE = 3.5426E+06 FLUENCE RATE = 6.5603E+01

	INTEGRATED DOSE	DOSE RATE
KERMA	= 7.1396E-03 rads	4.7598E-01 mrads/hr
H NCRP-38	= 8.7352E-02 rem	5.8235E+00 mrem/hr
H*(10) ICRP-74	= 1.0134E-03 Sv	6.7561E+01 µSv/hr
Hp(10,0) ICRP-74	= 1.0504E-03 Sv	7.0030E+01 µSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	2.63E+06	4.87E+01
Epi-thermal region:	5.35E+05	9.90E+00
Thermal region:	2.37E+05	4.40E+00
TOTAL:	3.40E+06	6.30E+01

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (µSv/hr)
50keV - 4.5 MeV:	6.64E-03	8.17E-02	9.56E-04	4.42E-01	5.45E+00	6.38E+01
Epi-thermal region:	2.89E-05	6.98E-04	6.60E-06	1.92E-03	4.66E-02	4.40E-01
Thermal region:	4.75E-06	2.42E-04	2.52E-06	3.17E-04	1.61E-02	1.68E-01
TOTAL:	6.67E-03	8.27E-02	9.66E-04	4.45E-01	5.51E+00	6.44E+01



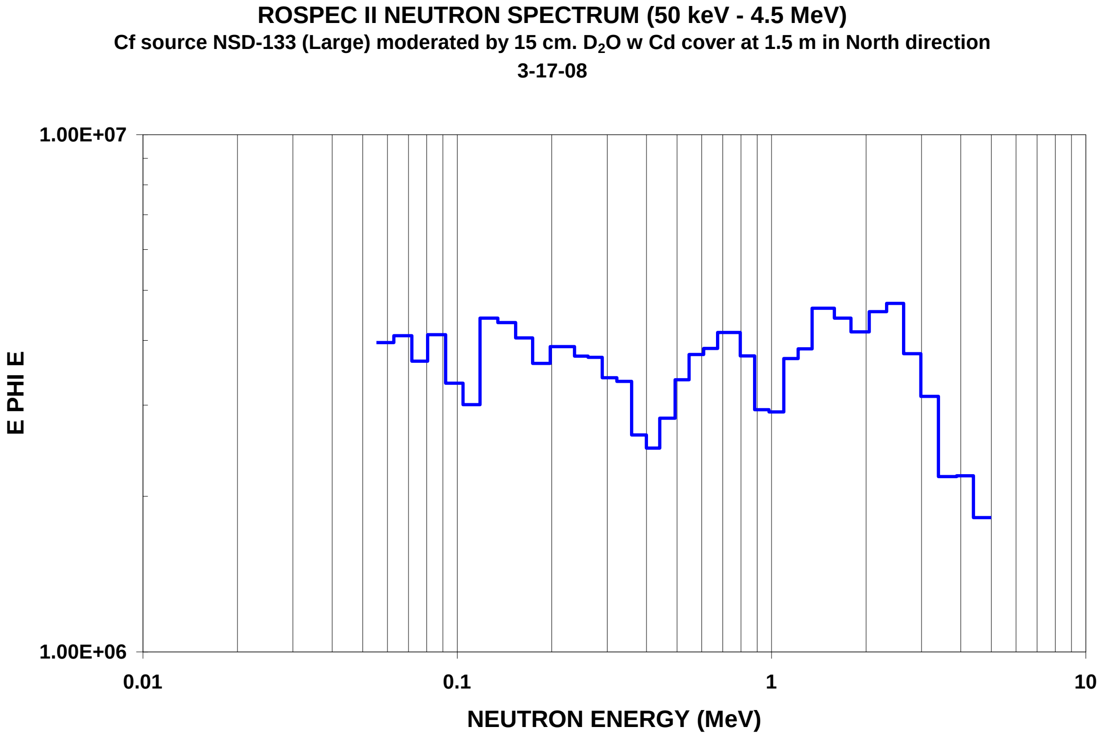


Figure D-7. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 1.5 m in North direction.

Table D-7. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 1.5 m in North direction

Date: 3-17-08
Exposure time = 55,500 sec

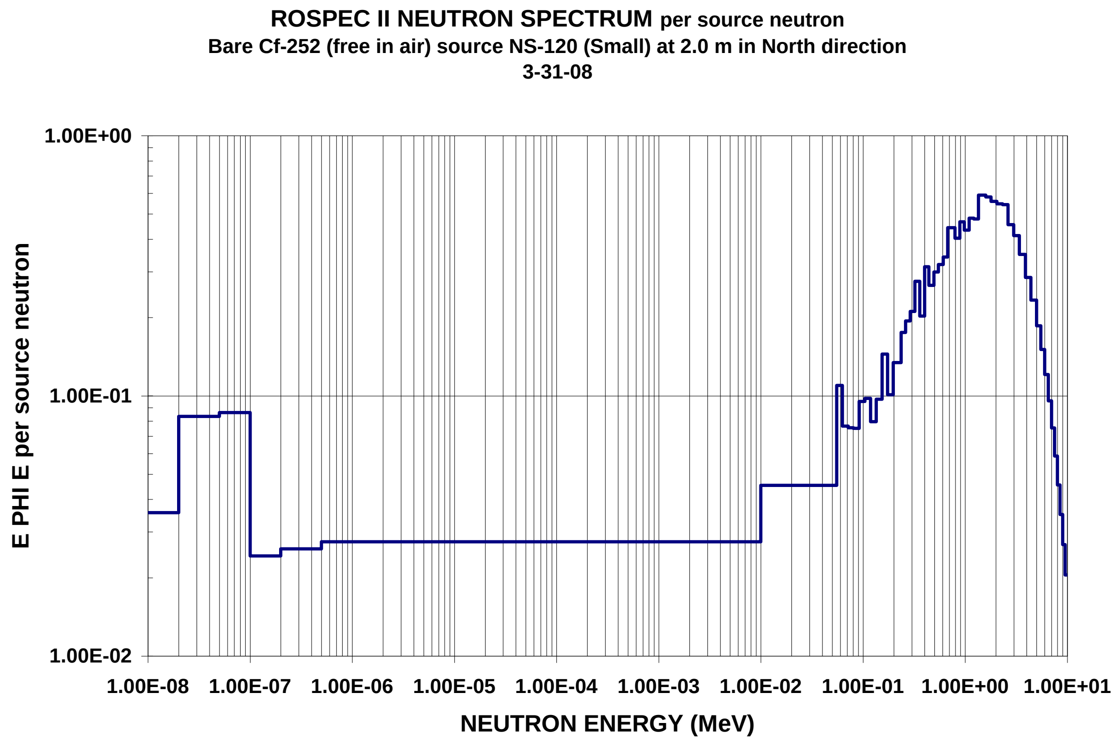
INTEGRATED FLUENCE = 1.6770E+07 FLUENCE RATE = 3.0216E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.0313E-02 rads	6.6893E+00 mrads/hr
H NCRP-38	= 1.2988E-01 rem	8.4249E+01 mrem/hr
H*(10) ICRP-74	= 1.4999E-03 Sv	9.7289E+02 μSv/hr
Hp(10,0) ICRP-74	= 1.5617E-03 Sv	1.0130E+03 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	4.37E+06	7.88E+02
Epi-thermal region:	1.02E+07	1.84E+03
Thermal region:	1.94E+06	3.49E+02
TOTAL:	1.65E+07	2.98E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	8.90E-03	1.07E-01	1.28E-03	5.77E+00	6.93E+01	8.30E+02
Epi-thermal region:	5.23E-04	1.32E-02	1.24E-04	3.39E-01	8.59E+00	8.03E+01
Thermal region:	3.88E-05	1.98E-03	2.06E-05	2.52E-02	1.28E+00	1.33E+01
TOTAL:	9.46E-03	1.22E-01	1.42E-03	6.14E+00	7.92E+01	9.23E+02



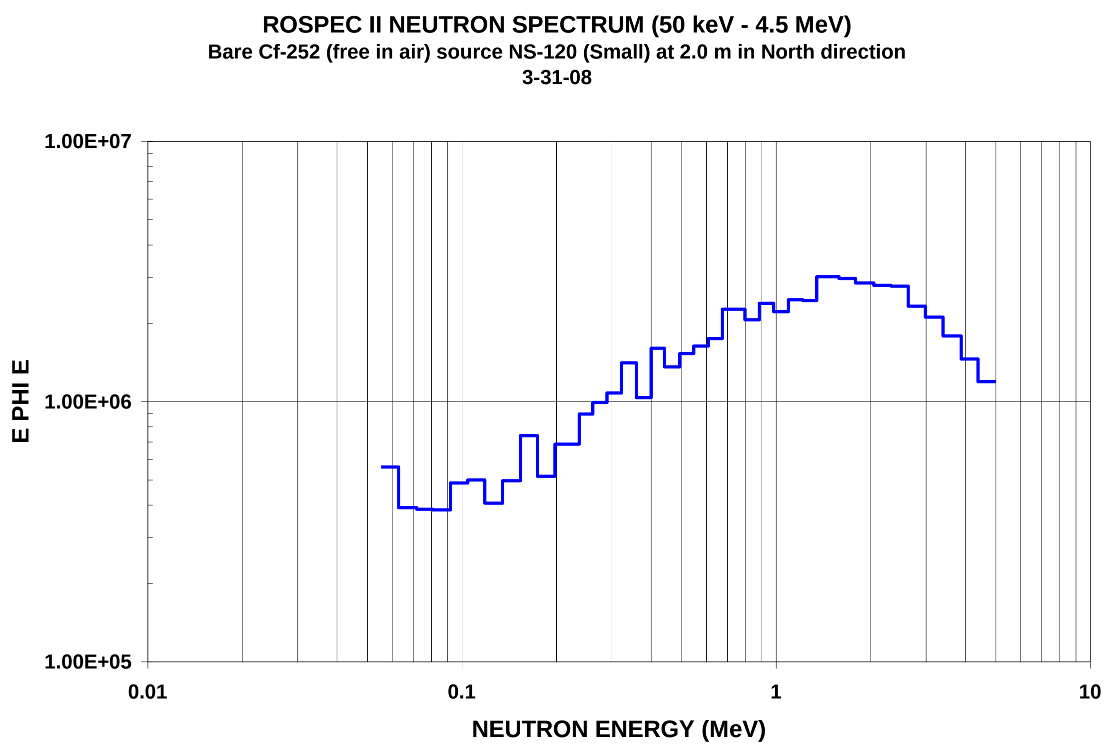


Figure D-8. Neutron spectra from bare ^{252}Cf (free in air) source NS-120 (Small) at 2.0 m in North direction.

Table D-8. Neutron fluence and dose from bare ^{252}Cf (free in air) source NS-120 (Small) at 2.0 m in North direction

Date: 3-31-08
Exposure time = 223,800 sec

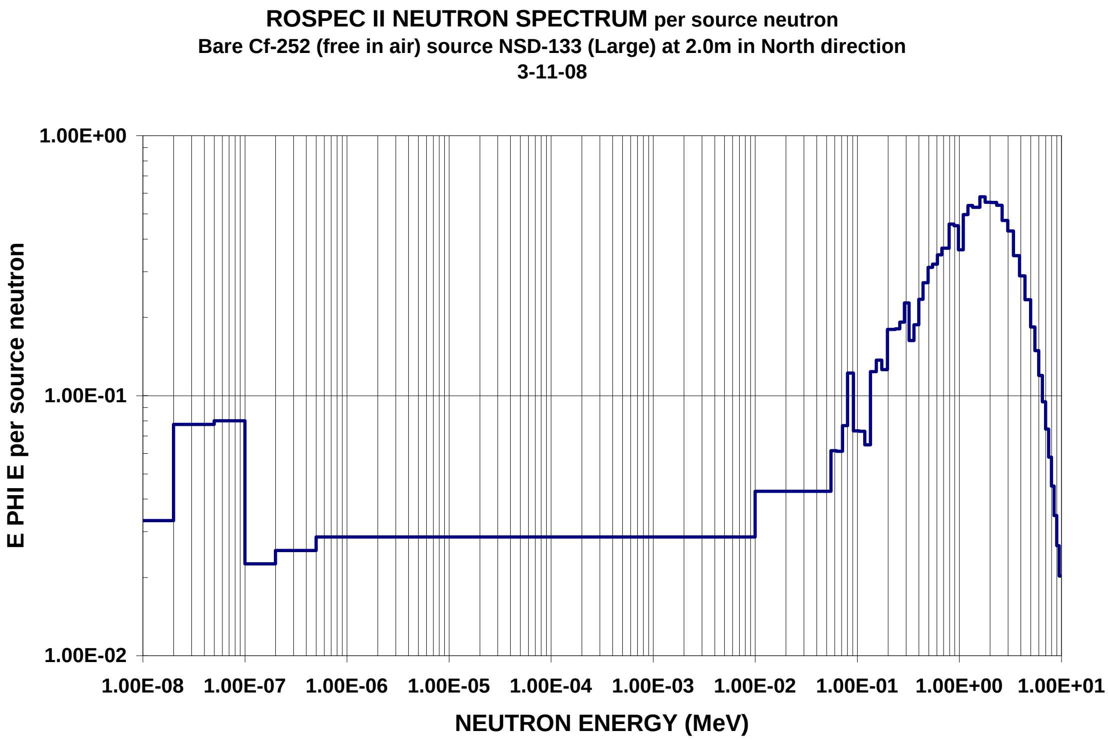
INTEGRATED FLUENCE = 1.0002E+07 FLUENCE RATE = 4.4690E+01

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.7845E-02 rads	2.8705E-01 mrads/hr
H NCRP-38	= 2.2037E-01 rem	3.5448E+00 mrem/hr
H*(10) ICRP-74	= 2.5633E-03 Sv	4.1232E+01 μSv/hr
Hp(10,0) ICRP-74	= 2.6563E-03 Sv	4.2729E+01 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	6.80E+06	3.04E+01
Epi-thermal region:	1.91E+06	8.52E+00
Thermal region:	9.70E+05	4.33E+00
TOTAL:	9.68E+06	4.32E+01

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.66E-02	2.06E-01	2.42E-03	2.68E-01	3.32E+00	3.89E+01
Epi-thermal region:	1.20E-04	2.56E-03	2.45E-05	1.93E-03	4.12E-02	3.94E-01
Thermal region:	1.94E-05	9.89E-04	1.03E-05	3.12E-04	1.59E-02	1.65E-01
TOTAL:	1.68E-02	2.10E-01	2.46E-03	2.70E-01	3.37E+00	3.95E+01



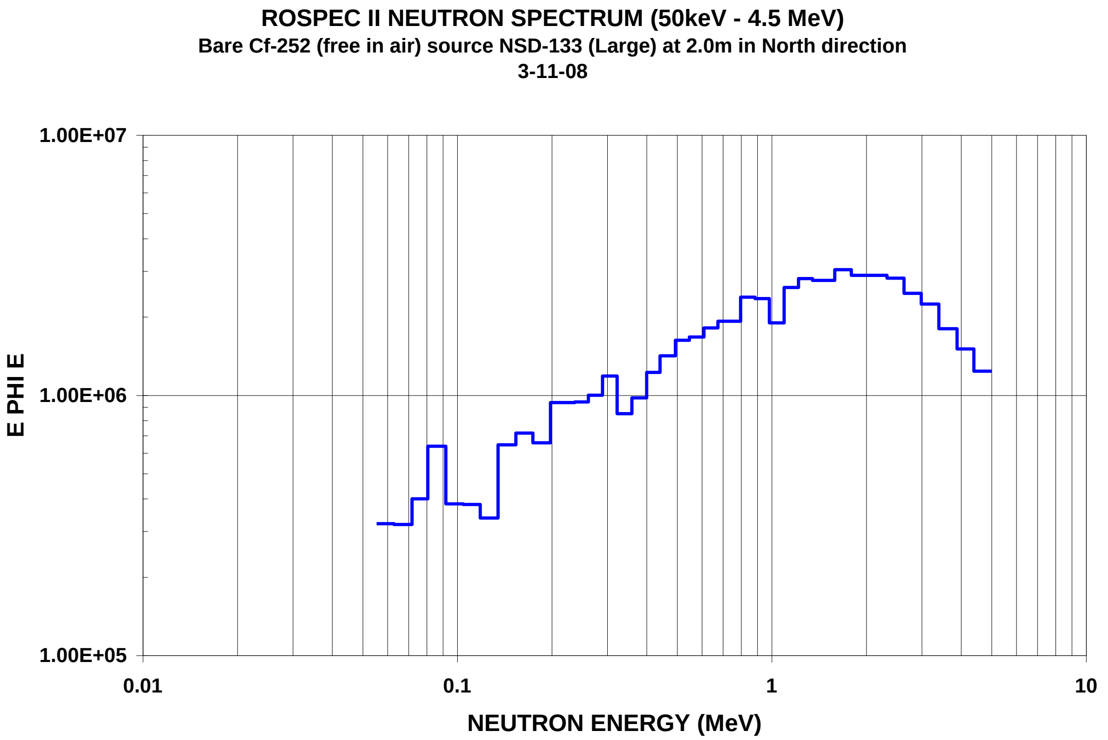


Figure D-9. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 2.0 m in North direction.

Table D-9. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 2.0 m in North direction

Date: 3-11-08
Exposure time = 3,840 sec

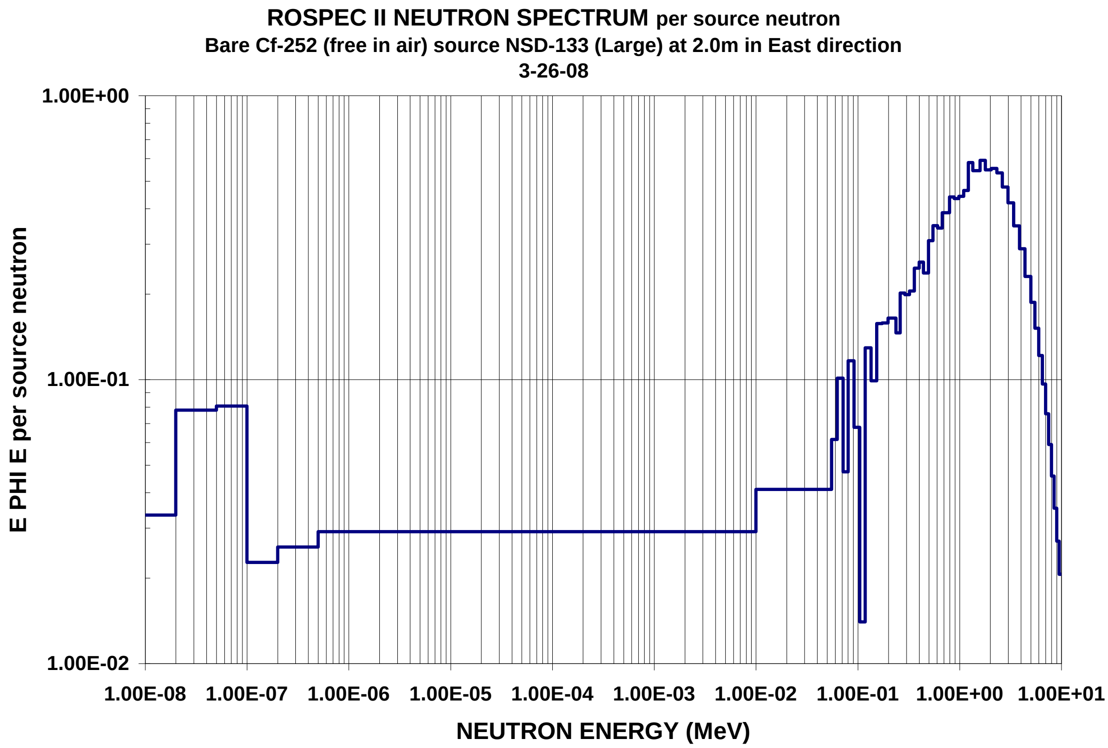
INTEGRATED FLUENCE = 1.0041E+07 FLUENCE RATE = 2.6148E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.7998E-02 rads	1.6873E+01 mrads/hr
H NCRP-38	= 2.2141E-01 rem	2.0757E+02 mrem/hr
H*(10) ICRP-74	= 2.5739E-03 Sv	2.4130E+03 μSv/hr
Hp(10,0) ICRP-74	= 2.6683E-03 Sv	2.5015E+03 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	6.81E+06	1.77E+03
Epi-thermal region:	1.98E+06	5.17E+02
Thermal region:	9.21E+05	2.40E+02
TOTAL:	9.72E+06	2.53E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.68E-02	2.07E-01	2.43E-03	1.57E+01	1.94E+02	2.28E+03
Epi-thermal region:	1.18E-04	2.64E-03	2.51E-05	1.11E-01	2.47E+00	2.35E+01
Thermal region:	1.84E-05	9.39E-04	9.76E-06	1.73E-02	8.80E-01	9.15E+00
TOTAL:	1.69E-02	2.11E-01	2.46E-03	1.59E+01	1.98E+02	2.31E+03



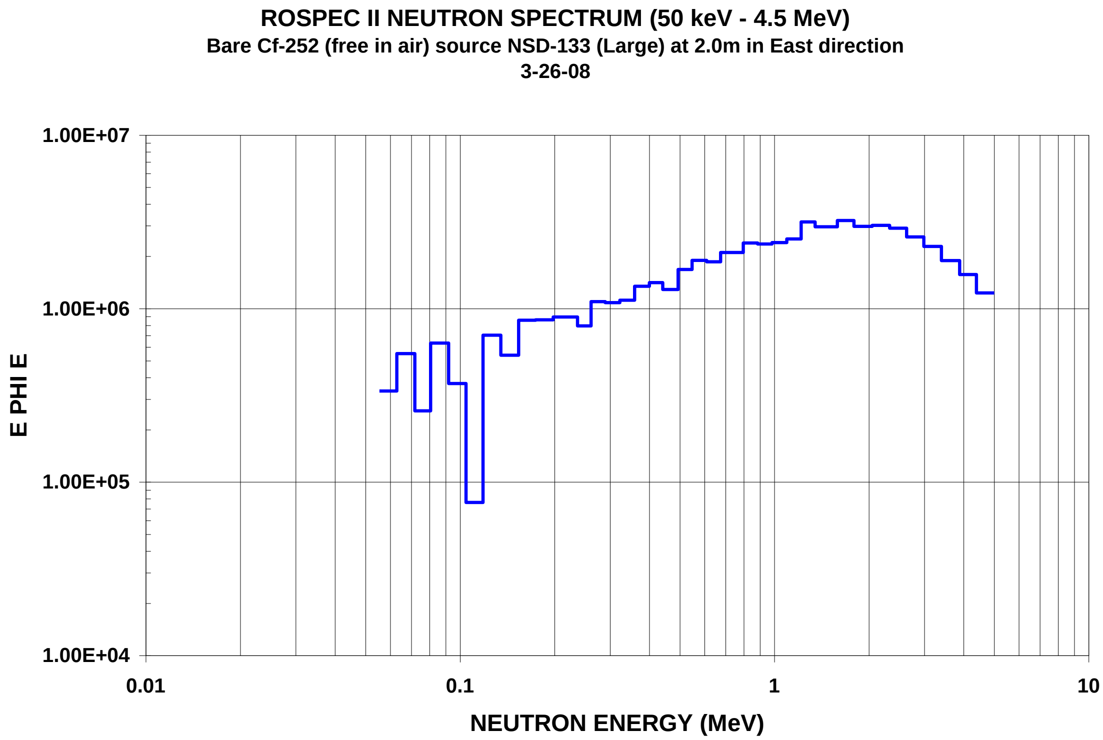


Figure D-10. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 2.0 m in East direction.

Table D-10. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 2.0 m in East direction

Date: 3-26-08
Exposure time = 4,000 sec

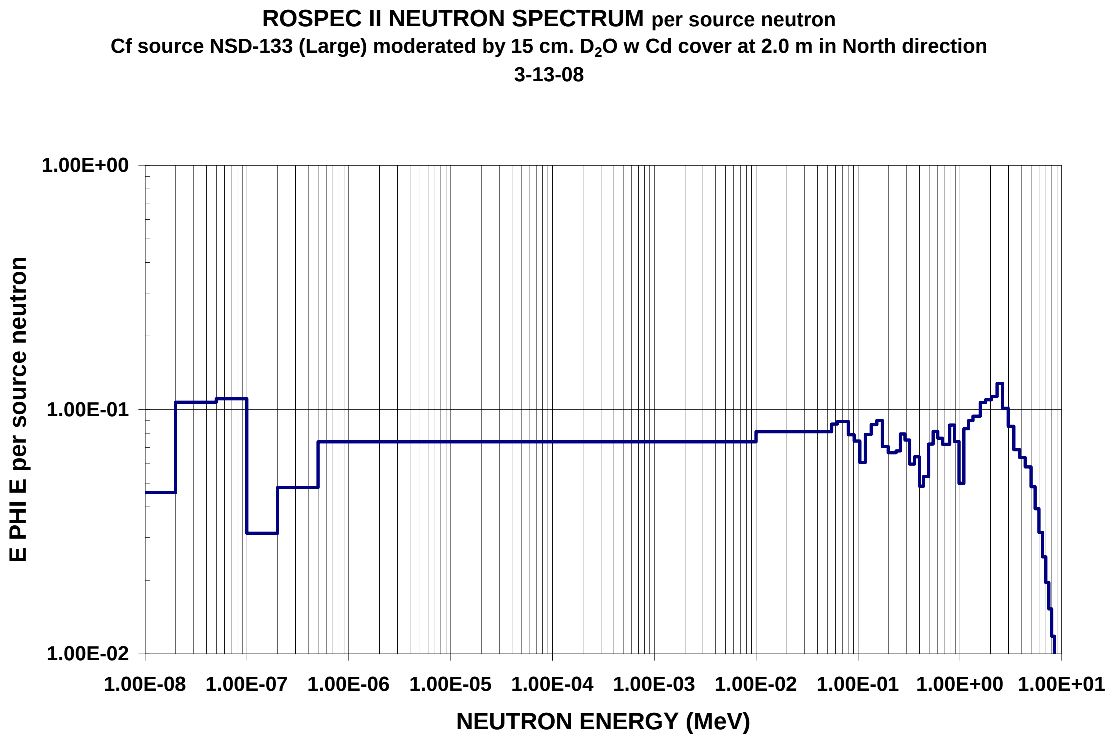
INTEGRATED FLUENCE = 1.0589E+07 FLUENCE RATE = 2.6474E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.8963E-02 rads	1.7067E+01 mrads/hr
H NCRP-38	= 2.3381E-01 rem	2.1043E+02 mrem/hr
H*(10) ICRP-74	= 2.7189E-03 Sv	2.4470E+03 μSv/hr
Hp(10,0) ICRP-74	= 2.8181E-03 Sv	2.5363E+03 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	7.19E+06	1.80E+03
Epi-thermal region:	2.08E+06	5.20E+02
Thermal region:	9.67E+05	2.42E+02
TOTAL:	1.02E+07	2.56E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.77E-02	2.18E-01	2.56E-03	1.59E+01	1.97E+02	2.31E+03
Epi-thermal region:	1.19E-04	2.74E-03	2.61E-05	1.07E-01	2.47E+00	2.35E+01
Thermal region:	1.93E-05	9.86E-04	1.02E-05	1.74E-02	8.87E-01	9.22E+00
TOTAL:	1.78E-02	2.22E-01	2.60E-03	1.60E+01	2.00E+02	2.34E+03



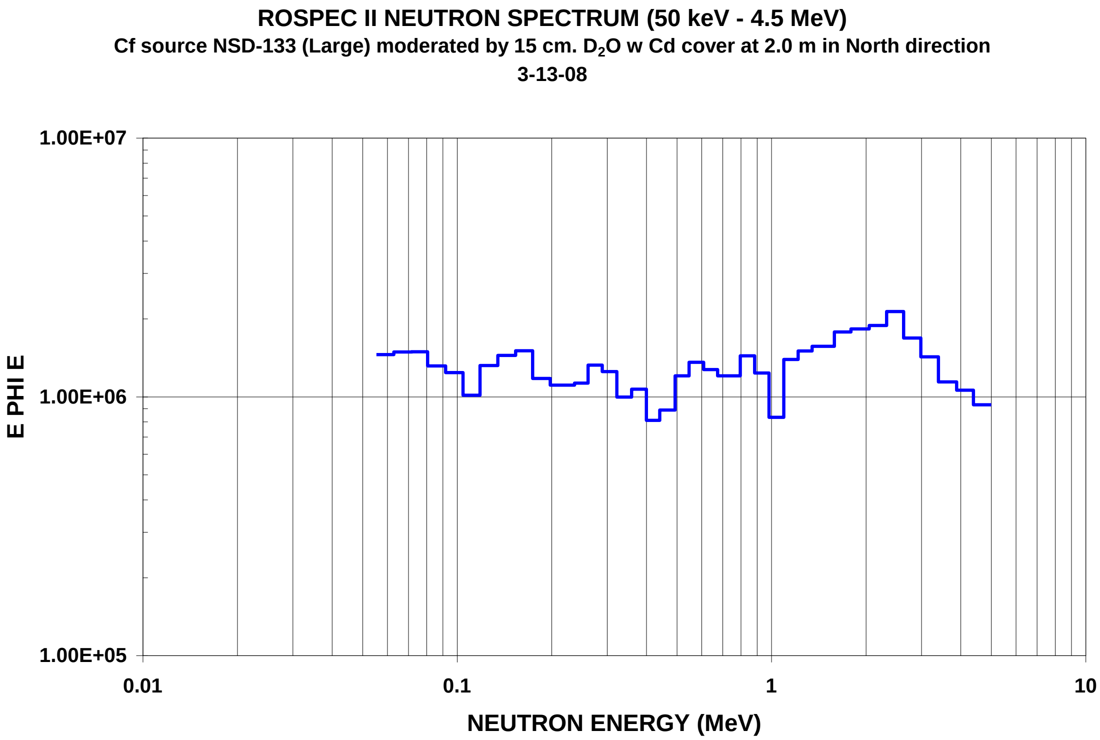


Figure D-11. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 2.0 m in North direction.

Table D-11. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 2.0 m in North direction

Date: 3-13-08
Exposure time = 12,270 sec

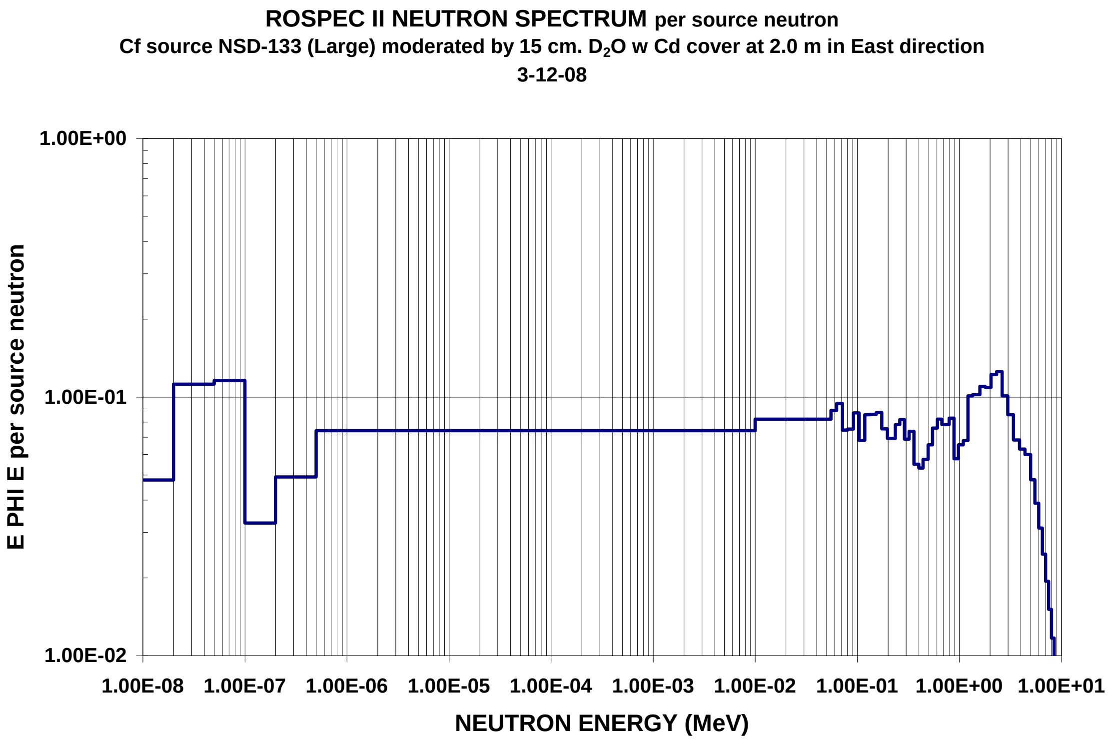
INTEGRATED FLUENCE = 2.5572E+07 FLUENCE RATE = 2.0841E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.3783E-02 rads	4.0439E+00 mrads/hr
H NCRP-38	= 1.7720E-01 rem	5.1989E+01 mrem/hr
H*(10) ICRP-74	= 2.0482E-03 Sv	6.0095E+02 μSv/hr
Hp(10,0) ICRP-74	= 2.1333E-03 Sv	6.2590E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	5.99E+06	4.88E+02
Epi-thermal region:	1.52E+07	1.24E+03
Thermal region:	4.07E+06	3.31E+02
TOTAL:	2.53E+07	2.06E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.20E-02	1.44E-01	1.73E-03	3.51E+00	4.24E+01	5.09E+02
Epi-thermal region:	7.61E-04	1.97E-02	1.84E-04	2.23E-01	5.77E+00	5.40E+01
Thermal region:	8.13E-05	4.15E-03	4.31E-05	2.39E-02	1.22E+00	1.26E+01
TOTAL:	1.28E-02	1.68E-01	1.96E-03	3.75E+00	4.93E+01	5.75E+02



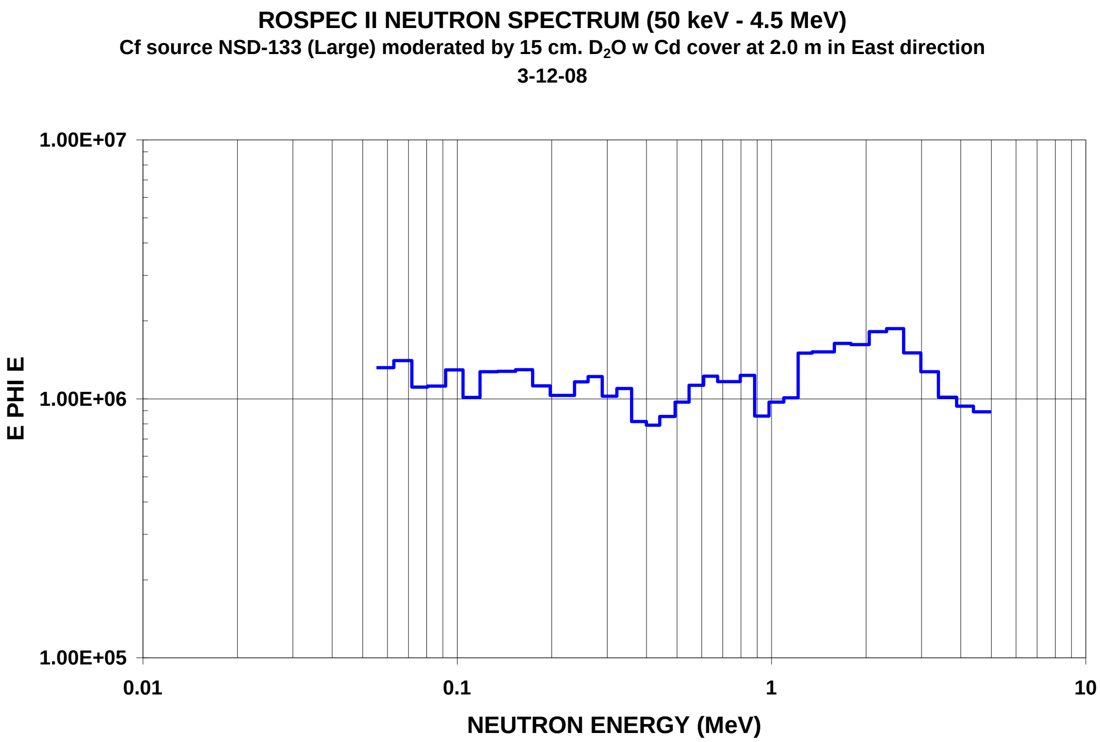


Figure D-12. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 2.0 m, in East direction.

Table D-12. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 2.0 m, in East direction

Date: 3-12-08
Exposure time = 10,927 sec

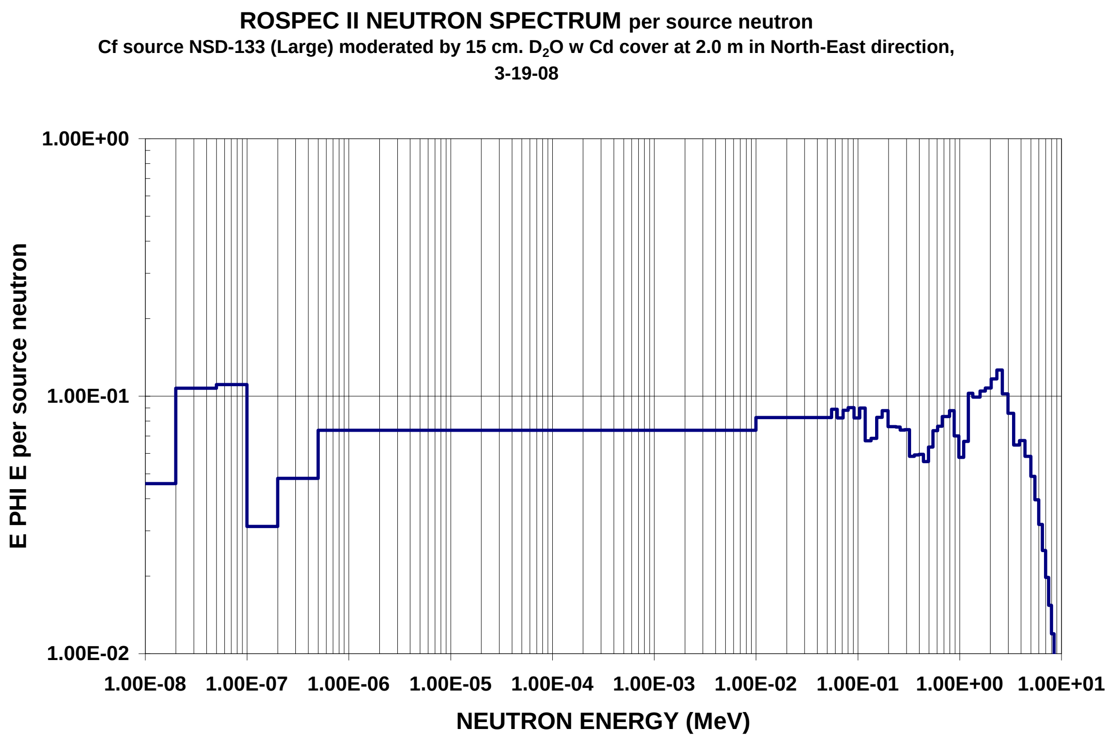
INTEGRATED FLUENCE = 2.3127E+07 FLUENCE RATE = 2.1165E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.2447E-02 rads	4.1008E+00 mrads/hr
H NCRP-38	= 1.6010E-01 rem	5.2747E+01 mrem/hr
H*(10) ICRP-74	= 1.8525E-03 Sv	6.1031E+02 μSv/hr
Hp(10,0) ICRP-74	= 1.9292E-03 Sv	6.3561E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	5.44E+06	4.98E+02
Epi-thermal region:	1.37E+07	1.25E+03
Thermal region:	3.79E+06	3.47E+02
TOTAL:	2.29E+07	2.10E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.08E-02	1.31E-01	1.57E-03	3.57E+00	4.31E+01	5.18E+02
Epi-thermal region:	6.85E-04	1.76E-02	1.65E-04	2.26E-01	5.81E+00	5.44E+01
Thermal region:	7.58E-05	3.86E-03	4.02E-05	2.50E-02	1.27E+00	1.32E+01
TOTAL:	1.16E-02	1.52E-01	1.78E-03	3.82E+00	5.02E+01	5.86E+02



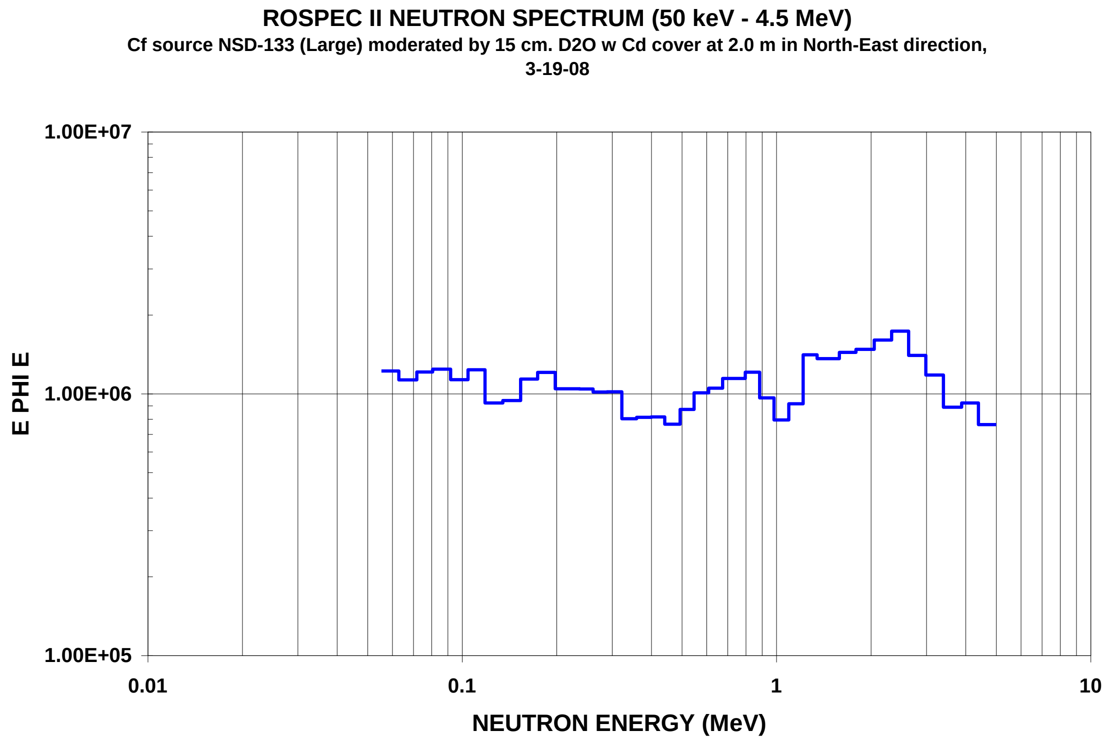


Figure D-13. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 2.0 m in Northeast direction.

Table D-13. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 2.0 m in Northeast direction

Date: 3-19-08
Exposure time = 10,100 sec

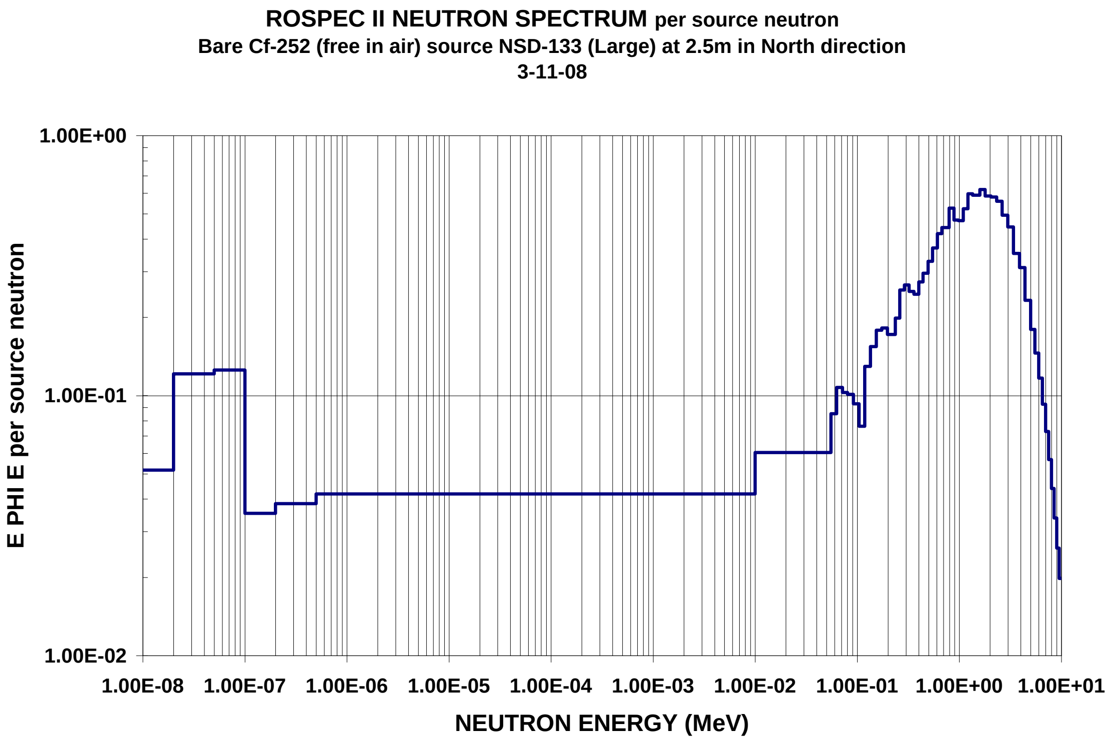
INTEGRATED FLUENCE = 2.1175E+07 FLUENCE RATE = 2.0965E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.1470E-02 rads	4.0883E+00 mrads/hr
H NCRP-38	= 1.4740E-01 rem	5.2537E+01 mrem/hr
H*(10) ICRP-74	= 1.7047E-03 Sv	6.0762E+02 μSv/hr
Hp(10,0) ICRP-74	= 1.7754E-03 Sv	6.3280E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	5.02E+06	4.97E+02
Epi-thermal region:	1.26E+07	1.25E+03
Thermal region:	3.35E+06	3.32E+02
TOTAL:	2.09E+07	2.07E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	9.95E-03	1.20E-01	1.44E-03	3.55E+00	4.28E+01	5.15E+02
Epi-thermal region:	6.35E-04	1.63E-02	1.52E-04	2.26E-01	5.79E+00	5.43E+01
Thermal region:	6.70E-05	3.42E-03	3.55E-05	2.39E-02	1.22E+00	1.27E+01
TOTAL:	1.06E-02	1.40E-01	1.63E-03	3.80E+00	4.99E+01	5.82E+02



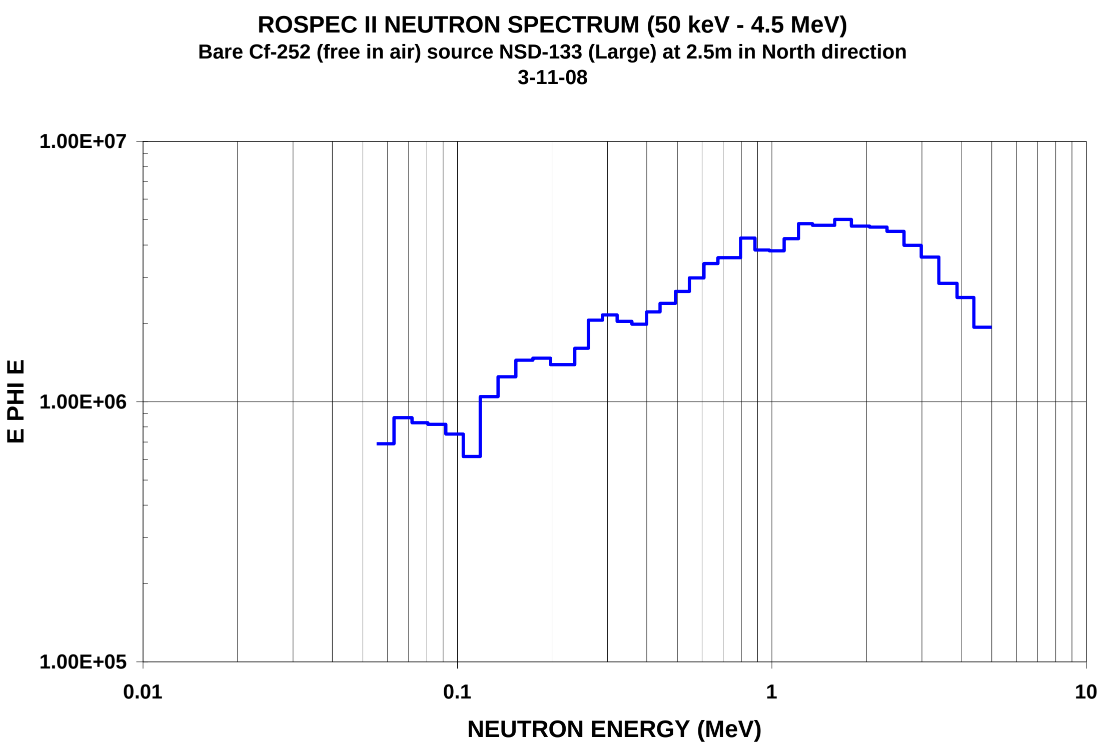


Figure D-14. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 2.5 m in North direction.

Table D-14. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 2.5 m in North direction

Date: 3-11-08
Exposure time = 9,273 sec

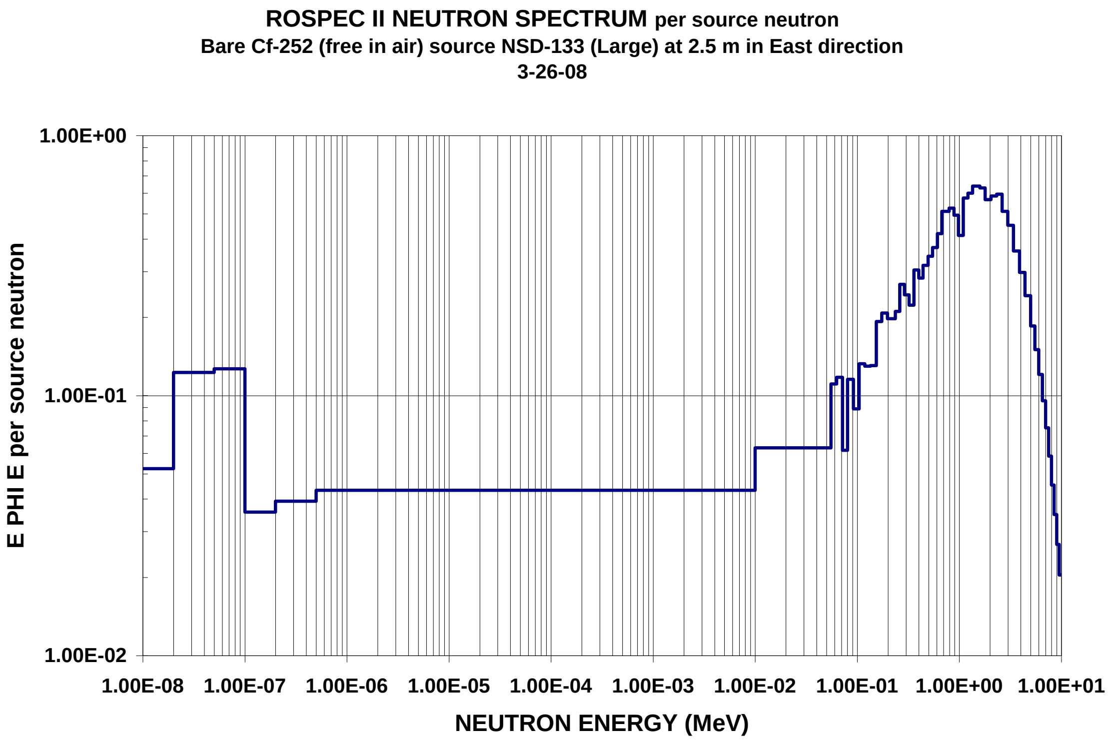
INTEGRATED FLUENCE = 1.9003E+07 FLUENCE RATE = 2.0493E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 3.0184E-02 rads	1.1718E+01 mrads/hr
H NCRP-38	= 3.7605E-01 rem	1.4599E+02 mrem/hr
H*(10) ICRP-74	= 4.3854E-03 Sv	1.7025E+03 μSv/hr
Hp(10,0) ICRP-74	= 4.5446E-03 Sv	1.7643E+03 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	1.18E+07	1.27E+03
Epi-thermal region:	4.47E+06	4.82E+02
Thermal region:	2.23E+06	2.40E+02
TOTAL:	1.85E+07	2.00E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	2.84E-02	3.53E-01	4.15E-03	1.10E+01	1.37E+02	1.61E+03
Epi-thermal region:	2.59E-04	5.91E-03	5.62E-05	1.00E-01	2.29E+00	2.18E+01
Thermal region:	4.45E-05	2.27E-03	2.36E-05	1.73E-02	8.82E-01	9.16E+00
TOTAL:	2.87E-02	3.61E-01	4.23E-03	1.11E+01	1.40E+02	1.64E+03



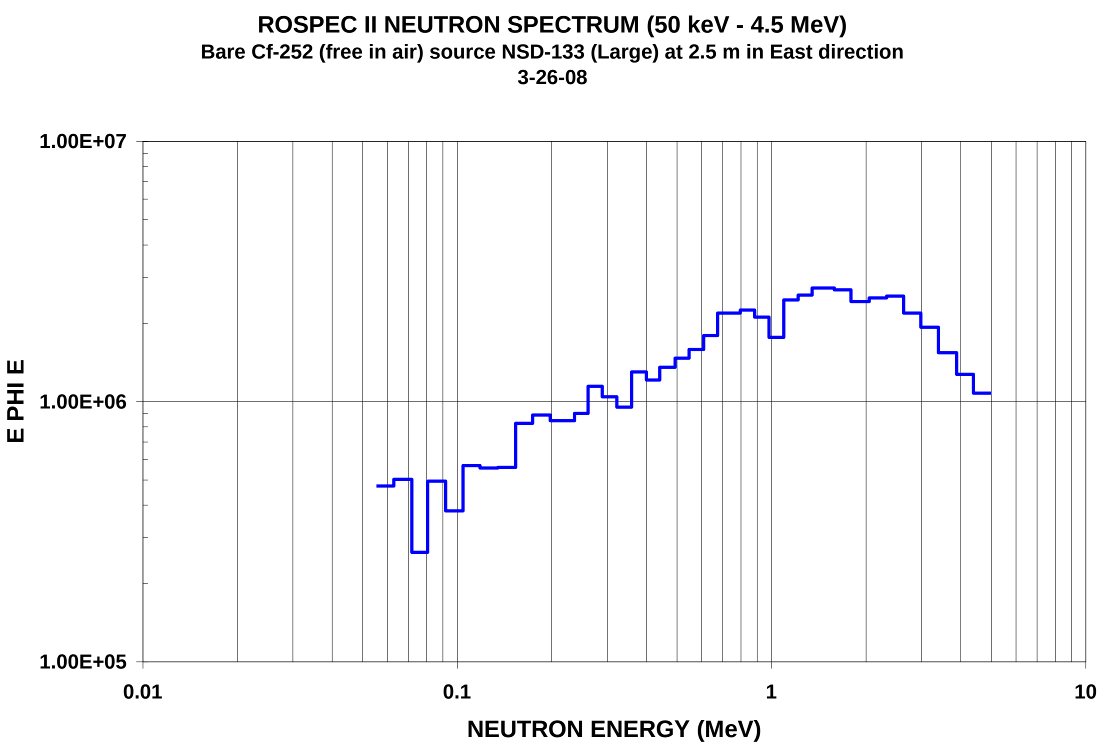


Figure D-15. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 2.5 m in East direction.

Table D-15. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 2.5 m in East direction

Date: 3-26-08
Exposure time = 4,910 sec

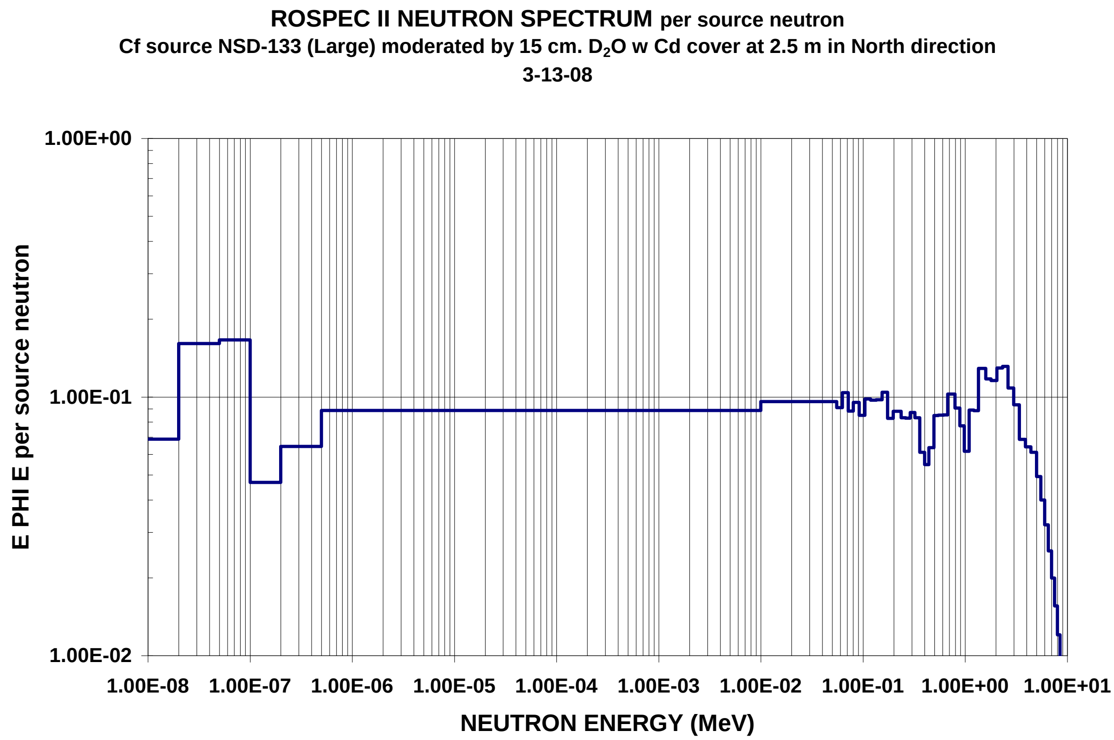
INTEGRATED FLUENCE = 1.0387E+07 FLUENCE RATE = 2.1154E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.6438E-02 rads	1.2052E+01 mrads/hr
H NCRP-38	= 2.0511E-01 rem	1.5038E+02 mrem/hr
H*(10) ICRP-74	= 2.3939E-03 Sv	1.7552E+03 μSv/hr
Hp(10,0) ICRP-74	= 2.4804E-03 Sv	1.8186E+03 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	6.49E+06	1.32E+03
Epi-thermal region:	2.45E+06	4.98E+02
Thermal region:	1.19E+06	2.43E+02
TOTAL:	1.01E+07	2.06E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.54E-02	1.92E-01	2.27E-03	1.13E+01	1.41E+02	1.66E+03
Epi-thermal region:	1.43E-04	3.24E-03	3.08E-05	1.05E-01	2.37E+00	2.26E+01
Thermal region:	2.39E-05	1.22E-03	1.26E-05	1.75E-02	8.92E-01	9.27E+00
TOTAL:	1.56E-02	1.97E-01	2.31E-03	1.14E+01	1.44E+02	1.69E+03



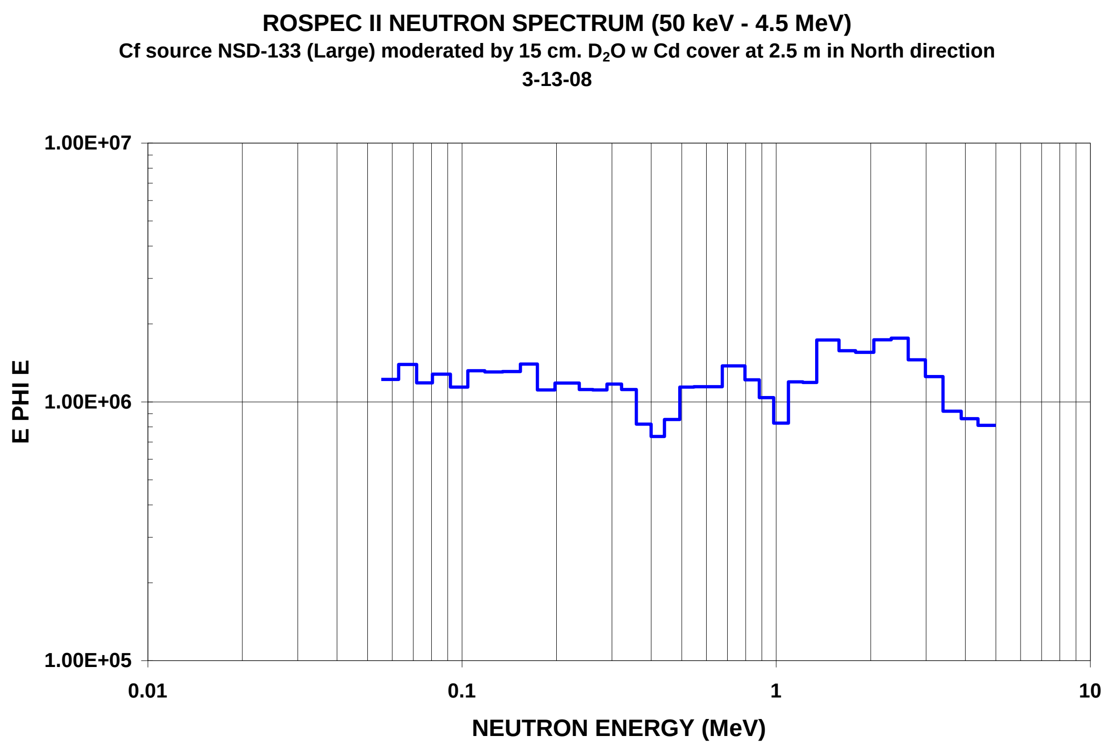


Figure D-16. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 2.5 m, in North direction.

Table D-16. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 2.5 m, in North direction

Date: 3-13-08
Exposure time = 15,400 sec

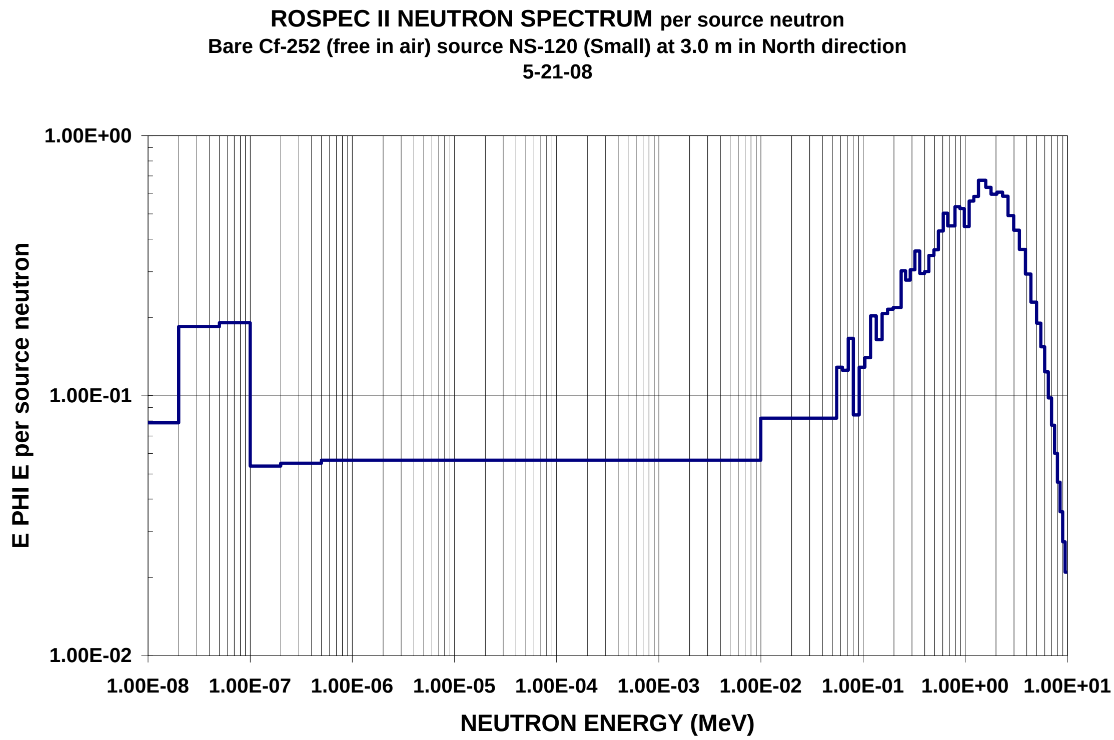
INTEGRATED FLUENCE = 2.5425E+07 FLUENCE RATE = 1.6509E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.2351E-02 rads	2.8872E+00 mrads/hr
H NCRP-38	= 1.6189E-01 rem	3.7844E+01 mrem/hr
H*(10) ICRP-74	= 1.8737E-03 Sv	4.3800E+02 μSv/hr
Hp(10,0) ICRP-74	= 1.9519E-03 Sv	4.5630E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	5.51E+06	3.58E+02
Epi-thermal region:	1.48E+07	9.60E+02
Thermal region:	4.91E+06	3.19E+02
TOTAL:	2.52E+07	1.64E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.08E-02	1.31E-01	1.58E-03	2.52E+00	3.06E+01	3.69E+02
Epi-thermal region:	7.27E-04	1.90E-02	1.78E-04	1.70E-01	4.45E+00	4.16E+01
Thermal region:	9.82E-05	5.01E-03	5.20E-05	2.30E-02	1.17E+00	1.22E+01
TOTAL:	1.16E-02	1.55E-01	1.81E-03	2.71E+00	3.62E+01	4.22E+02



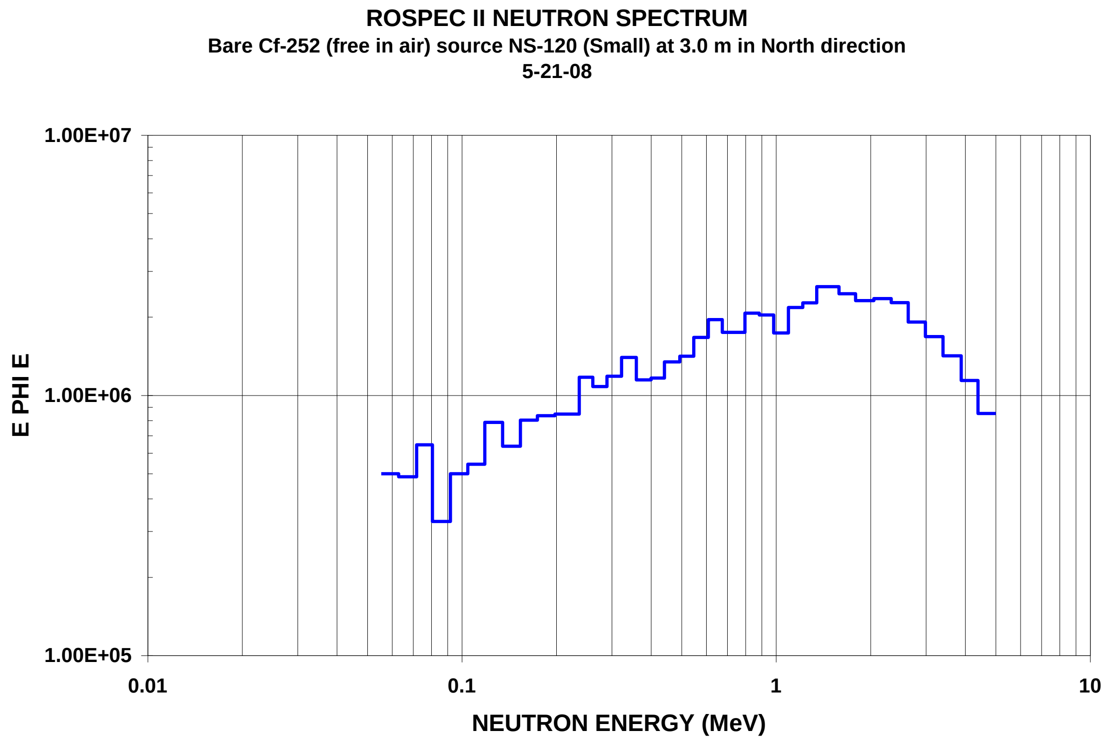


Figure D-17. Neutron spectra from bare ^{252}Cf (free in air) source NS-120 (Small) at 3.0 m in North direction.

Table D-17. Neutron fluence and dose from bare ^{252}Cf (free in air) source NS-120 (Small) at 3.0 m in North direction

Date: 5-21-08
Exposure time = 382,948 sec

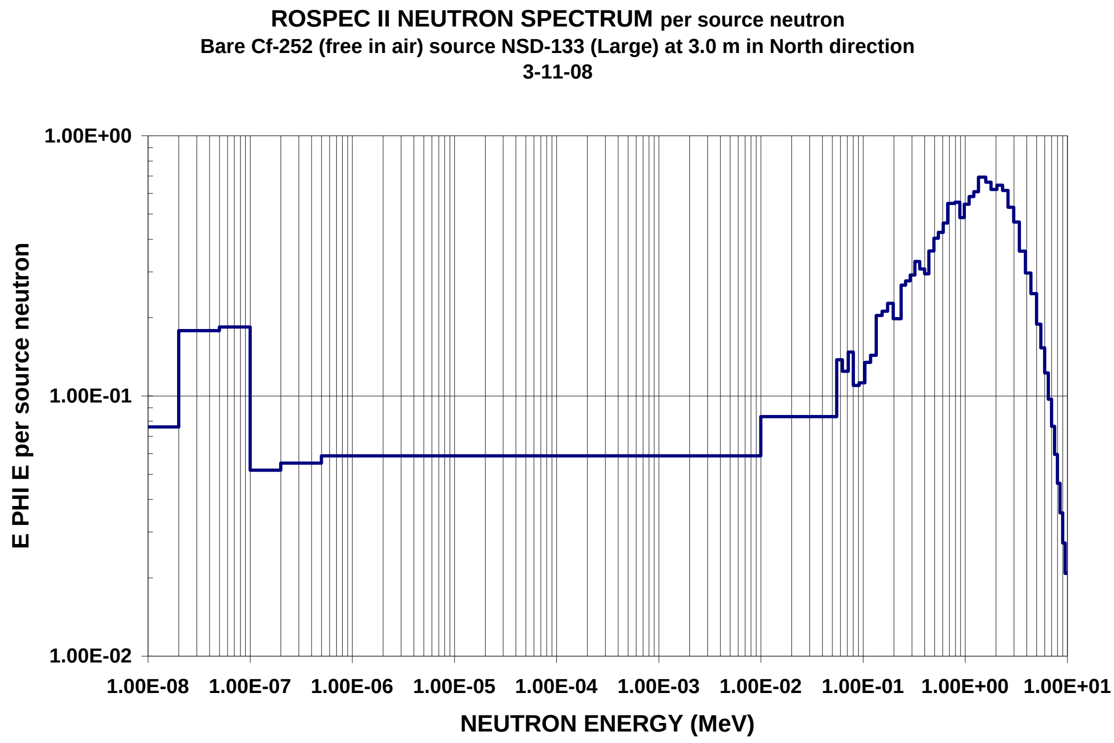
INTEGRATED FLUENCE = 1.1024E+07 FLUENCE RATE = 2.8787E+01

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.5389E-02 rads	1.4466E-01 mrads/hr
H NCRP-38	= 1.9325E-01 rem	1.8167E+00 mrem/hr
H*(10) ICRP-74	= 2.2620E-03 Sv	2.1264E+01 μSv/hr
Hp(10,0) ICRP-74	= 2.3439E-03 Sv	2.2034E+01 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	6.23E+06	1.63E+01
Epi-thermal region:	2.91E+06	7.60E+00
Thermal region:	1.63E+06	4.26E+00
TOTAL:	1.08E+07	2.81E+01

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.44E-02	1.80E-01	2.13E-03	1.35E-01	1.69E+00	2.00E+01
Epi-thermal region:	1.69E-04	3.85E-03	3.67E-05	1.59E-03	3.62E-02	3.45E-01
Thermal region:	3.26E-05	1.66E-03	1.73E-05	3.06E-04	1.56E-02	1.62E-01
TOTAL :	1.46E-02	1.85E-01	2.18E-03	1.37E-01	1.74E+00	2.05E+01



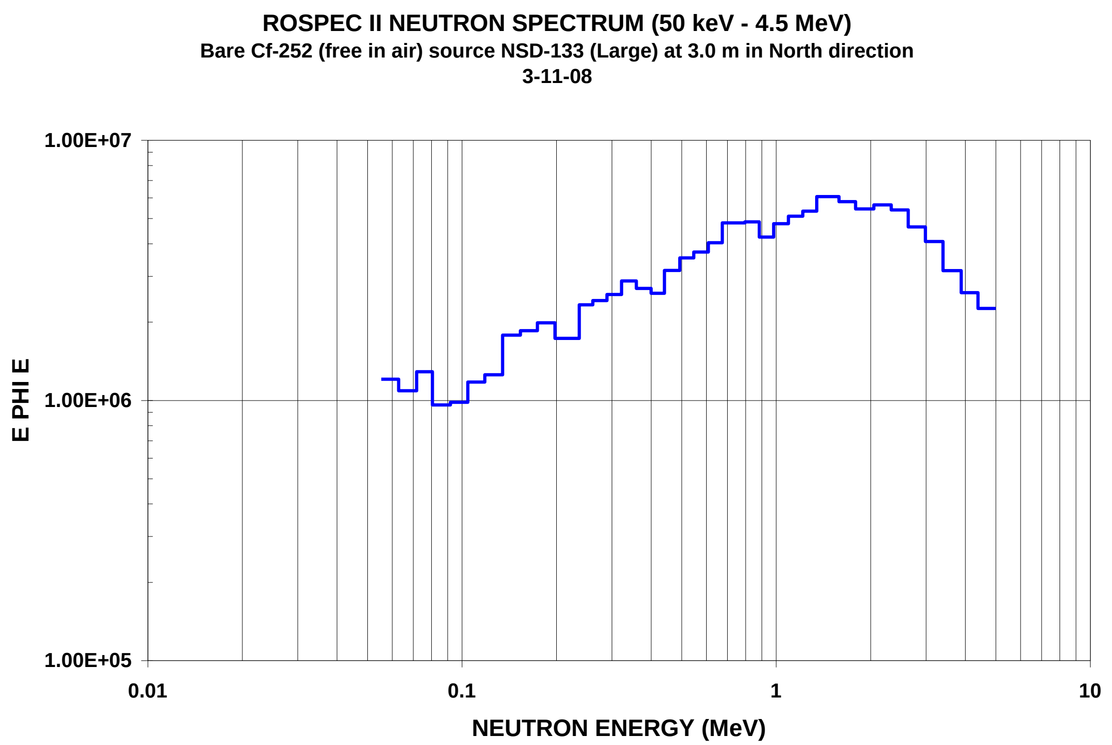


Figure D-18. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 3.0 m in North direction.

Table D-18. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 3.0 m in North direction

Date: 3-11-08
Exposure time = 14,475 sec

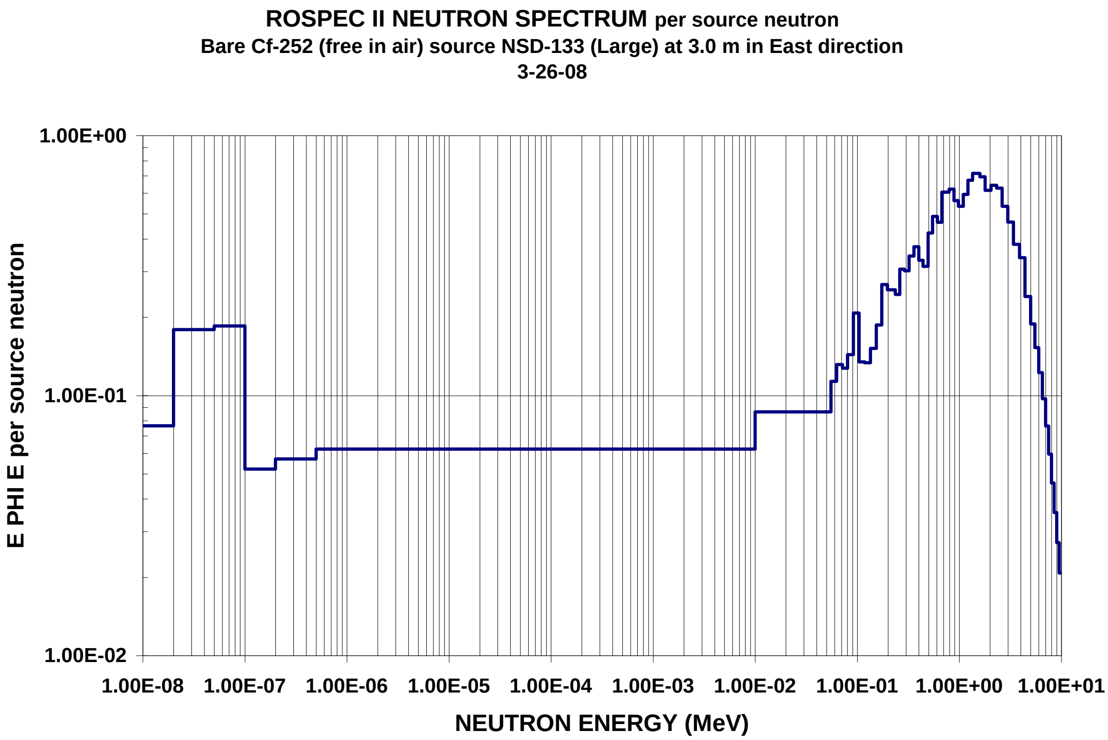
INTEGRATED FLUENCE = 2.5367E+07 FLUENCE RATE = 1.7525E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 3.5976E-02 rads	8.9474E+00 mrads/hr
H NCRP-38	= 4.5252E-01 rem	1.1254E+02 mrem/hr
H*(10) ICRP-74	= 5.2908E-03 Sv	1.3158E+03 μSv/hr
Hp(10,0) ICRP-74	= 5.4819E-03 Sv	1.3634E+03 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	1.45E+07	1.00E+03
Epi-thermal region:	6.79E+06	4.69E+02
Thermal region:	3.54E+06	2.45E+02
TOTAL:	2.48E+07	1.71E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	3.39E-02	4.23E-01	5.00E-03	8.42E+00	1.05E+02	1.24E+03
Epi-thermal region:	3.88E-04	8.96E-03	8.52E-05	9.66E-02	2.23E+00	2.12E+01
Thermal region:	7.09E-05	3.62E-03	3.76E-05	1.76E-02	8.99E-01	9.35E+00
TOTAL:	3.43E-02	4.36E-01	5.12E-03	8.53E+00	1.08E+02	1.27E+03



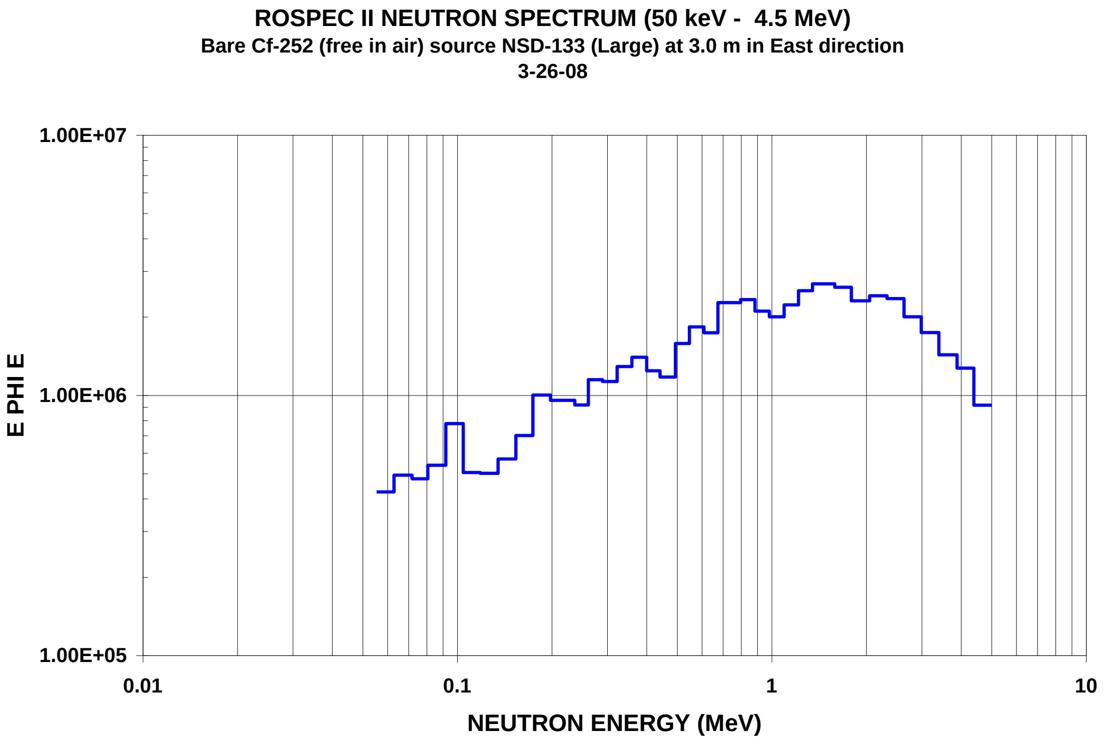


Figure D-19. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 3.0 m in East direction.

Table D-19. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 3.0 m in East direction

Date: 3-26-08
Exposure time = 6,200 sec

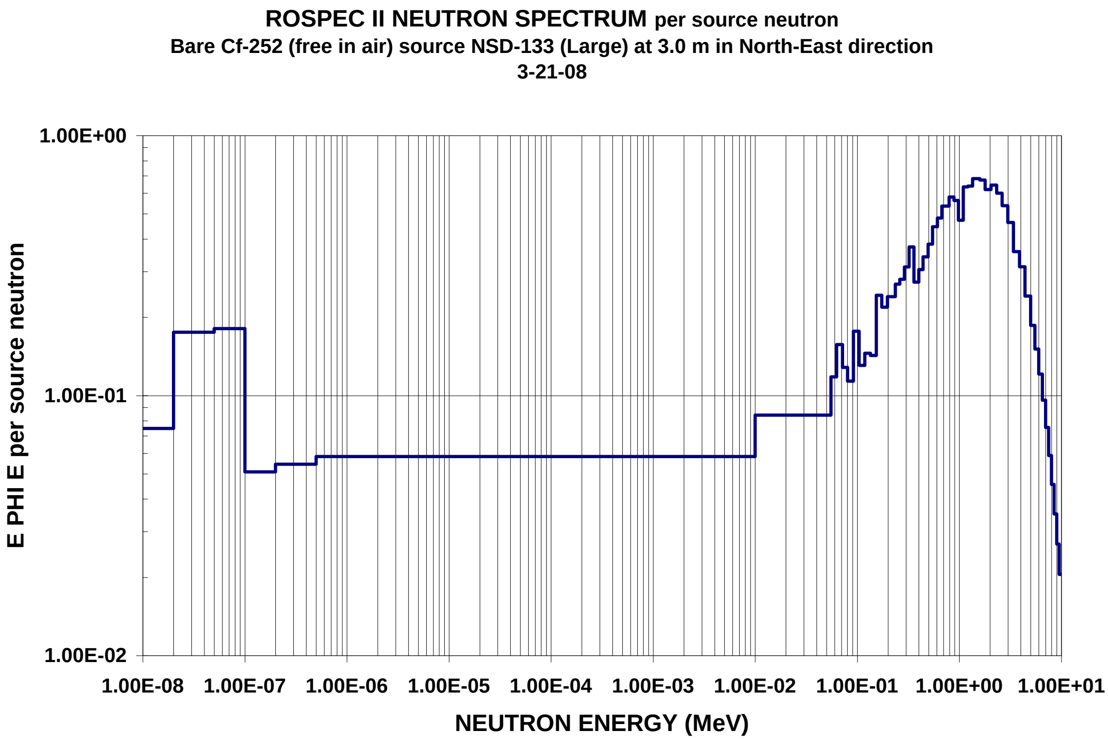
INTEGRATED FLUENCE = 1.1342E+07 FLUENCE RATE = 1.8294E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.6018E-02 rads	9.3011E+00 mrads/hr
H NCRP-38	= 2.0231E-01 rem	1.1747E+02 mrem/hr
H*(10) ICRP-74	= 2.3673E-03 Sv	1.3745E+03 μSv/hr
Hp(10,0) ICRP-74	= 2.4523E-03 Sv	1.4239E+03 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	6.51E+06	1.05E+03
Epi-thermal region:	3.07E+06	4.95E+02
Thermal region:	1.53E+06	2.47E+02
TOTAL:	1.11E+07	1.79E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.51E-02	1.90E-01	2.24E-03	8.77E+00	1.10E+02	1.30E+03
Epi-thermal region:	1.74E-04	4.04E-03	3.83E-05	1.01E-01	2.34E+00	2.23E+01
Thermal region:	3.06E-05	1.56E-03	1.62E-05	1.78E-02	9.06E-01	9.41E+00
TOTAL:	1.53E-02	1.95E-01	2.30E-03	8.89E+00	1.13E+02	1.33E+03



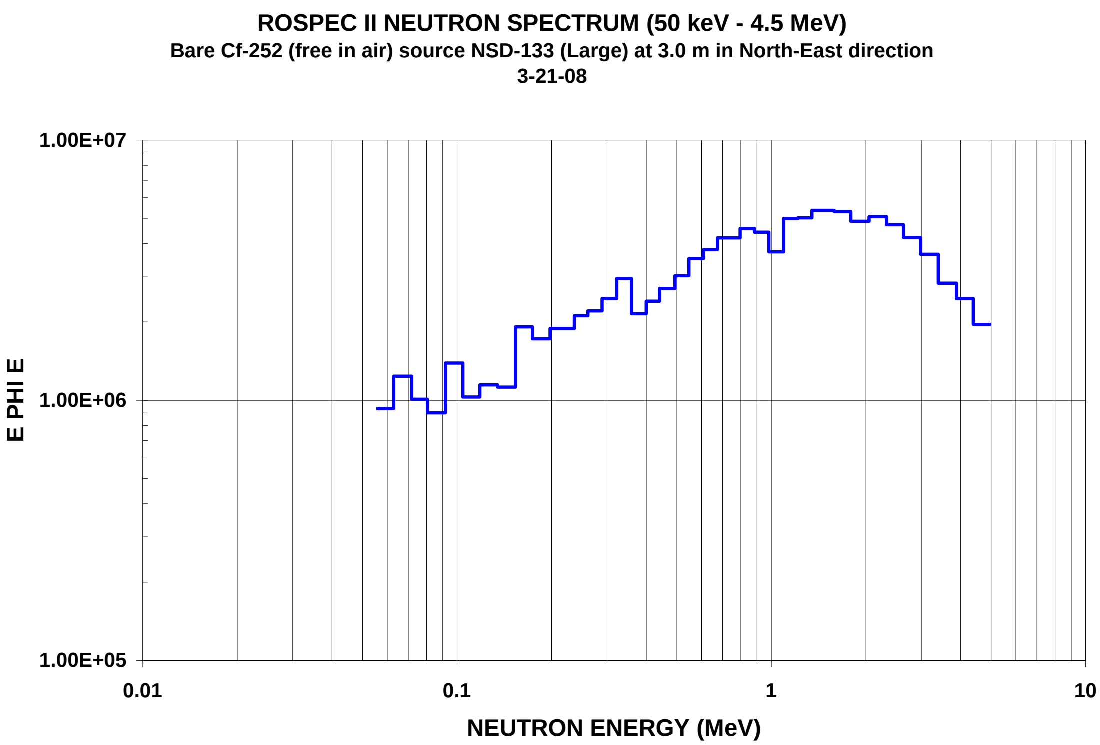


Figure D-20. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 3.0 m, in Northeast direction

Table D-20. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 3.0 m, in Northeast direction

Date: 3-21-08
Exposure time = 13,000 sec

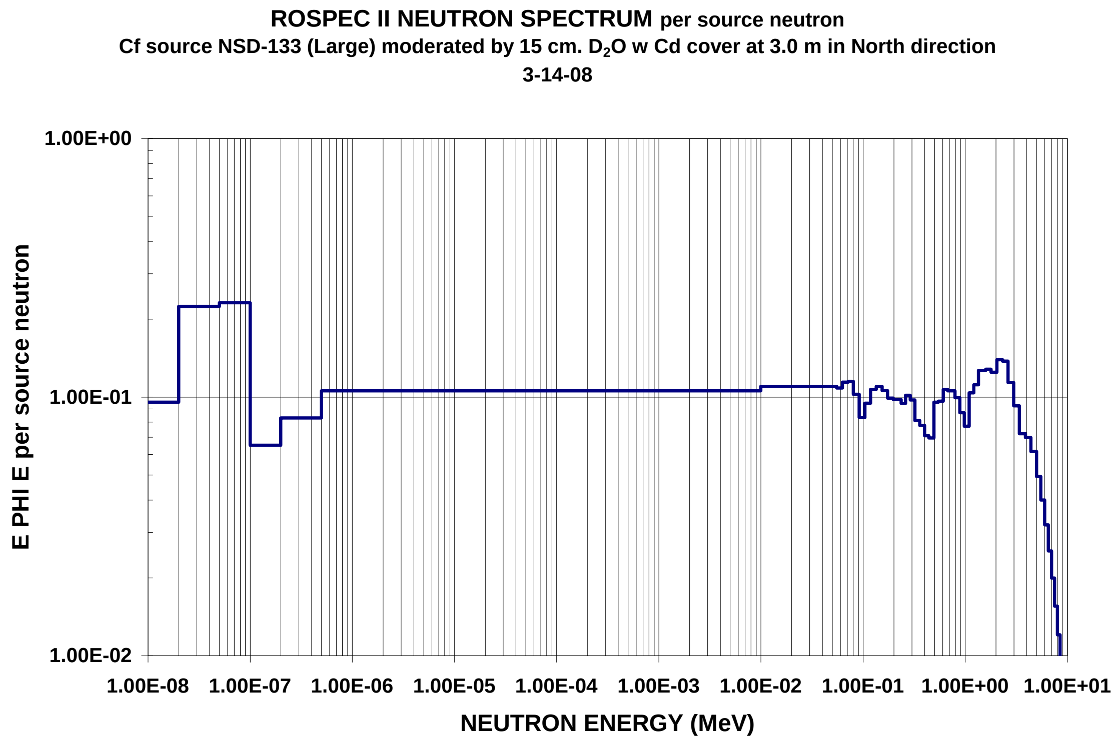
INTEGRATED FLUENCE = 2.2876E+07 FLUENCE RATE = 1.7597E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 3.2550E-02 rads	9.0137E+00 mrads/hr
H NCRP-38	= 4.0993E-01 rem	1.1352E+02 mrem/hr
H*(10) ICRP-74	= 4.7959E-03 Sv	1.3281E+03 μSv/hr
Hp(10,0) ICRP-74	= 4.9690E-03 Sv	1.3760E+03 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	1.32E+07	1.02E+03
Epi-thermal region:	6.06E+06	4.66E+02
Thermal region:	3.13E+06	2.41E+02
TOTAL:	2.24E+07	1.72E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	3.07E-02	3.84E-01	4.54E-03	8.49E+00	1.06E+02	1.26E+03
Epi-thermal region:	3.51E-04	8.02E-03	7.63E-05	9.73E-02	2.22E+00	2.11E+01
Thermal region:	6.26E-05	3.19E-03	3.32E-05	1.73E-02	8.85E-01	9.19E+00
TOTAL:	3.11E-02	3.95E-01	4.65E-03	8.61E+00	1.09E+02	1.29E+03



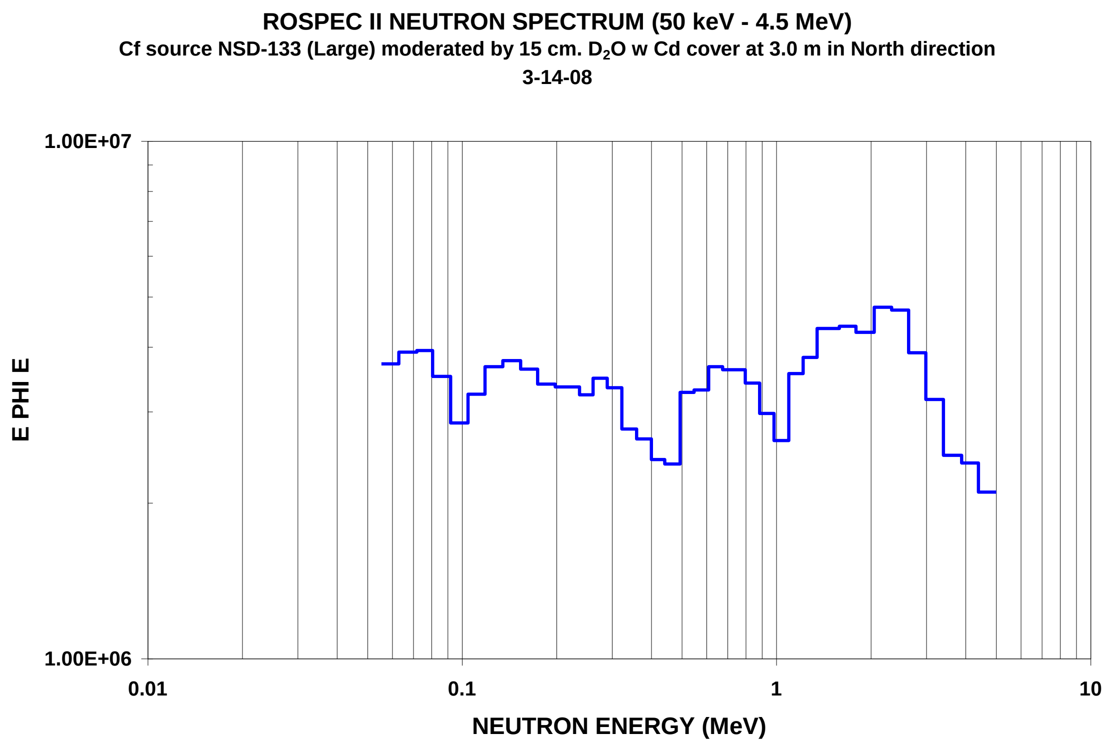


Figure D-21. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 3.0 m in North direction.

Table D-21. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 3.0 m in North direction

Date: 3-14-08
Exposure time = 56,671 sec

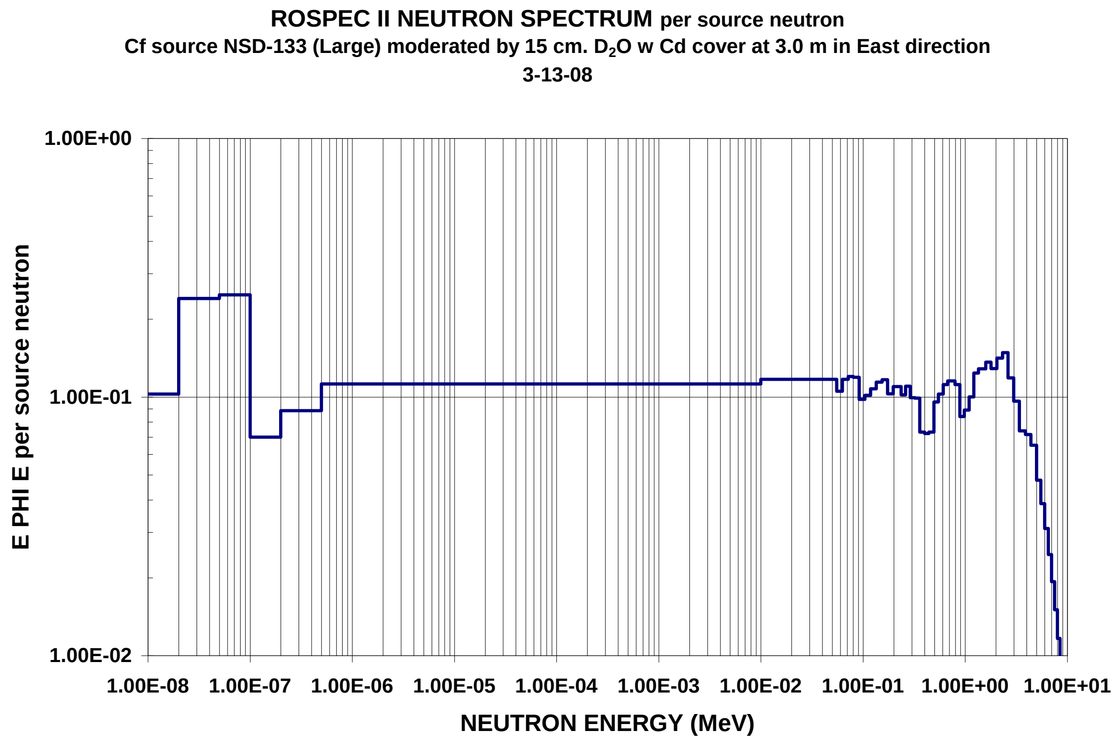
INTEGRATED FLUENCE = 7.8378E+07 FLUENCE RATE = 1.3830E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 3.4184E-02 rads	2.1715E+00 mrads/hr
H NCRP-38	= 4.5689E-01 rem	2.9024E+01 mrem/hr
H*(10) ICRP-74	= 5.2842E-03 Sv	3.3568E+02 μSv/hr
Hp(10,0) ICRP-74	= 5.5067E-03 Sv	3.4981E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	1.55E+07	2.73E+02
Epi-thermal region:	4.49E+07	7.93E+02
Thermal region:	1.75E+07	3.08E+02
TOTAL:	7.78E+07	1.37E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	2.98E-02	3.65E-01	4.40E-03	1.89E+00	2.32E+01	2.79E+02
Epi-thermal region:	2.15E-03	5.75E-02	5.38E-04	1.37E-01	3.65E+00	3.42E+01
Thermal region:	3.49E-04	1.78E-02	1.85E-04	2.22E-02	1.13E+00	1.18E+01
TOTAL:	3.23E-02	4.40E-01	5.12E-03	2.05E+00	2.79E+01	3.25E+02



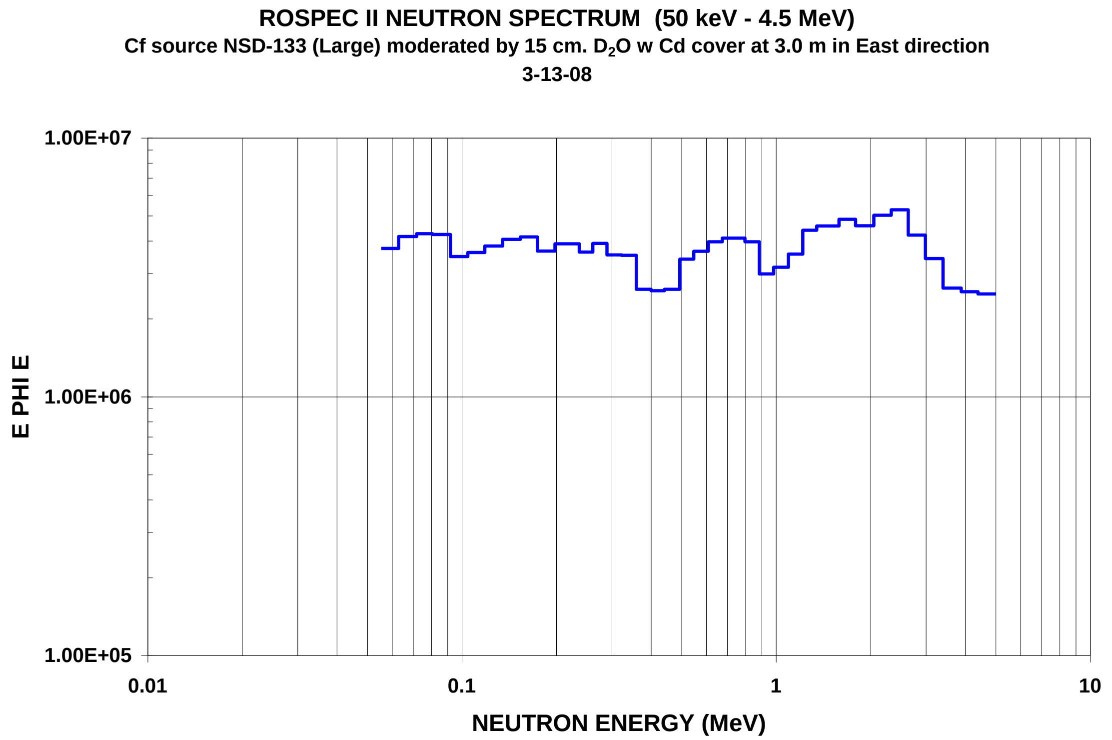


Figure D-22. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 3.0 m in East direction.

Table D-22. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 3.0 m in East direction

Date: 3-13-08
Exposure time = 58,800 sec

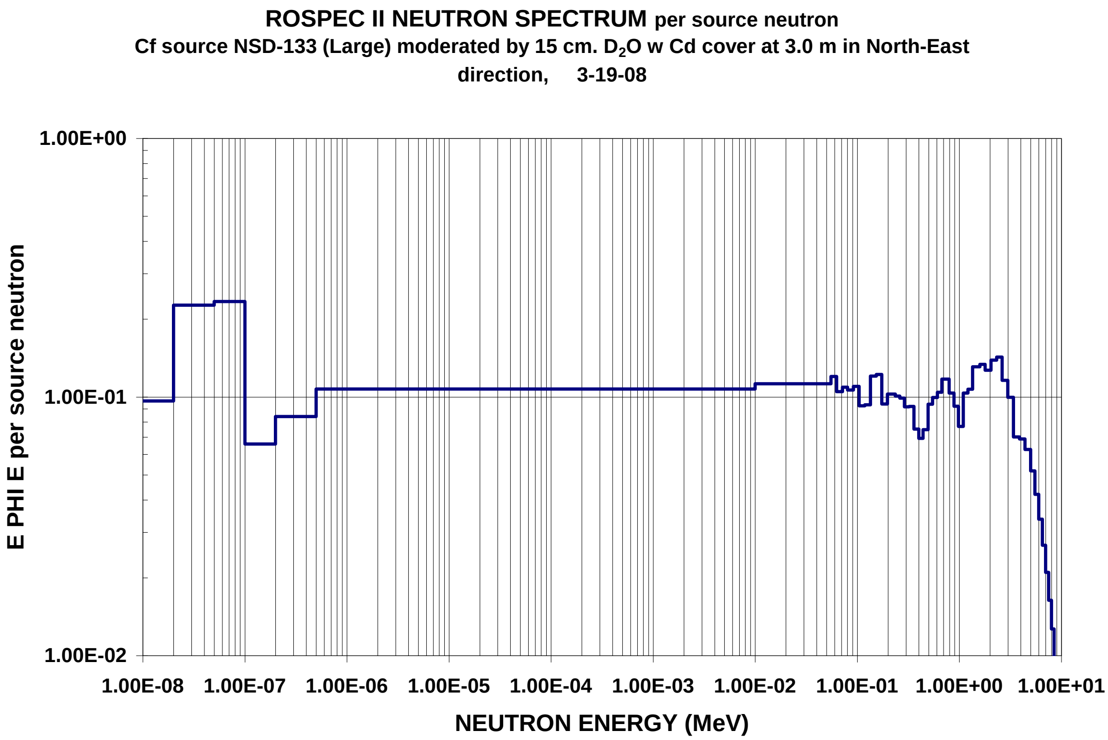
INTEGRATED FLUENCE = 8.6454E+07 FLUENCE RATE = 1.4703E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 3.7062E-02 rads	2.2691E+00 mrads/hr
H NCRP-38	= 4.9735E-01 rem	3.0450E+01 mrem/hr
H*(10) ICRP-74	= 5.7585E-03 Sv	3.5256E+02 μSv/hr
Hp(10,0) ICRP-74	= 6.0011E-03 Sv	3.6742E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	1.70E+07	2.89E+02
Epi-thermal region:	4.95E+07	8.42E+02
Thermal region:	1.95E+07	3.31E+02
TOTAL:	8.59E+07	1.46E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	3.26E-02	3.99E-01	4.81E-03	2.00E+00	2.44E+01	2.95E+02
Epi-thermal region:	2.37E-03	6.34E-02	5.94E-04	1.45E-01	3.88E+00	3.64E+01
Thermal region:	3.89E-04	1.98E-02	2.06E-04	2.38E-02	1.21E+00	1.26E+01
TOTAL:	3.54E-02	4.82E-01	5.61E-03	2.17E+00	2.95E+01	3.44E+02



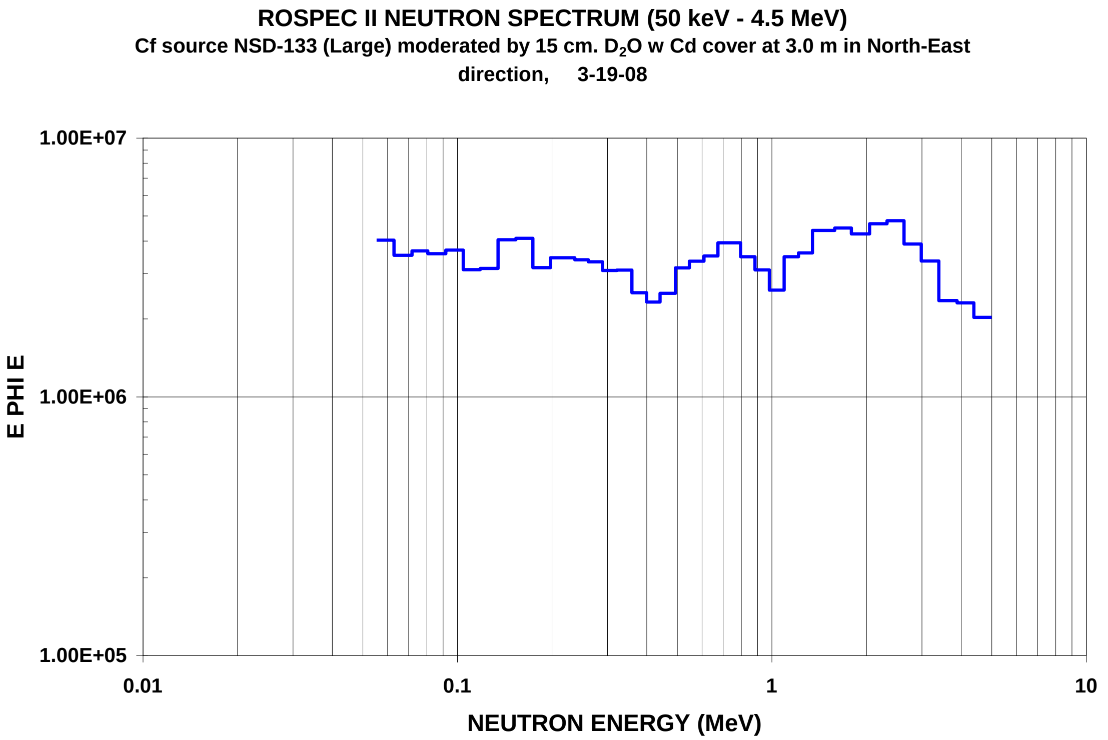


Figure D-23. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 3.0 m in Northeast direction.

Table D-23. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 3.0 m in Northeast direction

Date: 3-14-08
Exposure time = 55,500 sec

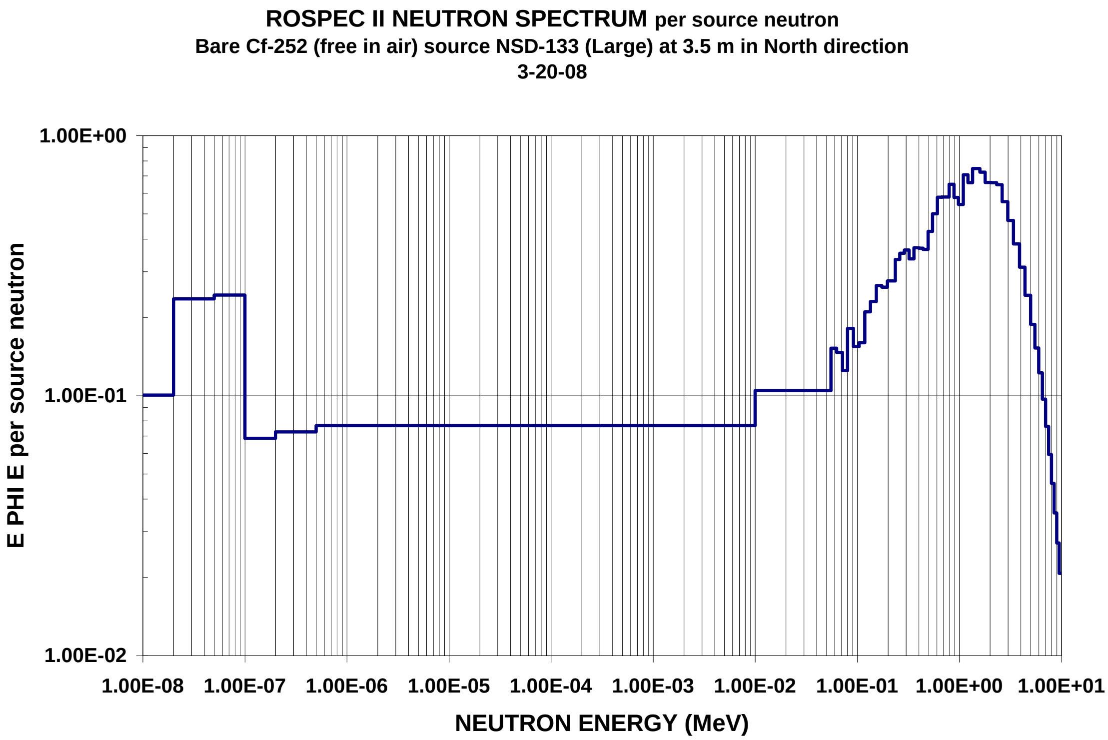
INTEGRATED FLUENCE = 7.8132E+07 FLUENCE RATE = 1.4078E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 3.4320E-02 rads	2.2261E+00 mrads/hr
H NCRP-38	= 4.5826E-01 rem	2.9725E+01 mrem/hr
H*(10) ICRP-74	= 5.3012E-03 Sv	3.4386E+02 μSv/hr
Hp(10,0) ICRP-74	= 5.5243E-03 Sv	3.5833E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	1.55E+07	2.80E+02
Epi-thermal region:	4.48E+07	8.06E+02
Thermal region:	1.73E+07	3.11E+02
TOTAL:	7.76E+07	1.40E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	2.98E-02	3.65E-01	4.41E-03	1.94E+00	2.37E+01	2.86E+02
Epi-thermal region:	2.15E-03	5.74E-02	5.37E-04	1.39E-01	3.72E+00	3.48E+01
Thermal region:	3.46E-04	1.76E-02	1.83E-04	2.24E-02	1.14E+00	1.19E+01
TOTAL:	3.23E-02	4.40E-01	5.13E-03	2.10E+00	2.86E+01	3.33E+02



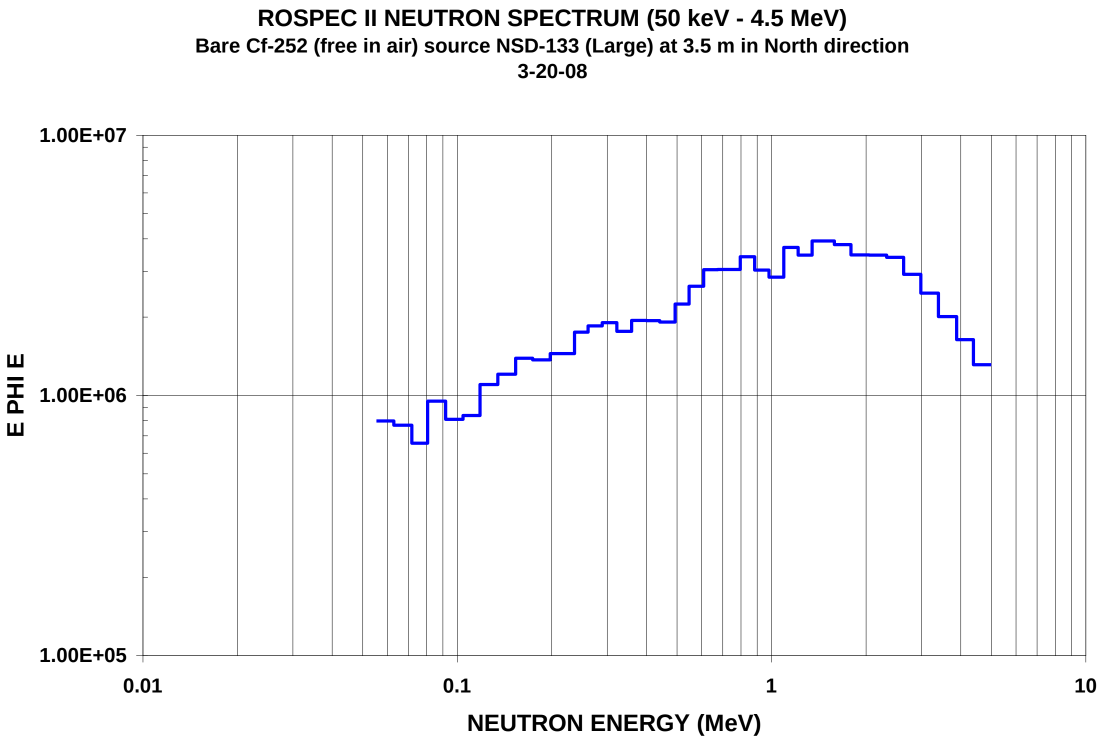


Figure D-24. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 3.5 m in North direction.

Table D-24. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 3.5 m in North direction

Date: 3-20-08
Exposure time = 11,800 sec

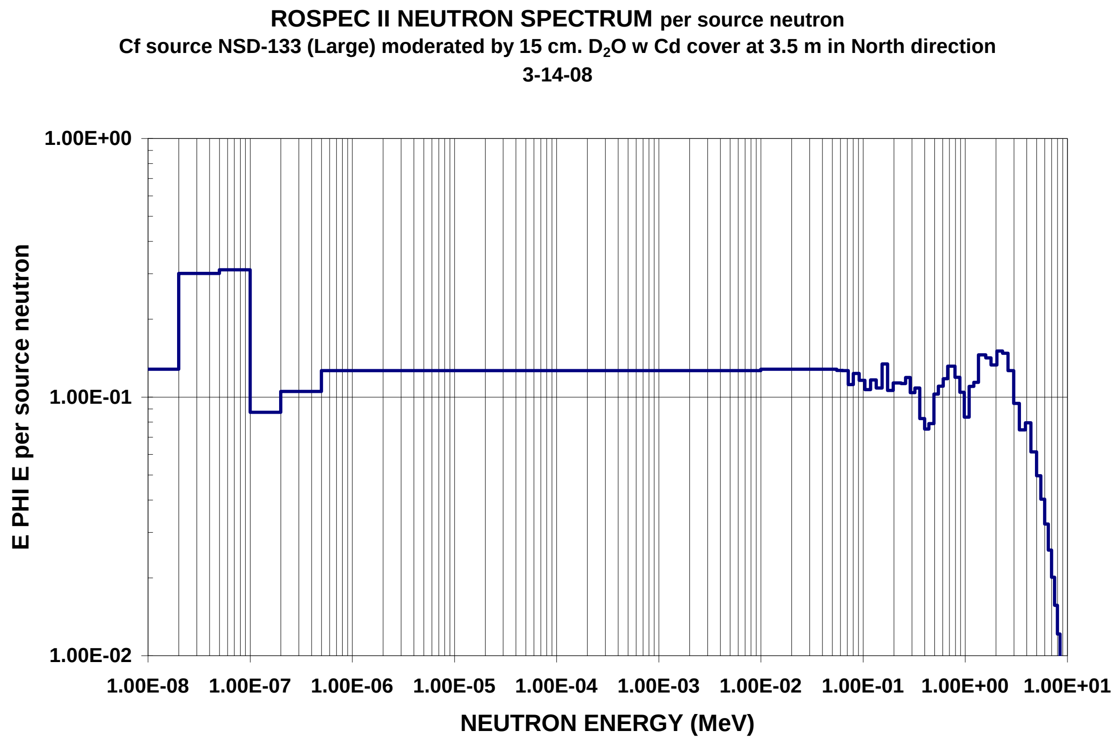
INTEGRATED FLUENCE = 1.8104E+07 FLUENCE RATE = 1.5342E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 2.3374E-02 rads	7.1309E+00 mrads/hr
H NCRP-38	= 2.9700E-01 rem	9.0611E+01 mrem/hr
H*(10) ICRP-74	= 3.4828E-03 Sv	1.0625E+03 μSv/hr
Hp(10,0) ICRP-74	= 3.6082E-03 Sv	1.1008E+03 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	9.70E+06	8.22E+02
Epi-thermal region:	5.26E+06	4.46E+02
Thermal region:	2.81E+06	2.38E+02
TOTAL:	1.78E+07	1.51E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	2.21E-02	2.78E-01	3.29E-03	6.73E+00	8.48E+01	1.00E+03
Epi-thermal region:	2.94E-04	6.92E-03	6.56E-05	8.97E-02	2.11E+00	2.00E+01
Thermal region:	5.62E-05	2.87E-03	2.98E-05	1.71E-02	8.74E-01	9.09E+00
TOTAL:	2.24E-02	2.88E-01	3.39E-03	6.84E+00	8.78E+01	1.03E+03



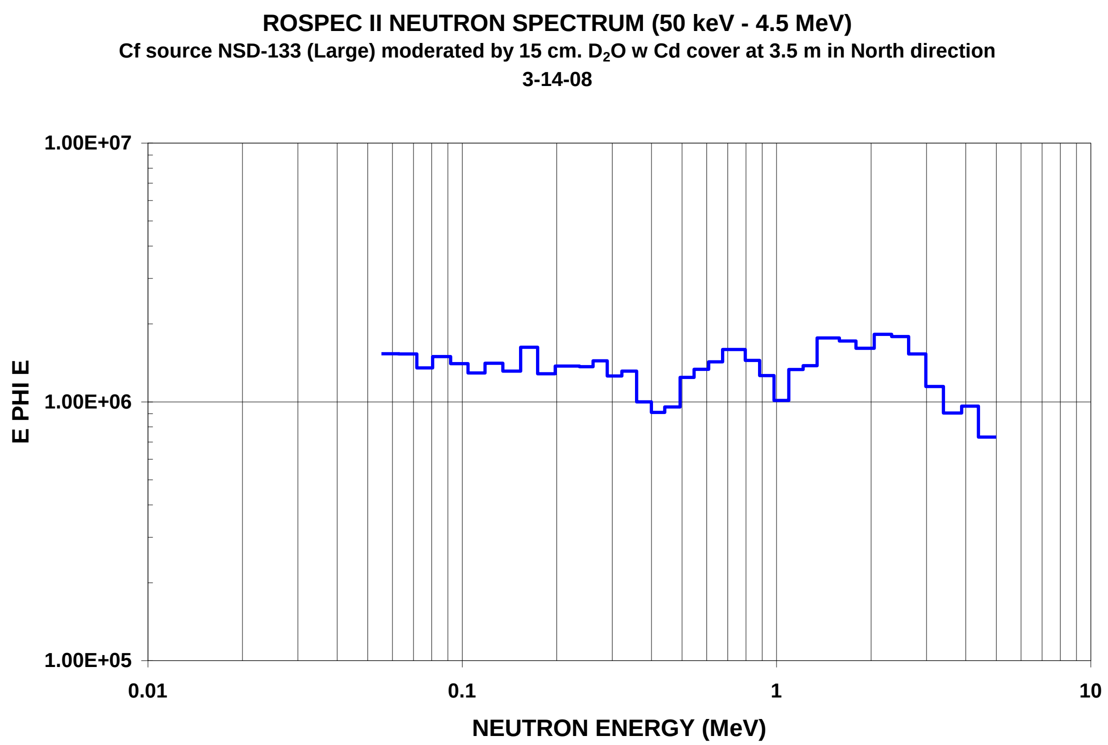


Figure D-25. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 3.5 m in North direction.

Table D-25. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 3.5 m in North direction

Date: 3-14-08
Exposure time = 27,250 sec

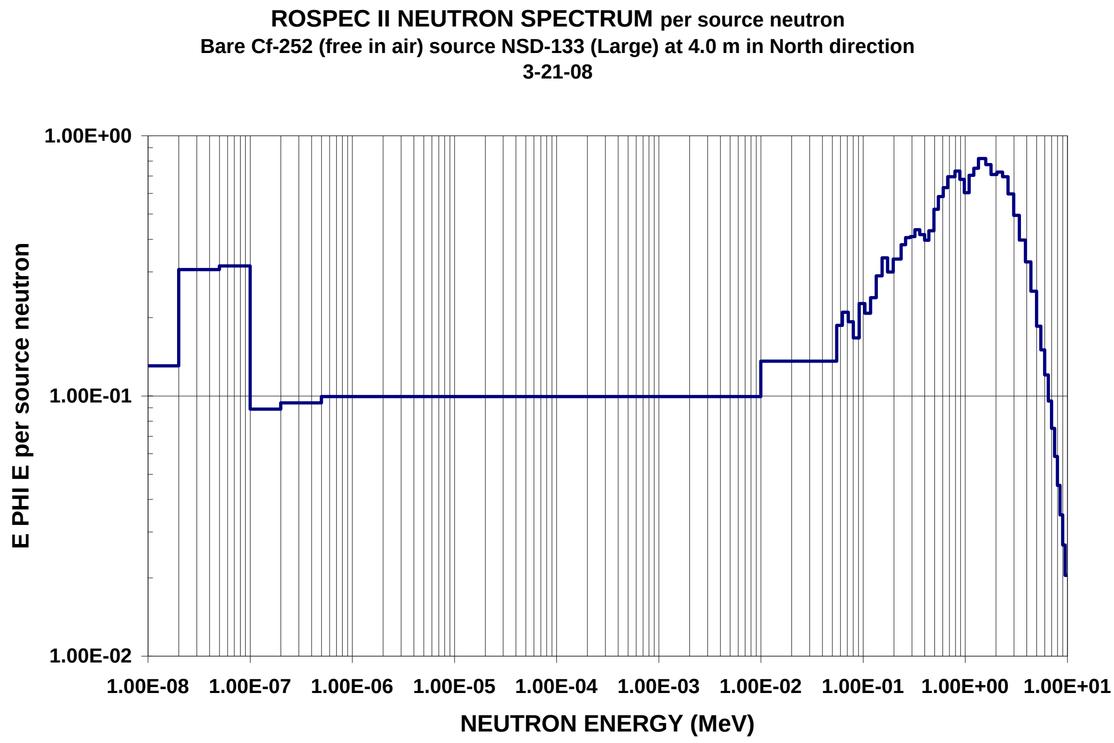
INTEGRATED FLUENCE = 3.3559E+07 FLUENCE RATE = 1.2315E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.3330E-02 rads	1.7610E+00 mrads/hr
H NCRP-38	= 1.8145E-01 rem	2.3971E+01 mrem/hr
H*(10) ICRP-74	= 2.0979E-03 Sv	2.7715E+02 μSv/hr
Hp(10,0) ICRP-74	= 2.1870E-03 Sv	2.8892E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	6.12E+06	2.25E+02
Epi-thermal region:	1.90E+07	6.97E+02
Thermal region:	8.27E+06	3.03E+02
TOTAL:	3.34E+07	1.22E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.16E-02	1.43E-01	1.73E-03	1.54E+00	1.89E+01	2.28E+02
Epi-thermal region:	8.92E-04	2.42E-02	2.27E-04	1.18E-01	3.20E+00	3.00E+01
Thermal region:	1.65E-04	8.43E-03	8.76E-05	2.18E-02	1.11E+00	1.16E+01
TOTAL:	1.27E-02	1.76E-01	2.04E-03	1.68E+00	2.32E+01	2.70E+02



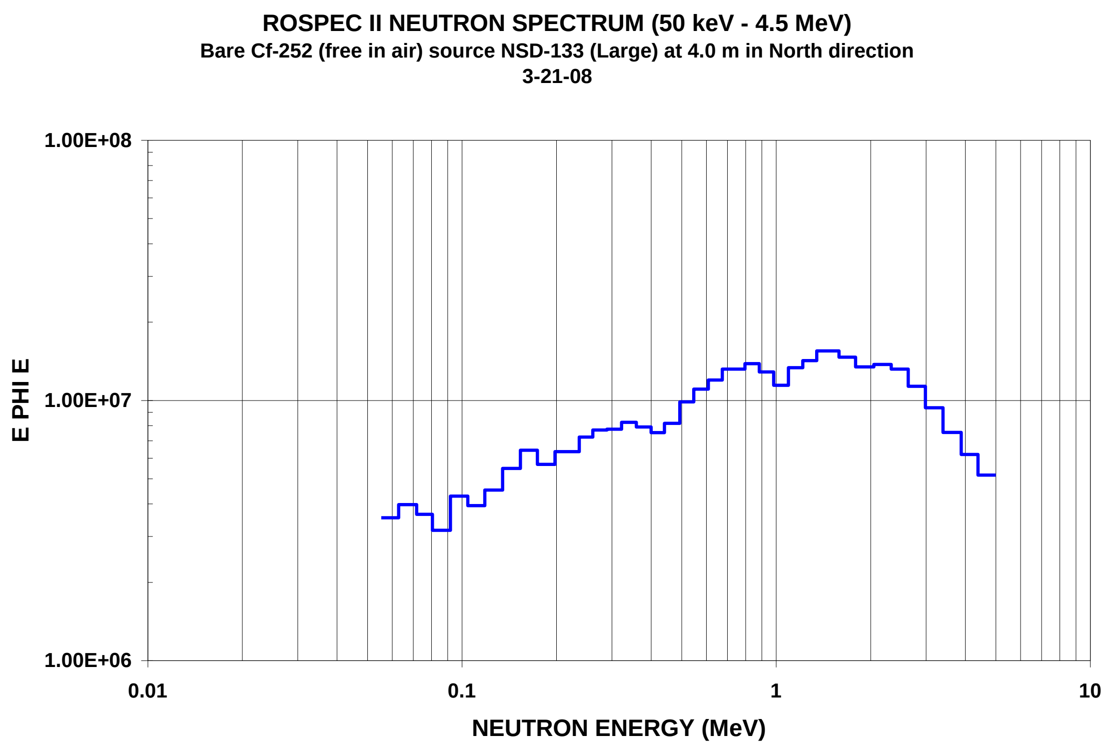


Figure D-26. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 4.0 m in North direction.

Table D-26. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 4.0 m in North direction

Date: 3-21-08
Exposure time = 55,700 sec

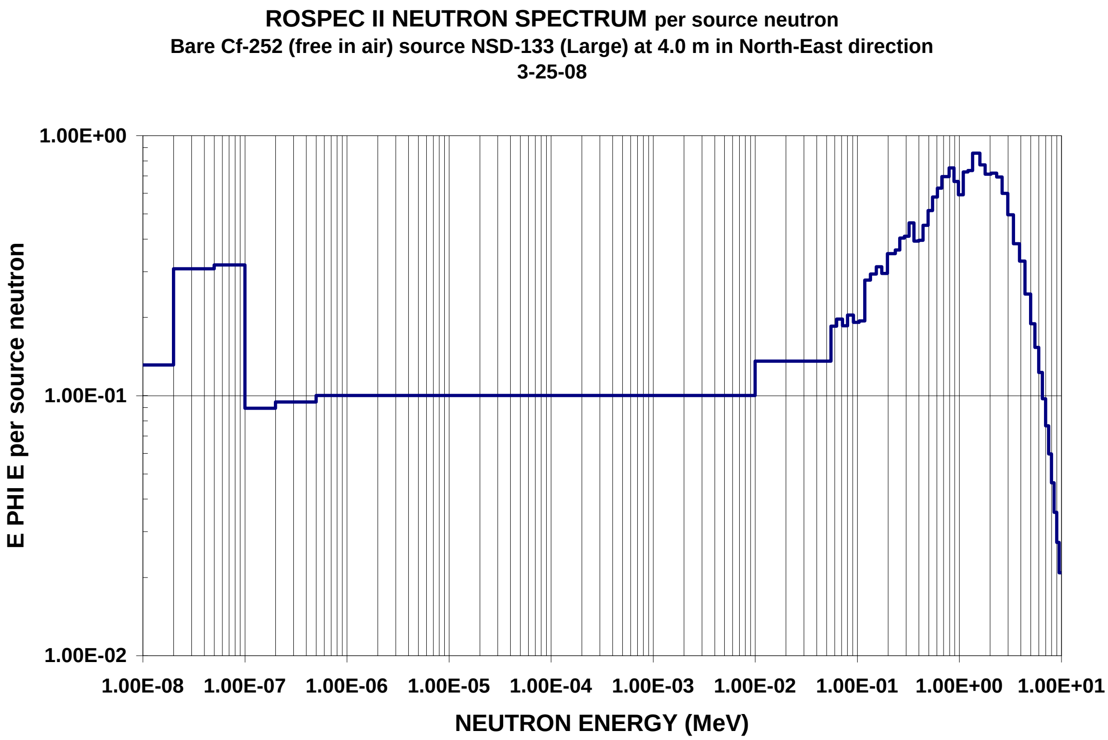
INTEGRATED FLUENCE = 7.8641E+07 FLUENCE RATE = 1.4119E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 9.2672E-02 rads	5.9895E+00 mrads/hr
H NCRP-38	= 1.1887E+00 rem	7.6831E+01 mrem/hr
H*(10) ICRP-74	= 1.3975E-02 Sv	9.0323E+02 μSv/hr
Hp(10,0) ICRP-74	= 1.4478E-02 Sv	9.3573E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	3.96E+07	7.12E+02
Epi-thermal region:	2.47E+07	4.43E+02
Thermal region:	1.32E+07	2.37E+02
TOTAL:	7.75E+07	1.39E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	8.81E-02	1.11E+00	1.32E-02	5.69E+00	7.20E+01	8.55E+02
Epi-thermal region:	1.38E-03	3.25E-02	3.08E-04	8.93E-02	2.10E+00	1.99E+01
Thermal region:	2.64E-04	1.34E-02	1.40E-04	1.70E-02	8.69E-01	9.03E+00
TOTAL:	8.97E-02	1.16E+00	1.37E-02	5.80E+00	7.49E+01	8.84E+02



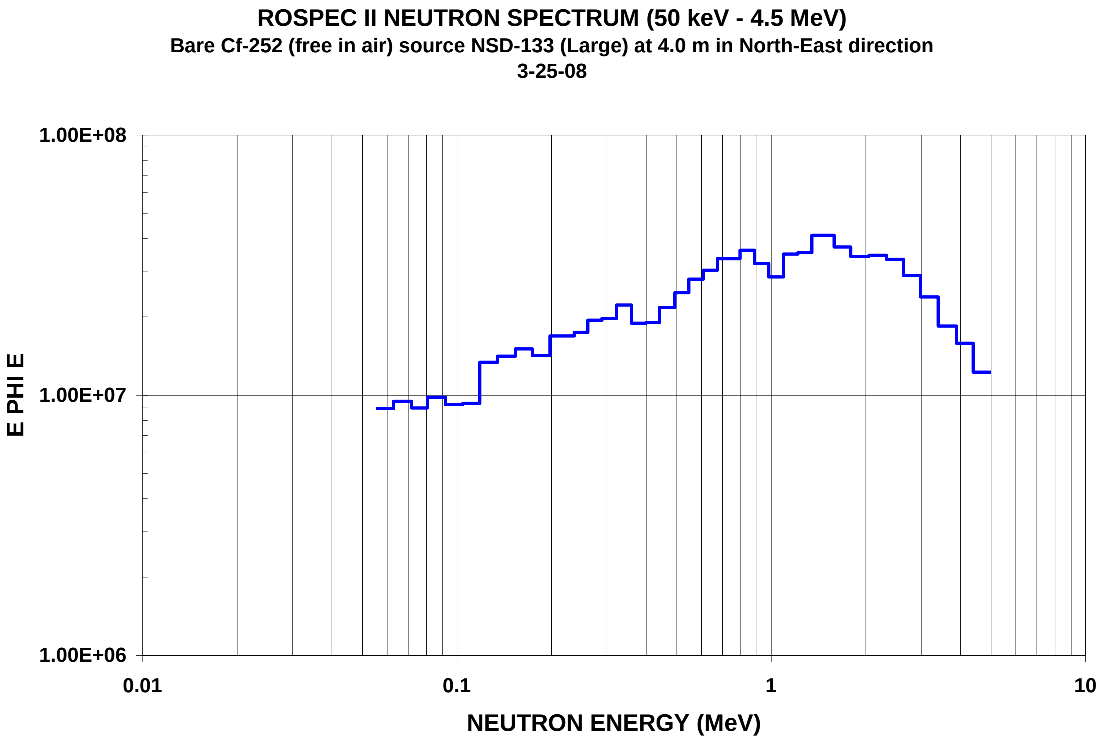


Figure D-27. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 4.0 m in Northeast direction.

Table D-27. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 4.0 m in Northeast direction

Date: 3-25-08
Exposure time = 141,300 sec

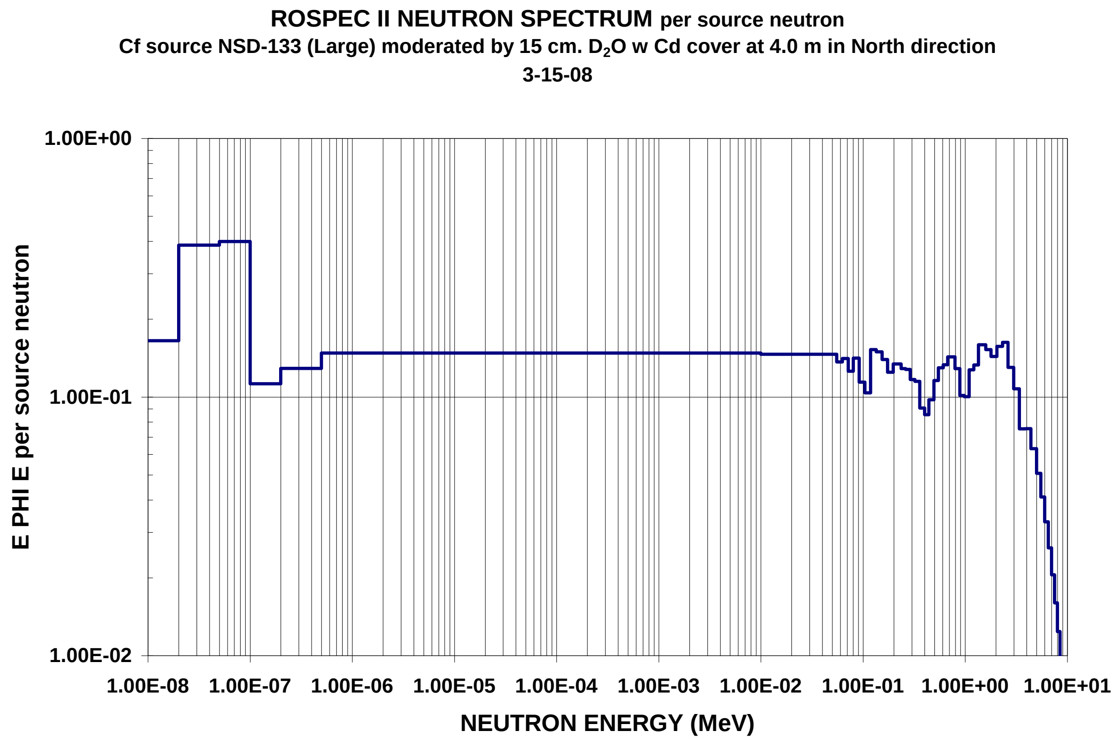
INTEGRATED FLUENCE = 2.0016E+08 FLUENCE RATE = 1.4165E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 2.3552E-01 rads	6.0004E+00 mrads/hr
H NCRP-38	= 3.0234E+00 rem	7.7031E+01 mrem/hr
H*(10) ICRP-74	= 3.5541E-02 Sv	9.0550E+02 μSv/hr
Hp(10,0) ICRP-74	= 3.6818E-02 Sv	9.3805E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	1.01E+08	7.12E+02
Epi-thermal region:	6.29E+07	4.45E+02
Thermal region:	3.36E+07	2.38E+02
TOTAL:	1.97E+08	1.40E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	2.23E-01	2.83E+00	3.36E-02	5.69E+00	7.20E+01	8.56E+02
Epi-thermal region:	3.50E-03	8.26E-02	7.84E-04	8.93E-02	2.11E+00	2.00E+01
Thermal region:	6.73E-04	3.43E-02	3.56E-04	1.71E-02	8.74E-01	9.08E+00
TOTAL:	2.27E-01	2.94E+00	3.47E-02	5.80E+00	7.50E+01	8.85E+02



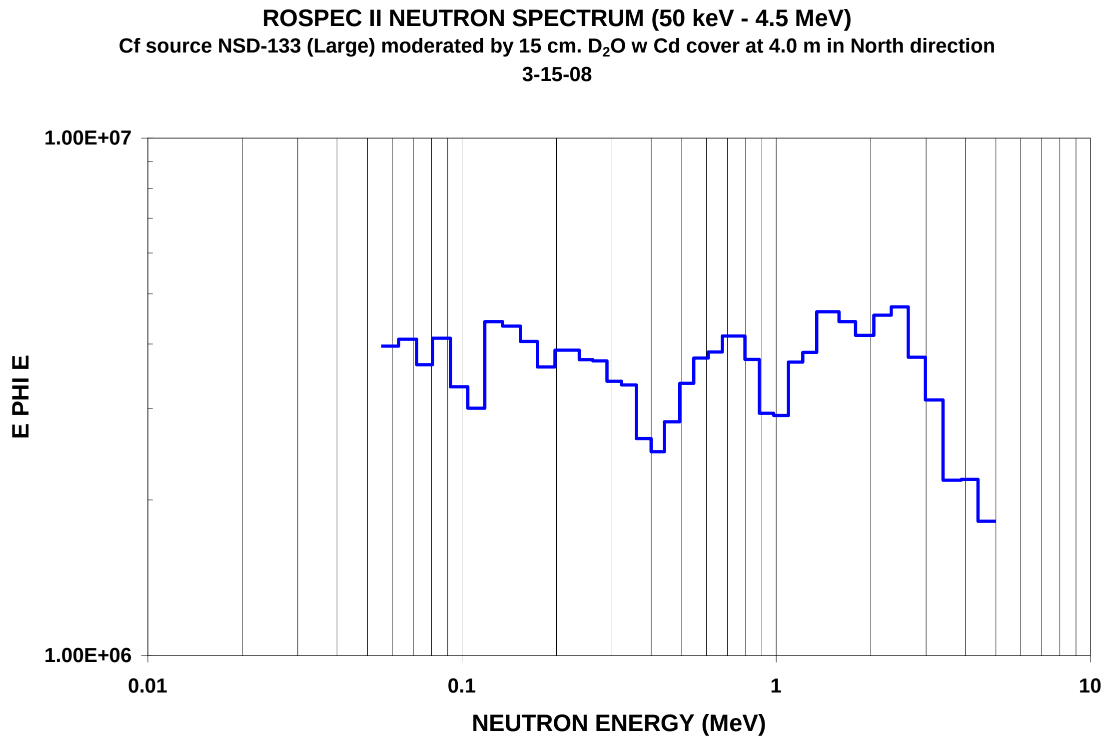


Figure D-28. Neutron spectra from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 4.0 m in North direction.

Table D-28. Neutron fluence and dose from ^{252}Cf source NSD-133 (Large) moderated by 15 cm. D_2O with Cd cover at 4.0 m in North direction

Date: 3-15-08
Exposure time = 85,200 sec

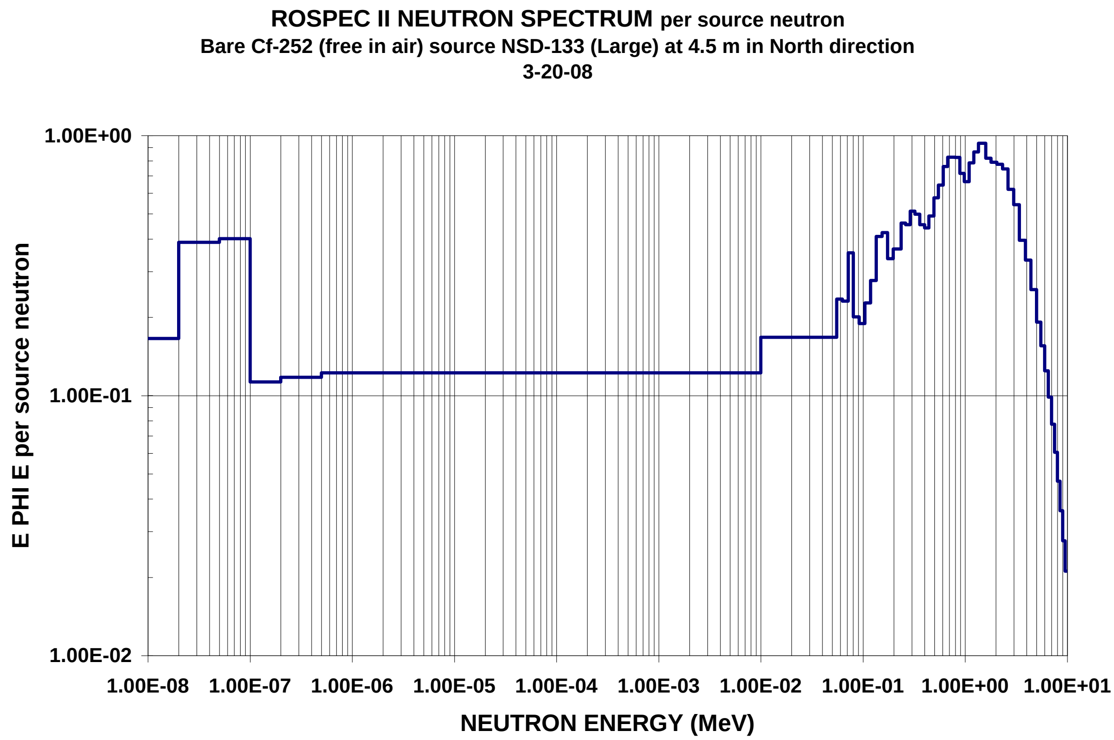
INTEGRATED FLUENCE = 9.5331E+07 FLUENCE RATE = 1.1189E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 3.4847E-02 rads	1.4724E+00 mrads/hr
H NCRP-38	= 4.8215E-01 rem	2.0372E+01 mrem/hr
H*(10) ICRP-74	= 5.5755E-03 Sv	2.3558E+02 μSv/hr
Hp(10,0) ICRP-74	= 5.8145E-03 Sv	2.4568E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	1.62E+07	1.91E+02
Epi-thermal region:	5.32E+07	6.24E+02
Thermal region:	2.55E+07	2.99E+02
TOTAL:	9.49E+07	1.11E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	3.04E-02	3.75E-01	4.55E-03	1.28E+00	1.59E+01	1.92E+02
Epi-thermal region:	2.45E-03	6.77E-02	6.33E-04	1.04E-01	2.86E+00	2.68E+01
Thermal region:	5.10E-04	2.60E-02	2.70E-04	2.15E-02	1.10E+00	1.14E+01
TOTAL:	3.34E-02	4.69E-01	5.45E-03	1.41E+00	1.98E+01	2.30E+02



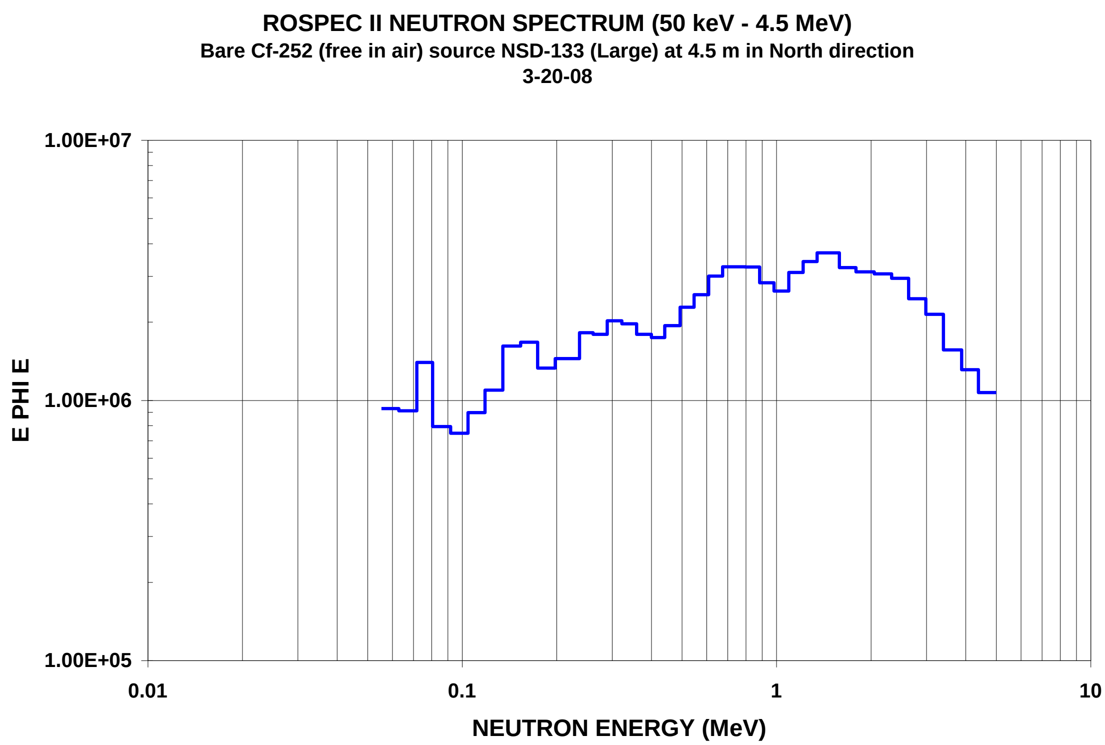


Figure D-29. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 4.5 m in North direction.

Table D-29. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 4.5 m in North direction

Date: 3-20-08
Exposure time = 14,700 sec

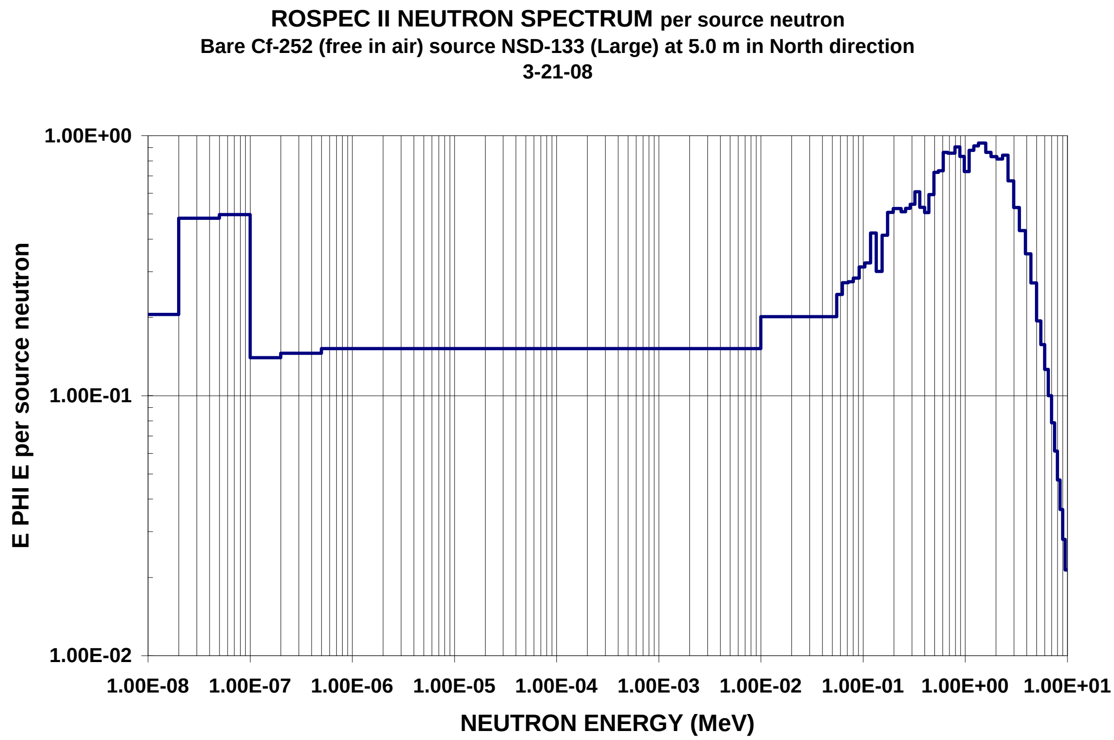
INTEGRATED FLUENCE = 1.9378E+07 FLUENCE RATE = 1.3182E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 2.1260E-02 rads	5.2066E+00 mrads/hr
H NCRP-38	= 2.7516E-01 rem	6.7387E+01 mrem/hr
H*(10) ICRP-74	= 3.2407E-03 Sv	7.9365E+02 μSv/hr
Hp(10,0) ICRP-74	= 3.3568E-03 Sv	8.2207E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	9.30E+06	6.33E+02
Epi-thermal region:	6.34E+06	4.32E+02
Thermal region:	3.49E+06	2.37E+02
TOTAL:	1.91E+07	1.30E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	2.02E-02	2.57E-01	3.06E-03	4.95E+00	6.30E+01	7.50E+02
Epi-thermal region:	3.55E-04	8.34E-03	7.91E-05	8.70E-02	2.04E+00	1.94E+01
Thermal region:	6.98E-05	3.56E-03	3.70E-05	1.71E-02	8.72E-01	9.06E+00
TOTAL:	2.07E-02	2.69E-01	3.18E-03	5.06E+00	6.59E+01	7.79E+02



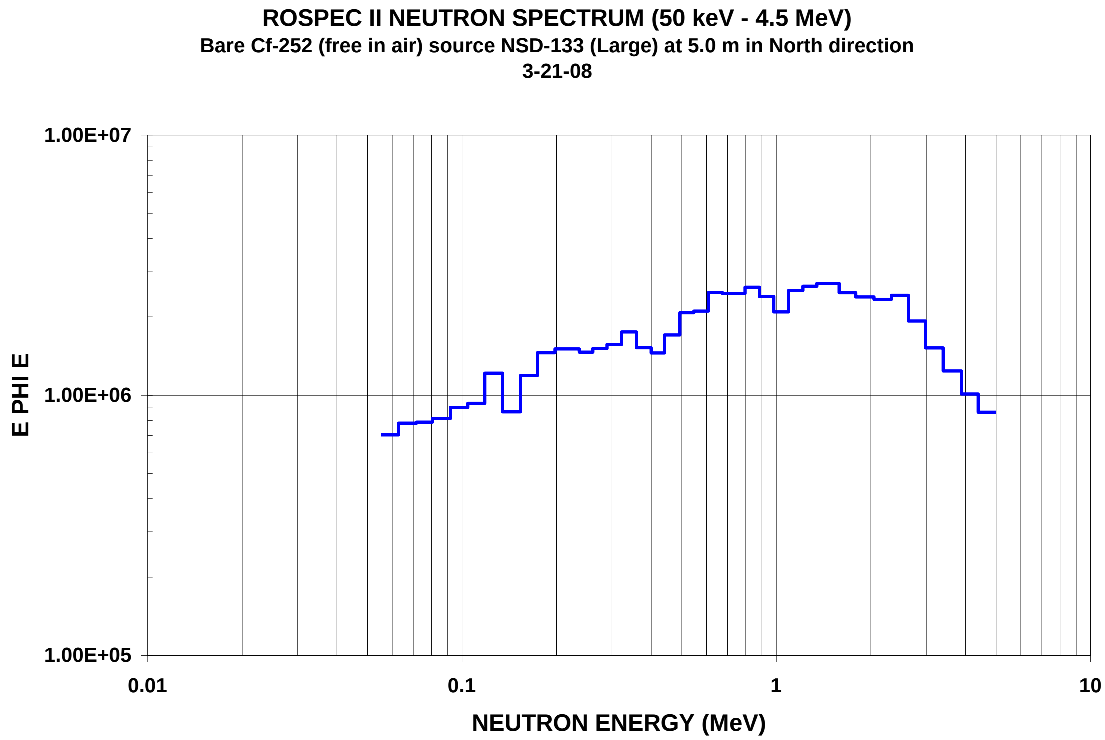


Figure D-30. Neutron spectra from bare ^{252}Cf (free in air) source NSD-133 (Large) at 5.0 m in North direction.

Table D-30. Neutron fluence and dose from bare ^{252}Cf (free in air) source NSD-133 (Large) at 5.0 m in North direction

Date: 3-21-08
Exposure time = 13,200 sec

INTEGRATED FLUENCE = 1.6539E+07 FLUENCE RATE = 1.2530E+03

	INTEGRATED DOSE	DOSE RATE
KERMA	= 1.6814E-02 rads	4.5855E+00 mrads/hr
H NCRP-38	= 2.1897E-01 rem	5.9718E+01 mrem/hr
H*(10) ICRP-74	= 2.5858E-03 Sv	7.0522E+02 μSv/hr
Hp(10,0) ICRP-74	= 2.6789E-03 Sv	7.3060E+02 μSv/hr

	FLUENCE (n cm-2)	FLUENCE RATE (n cm-2 s-1)
50 keV - 4.5 MeV:	7.53E+06	5.71E+02
Epi-thermal region:	5.69E+06	4.31E+02
Thermal region:	3.14E+06	2.38E+02
TOTAL:	1.64E+07	1.24E+03

DOSIMETRIC DATA

	KERMA (rads)	NCRP-38 (rem)	H*(10) (Sv)	KERMA (mrads/hr)	NCRP-38 (mrem/hr)	H*(10) (μSv/hr)
50keV - 4.5 MeV:	1.60E-02	2.05E-01	2.44E-03	4.38E+00	5.58E+01	6.67E+02
Epi-thermal region:	3.12E-04	7.45E-03	7.06E-05	8.52E-02	2.03E+00	1.93E+01
Thermal region:	6.29E-05	3.21E-03	3.33E-05	1.71E-02	8.74E-01	9.09E+00
TOTAL:	1.64E-02	2.15E-01	2.55E-03	4.48E+00	5.87E+01	6.95E+02

APPENDIX E
Neutron Dose Rates Measured with ROSPEC, SWENDI-II and NRD

Table E-1. Neutron dose rate measurements with ROSPEC

Bare ^{252}Cf NSD-133 Large

Distance (m)	NORTH			EAST			NORTHEAST		
	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)
2.0	207.9	241.6	250.5	210.4	244.7	253.6			
2.5	145.9	170.2	176.4	150.4	175.5	181.9			
3.0	112.5	131.6	136.3	117.5	137.5	142.4	113.5	132.8	137.6
3.5	90.6	106.3	110.1						
4.0	76.8	90.3	93.6				77.0	90.6	93.8
4.5	67.4	79.4	82.2						
5.0	59.7	70.5	73.1						

D_2O moderated ^{252}Cf NSD-133 Large

Distance (m)	NORTH			EAST			NORTHEAST		
	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)
1.5	84.25	97.29	101.30						
2.0	51.99	60.09	62.59	52.74	61.03	63.56	52.54	60.76	63.28
2.5	37.84	43.80	45.63						
3.0	29.02	33.57	34.98	30.45	35.26	36.74	29.72	34.39	35.83
3.5	23.97	27.71	28.89						
4.0	20.37	23.56	24.57						

Bare ^{252}Cf NS-120 Small

Distance (m)	NORTH			EAST		
	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)
1.0	12.35	14.29	14.82	12.33	14.26	14.79
1.5	5.57	6.47	6.70	5.82	6.76	7.00
2.0	3.55	4.12	4.27			
3.0	1.82	2.13	2.20			

D_2O moderated ^{252}Cf NS-120 Small

Distance (m)	NORTH			EAST		
	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	Ambient ICRP-74 (mrem/hr)	Personal ICRP-74 (mrem/hr)
1.0	2.89	3.34	3.47	2.92	3.37	3.51

Table E-2 Neutron dose rate measurements with SWENDI-II

Bare ^{252}Cf — Large # NSD-133 — Small, # NS-120

Distance (m)	NORTH	EAST	NORTH-EAST	Ratio	NORTH	EAST	Ratio
	SWENDI (mrem/hr)	SWENDI (mrem/hr)	SWENDI (mrem/hr)	EAST/ NORTH	SWENDI (mrem/hr)	SWENDI (mrem/hr)	EAST/ NORTH
1.0	723.7	741.7	753.3	102.5%	11.9	11.9	100.0%
1.5	351.2	346.5		98.7%	5.8	5.67	97.8%
2.0	214.9	218.4	216	101.6%	3.6	3.6	100.0%
2.5	153.3	158.0		103.1%			
3.0	119.0	122.7	121.7	103.1%	2.0	2.1	105.0%
3.5	98.4	103		104.7%			
4.0	83.8	93.9	84.9	112.1%	1.4	1.53	109.3%
4.5	74.1						
5.0	67.1						

D_2O moderated ^{252}Cf — Large, # NSD-133 — Small, # NS-120

Distance (m)	NORTH	EAST	NORTH-EAST	Ratio	NORTH	EAST	Ratio
	SWENDI (mrem/hr)	SWENDI (mrem/hr)	SWENDI (mrem/hr)	EAST/ NORTH	SWENDI (mrem/hr)	SWENDI (mrem/hr)	EAST/ NORTH
0.5	657.8				11		
1.0	175.7	173.9	180.2	99.0%	2.92	2.9	99.3%
1.5	87.9	85.6	88.2	97.4%		1.4	
2.0	55.8	55.0	56.1	98.6%	0.9	0.9	
2.5	40.3		39.2				
3.0	31.7	32.9	32.5	103.8%		0.6	
3.5	26.4		26.8				
4.0	22.9	25.6	23.3	111.8%			
4.5	20.3						
5.0	18.5		18.5				

Table E-3. Neutron dose rate measurements with NRD calibrated by NIST

Measurements performed in the North direction with the Large ^{252}Cf source (# NSD-133)

Bare ^{252}Cf		NRD measurement					
Date	Meters	Exposure time (min)	Exposure (mrem)	Dose rate (mrem/h) 8/22/08	Days since 3/10/08	Dose rate (mrem/h) 3/10/08	Dose rate corrected by NIST*
8/22/2008	0.5	10	434	2604.0	165	2932.2	2756.3
8/22/2008	1.0	10	110.1	660.6	165	743.9	699.2
8/22/2008	1.5	10	53	318.0	165	358.1	336.6
8/22/2008	2.0	10	32.1	192.6	165	216.9	203.9
8/21/2008	2.5	10	22.6	135.6	164	152.6	143.4
8/21/2008	3.0	10	17.3	103.8	164	116.8	109.8
8/21/2008	3.5	10	14.1	84.6	164	95.2	89.5
8/21/2008	4.0	10	11.9	71.4	164	80.3	75.5

D_2O Moderated ^{252}Cf		NRD measurement					
Date	Meters	Exposure time (min)	Exposure (mrem)	Dose rate (mrem/h) 8/13/08	Days since 3/10/08	Dose rate (mrem/h) 3/10/08	Dose rate corrected by NIST*
8/13/2008	0.5	10	124.3	745.8	156	834.4	575.7
8/13/2008	1.0	10	34.1	204.6	156	228.9	157.9
8/13/2008	1.5	10	16.6	99.6	156	111.4	76.9
8/13/2008	2.0	10	10.4	62.4	156	69.8	48.2
8/13/2008	2.5	10	7.4	44.4	156	49.7	34.3
8/13/2008	3.0	10	5.9	35.4	156	39.6	27.3
8/13/2008	3.5	10	4.8	28.8	156	32.2	22.2
8/13/2008	4.0	10	4.2	25.2	156	28.2	19.5

* NIST calibration coefficient for this meter is 0.94 for bare Cf-252 and 0.69 for D2O moderated Cf-252.

Table E-4. Comparison of the neutron dose rates measured with SWENDI and ROSPEC using NCRP-38 fluence-to-dose conversion factors

Bare Cf NSD-133 Large

Distance (m)	NORTH			EAST			NORTH-EAST		
	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)
1.0	723.7			741.7			753.3		
1.5	351.2			346.5					
2.0	214.9	207.9	103.4%	218.4	210.4	103.8%	216		
2.5	153.3	145.9	105.1%	158.0	150.4	105.1%			
3.0	119.0	112.5	105.8%	122.7	117.5	104.4%	121.7	113.52	107.2%
3.5	98.4	90.61	108.6%						
4.0	83.8	76.83	109.1%	93.9			84.9	77.03	110.2%
4.5	74.1	67.39	110.0%						
5.0	67.1	59.72	112.4%						

D_2O moderated Cf NSD-133 Large

Distance (m)	NORTH			EAST			NORTH-EAST		
	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)
0.5	657.8								
1.0	175.7			173.9			180.2		
1.5	87.9	84.25	104.3%	85.6			88.2		
2.0	55.8	51.99	107.3%	55.0	53.97	101.9%	56.1	52.54	106.8%
2.5	40.3	37.8	106.6%				39.2		
3.0	31.7	29.02	109.2%	32.9	30.4	108.2%	32.5	29.72	109.4%
3.5	26.4	23.97	110.1%				26.8		
4.0	22.9	20.37	112.4%	25.6			23.3		
4.5	20.3								
5.0	18.5						18.5		

Bare Cf NS-120 Small

Distance (m)	NORTH			EAST		
	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)
1.0	11.9	12.3	96.7%	11.9	12.33	96.5%
1.5	5.8	5.57	104.1%	5.67	5.823	97.4%
2.0	3.6	3.54	101.6%	3.6		
3.0	2.0	1.82	109.9%	2.1		
4.0	1.4			1.53		

D_2O moderated Cf NS-120 Small

Distance (m)	NORTH			EAST		
	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)	SWENDI (mrem/hr)	ROSPEC (mrem/hr)	Ratio SWENDI/ ROSPEC (%)
0.5	11					
1.0	2.92	2.89	101.0%	2.9	2.92	99.3%
1.5				1.4		
2.0	0.9			0.9		

APPENDIX F
MCNPX Calculated Neutron Dose Rates

Table F-1. Neutron dose rates calculated by MCNPX

Bare ^{252}Cf	NSD-133, Large					
	NORTH		EAST		NORTH-EAST	
Distance (m)	NCRP-38 (mrem/hr)	ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	ICRP-74 (mrem/hr)
0.5	3063	3536	3063	3537	2882	3326
1.0	810	938	810	938	765	885
1.5	388	451	390	453	368	428
2.0	239	278	241	281	228	266
2.5	168	197	172.0	201	162	189
3.0	129	151	134	158	125	147
3.5	104	123	112	133	102	120
4.0	88.3	104	99.4	118	86.2	102
4.5	77.1	91.5			75.1	89.1
5.0	69.4	82.5			67	80

^{252}Cf D_2O moderated	NSD-133, Large					
	NORTH		EAST		NORTH-EAST	
Distance (m)	NCRP-38 (mrem/hr)	ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	ICRP-74 (mrem/hr)	NCRP-38 (mrem/hr)	ICRP-74 (mrem/hr)
0.5	636.0	728.0	635.0	728.0	627.0	719.0
1.0	172.0	197.0	172.0	198.0	170.0	195.0
1.5	85.0	98.0	85.4	98.5	84.1	97.0
2.0	53.8	62.1	54.4	62.8	53.4	61.7
2.5	38.8	44.9	39.8	46.0	38.7	44.8
3.0	30.4	35.2	31.8	36.9	30.4	35.2
3.5	25.1	29.1	27.0	31.4	25.2	29.3
4.0	21.6	25.1	24.2	28.1	21.7	25.1
4.5	19.1	22.2			19.1	22.2
5.0	17.4	20.2			17.2	20.0

APPENDIX G

Neutron Dose Rates Comparison Between the Old Calibration System "Wabbit" and the New Hopewell N40 Calibrator

Table G-1. Neutron dose rates from the old WABBIT system and from measurements with SWENDI-II and ROSPEC in the new N40 configuration

Bare ^{252}Cf — Large source - NSD-133 — North direction

Distance (m)	Old Wabbit (mrem/hr)	SWENDI (mrem/hr)	Dose rate ratio SWENDI/Wabbit (%)	ROSPEC (NCRP-38) (mrem/hr)	Dose rate ratio ROSPEC/Wabbit (%)
0.5	2687.3				
1.0	700.2	723.7	103.4%		
1.5	327.9	351.2	107.1%		
2.0	198.5	214.9	108.3%	207.9	104.7%
2.5		153.3		145.99	
3.0	105.0	119	113.3%	112.54	107.2%
3.5		98.4		90.61	
4.0	75.4	83.9	111.3%	76.83	101.9%

D_2O Moderated ^{252}Cf — Large source - NSD-133 — North direction

Distance (m)	Old Wabbit (mrem/hr)	SWENDI (mrem/hr)	Dose rate ratio SWENDI/Wabbit (%)	ROSPEC (NCRP-38) (mrem/hr)	Dose rate ratio ROSPEC/Wabbit (%)
0.5	579.40	657.8	113.5%		
1.0	151.90	175.7	115.7%		
1.5	73.00	87.9	120.4%		
2.0	45.18	55.8	123.5%	51.99	115.1%
2.5		40.3		37.84	
3.0	25.40	31.7	124.8%	29.02	114.3%
3.5		26.4		23.97	
4.0	19.06	22.9	120.2%	20.37	106.9%

Bare ^{252}Cf Small source - NS-120 North direction

Distance	Old Wabbit	SWENDI	Dose rate ratio SWENDI/Wabbit	ROSPEC (NCRP-38)	Dose rate ratio ROSPEC/Wabbit
(m)	(mrem/hr)	(mrem/hr)	(%)	(mrem/hr)	(%)
0.5	37.709				
1.0	9.825	11.9	121.1%	12.3	125.2%
1.5	4.601	5.8	126.1%	5.43	118.0%
2.0	2.785	3.6	129.3%	3.54	127.1%
2.5					
3.0	1.474	2	135.7%		
3.5					
4.0	1.059	1.4	132.2%		

D_2O Moderated ^{252}Cf Small source - NS-120 North direction

Distance	Old Wabbit	SWENDI	Dose rate ratio SWENDI/Wabbit	ROSPEC (NCRP-38)	Dose rate ratio ROSPEC/Wabbit
(m)	(mrem/hr)	(mrem/hr)	(%)	(mrem/hr)	(%)
0.5	8.130	11	135.3%		
1.0	2.131	2.92	137.0%	2.89	135.6%
1.5	1.024				
2.0	0.633	0.9	142.2%		