LUDLUM MODEL 42-38 WENDI-2
WIDE ENERGY NEUTRON DETECTOR

November 2018

Serial Number PR161245 and Succeeding
Serial Numbers

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LUDLUM MEASUREMENTS, INC
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Ludlum Measurements, Inc. warrants the products covered in this manual to be free of defects due to workmanship, material, and design for a period of twelve months from the date of delivery. The calibration of a product is warranted to be within its specified accuracy limits at the time of shipment. In the event of instrument failure, notify Ludlum Measurements to determine if repair, recalibration, or replacement is required.

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1. GENERAL

The Ludlum Model 42-38 WENDI-2 (Wide Energy Neutron Detection Instrument) neutron detector is designed for detection of thermal and fast neutrons (0.025 eV to approximately 5 GeV). The neutrons are not directly detected, but through nuclear reactions, which result in energetically charged particles such as protons and tritons. In many instances, intense fields of gamma rays are also found with neutrons. Therefore, it is important to choose a method of neutron detection with the ability to discriminate against these gamma rays in the detection process.

A common reaction for the conversion of slow neutrons into directly detectable particles is $n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 0.764$ MeV. The Ludlum Model 42-38 utilizes this reaction in the form of helium-3 (${}^{3}He$), which fills the gas proportional tube of the detector.

Note: *Learn more about this instrument in the attached appendix in back of this manual, an abstract submitted to the Health Physics Journal by Los Alamos National Laboratory.*

2. SPECIFICATIONS

DETECTOR: 2 atm ${}^{3}He$ tube LND 252180 or equivalent

MODERATOR: 22.9 x 21.2 cm (9 x 8.36 in.) diameter polyethylene sphere

COMPATIBLE INSTRUMENTS: Typically used with area monitors such as Models 375, 3276, and 177-61

SENSITIVITY: 450 cpm/mrem/hr (^{241}AmBe fast neutrons)

GAMMA REJECTION: 10 cpm or less through 10 R/hr (100mSv/hr) (^{137}Cs)

DETECTION RANGE: Thermal to approximately 5 GeV

ENERGY RESPONSE: 0.1 MeV to 5 GeV, closely follows the radiation protection guide curve for neutron dose. *For more information, see Los Alamos report in Appendix A in the back of this manual.*

INPUT SENSITIVITY: –2 mV

OPERATING VOLTAGE: 1000-1200 Vdc

CONNECTOR: Series "C" (others available)

SIZE: 22.9 diameter x 33 cm (9 diameter x 13 in.), including handle

TEMPERATURE RANGE: -20 to 50 °C (-4 to 122 °F)

WEIGHT: 13.6 kg (30 lb)

3. CALIBRATION

The following calibration procedures assume the following:

- Counting instrument: Ludlum Model 2200 Scaler/Ratemeter
- ^{241}AmBe neutron source
- ^{137}Cs gamma source for gamma rejection check

3.1 Determining Operating Voltage

☐ Connect the Model 42-38 to a Model 2200.

☐ Set the Model 2200 input sensitivity to –2 mV.

☐ Expose the detector to a 20 mrem/hr ^{241}AmBe neutron source.

☐ Adjust HV until approximately 9000 cpm is obtained.

☐ Calculate the sensitivity (cpm/mrem/hr) for the assumed operating voltage as follows:

$$Sensitivity = \frac{CountRate}{Dose - EquivalentRate}$$

For example, an assumed operating voltage is 1100 volts, based upon the previous step. The count rate at that voltage is 9000 counts per minute (cpm), and the neutron field dose-equivalent rate is 20 mrem/hr. The sensitivity is calculated as:

$$Sensitivity = \frac{9000\,cpm}{20\,mrem/hr}$$

$$= 450\,cpm/mrem/hr$$

This value should be approximately 450 cpm/mrem/hr.

3.2 Gamma Rejection Check

☐ With the Model 42-38 connected to the Model 2200, adjust the Model 2200 HV to the assumed operating voltage determined above.

☐ Place the Model 42-38 in a 10 R/hr ^{137}Cs gamma radiation field.

☐ Take a one-minute count. If more than 10 counts are observed for the one-minute period, decrease the operating voltage until the count rate drops below 10 cpm; however, ensure that the HV remains in a region that yields 450 cpm/mrem/hr ±10%.

3.3 Conversion Chart

☐ Expose the detector to ^{241}AmBe neutron source at dose-equivalent rate of 400 mrem/hr. Take a one-minute count and record the value, including the range/scale setting of the counting instrument.

☐ Repeat for the dose-equivalent rates shown in Table 1.

The values in Table 1 and their corresponding measured values represent a conversion chart for use in relating other measured values to actual dose-equivalent rates.

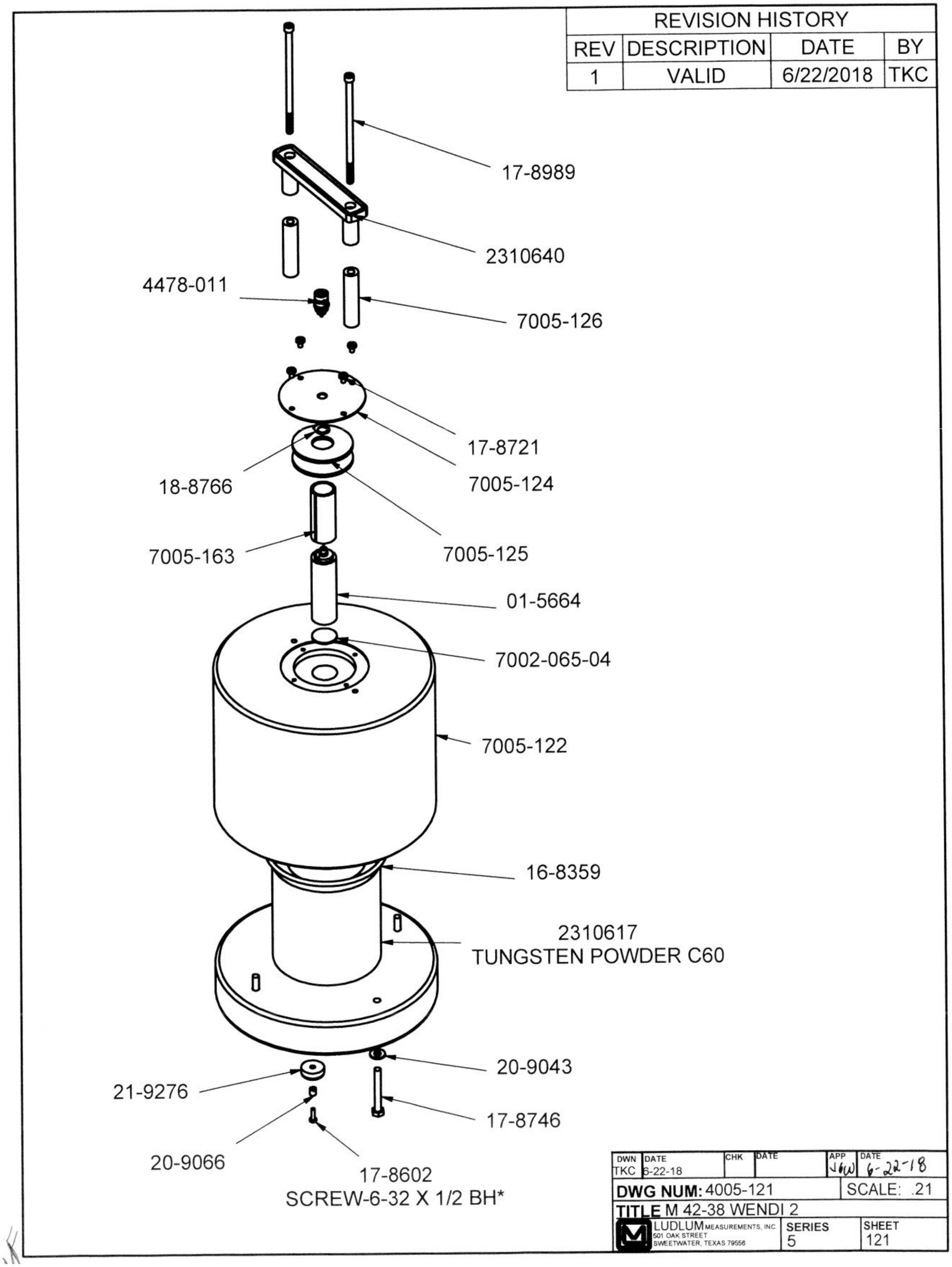
Ref. Point (mrem/hr)	Reading (cpm)	Range/Scale
400		
200		
80		
20		
8		
2		

Table 1

4. PARTS LIST

Reference	**Description**	**Part Number**
Model 42-38 Neutron Detector		
UNIT	Completely Assembled Model 42-38 Neutron Detector	47-3127
*	^{3}He Tube 252180 2 ATM	01-5664
*	RECPT-UG706/U “C” LMI	4478-011
*	Handle	2310640
*	Rubber bumper	21-9276
*	Handle spacer	7005-126
*	Tube spacer	7005-163
*	O-ring	16-8259
*	Tungsten powder	2310617
*	Model 43-38 detector cap	9005-127
*	Model 42-38 boron shield	7005-125

5. DRAWINGS



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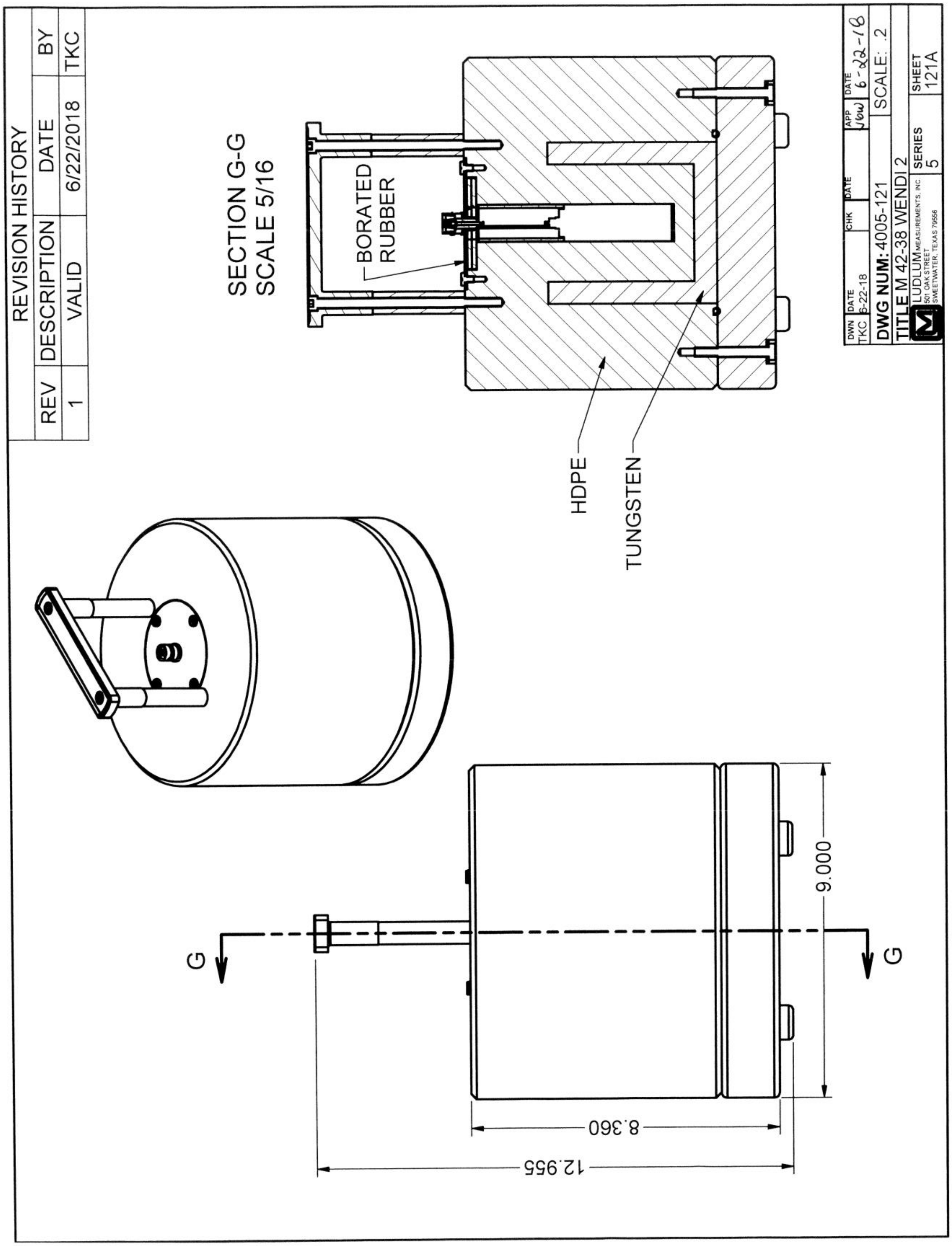
LUDLUM MEASUREMENTS, INC. 501 OAK STREET SWEETWATER, TEXAS 79556	SERIES 5
	SHEET 121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6. APPENDIX A

The following attachment, LA-UR-99-6551, titled WENDI: An Improved Neutron Meter, is an abstract written by the Health Physics Measurements Group of the Los Alamos National Laboratory and submitted to the Health Physics Journal. This is to provide additional detailed information to our customers.

LA-UR- 99-6551

Title: WENDI: AN IMPROVED NEUTRON REM METER

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Submitted to: Health Physics Journal

WENDI: AN IMPROVED NEUTRON REM METER

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ABSTRACT-Neutron rem meters are routinely used for real-time field measurements of neutron dose equivalent where neutron spectra are unknown or poorly characterized. These meters are designed so that their response per unit fluence approximates an appropriate fluence-to-dose conversion function. Typically, a polyethylene moderator assembly surrounds a thermal neutron detector, such as a BF_3 counter tube. Internal absorbers may also be used to further fine-tune the detector response to the shape of the desired fluence conversion function. Historical designs suffer from a number of limitations. Accuracy for some designs is poor at intermediate energies (50 keV – 250 keV) critical for nuclear power plant dosimetry. The well-known Andersson-Braun design suffers from angular dependence, because of its lack of spherical symmetry. Furthermore, all models using a pure polyethylene moderator have no useful high-energy response, which makes them inaccurate around high-energy accelerator facilities. This paper describes two new neutron rem meter designs with improved accuracy over the energy range from thermal to 5 GeV. The Wide Energy Neutron Detection Instrument (WENDI) makes use of both neutron generation and absorption to contour the detector response function. Tungsten or Tungsten Carbide (WC) powder is added to a polyethylene moderator with the expressed purpose of generating spallation neutrons in tungsten nuclei and thus enhance the high-energy response of the meter beyond 8 MeV. Tungsten's absorption resonance structure below several keV was also found to be useful in contouring the meter's response function. The WENDI rem meters were designed and optimized using the Los Alamos Monte Carlo codes MCNP, MCNPX, and LAHET. A first generation prototype (WENDI-I) was built in 1995 and its testing was completed in 1996. This design placed a BF_3 counter in the center of a spherical moderator assembly, whose outer shell consisted of 30% by weight WC in a matrix of polyethylene. A borated silicone rubber (5% Boron by weight) absorber covered an inner polyethylene sphere to control the meter's response at intermediate energies. A second generation design (WENDI-II) was finalized and tested in 1999. It further extended the high-energy response beyond 20 MeV, increased sensitivity, and greatly facilitated the manufacturing process. A ^{3}He counter tube is located in the center of a cylindrical polyethylene moderator assembly. Tungsten powder surrounds the counter tube at an inner radius of 4 cm and performs the double duty of neutron generation above 8 MeV and absorption below several keV. WENDI-II is suitable for field use as a portable rem meter in a variety of work place environments, and has been recently commercialized under license by Eberline Instruments, Inc. and Ludlum Measurements, Inc. Sensitivity is about a factor of 12 higher than that of the Hankins Modified Sphere (Eberline NRD meter) in a bare ^{252}Cf field. Additionally, the energy response for WENDI-II closely follows the contour of the Ambient Dose Equivalent per unit fluence function [$H^*(10)/\Phi$] above 0.1 MeV. Its energy response at 500 MeV is approximately 15 times higher than that of the Hankins and Andersson-Braun meters. Measurements of the energy and directional response of the improved meter are presented and the measured response function is shown to agree closely with the predictions of the Monte Carlo simulations in the range from 0.144 MeV to 19 MeV.

INTRODUCTION

Historical Perspective

Neutron rem meters are used universally by health physicists for real-time measurement of neutron dose equivalent. It is the instrument of choice in radiation fields where the neutron spectrum is unknown or poorly characterized. Although rem meters may take different forms, the underlying design principle is similar. The rem meter's response function is made is to match, at least reasonably well over a particular energy range, an appropriate fluence-to-dose conversion function. To comply with ICRP effective dose recommendations, the operational quantity appropriate for rem meter calibration is Ambient Dose Equivalent [H*(10)]. Equation (1) defines H*(10) for a known neutron spectrum:

$$H^*(10) = \int h_\Phi(E)\, \Phi(E)\, dE\,, \qquad (1)$$

where $h_\Phi(E)$ is the fluence to ambient dose equivalent conversion function, and $\Phi(E)$ is the neutron fluence as a function of energy for a given neutron field. The rem meter response, R, in that field is given by Equation (2):

$$R = \int C\, d_\Phi(E)\, \Phi(E)\, dE, \qquad (2)$$

where $d_\Phi(E)$ is the rem meter's response function in units of counts per unit fluence, and C is the calibration constant in units of Sievert per count. As long as $d_\Phi(E)$ has a similar energy response to that of $h_\Phi(E)$, the rem meter measurement can be said to be accurate. The ratio $d_\Phi(E)/\, h_\Phi(E)$ defines the traditional energy response of the rem meter in terms of counts per unit dose equivalent.

The essential elements of most commercial rem meters are a neutron moderator assembly (e.g., polyethylene) surrounding a thermal neutron detector (e.g., a ^{10}B enriched BF_3 detector or ^{3}He counter tube). Bramblett et al. (1960) were probably the first to point out that the response of a 12-inch diameter polyethylene sphere and a small Li^{6}I(Eu) scintillator approximate the fluence-to-dose conversion function, and that such an instrument could be used for monitoring without regard to the actual neutron spectrum. When expressed on a unit dose basis, the energy response of this instrument was shown to be fairly uniform (+/- 46%) from thermal to 15 MeV. Hankins (1962) advocated the use of a 10-inch spherical polyethylene moderator as part of a portable rem meter for measurements over the energy range from thermal to 7 MeV. He reported a large dose overestimate for intermediate energy neutrons (eV range to 0.2 MeV) and an increasing underestimate for energies above 7 MeV.

Andersson and Braun (1962) designed and refined a rem meter (AB meter) based on a cylindrical polyethylene moderator and a BF_3 counter tube with the goal of achieving a dose equivalent like response from thermal to 10 MeV. A novel feature of the design was the use of a neutron absorber in the form of a borated plastic sleeve around the counter tube to more accurately match the meter response per unit fluence to the shape of the fluence-to-dose conversion function at intermediate energies. Holes were drilled in the sleeve to increase the response at thermal energies. The position of the sleeve and the total area of the holes were experimentally adjusted to give a more satisfactory overall response. However, the cylindrical moderator geometry of the AB meter adversely impacts the directional response. Both Hankins and Cortez (1974) and Cosack and Lesiecki (1981) measured the change in response for fast neutrons. The latter reported a change in response with instrument orientation as much as 35% for a neutron energy of 1 MeV. Also, with its side oriented to a source of thermal neutrons, there was about a 65%

underestimate in the true dose equivalent (Hankins and Cortez, 1974). Leake (1966) introduced a spherical version of the AB meter which was commercialized as the Harwell type 95/0072. This design uses a 20.8-cm diameter polyethylene moderator surrounding a ^{6}LiI(Eu) scintillator, and an internal absorber of 1-mm thick perforated cadmium foil. A later version of the Leake rem meter (Leake 1968) incorporated a spherical ^{3}He counter tube.

Motivated primarily by the need for a lighter weight survey instrument (relative to a 10-inch sphere), and using the idea of an internal absorber introduced by the AB meter, Hankins (1967) designed a "modified sphere" rem meter with an energy response similar to that of a 10-inch spherical moderator. This design consists of a 22-cm diameter polyethylene external spherical shell and a 0.0028-cm thick cadmium layer positioned at a 3-cm radius over an internal polyethylene sphere. The spherical symmetry of the design ensured more optimal directional response than the AB meter, but as with other pure polyethylene moderator based designs, the high-energy response decreases steadily above 7 MeV. The cadmium-layered Hankins design was commercialized by Eberline Instruments as the model NRD and it is still in production today.

Recent Design Efforts

An updated version of the Leake detector was designed by the Nuclear Research Center Karlsrhue, Germany, using Monte Carlo techniques to match the $h_{\Phi}(E)$ function (Burgkhardt et al. 1997). This meter was commercialized by EG&G Berthold as the model LB 6411. It consists of a spherical polyethylene moderator with a diameter of 25 cm, a cylindrical ^{3}He detector, and internal cadmium absorbers and perforations. Response accuracy is excellent (+10% to –30%) over the energy range important for nuclear power plant applications, from 50 keV to 10 MeV. Its nominal sensitivity is 44 counts per minute per μSvh^{-1} ($cpm/\mu Svh^{-1}$).

The proliferation of high-energy accelerators for medical and industrial applications has intensified the need to monitor neutron fields whose spectra extend to several hundred MeV (Klein 1997). Unfortunately, traditional rem meters in use today do not possess an accurate energy response above 10 MeV. The dose equivalent response of these meters drops monotonically above 7 MeV, resulting in an under response of about a factor of 6 at 100 MeV, and a factor of 12 at 500 MeV. Over the past decade, considerable effort has been directed at enhancing and extending the high-energy response of conventional rem meters. Birattari et al. (1990) were the first to investigate the use of a "heavy metal" insert such as lead as a means of enhancing response above the (n,2n) reaction threshold at about 8 MeV. Their work involved extensive Monte Carlo calculations to evaluate the possibility of enhancing the high-energy response of a commercial AB meter by the addition of a lead insert. Birattari et al. (1993) went on to test and qualify the response of LINUS, a modified AB meter with a 1-cm thick cylindrical lead insert, over the range from thermal to 19 MeV. The response of LINUS relative to a standard AB meter was shown to be about 40% higher at 14 MeV and 55% higher at 19 MeV. An improved version of LINUS was subsequently developed (Birattari et al. 1998), which uses a spherical ^{3}He proportional detector inside of a spherical polyethylene moderator in order to improve the directional response of the instrument.

Following the work of Birattari et al., a version of LINUS (using a cylindrical moderator assembly with a hemispherical bullet-nosed end) was investigated at the Lawrence Berkeley Laboratory (LBL) and the Institute of High Energy Physics, Academia Sinica, China. Monte Carlo simulations of the response function were performed over the range from thermal to 2 GeV (Sun et al. 1992; Hsu and Sun 1995). Experiments to verify the instrument's response function were carried out in the high-energy range from 20 MeV to 1 GeV (Li Jianping et al. 1996). This work led to a commercial model (Health Physics, Inc. Model 6060).

A novel spherical high-energy rem meter was simulated by Hsu et al. (1995) using some of the WENDI technology elements. In the Monte Carlo simulations, several doping materials were added as spherical layers around a ^{3}He detector. This 3-layer design consists of an inner polyethylene sphere (3.81 cm radius) loaded with ^{9}Be (30% by weight), a 0.4-cm thick middle layer of Reactor Experiments, Inc.'s Flex Boron^{tm} (25% B by weight), and a 4.3-cm thick outer polyethylene layer loaded with W-powder (30% by weight). The low threshold (1.868 MeV) (n,2n) reaction in ^{9}Be enhances neutron production for the several MeV spallation neutrons produced in the tungsten loaded layer. This design closely follows the Stevenson (1986) H*(10) fluence-to-dose conversion function between 14 MeV and 1 GeV. However, since the design was optimized for high-energy performance, there is much room for improvement at intermediate neutron energies.

The WENDI Research Program

Research on the Wide Energy Neutron Detection Instrument (WENDI) began in 1992 with the goal of designing a universal rem meter, with good high-energy response, isotropic directional response, reasonable weight, excellent sensitivity, and improved accuracy at intermediate energies. Accuracy in the energy range from 50 keV to 250 keV was deemed to be critical because it dominates personnel dose at nuclear power plants. In contrast, the Hankins rem meter is known to over respond by up to a factor of two to nuclear power plant spectra (Endres et al., 1981). Rather than modify an existing commercial rem meter, the intent was to develop an entirely new design from basic principles. WENDI is the result of a collaborative effort between the Los Alamos National Laboratory, San Jose State University, and Varian Associates. United States patent number 5,578,830 was granted to the University of California on November 26, 1996 for the WENDI neutron rem meter. In 1999, a second generation WENDI design (WENDI-II) was finalized using the WENDI technology platform. WENDI-II was designed for ease of manufacturing (it does not require a tungsten-loaded plastic), better high-energy response at the cost of some increase in weight, and increased sensitivity. The WENDI-II design has now been commercialized under license by Eberline Instruments, Inc. and Ludlum Measurements, Inc. This paper outlines the design process and testing of the WENDI-I and WENDI-II final prototypes.

DESIGN METHODOLOGY

Several factors affect a rem meter's response function. These are the size, shape, and type of the moderator, the amount and location of neutron absorbers relative to the detector, and the addition of neutron generating materials. A spherical moderator was chosen for WENDI-I to take advantage of the uniform directional response afforded by a spherical geometry. This requirement was relaxed during the WENDI-II design phase by selecting a cylindrical geometry to simplify the manufacturing process. However, through an extensive series of Monte Carlo simulations it was possible to design the assembly so that the side and end response functions agreed closely above a neutron energy of 1 MeV. Borated silicone rubber was chosen as the absorber element for WENDI-I because it is non-toxic and is easier to fabricate and work with than the cadmium foil used by Leake and Hankins. WENDI-II dispenses entirely with separate internal absorbers, as it was discovered that the tungsten powder additive could perform double duty as both a neutron generator material above 8 MeV and as an absorber below several keV.

Two mechanisms were considered in selecting neutron generator materials: fast fission and spallation neutrons at energies exceeding the average nucleon binding energy. The (n,2n) reaction becomes feasible above a threshold of 8 MeV in heavy nuclei such as uranium, lead, and tungsten. Similarly, above 14 MeV, the (n,3n) reaction becomes energetically feasible. At higher energies yet, the spallation process becomes more complex as the intranuclear cascade generates a spectrum of additional particles, including high energy protons and pions which are capable of producing new neutrons via an internuclear cascade. On this basis, depleted uranium loading seemed attractive because of its 1 MeV threshold for fast fission and satisfactory (n,2n) and (n,3n) cross sections. However, its intrinsic radioactivity and attendant control issues led us to reject ^{238}U as an additive. The (n,xn) reaction in lead was initially considered promising in view of previous experience with lead. However, since lead, gold, tantalum, and tungsten all have similar (n,xn) cross sections (about 2 barns) - all of these materials received attention. From this list, tungsten in the form of tungsten powder or Tungsten Carbide stood out for a number of reasons. These materials are neither toxic nor exotic, and are cost effective. Tungsten also has a high absorption resonance structure in the energy region of 0.1 keV to 1.5 keV, which facilitates contouring the detector response function at intermediate neutron energies. Reactor Experiments, Inc., fabricated a plug of Tungsten Carbide loaded polyethylene (30% tungsten by weight) for the WENDI-I rem meter. The plug was machined at Varian Associates into the required configuration for the outer layer of the moderator assembly. Tungsten powder at a nominal tap density of 9.5 g/cm^3 was obtained from Buffalo Tungsten, Inc. for the WENDI-II prototype.

The Los Alamos Monte Carlo transport code MCNP4B (Briesmeister 1997) was used to perform all neutron transport simulations below 20 MeV. The $S(\alpha,\beta)$ thermal treatment for hydrogen in polyethylene was used to increase the accuracy of the simulation below 4 eV. This treatment explicitly takes into account the effects of chemical binding and crystal lattice. All of the Monte calculations performed were of the forward type so as to allow use of the most recent continuous energy cross section tables. A simple neutron importance function was found to be adequate to obtain statistically valid results. A sufficient number of histories were calculated to always keep statistical uncertainties below 3% (1 sigma), and below 1% (1 sigma) in many cases.

The LAHET code system, Version 2.7, (Prael and Lichtenstein 1989) was used to characterize the WENDI-I response over the energy range from 20 MeV to 1 GeV. The MCNPX code, Version 2.1.5, (Waters 1999), which merges the functionality of MCNP4B and the LAHET (Version 3.0) code systems, was used to perform all of the high-energy simulations for the WENDI-II and LINUS rem meters, from 20 MeV to 5 GeV, and the Hankins-NRD and AB rem meters over the range from 20 MeV to 500 MeV. MCNPX incorporates all of the LAHET physics modules, and includes new evaluated nuclear data (Chadwick et al. 1999) to permit neutron transport via cross section tables up to an energy of 150 MeV. All of the LAHET calculations, were performed with the default settings of the Bertini intranuclear cascade and standard evaporation models. All of the MCNPX simulations above 150 MeV, however, used the new Cascade Exciton Model (CEM) which allows neutrons and protons up to 5 GeV, and pions up to 2.5 GeV, to initiate nuclear reactions. CEM consists of the improved Dubna intranuclear cascade model, followed by a pre-equilibrium model, and an evaporation model. It has been found to be superior to the Bertini model for production cross sections of activation products and angular spectra of emitted particles (Mashnik et al. 1998), partly because it uses the latest available experimental data. However, even the best nuclear models at present (Blann et al. 1994, Michel and Nagel 1997)) can only give results for some reaction rates within a factor of two. For calculations such as the rem meter response functions, which involve integral neutron fluence quantities, the uncertainties are much lower. The estimated 2-sigma variance for the calculations in various neutron energy ranges are 5% below 20 MeV, 15% in the range covered by the LA-150 tables (20 MeV to 150 MeV), 25% from 150 MeV to 500 MeV, and 40% from 500 MeV to 5 GeV.

A BF_3 detector (N. Wood model G-10-2A), similar to that used in many commercial AB rem meters was used in the original WENDI-I design. However, for increased sensitivity, WENDI-II incorporates a ^{3}He counter tube (Gamma Labs GL-2500802-NS or LND 252139) pressurized at 2 atmospheres. It is typically operated at a high voltage of 1200 V and a discriminator setting of 1 mV.

The rem meter simulation model takes into account the main count rate production mechanism; namely, the capture reaction of a thermalized neutron in the counter's active gas volume. However, at neutron energies well above 20 MeV, there are two additional but minor contributions to the count rate. The first of these is via the production of photoneutrons in tungsten nuclei. During the internuclear cascade, neutral pions decay into highly energetic photons which are capable of inducing photonuclear reactions. The resultant photon fluence is, however, quite low relative to the neutron fluence, so that this mechanism is estimated to contribute less than 1% of the count rate at any incident neutron energy up to 5 GeV. The second contribution is due to charged particle tracks through the counter tube's active volume. The most prevalent and important species of charged particle is the proton, while pion, deuteron, and triton interactions are much less significant. A series of MCNPX calculations were performed for the WENDI-II rem meter to determine the relative contribution of charged particles to the count rate. The charged particle current through the active detector volume was calculated in several energy bins based on particle stopping power. The criterion was that the stopping power be sufficiently high to ensure that a particle deposits a minimum of 50 keV along an average track length in the counter gas, where the 50 keV cutoff corresponds to the counter's lower discriminator setting of 1 mV. At an incident neutron energy of 500 MeV, the charged particle contribution was determined to be about 2.5% of the neutron-induced count rate, while at 2 GeV, the percentage increased slightly to 3%. Most of these counts are due to proton tracks, with only minor contributions from deuterons, tritons, ^{3}He ions, pions, and muons. In light of the large uncertainly of the nuclear model calculations in the energy range from 500 to 5 GeV (25% to 40%), it was considered safe to ignore these minor contributions to the total count rate.

To determine the expected count rate for a particular rem meter design, at a given neutron energy or spectrum, the average fluence was first calculated in the active volume of the counter tube. In all of the calculations a point isotropic source was positioned at 50 cm from the center of the assembly. For WENDI-I and all other BF_3 based meters, the (n,α) reaction rate for ^{10}B was then folded in to give the alpha particle production rate, or the total alpha production when normalized to the total number of boron atoms in the active volume. It was assumed that the detection efficiency is 100%; that is, every alpha particle generated gives rise to a count in the external counting circuitry. This is a reasonable assumption for a BF_3 detector in the count rate regime where pulse pile up and dead time issues are insignificant. This basic BF_3 detector model was originally used at Los Alamos by Olsher (1991) to calculate the Hankins-NRD response function, and was found to benchmark very well with experimental data. For WENDI-II, the ^{3}He(n,p)t reaction rate was folded in with the average fluence to give the proton-triton ion pair production rate, or the total number of ion pairs produced when normalized to the total number of ^{3}He atoms at a fill pressure of 2 atm. For incident neutron energies above 20 MeV, the ^{3}He(n,d)p reaction was included as well, though its contribution is very small. It was necessary to multiply the calculated count per unit fluence by a factor of 0.743 in order to account for wall effects in the counter tube and for the action of the lower discriminator in the external counting circuitry. This factor was determined experimentally by comparing WENDI-II's calculated response to its measured response in a bare ^{252}Cf neutron field.

This procedure was repeated many times, with different input energies or spectra, to obtain the rem meter response function over the desired energy grid. It was considered important to independently calculate the response functions of competing rem meters, so as to be able to judge the energy response and sensitivity differences on the basis of identical radiation transport codes and cross section tables. Otherwise, the dispersion due to the physics models and cross section evaluations can easily mask intrinsic performance differences. For example, the CEM and Bertini models give results that differ by 26% at 500 MeV, 32% at 2 GeV, and 11% at 5 GeV. The Bertini model consistently gives a higher count rate because of its larger neutron multiplicity and softer emission spectra.

Similarly, use of the default free-gas thermal treatment in MCNP instead of the explicit S(α,β) thermal treatment for hydrogen in polyethylene can generate significant errors. For WENDI-II, the free-gas model over estimates the response by 22.5% for 0.1 MeV incident neutrons, and by 42% for 0.01 MeV neutrons. Therefore, in order to allow an accurate intercomparison, independent response functions were calculated for the AB meter (side and end irradiations), the Eberline Hankins-NRD, and the cylindrical LINUS design (side and end irradiations). The construction details used in the simulations are based on information obtained directly from the rem meter manufacturers (Eberline Instruments for the model NRD and from Nuclear Research Corporation for the AB meter).

THE WENDI DESIGN AND CALCULATED RESPONSE FUNCTIONS

Two versions of WENDI-I were designed to match the $h_\Phi(E)$ function (ICRP 60 version) as well as the NCRP-38 (1971) fluence-to-dose conversion function (almost identical to the now obsolete ICRP 21 curve), that is mandated in the US by both the Department of Energy and the Nuclear Regulatory Commission. The WENDI-II design was optimized to match $h_\Phi(E)$ as given by ICRP 74 (1996), Table A.42, and supplemented by the calculations of Sannikov and Savitskaya (1997) from 300 MeV to 5 GeV. Figure 1 shows a cut-away schematic view of the NCRP-38 version of WENDI-I (WENDI-38). Total weight of the assembly is about 10.5 kg. The $h_\Phi(E)$ version of WENDI-I (WENDI-60) is identical to that shown in Fig. 1, except that the radius of the outer shell is only 11.6 cm and the weight of the assembly is about 8.5 kg. A three-dimensional cutaway view of WENDI-II is shown in Fig. 2. The weight of the tungsten powder fill is nominally 6 kg, with about a 5% variation due to batch differences in tap density. The total weight of the assembly is 14 kg. Photographs 1 and 2 show two views of a finished WENDI-38 detector - with and without an external commercial counter. Two views of WENDI-II are shown in Photographs 3 and 4.

The absolute response functions [$d_{\Phi}(E)$] in units of counts-cm^2 for the following rem meters are plotted in Fig. 3: WENDI-38, WENDI-II (side and end irradiations), cylindrical LINUS (side irradiation), Eberline Hankins-NRD, and the AB meter (side and end irradiations). The response matrices for all of these functions are available from the lead author (R.H. Olsher) in either tabular form or as a Microsoft Excel spreadsheet. The curves reflect the sensitivity variations of these meters, which are, of course, in large part due to the choice of internal counter tube. For example, the Hankins-NRD meter uses a small BF_3 detector, with only about a quarter of the ^{10}B loading in the active volume of the AB meter's counter tube. Not surprisingly, the corresponding $d_{\Phi}(E)$ curves clearly reflect this difference.

Fig. 4 shows all of the rem meter response functions normalized to both $h_{\Phi}(E)$ and the NCRP-38 conversion functions, at an energy of 2 MeV. The energy range from 1 MeV to 5 GeV is expanded in Fig. 5 to better show the high-energy response variation. The traditional energy response for the WENDI-II (side irradiation) meter versus the two most popular commercial rem meters in use today, the Eberline Hankins-NRD and AB (side irradiation), is shown in Fig. 6 for a bare ^{252}Cf calibration relative to H*(10). The energy range from 0.1 MeV to 5 GeV is expanded in Fig. 7 to better display the high-energy response variation. The ideal rem meter response would be flat at 1.0 at all energies. It is clear that the response of real-world rem meters is far from ideal. The most prominent response feature below 2 MeV is the over response centered at a neutron energy of 5 keV. The Hankins-NRD meter over responds at this energy by a factor of 9.6, while the AB meter over response is a factor of 4.6. The WENDI-II response is seen to be intermediate to these two meters, at a factor of 7.9. Above 7 MeV, the response for both the AB and Hankins NRD meters decreases monotonically, being a factor of two lower than that of WENDI-II at 20 MeV, a factor of six lower at 100 MeV, and a factor of 15 lower at an energy of 500 MeV. Over the energy range from 0.1 MeV to 5 GeV, the WENDI-II energy response minimum is 0.53 at 20 MeV while the maximum is 1.86 at 5 GeV. Relative to the cylindrical LINUS design, the WENDI-II response per unit dose above 20 MeV is greater by 15% at 20 MeV, 40% at 100 MeV, 35% at 1 GeV, and 30% at 5 GeV.

PERFORMANCE TESTING

Sensitivity, energy response, and directional dependence, were investigated for a WENDI-38 prototype built to exact specifications at Varian, and for a WENDI-II prototype built by Eberline Instruments. The sensitivity (cpm/μSvh^{-1}) was measured free-in-air in a ^{252}Cf reference field. The measurements and calculations are summarized in Table 1 together with results for the Hankins-NRD and AB meters. The calculations are based on the bare and moderated ^{252}Cf spectra recommended by International Standard ISO 8529 (1989). The measured sensitivity for WENDI-II is a factor of 12.6 greater than that of the Hankins NRD meter and exceeds the AB meter sensitivity by a factor of 3.3 for a side irradiation. The agreement between the measurements and calculations is within 10%, which is about as good as can be expected considering that differences in response between production samples of commercial rem meters are typically in the range of 10% due to variations in absorber thickness and detector fill pressure.

The energy response of the WENDI-38 and WENDI-II rem meters was verified on the basis of measurements with isotopic neutron sources at the Los Alamos National Laboratory's Health Physics Instrument Evaluation Facility and at the Physikalisch-Technische Bundesanstalt (PTB) in Germany using accelerator-produced reference fields. The PTB Accelerator Facility features a 4 MeV Van de Graaff Accelerator and a variable energy cyclotron (Brede et al. 1980). The PTB irradiations were to well-characterized monoenergetic neutron beams produced via nuclear reactions at the following energies: 0.144 MeV, 0.25 MeV, 0.565 MeV, 1.2 MeV, 2.5 MeV, 5.0 MeV, 8 MeV, 14.8 MeV, and 19 MeV. At each energy, two runs of equal time were performed, one with and one without a shadow cone. The difference between these two runs, establishes a net rem meter reading corrected for background and room return. For the 19 MeV technique, which involves deuteron bombardment of a tritiated solid Ti target [$T(d,n)^4He$], there is considerable contamination (on the order of 27%) of the neutron spectrum due to deuteron reactions in the Ti target material itself. Another possible source of background neutrons at an energy of 5.8 MeV is from the $D(d,n)^3He$ reaction with residual deuterium in the target (Böttger et al. 1989). The targets used at PTB are carefully selected for very low deuterium content, so that this source of contamination is minimal. However, to account for the rem meter response due to reactions in the Ti target, irradiations were also performed with a blank target. The blank target response measurements were subtracted from the tritiated target measurements to obtain the response due to the 19 MeV neutron line. The stated uncertainty for the PTB measurements is in the range of 5.5% to 7.0% at the 95% confidence level. Table 2 summarizes the energy response measurements and

MCNP calculations. For WENDI-II, the MCNP model is able to reproduce the PTB data within 9%. In Fig. 8, the PTB results have been superimposed over the calculated WENDI-II energy response to show the overall agreement.

Directional response measurements were performed for both side view X-Y plane and top view Y-Z plane rotations. The results for WENDI-38 are shown in Figs. 9 and 10 for both bare and moderated ^{252}Cf irradiation. The moderated source consisted of a ^{252}Cf source in the center of a 30-cm diameter D_2O sphere. The normalized response is typically within 3% of the 0-degree response for bare ^{252}Cf. For moderated ^{252}Cf, the maximum deviation of 17% occurs when the source is aligned with the cut out for the detector tube. The results for WENDI-II are shown in Figs. 11 and 12 for bare and moderated ^{252}Cf, and for ^{241}AmBe source spectra. The maximum deviation (44%) occurs in the Y-Z view when the moderated ^{252}Cf source is aligned with the detector tube's cable cutout. This is an issue with all commercial rem meters, and one that becomes progressively worse at lower energies, as neutrons leak directly through the cable opening to the detector.

Gamma Rejection was measured for WENDI-II over the Los Alamos Gamma Range in a ^{137}Cs field. The base line at zero exposure rate is 3 cpm, which is typical background at Los Alamos altitude. Results are shown in Fig. 13 for a side irradiation. The response is within three times background up to a kerma rate of 0.876 $\mathrm{Gyh^{-1}}$ (100 $\mathrm{Rh^{-1}}$) At the maximum kerma rate of 4.38 $\mathrm{Gyh^{-1}}$ (500 $\mathrm{Rh^{-1}}$) the gamma breakthrough is 219 cpm, which is equivalent to 4.8 $\mu\mathrm{Svh^{-1}}$ for a bare ^{252}Cf calibration. These results are considerably better than what might be expected for a ^{3}He detector with a conventional moderator assembly, as the 1.5-cm thick tungsten powder shell provides effective photon shielding for the detector. Irradiation of WEND-II through the top – the only unshielded face – gave a net count rate of 89.9 cpm at 0.876 Gyh^{-1} and 1,429 cpm at 4.38 Gyh^{-1}.

CONCLUSIONS

The WENDI technology platform realizes the performance goals of a universal neutron rem meter with excellent sensitivity and a useful energy response over the range from thermal to 5 GeV. Relative to traditional rem meters such as the Hankins-NRD and AB types, WENDI-II's extended high-energy response gives it a considerably more accurate dose equivalent response in accelerator-produced neutron fields. Its response closely follows $h_\Phi(E)$ (-48%, +82%) over the range from 0.1 MeV to 5 GeV. Accuracy at intermediate energies is comparable to that of traditional rem meters. The directional response for the cylindrical WENDI-II commercial meter is excellent above 1 MeV and slightly better than that of the AB meter at lower energies. With a nominal sensitivity of 45.7 cpm/μSvh^{-1} relative to H*(10), WENDI-II is capable of real-time measurements in environmental-level neutron fields. Real-time field measurements have been performed in the regime of 0.1 to 0.2 μSvh^{-1}. Its weight penalty (a consequence of the tungsten loading) relative to traditional rem meters is about 5 kg, which places it at the limit of comfort for a portable instrument, but does not affect its suitability as a fixed area or environmental monitor. Finally, gamma rejection is excellent up to 1 Gyh^{-1} (100 Rh^{-1}), and adequate to several Gyh^{-1}.

The Monte Carlo codes, MCNP and MCNPX, have proved to be well suited for simulating rem meter response functions. Over the energy range from 0.1 MeV to 19

MeV, the calculations have benchmarked very well with the experimental results (typically within 10%). In the future, the WENDI-II energy response will also be tested in high-energy cyclotron-produced neutron fields (30 MeV to 65 MeV), which will provide additional benchmarking for these codes.

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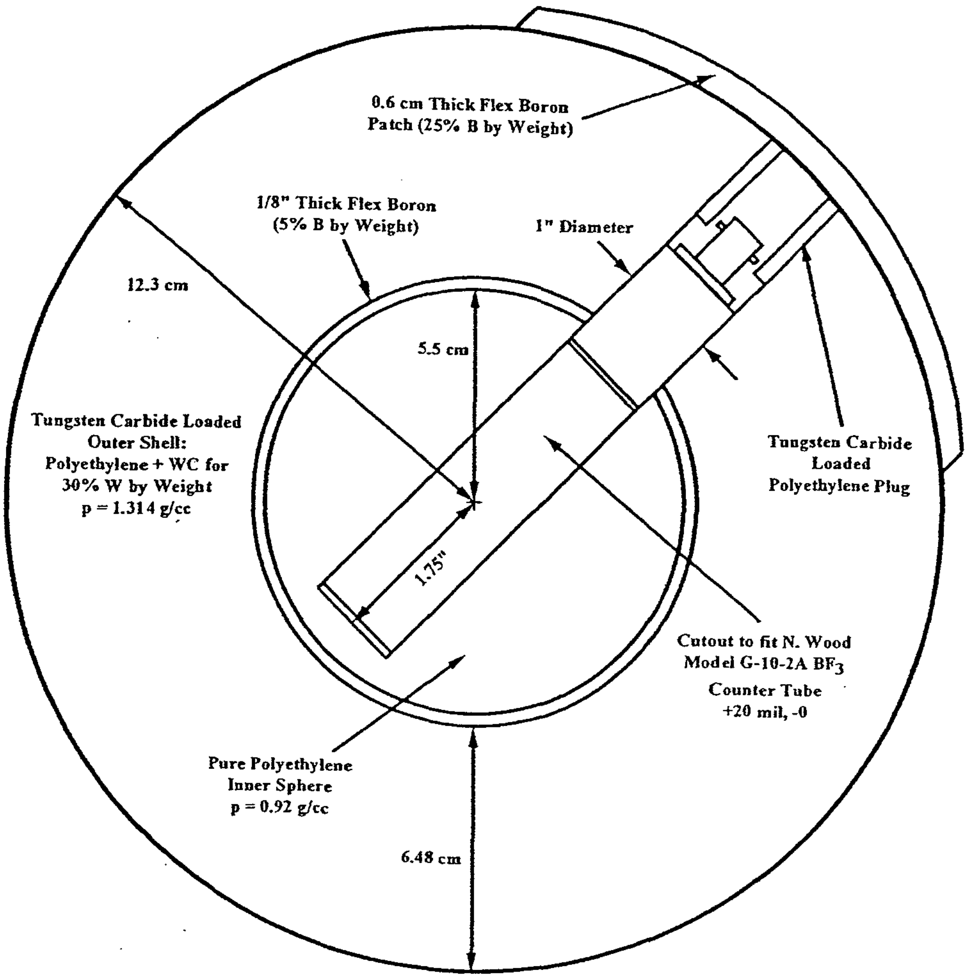
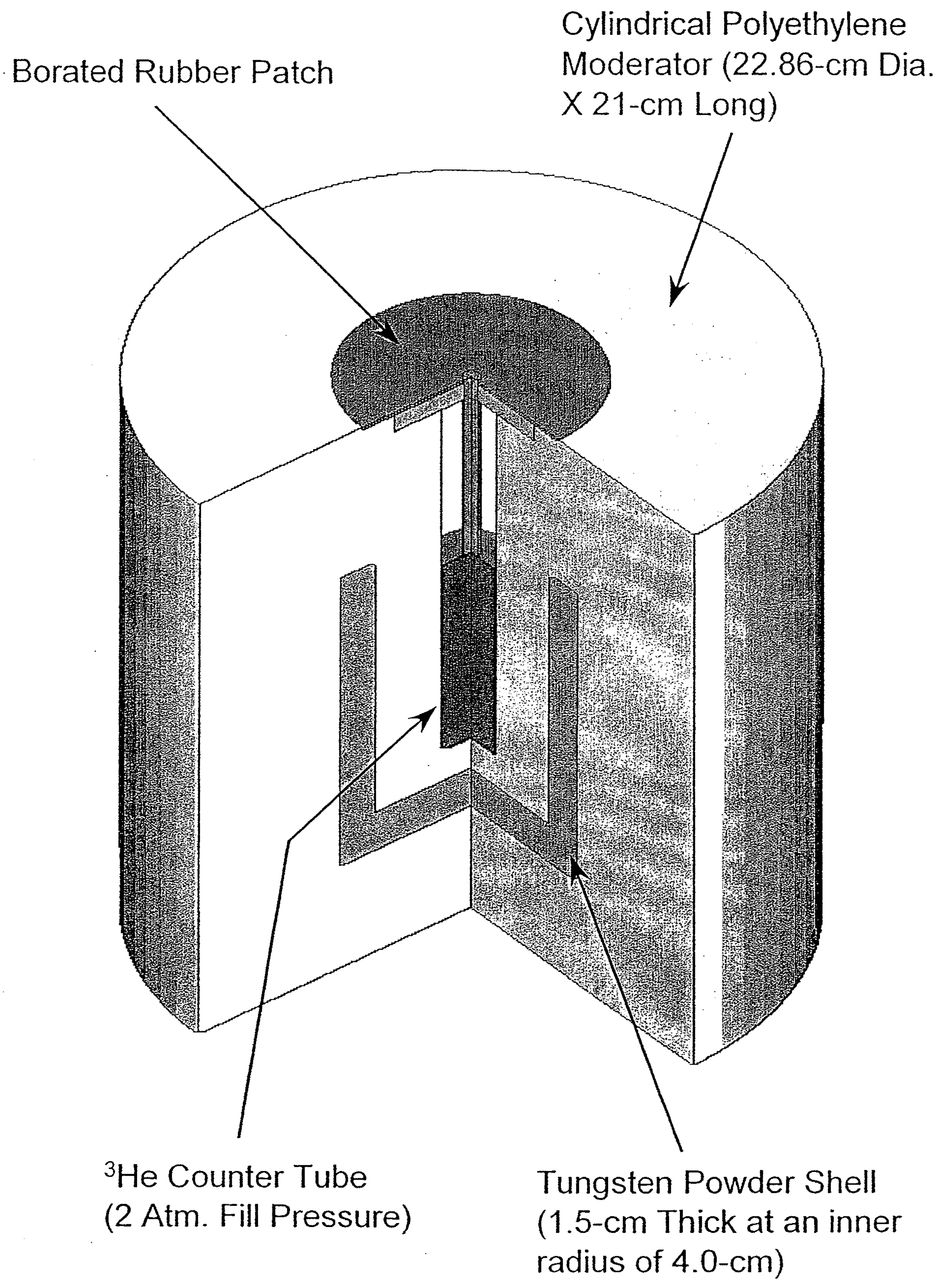


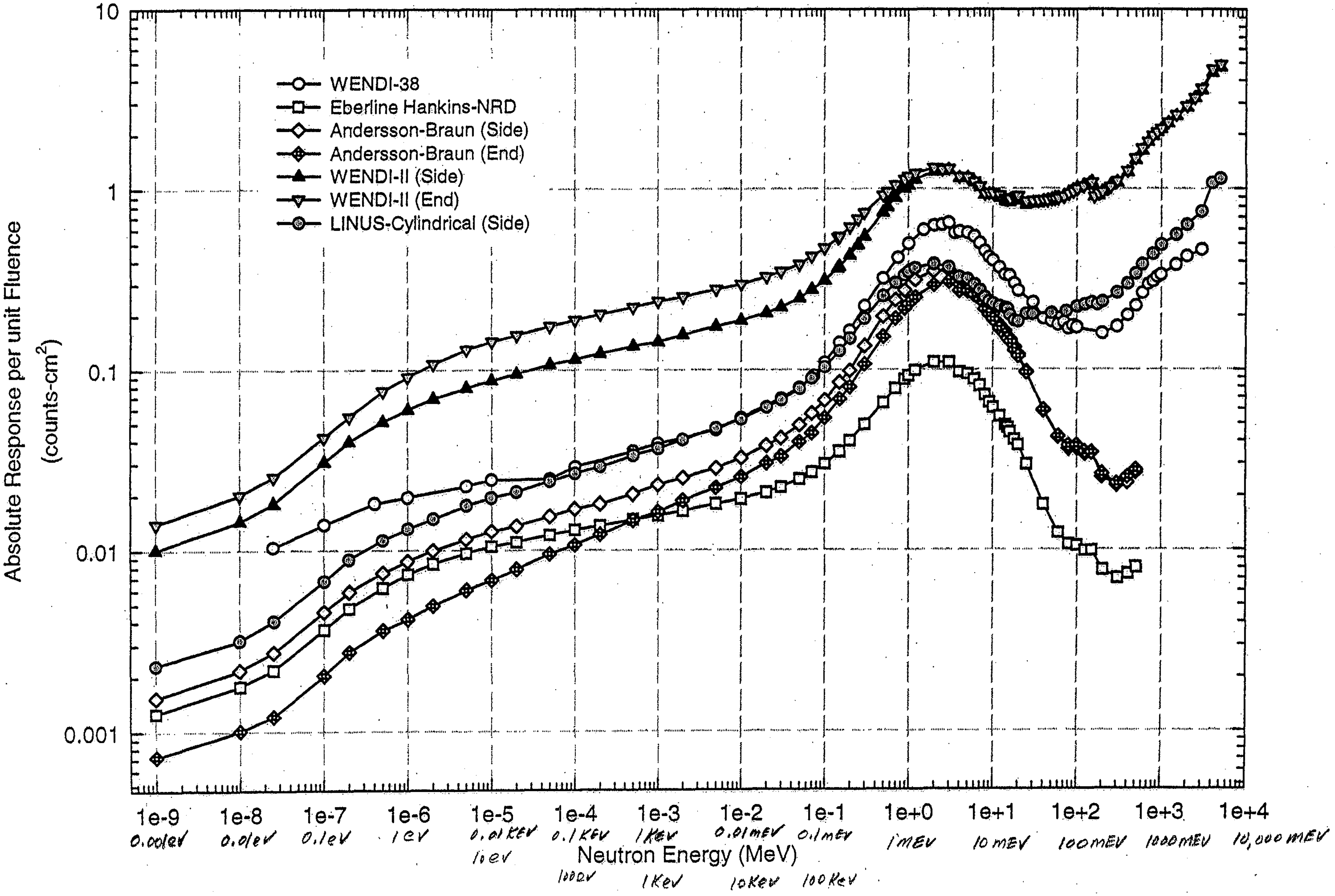
0.6 cm Thick Flex Boron Patch (25% B by Weight)
1/8" Thick Flex Boron (5% B by Weight)
1" Diameter
12.3 cm
5.5 cm
Tungsten Carbide Loaded Outer Shell: Polyethylene + WC for 30% W by Weight p = 1.314 g/cc
Tungsten Carbide Loaded Polyethylene Plug
1.75"
Cutout to fit N. Wood Model G-10-2A BF3 Counter Tube +20 mil, -0
Pure Polyethylene Inner Sphere p = 0.92 g/cc
6.48 cm

Fig. 1



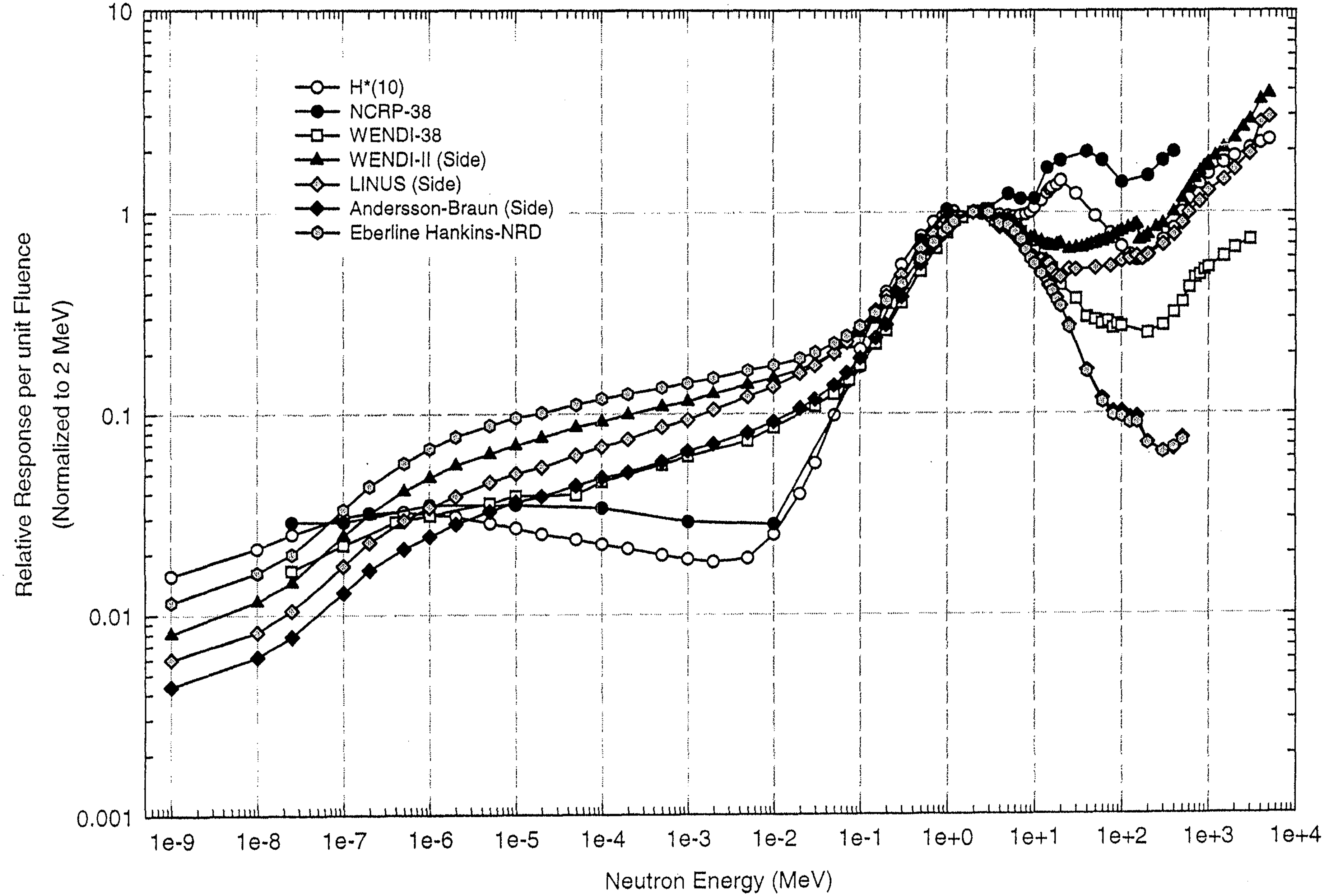
WENDI-II REM Meter: Cutaway View

Fig. [illegible]


-○- WENDI-38
-□- Eberline Hankins-NRD
-◇- Andersson-Braun (Side)
-◈- Andersson-Braun (End)
-▲- WENDI-II (Side)
-▽- WENDI-II (End)
-◎- LINUS-Cylindrical (Side)
Absolute Response per unit Fluence
(counts-cm^2)
10
1
0.1
0.01
0.001
1e-9
1e-8
1e-7
1e-6
1e-5
1e-4
1e-3
1e-2
1e-1
1e+0
1e+1
1e+2
1e+3
1e+4
Neutron Energy (MeV)
0.001eV
0.01eV
0.1eV
1eV
0.01KEV
10eV
0.1KEV
100eV
1KEV
1KeV
0.01MEV
10KeV
0.1MEV
100KeV
1MEV
10MEV
100MEV
1000MEV
10,000MEV

Fig, 3

I



10
1
0.1
0.01
0.001
Relative Response per unit Fluence
(Normalized to 2 MeV)
H*(10)
NCRP-38
WENDI-38
WENDI-II (Side)
LINUS (Side)
Andersson-Braun (Side)
Eberline Hankins-NRD
1e-9
1e-8
1e-7
1e-6
1e-5
1e-4
1e-3
1e-2
1e-1
1e+0
1e+1
1e+2
1e+3
1e+4
Neutron Energy (MeV)

Fig. 4

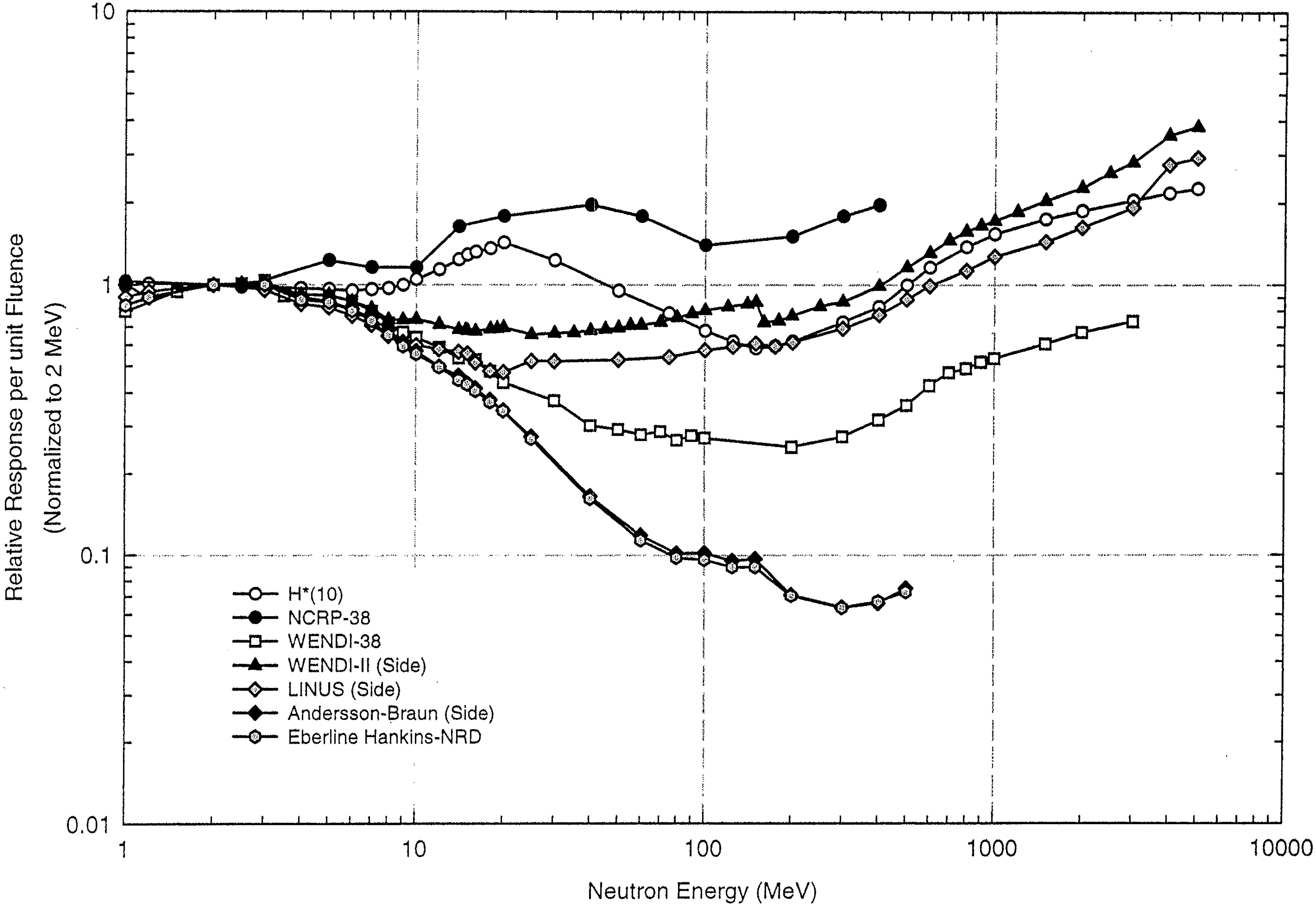

10
1
0.1
0.01
1
10
100
1000
10000
Neutron Energy (MeV)
Relative Response per unit Fluence
(Normalized to 2 MeV)
H*(10)
NCRP-38
WENDI-38
WENDI-II (Side)
LINUS (Side)
Andersson-Braun (Side)
Eberline Hankins-NRD

Fig. 5

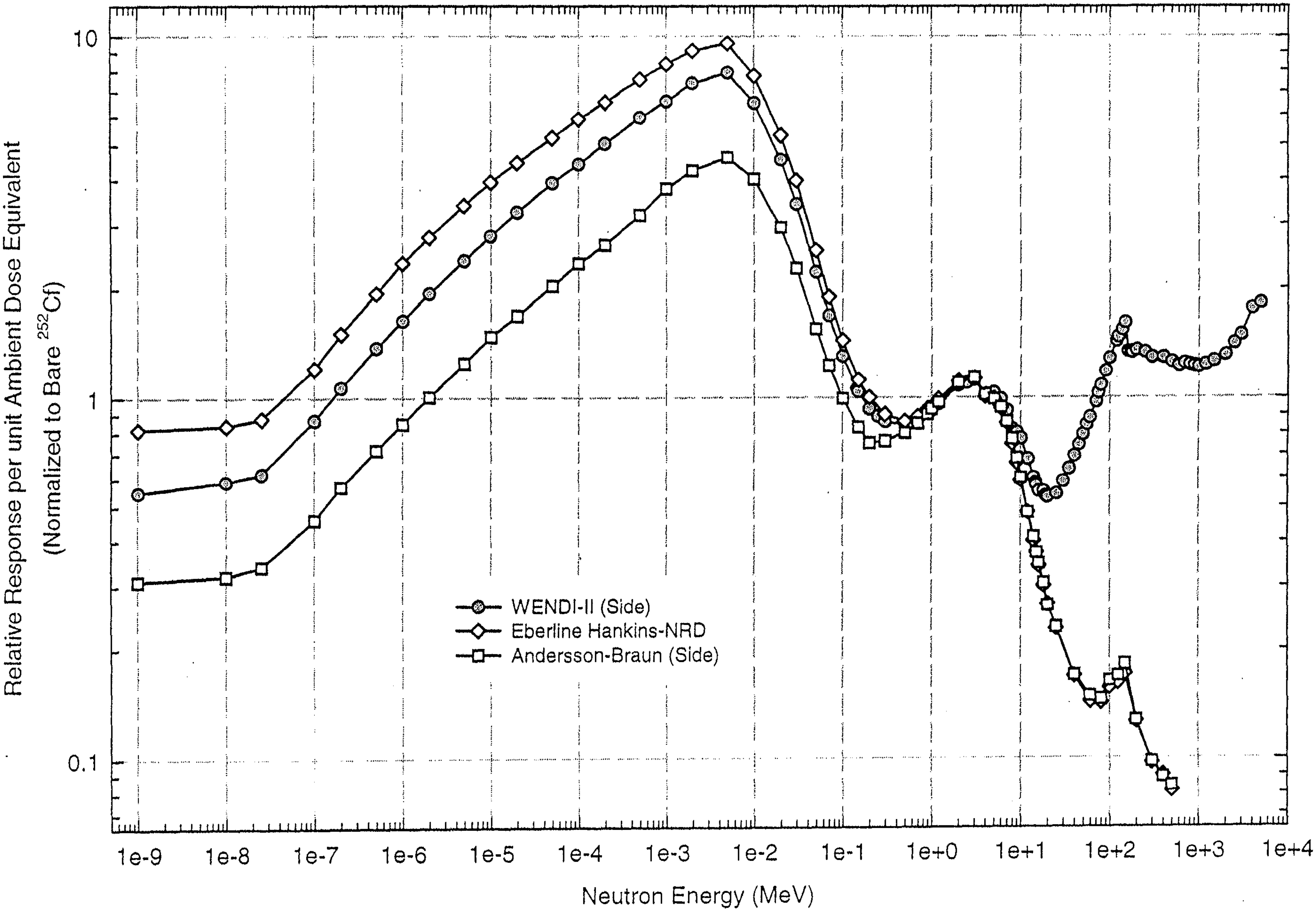
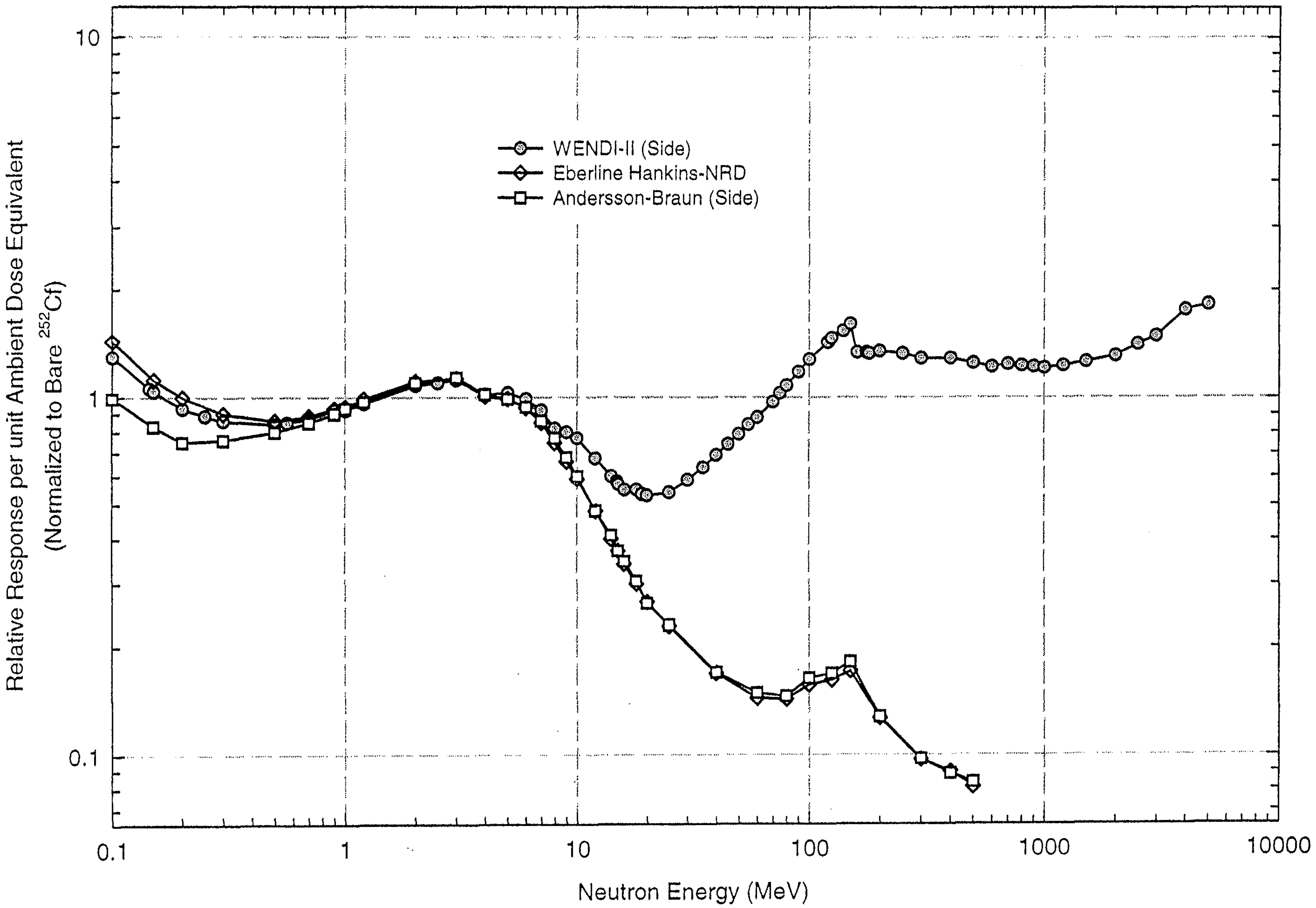
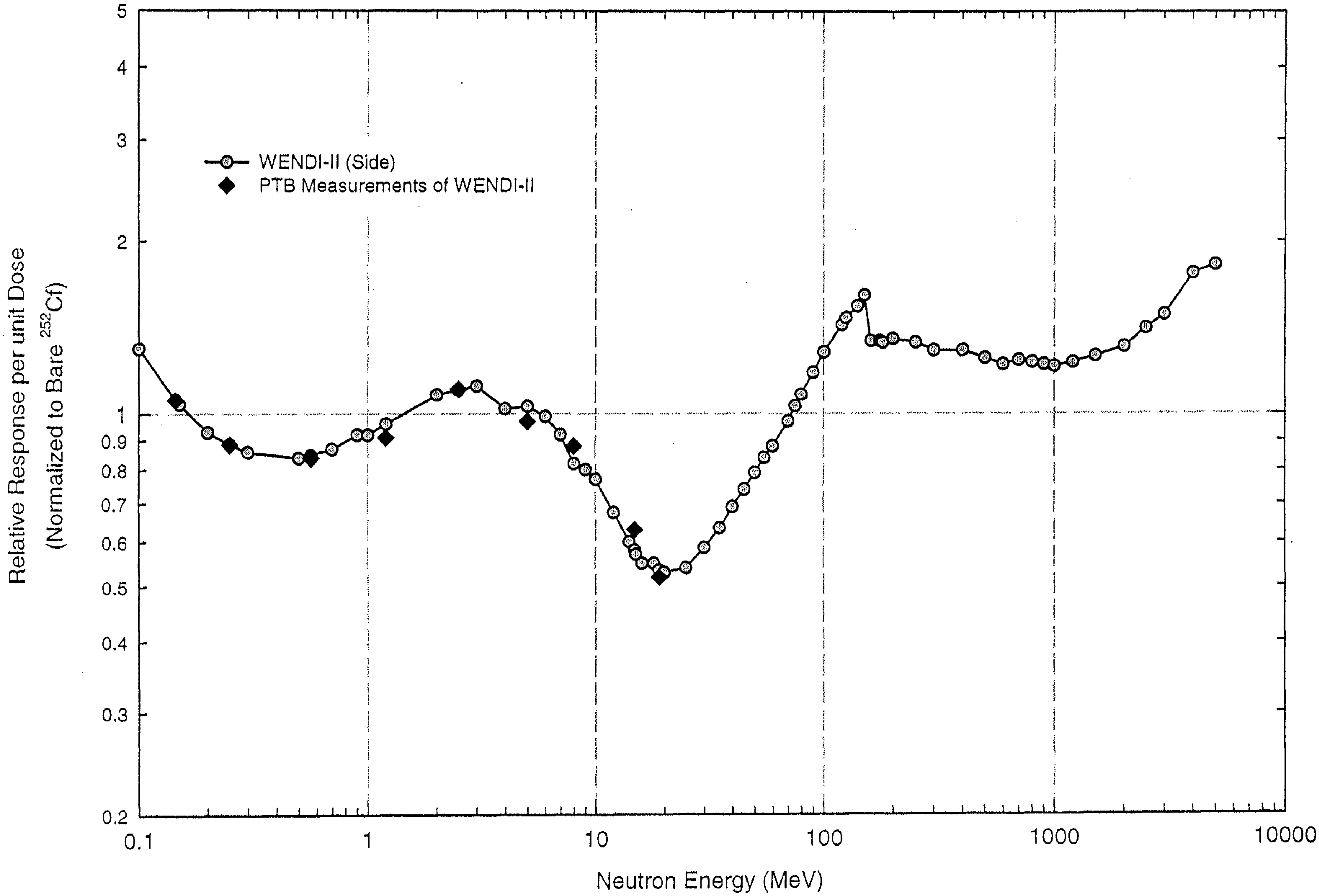

10
1
0.1
Relative Response per unit Ambient Dose Equivalent
(Normalized to Bare ^{252}Cf)
1e-9
1e-8
1e-7
1e-6
1e-5
1e-4
1e-3
1e-2
1e-1
1e+0
1e+1
1e+2
1e+3
1e+4
Neutron Energy (MeV)
WENDI-II (Side)
Eberline Hankins-NRD
Andersson-Braun (Side)

Fig. 6



WENDI-II (Side)
Eberline Hankins-NRD
Andersson-Braun (Side)
Relative Response per unit Ambient Dose Equivalent
(Normalized to Bare ^{252}Cf)
10
1
0.1
0.1
1
10
100
1000
10000
Neutron Energy (MeV)

Fig. 7



WENDI-II (Side)
PTB Measurements of WENDI-II
Relative Response per unit Dose
(Normalized to Bare ^{252}Cf)
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
10
100
1000
10000
Neutron Energy (MeV)

Fig. 8

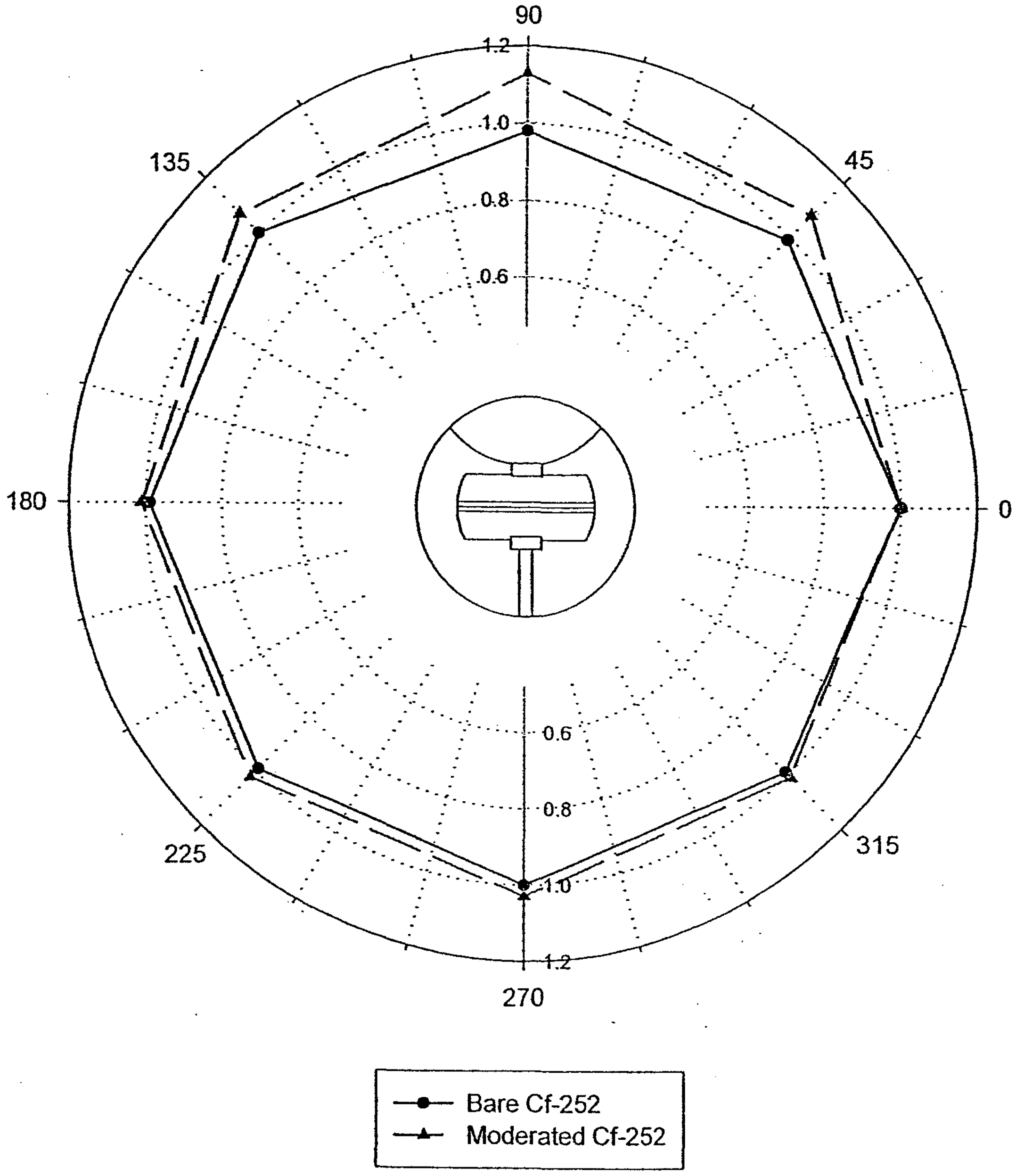

90
1.2
1.0
0.8
0.6
45
135
180
0
225
315
270
Bare Cf-252
Moderated Cf-252

FIG. 9

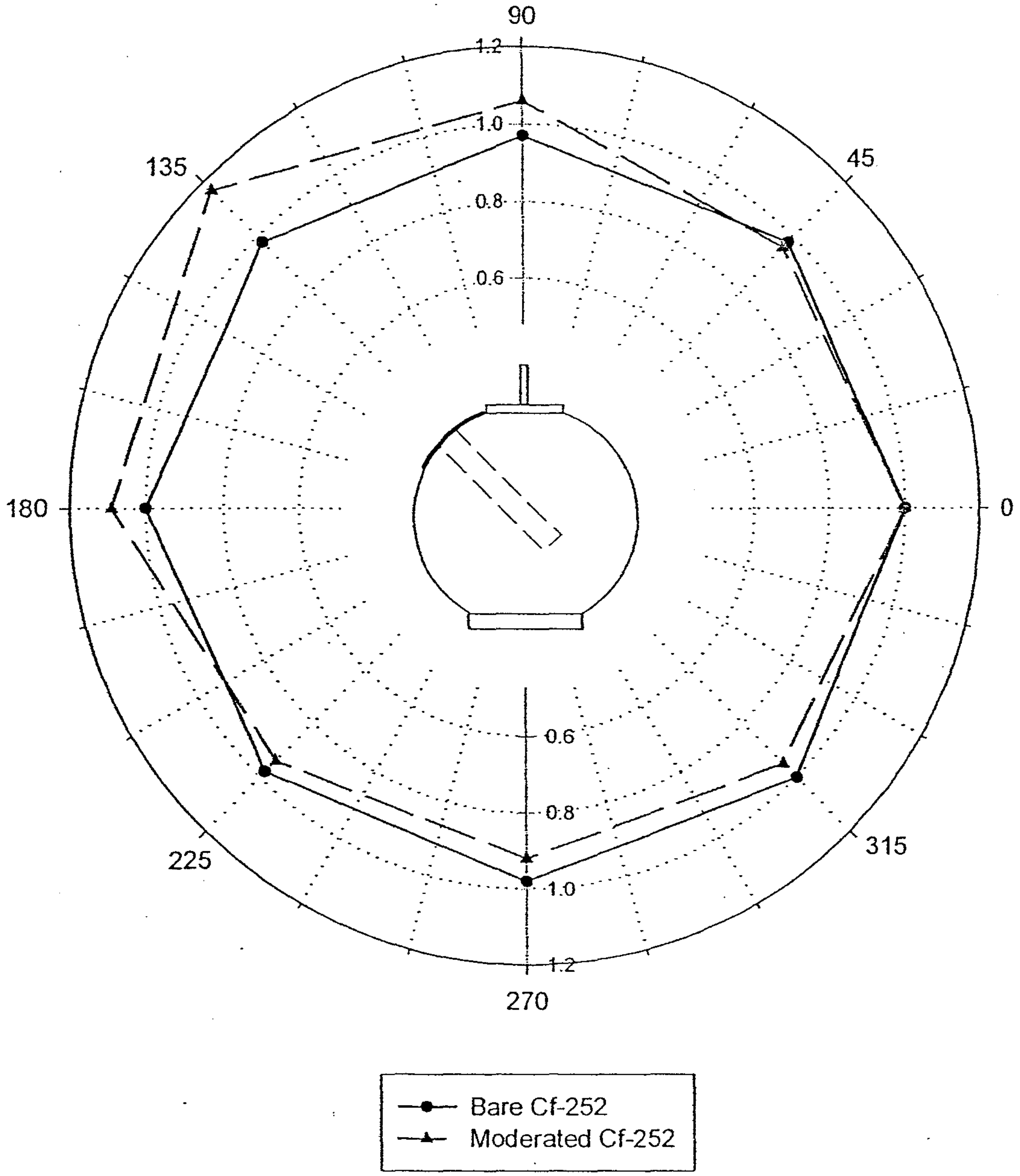
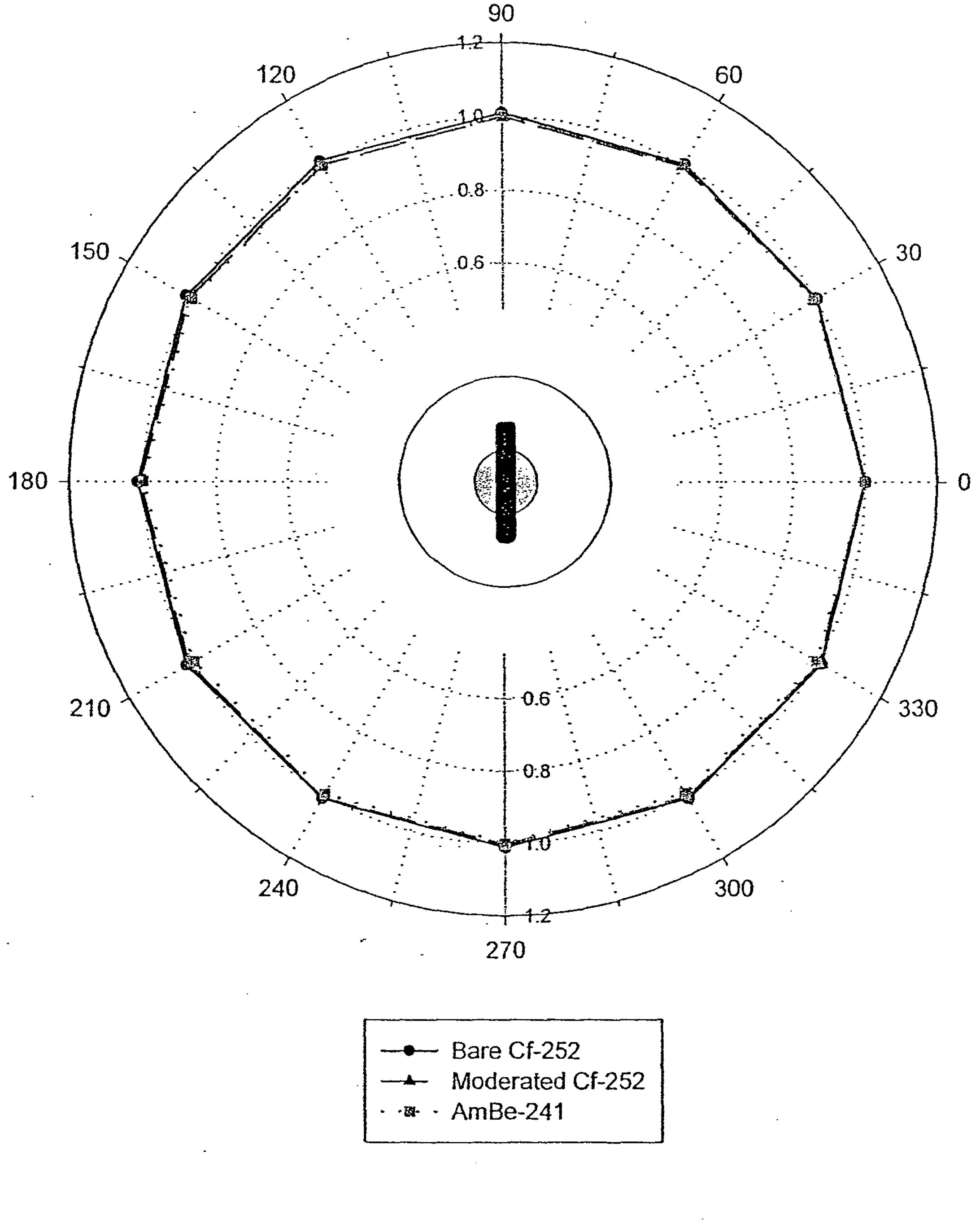

90
1.2
1.0
0.8
0.6
45
135
180
0
0.6
0.8
1.0
1.2
315
225
270
Bare Cf-252
Moderated Cf-252

Fig. 10


90
60
30
0
330
300
270
240
210
180
150
120
1.2
1.0
0.8
0.6
0.6
0.8
1.0
1.2
Bare Cf-252
Moderated Cf-252
AmBe-241

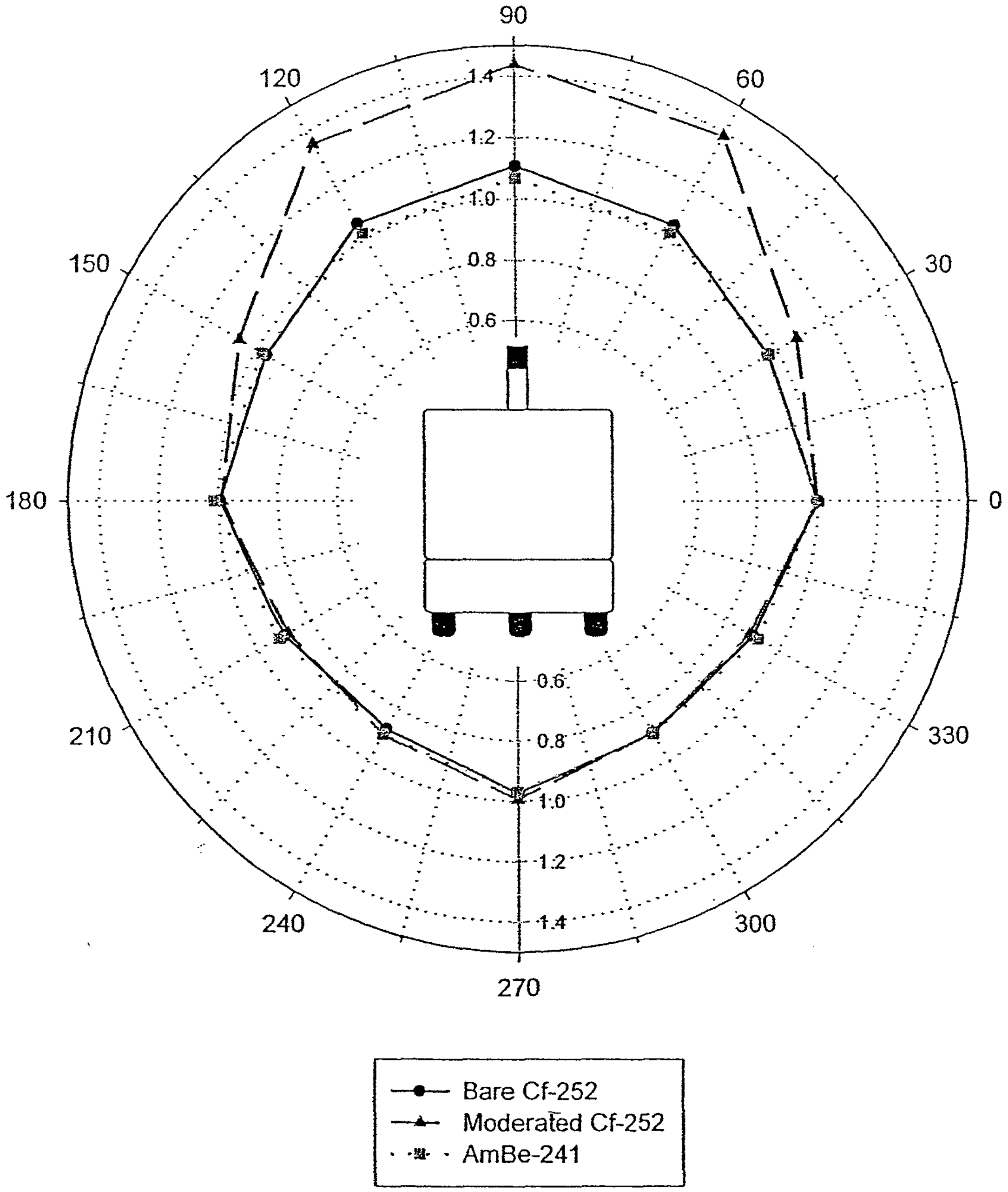

90
60
30
0
330
300
270
240
210
180
150
120
1.4
1.2
1.0
0.8
0.6
0.6
0.8
1.0
1.2
1.4
● Bare Cf-252
▲ Moderated Cf-252
▨ AmBe-241

Fig. [illegible]

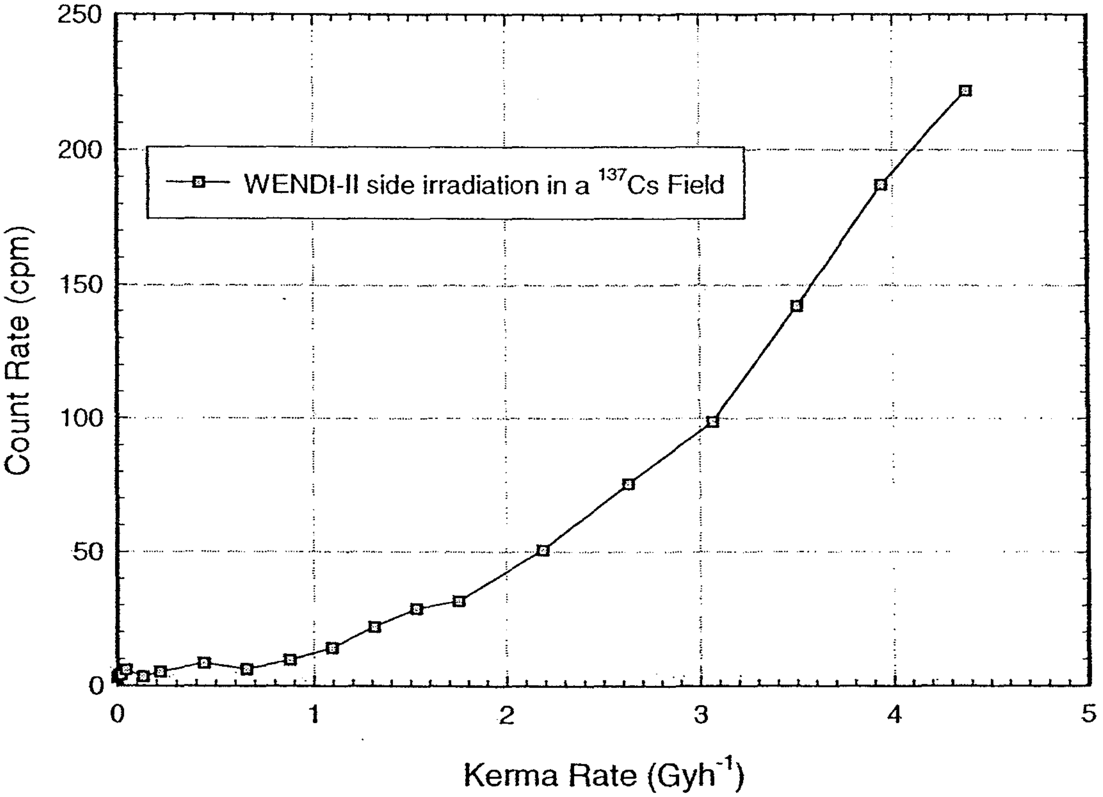

250
200
150
100
50
0
Count Rate (cpm)
0
1
2
3
4
5
Kerma Rate (Gyh^{-1})
WENDI-II side irradiation in a ^{137}Cs Field

Fig. 13