Neutron Detectors

10/13/2010

General

General

Challenges

- Neutron Energy, Quality Factor and Detector Response

  Detector efficiency, as well as the neutron quality factor (radiation weighting factor), vary significantly with neutron energy.

  Neutron fields typically include a wide range of neutron energies.

General

Challenges

- Gamma Rays

  Where there are neutrons, there are always gamma rays.

  Some neutron detectors can respond to gamma rays if they are not set up properly (e.g., use too high an operating voltage).

General

Challenges

- Pulsed Neutron Fields

  Neutron fields around accelerators are usually pulsed.

  Pulsed neutrons can be impossible to measure with some types of active detectors systems.

  Passive monitors (e.g., dosimeters) are commonly used to evaluate pulsed neutron fields.

General

Detector Response and Neutron Energy

- Unmodified neutron detectors (e.g., BF_3 or He-3) usually respond to slow or fast neutrons, but not both.
- Slow neutron detectors are far more common.
- A slow neutron detector can be modified so that it responds to both slow and fast neutrons.
- It can even be modified so that it only responds to fast neutrons!

General

Detector Response and Neutron Energy

- Surrounding a slow neutron detector with an appropriate thickness of a moderator (e.g., polyethylene) will slow some of the fast neutrons down to energies that the detector can respond to.
- The moderator increases the detector response to fast neutrons, but reduces the response to slow neutrons.
- If the moderator is too thick, all of the neutrons will be moderated and absorbed before they can reach the detector.

General

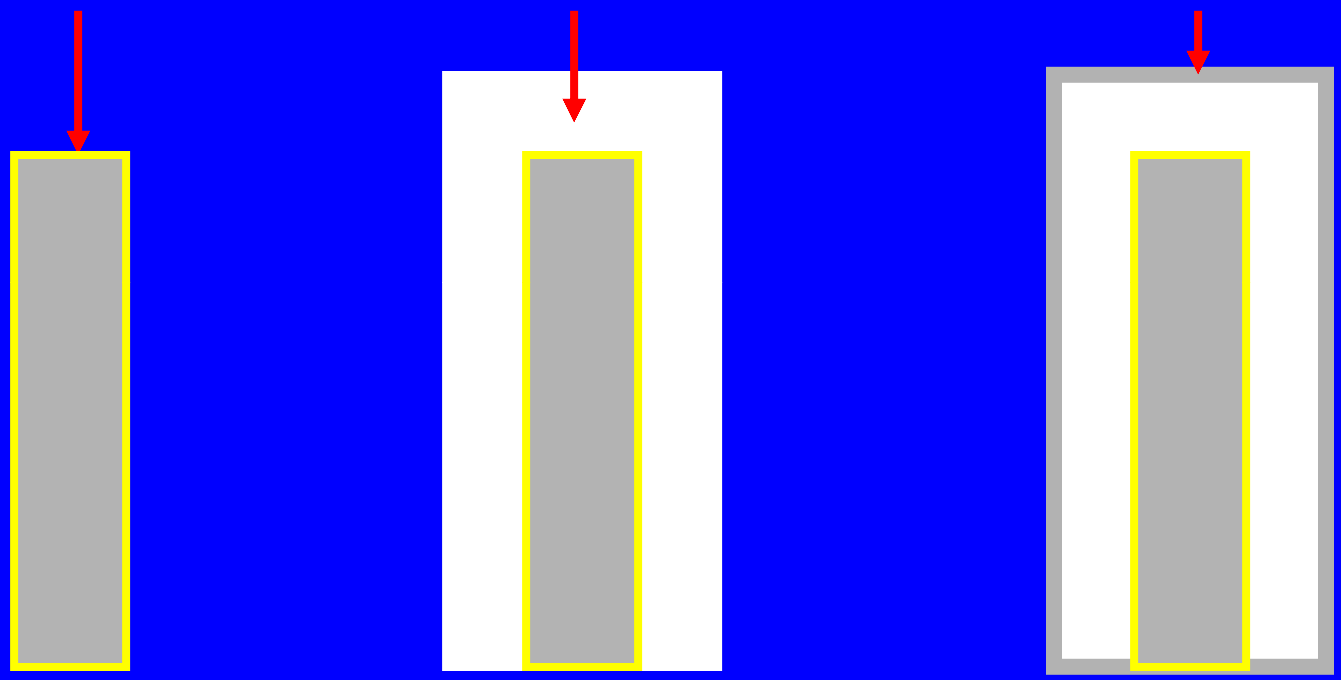
Detector Response and Neutron Energy

- Since slow neutrons (<0.5 eV) cannot penetrate cadmium, surrounding the moderator with cadmium means that the detector will only respond to fast neutrons!

General

Detector Response and Neutron Energy

Bare detector | Moderator | Cadmium



Responds only to slow neutrons | Responds to fast and slow neutrons | Responds only to fast neutrons

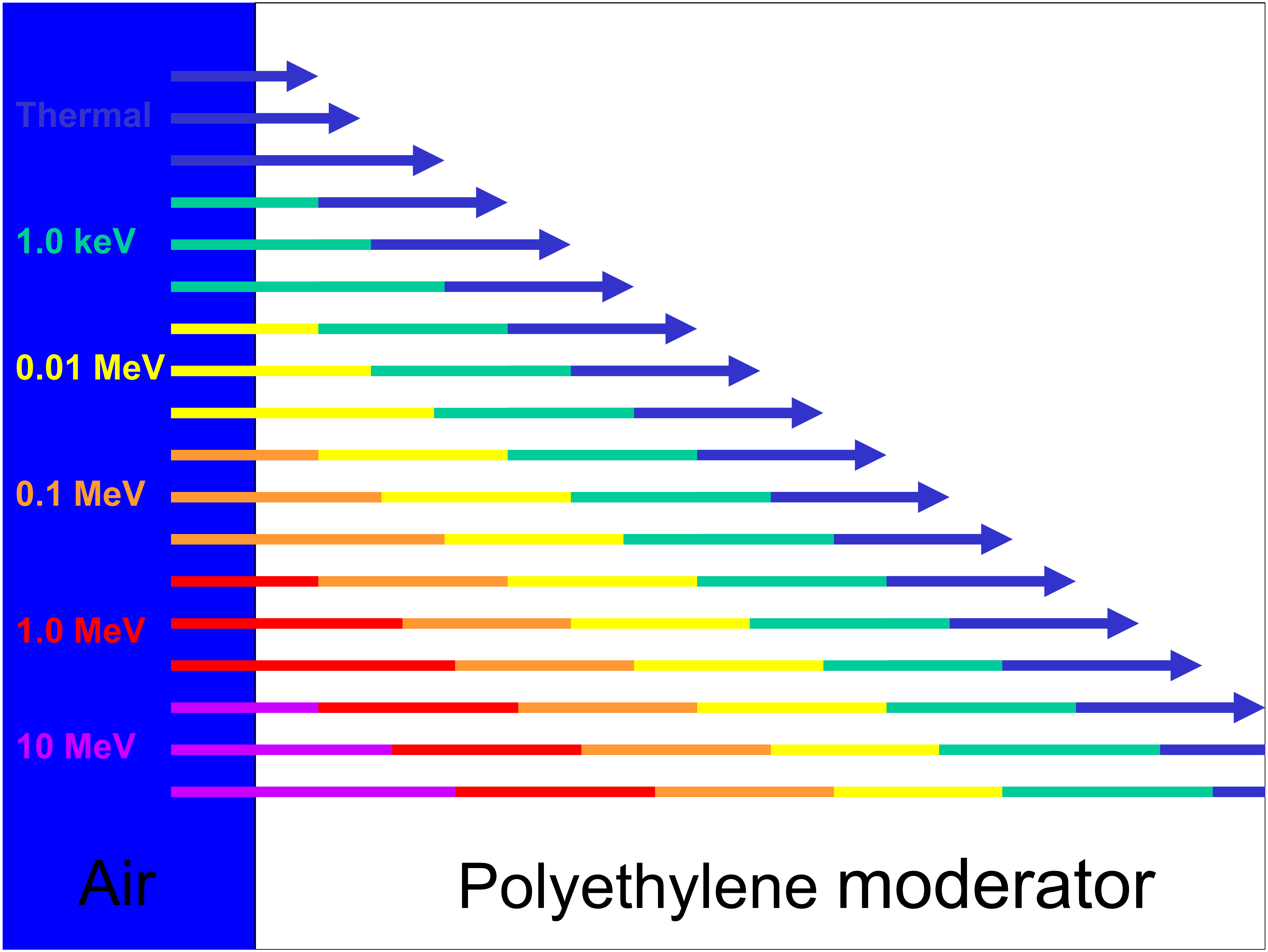
General

Detector Response and Neutron Energy

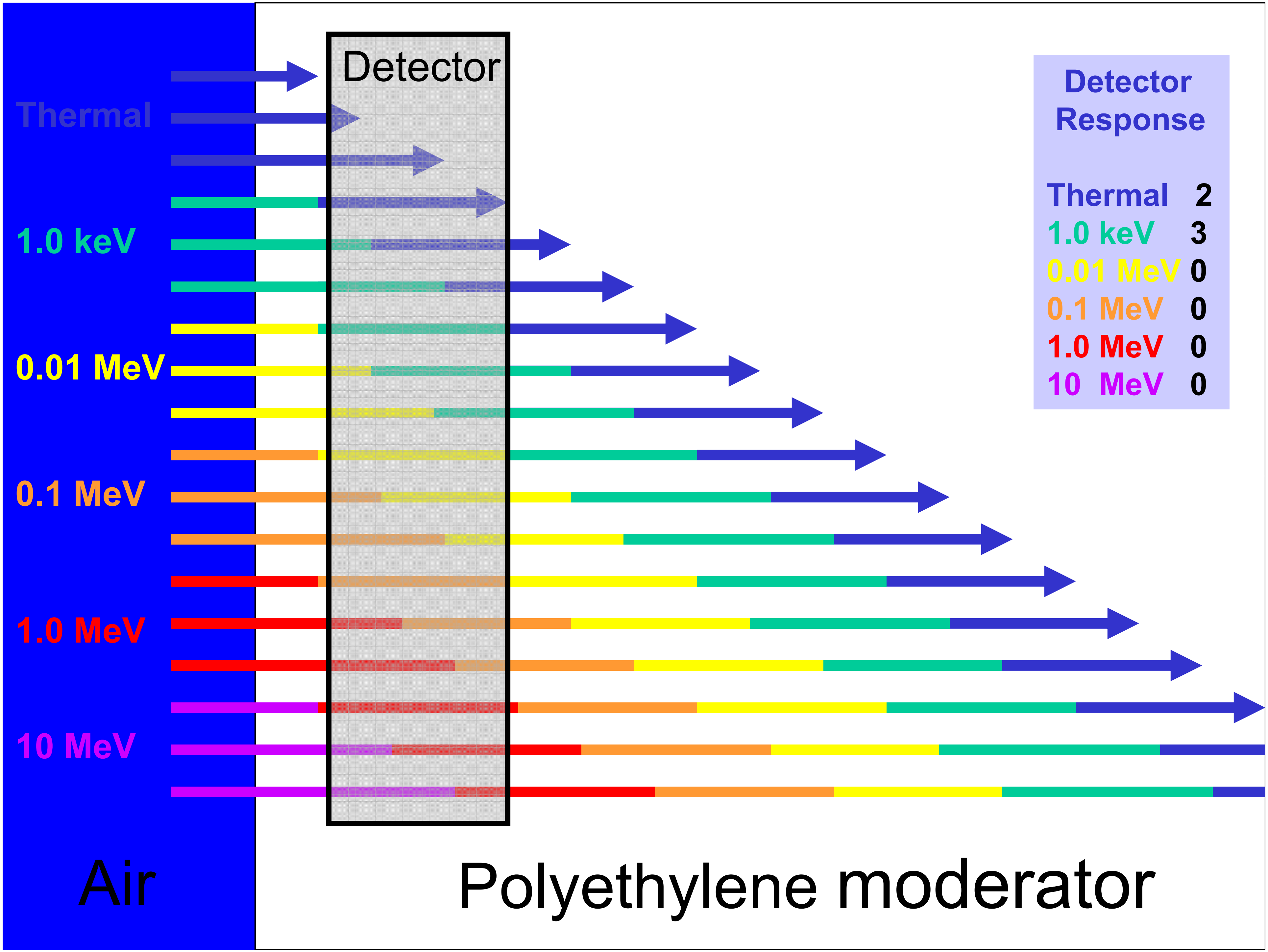
- The thickness of moderator that produces the highest count rate depends on the neutron energy spectrum.

- A detector with a thin moderator has a higher detection efficiency for low energy neutrons.

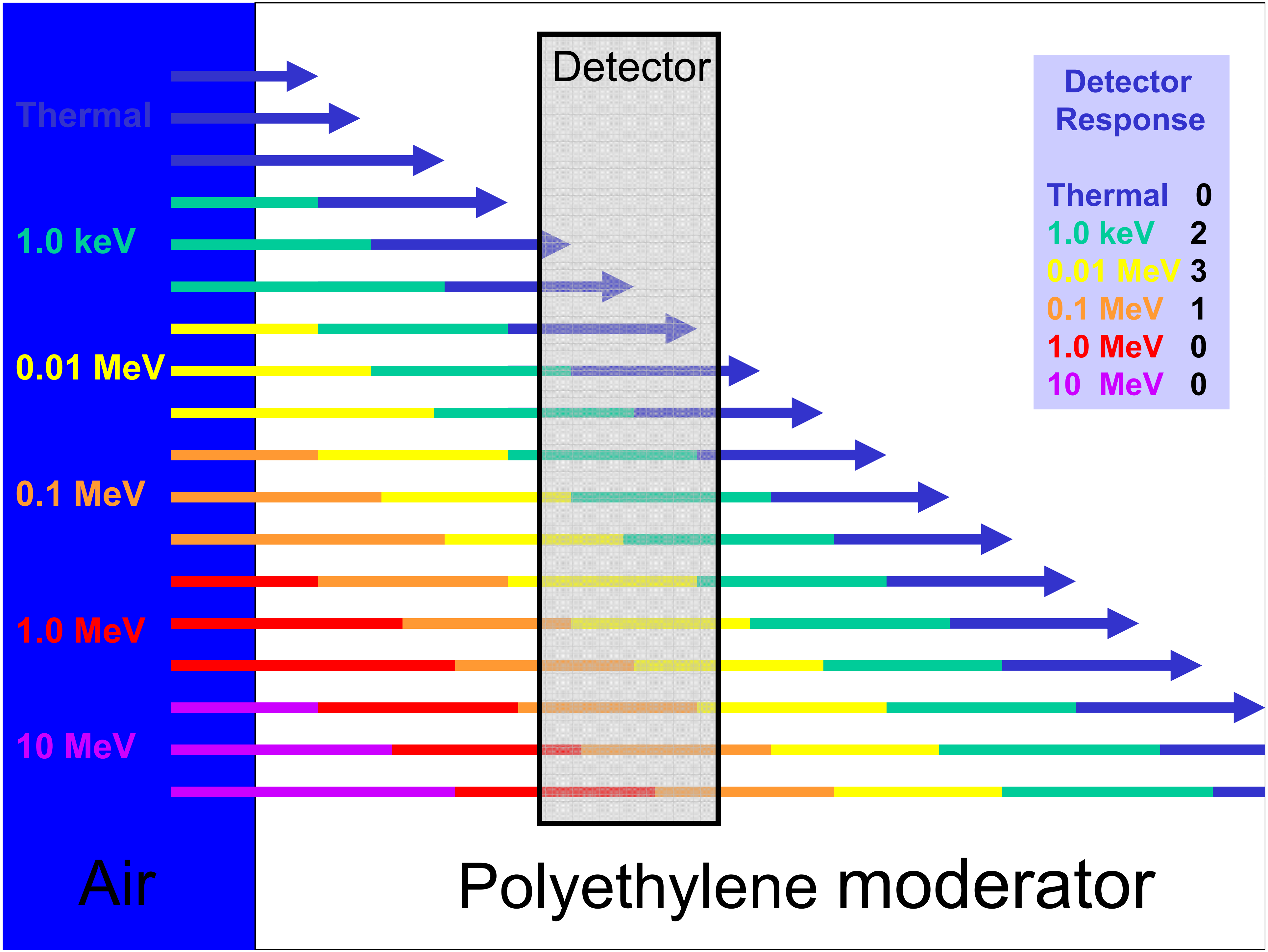
- A detector with a thick moderator has a higher detection efficiency for high energy neutrons.



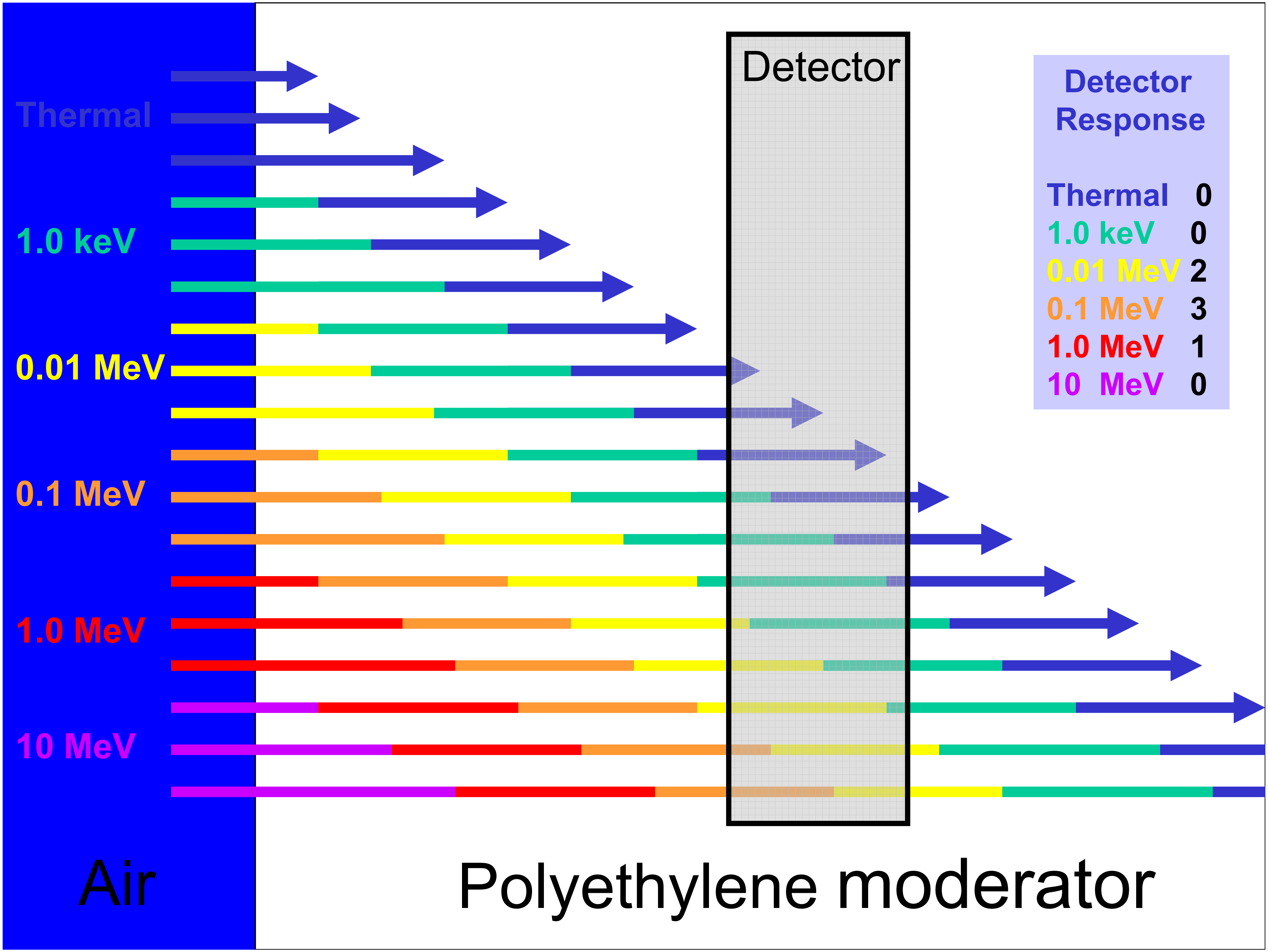
Thermal
1.0 keV
0.01 MeV
0.1 MeV
1.0 MeV
10 MeV
Air
Polyethylene moderator



Detector
Thermal
1.0 keV
0.01 MeV
0.1 MeV
1.0 MeV
10 MeV
Detector Response
Thermal 2
1.0 keV 3
0.01 MeV 0
0.1 MeV 0
1.0 MeV 0
10 MeV 0
Air
Polyethylene moderator



Thermal
1.0 keV
0.01 MeV
0.1 MeV
1.0 MeV
10 MeV
Air
Detector
Polyethylene moderator
Detector Response
Thermal 0
1.0 keV 2
0.01 MeV 3
0.1 MeV 1
1.0 MeV 0
10 MeV 0



Thermal
1.0 keV
0.01 MeV
0.1 MeV
1.0 MeV
10 MeV
Air
Detector
Polyethylene moderator
Detector Response
Thermal 0
1.0 keV 0
0.01 MeV 2
0.1 MeV 3
1.0 MeV 1
10 MeV 0

Detector Types

Detector Types

General

There are many different types of neutron detectors.

In part, this is because many of them have a very specialized (i.e., limited) application.

Detector Types

General

Neutron detectors are designed to measure one of the following:

1. Fluence rate (e.g., n/cm^2 s)
2. Dose equivalent rate (e.g., mrem/hr, mSv/hr)
3. Energy spectrum
4. Dose equivalent (e.g., mrem, mSv)

Detector Types

1. Detectors to Measure Fluence Rate

The following might read out in $n/cm^2/s$

- Boron-lined proportional counters
- Fission counters
- Self-powered detectors
- Compensated ion chambers
- Proton recoil scintillators
- Long counter
- Lithium iodide scintillators
- Lithium glass scintillators

Detector Types

2. Detectors to Measure Dose Equivalent Rate

The following might read out in mrem/hr or mSv/hr:

- Rem ball
- Snoopy
- Leake detector
- Dineutron
- REMbrandt
- Tissue equivalent proportional counters

Detector Types

3. Detectors for Neutron Spectroscopy

These detector systems are used to measure the energy of the neutrons:

- Bonner spheres
- ROSPEC
- Threshold activation foils
- Bubble detector spectrometer

Detector Types

4. Neutron Dosimeters

The following can be used to measure the dose to personnel in mrem or mSv:

- TLDs
- Track Etch
- Neutron track emulsion
- Film
- Bubble/superheated drop dosimeters
- Proton recoil detectors
- Fission track dosimeters
- Electronic (diode) detectors

BF_3 and He-3 Detectors

BF_3 and He-3 Detectors

General

- Many of the detector types listed in the previous section (Detector Types) employ:

  1. BF_3, or
  2. He-3 tubes.

- BF_3 and He-3 tubes operate in the proportional counting mode.

BF_3 and He-3 Detectors

1. Boron Trifluoride (BF_3) Detectors

- A typical BF_3 detector consists of a cylindrical aluminum tube filled with a BF_3 fill gas.

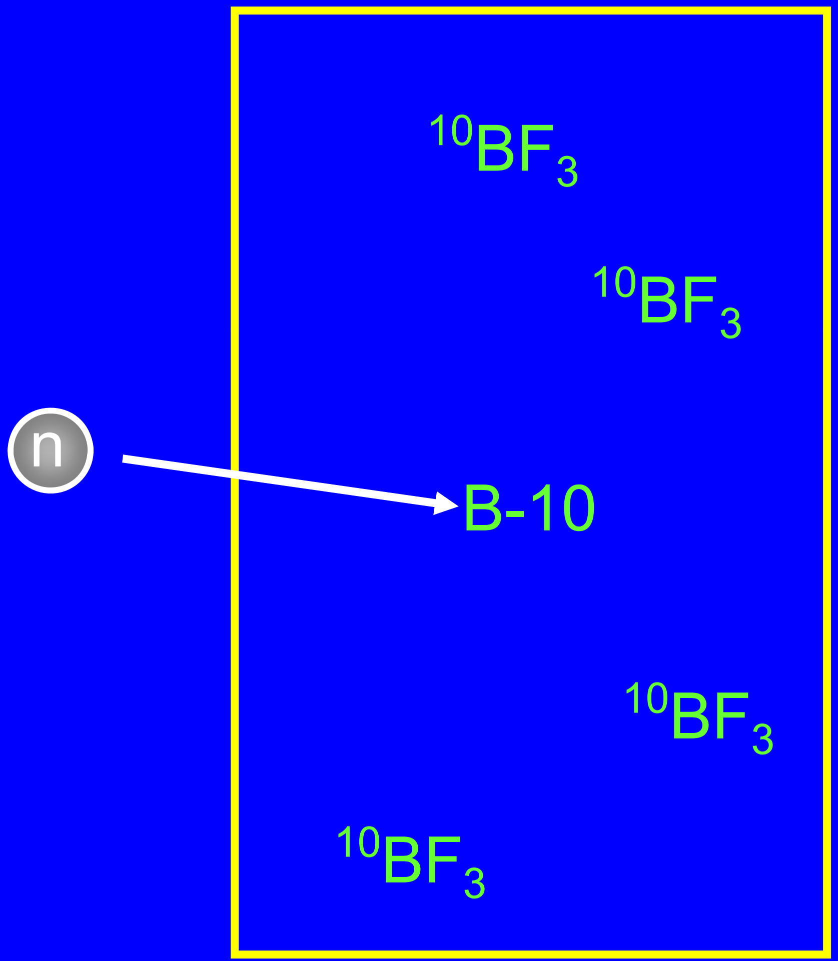
- The boron trifluoride:
  - functions as a proportional fill gas
  - undergoes an n-alpha interaction with thermal neutrons: B-10 (n, α) Li-7

$$\text{B-10} \quad + \quad \text{n} \quad \rightarrow \quad \text{Li-7} \quad + \quad \alpha$$

BF_3 and He-3 Detectors

1. Boron Trifluoride (BF_3) Detectors

A slow neutron combines with the B-10 atom of a BF_3 gas molecule.

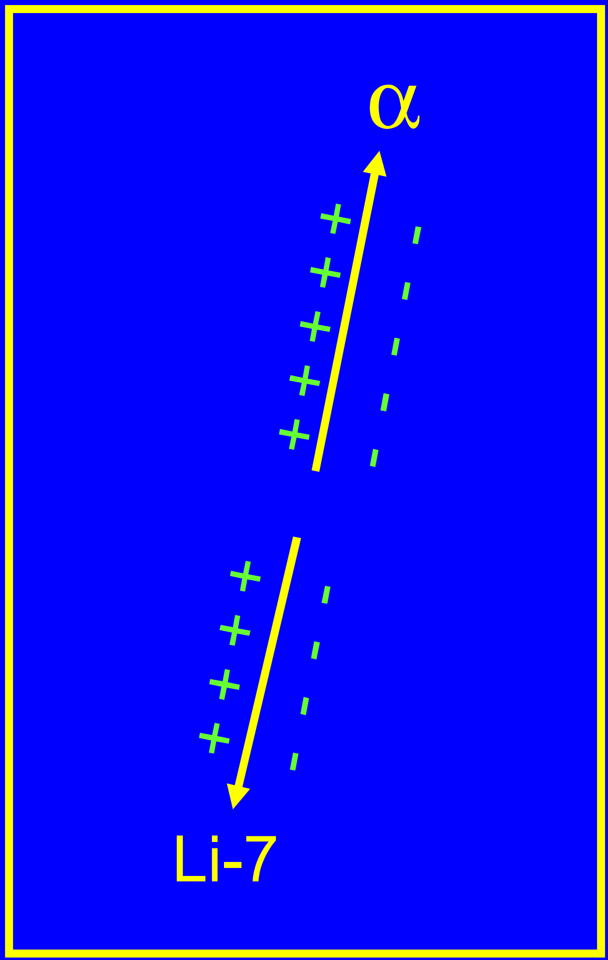


BF_3 and He-3 Detectors

1. Boron Trifluoride (BF_3) Detectors

The reaction results in a Li-7 atom and an alpha particle heading off in opposite directions.

As they travel through the BF_3 gas, they ionize it to create ion pairs.



BF_3 and He-3 Detectors

2. He-3 Detectors

- He-3 detectors are more popular than BF_3 detectors because the gas is less hazardous. Among other things, this facilitates shipping.
- Unfortunately, the smaller pulses of the He-3 detectors make them poorer than BF_3 detectors at rejecting gamma rays.
- A typical He-3 detector consists of a cylindrical aluminum tube filled with helium at a pressure of several atmospheres.

BF_3 and He-3 Detectors

2. He-3 Detectors

The helium gas accomplishes two things:

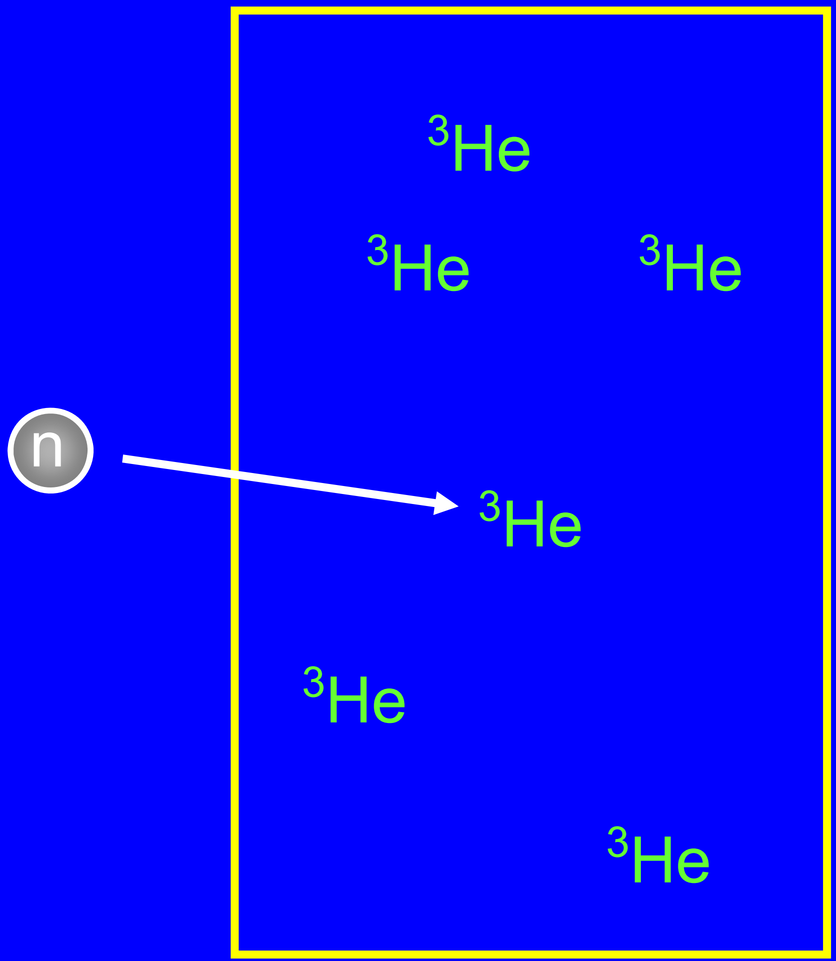
- it functions as the proportional fill gas.
- it undergoes an n p interaction with thermal neutrons: He-3 (n, p) H-3

$$\text{He-3} \quad + \quad n \quad \rightarrow \quad \text{H-3} \quad + \quad p$$

BF_3 and He-3 Detectors

2. He-3 Detectors

A slow neutron combines with the He-3 atom.

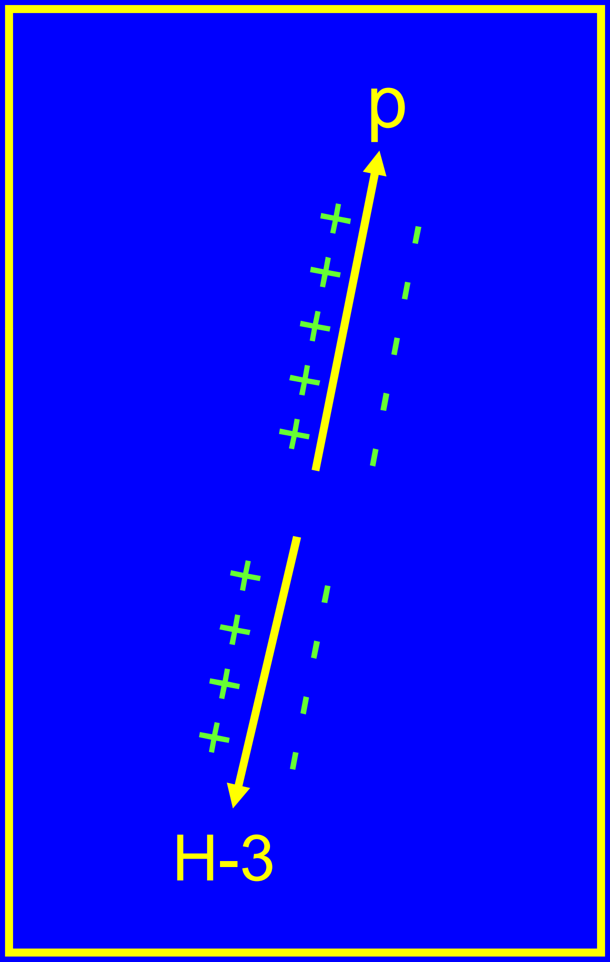


BF_3 and He-3 Detectors

2. He-3 Detectors

The reaction results in a H-3 atom and a proton heading off in opposite directions.

As they travel through the He-3 gas, they ionize it to create ion pairs.



Neutron Dose Equivalent Rate Measurements

Dose Equivalent Rate Measurements

General

- Several different detector types can be employed to measure the neutron dose equivalent. This presentation considers:

- Moderator-type Rem detectors

- Single detector:	Hankins-type
	Anderson-Braun
	Leake-type
- Dual detector:	Dineutron

- Tissue Equivalent Proportional Counters
  - REM 500

Dose Equivalent Rate Measurements

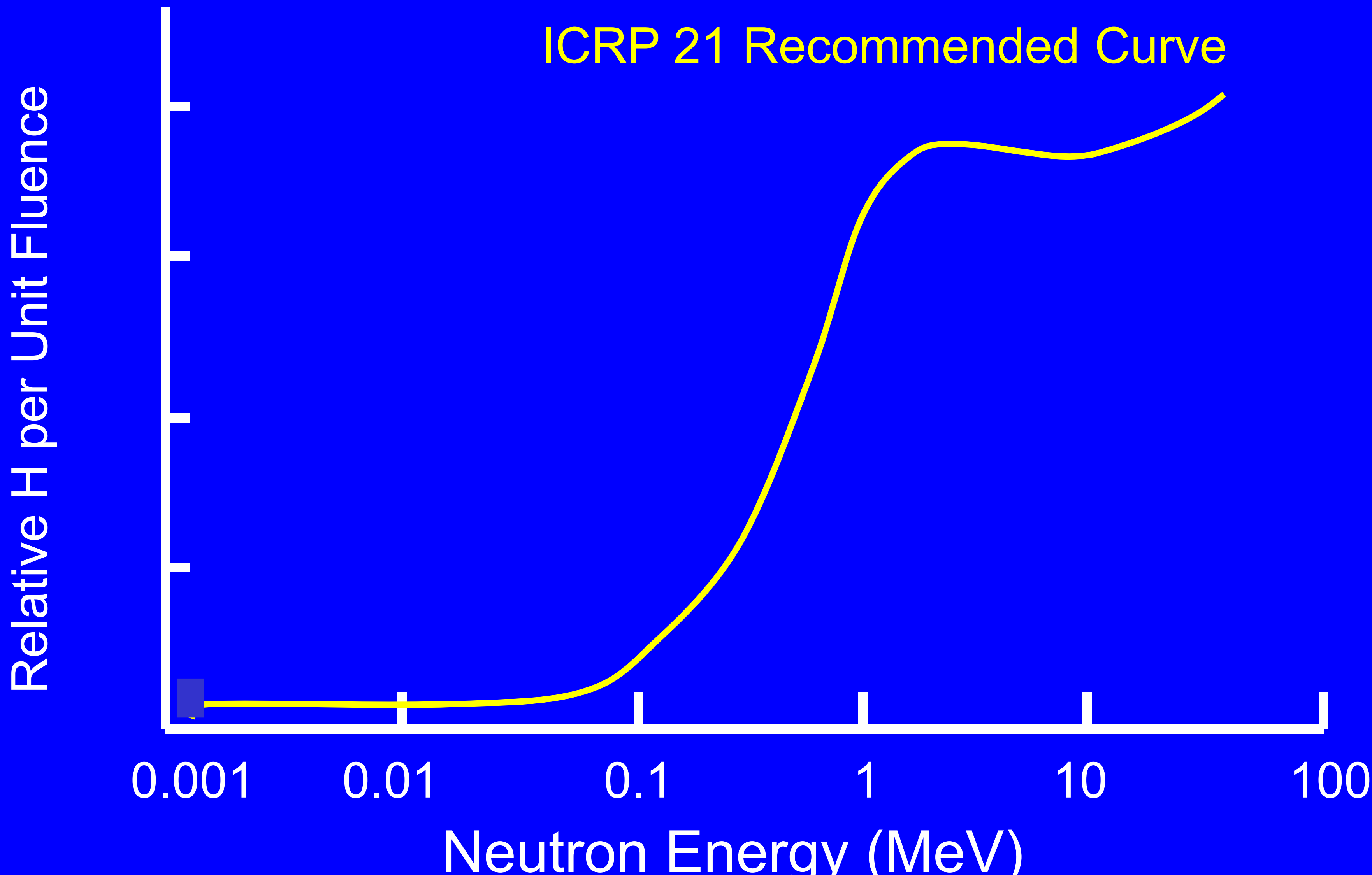
General

- The dose equivalent (H) per neutron fluence (i.e., rem per neutron) varies with the neutron energy because both the absorbed dose (D) and the quality factor/radiation weighting factor (Q, w_R) vary with the neutron energy.

$$H = D\,Q = D\,w_R$$

- Due to a combination of factors, the dose equivalent per unit fluence (e.g., rem or sievert per neutron/cm^2) as a function of neutron energy shows the following relationship.

Dose Equivalent per Unit Neutron Fluence (rem per neutron) as a Function of Energy



Dose Equivalent Rate Measurements

General

- It turns out that it is possible to design a moderated detector whose counting efficiency (counts per neutron) varies with neutron energy in the same way that the dose equivalent per unit neutron fluence varies with neutron energy.
- Such an instrument can be calibrated to read out in units of dose equivalent (or rate).
- This requires a judicious choice of moderator thickness, and possibly the incorporation of neutron absorbers to "tweak" the response.

Dose Equivalent Rate Measurements

General

- The two most widely used moderated neutron rem meters are the:
    - Hankins Rem Ball
    - Andersson-Braun rem meter (“snoopy”)
- Even though they operate in the pulse mode, they can be used to measure dose equivalent rates in the pulsed fields around accelerators because the neutron moderation broadens the duration of the pulses.

Dose Equivalent Rate Measurements

Hankins Rem Ball

- Hankins' original design consisted of a cadmium loaded 9 inch polyethylene moderator housing a small BF_3 detector. Its response (counts per neutron) as a function of neutron energy approximated the neutron fluence to dose equivalent conversion factors.

- Such an instrument could be calibrated to indicate neutron dose equivalent without the need to determine the neutron spectrum.

Dose Equivalent Rate Measurements

Hankins Rem Ball

- The cadmium loading consisted of a 0.0028 cm thick cadmium foil covering a 6 cm inner polyethylene sphere.

- Current versions of the Hankins design:

  - Ludlum Model 12-4

  - Eberline NRD detectors

Dose Equivalent Rate Measurements

Ludlum Model 12-4 Neutron Counter

- Detector: BF_3 or He-3 surrounded by 9 inch (22.9 cm) cadmium loaded polyethylene sphere.
- Weight: 21 lbs.
- Readout: mrem/hr
- Dose rate: 0-10,000 mrem/h
  0-100 mSv/hr
- Sensitivity: ca. 30 cpm per mrem/hr.
  ca. 50 cps per mSv/hr.
- Gamma response: <10 cpm at 10 R/hr.
  <10 cpm at 0.1 Sv/hr
- Temperature range: -20 to +50°C.
- Battery life: 600 hours.

Dose Equivalent Rate Measurements

Eberline E-600/NRD

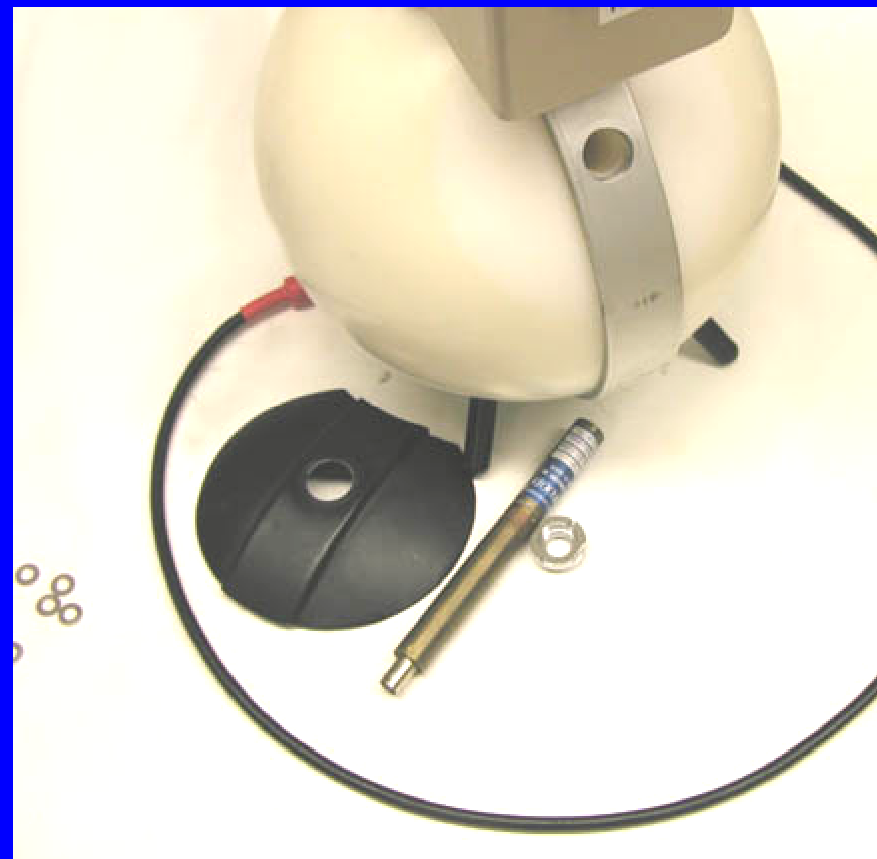
- Detector: BF_3 or He-3 surrounded by 9 inch (22.9 cm) cadmium loaded polyethylene sphere.
- Weight: 18 lbs.
- Energy range: 0.025 eV-10 MeV
- Readout: mrem/hr, mrem
- Dose rate: 0-10,000 mrem/h
  0-100 mSv/hr

- Sensitivity: ca. 45 cpm per mrem/hr.
  ca. 75 cps per mSv/hr.
- Gamma response: rejection up to 500 R/hr.
- Temperature range: -20 to +50°C.

Dose Equivalent Rate Measurements

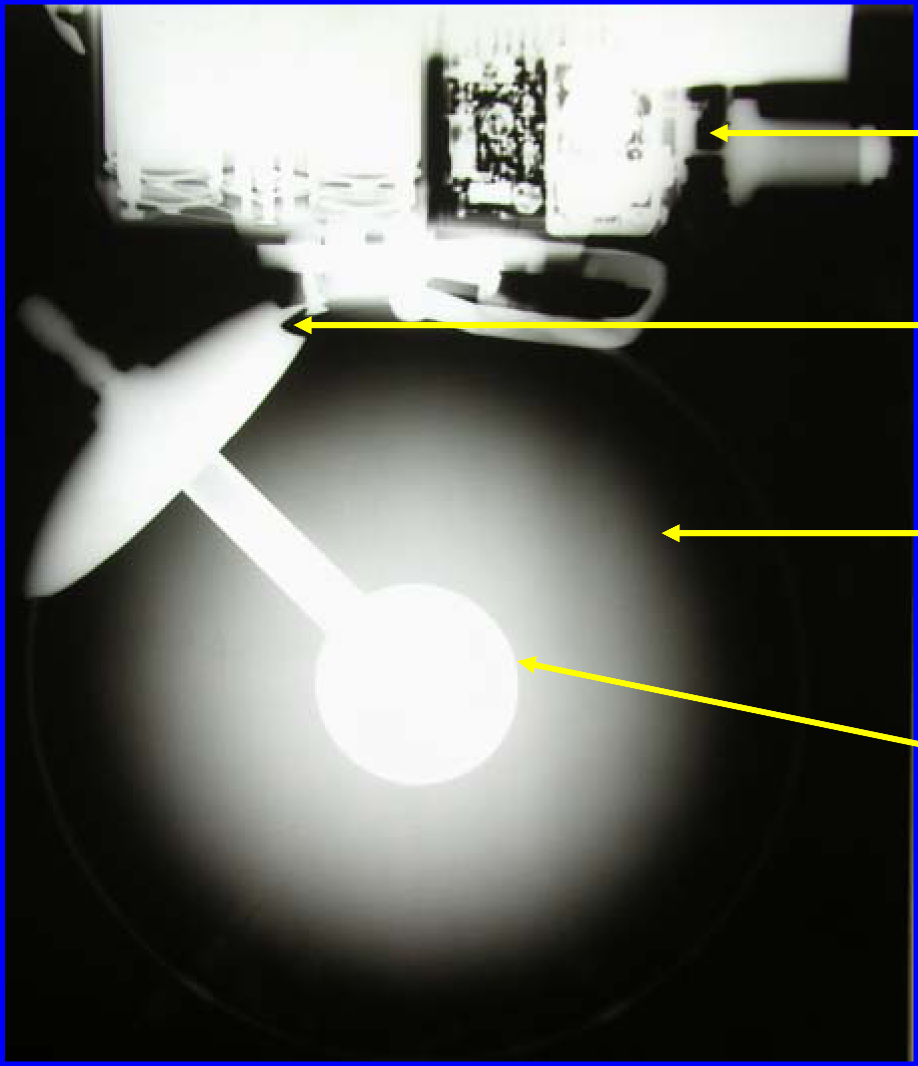
Hankins "Rem Ball"

Ludlum 12-4
Neutron Counter



Dose Equivalent Rate Measurements

Hankins "Rem Ball"



Meter electronics

Cadmium cap

Outer polyethylene spherical moderator

Cadmium foil surrounding inner spherical moderator (6 cm diameter) and detector

Dose Equivalent Rate Measurements

“Snoopy” Andersson-Braun “Rem Meter”

- In 1963, Andersson and Braun designed a neutron rem meter with a cylindrical polyethylene moderator - 21.6 cm diameter by 24.4 cm long (Model NRC III). These devices employ a cylindrical BF_3 or He-3 tube.

- To reduce the instrument’s over-response to low energy neutrons, they incorporated a borated plastic sleeve (7.6 cm diameter) around the detector tube and inner moderator.

Dose Equivalent Rate Measurements

Andersson-Braun "Rem Meter"

- Current versions of the Andersson-Braun "snoopy" design:
  - Alnor (Studsvik) 2202
  - NE Technology NM1, NM2
  - Eurisys Mesures NG2A

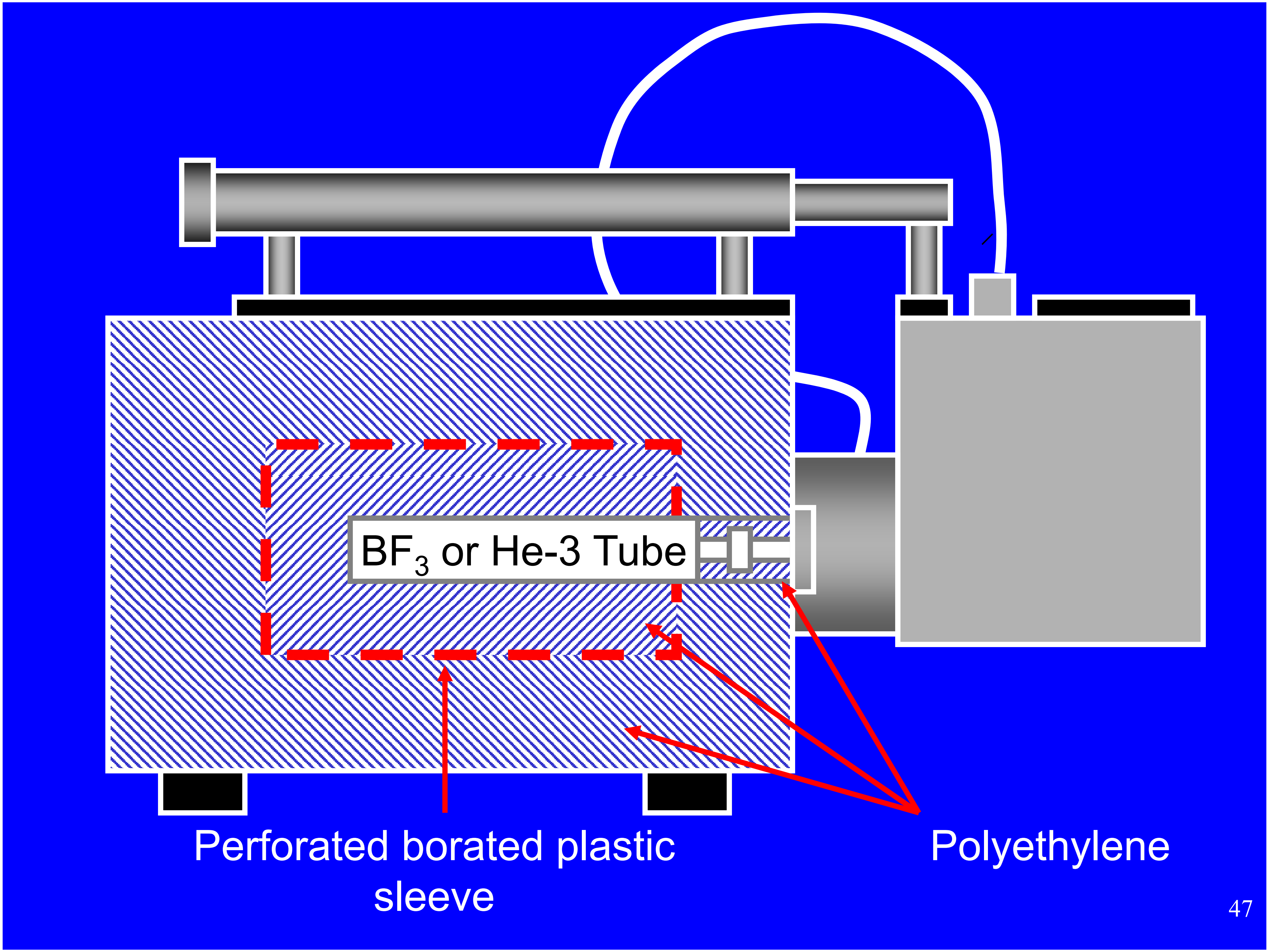
Dose Equivalent Rate Measurements
Eurisys Mesures/Canberra/APTEC/NRC NG-2A

- Neutron Detector: BF_3 or He-3 detector with cylindrical polyethylene moderator.
- Gamma detector: GM
- Weight: 25 lbs
- Readout: mrem/hr, mrem, Sv/hr, Sv, uR, uR/hr
- Dose rate: 10 urem – 10 rem/h (0.1 uSv/hr – 0.1 Sv/hr)
- Energy Range: 0.025 ev to 15 MeV (neutrons)
- Sensitivity: ca. 6000 counts per mrem (600 counts/uSv)
- Gamma response: no response up to 500 R/hr (5 Sv/hr)
- Temperature range: -20 to +50°C
- Battery life: 40 hours
- GM detector gamma response: 0.1 uR/hr – 10 R/hr
1 nSv/hr – 0.1 Sv/hr

Dose Equivalent Rate Measurements

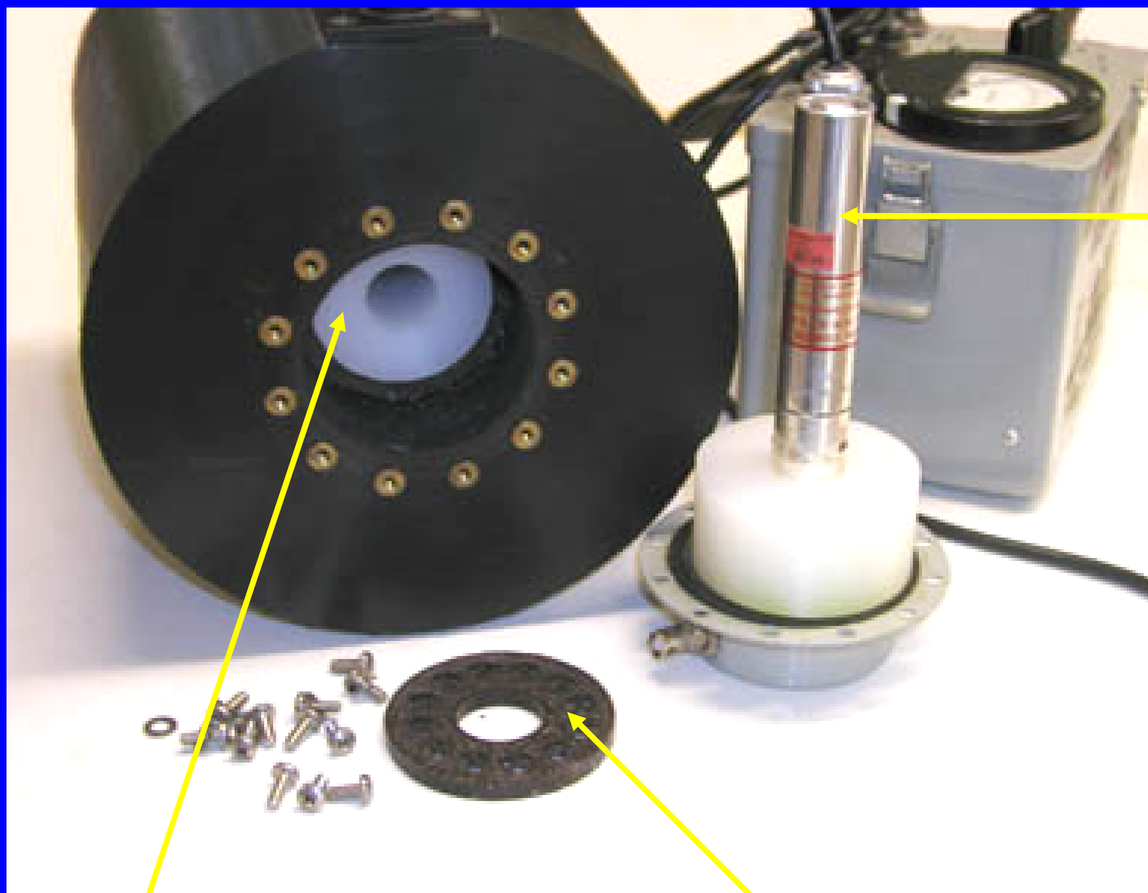
Andersson-Braun Rem Meter

EURISYS MESURES “Snoopy” NG-2A


BF_3 or He-3 Tube
Perforated borated plastic sleeve
Polyethylene

Dose Equivalent Rate Measurements

Andersson-Braun Rem Meter



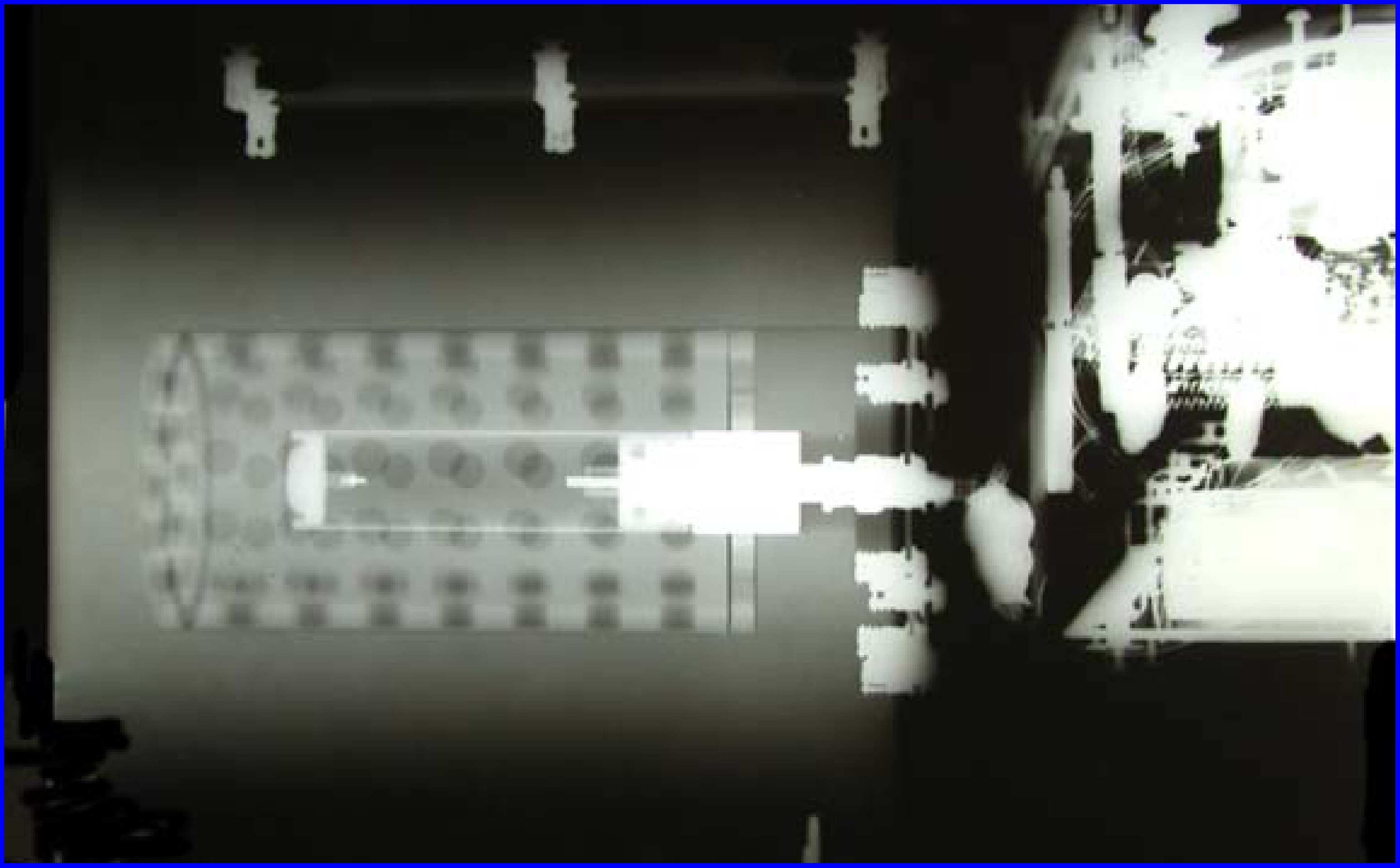
BF_3 detector tube

Inner polyethylene moderator

End section of perforated borated plastic sleeve

Dose Equivalent Rate Measurements

Andersson-Braun Rem Meter



Dose Equivalent Rate Measurements

Leake Rem Meter

- In 1966 Leake described a rem meter that had some of the features of both the Andersson-Braun detector and the Hankins detector.

- The original version employed a 20.8 cm diameter spherical polyethylene moderator and a lithium iodide scintillator.

Dose Equivalent Rate Measurements

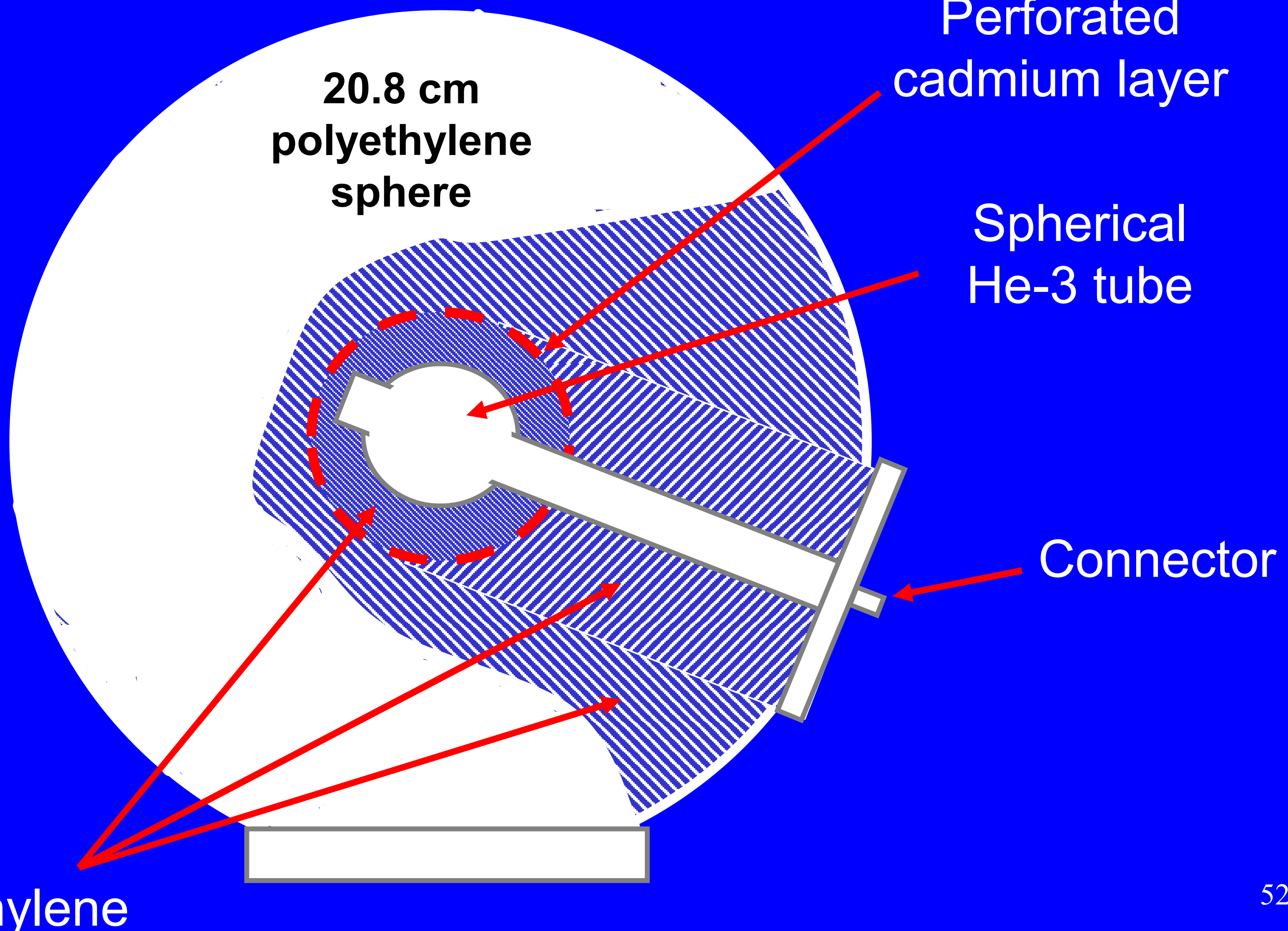
Leake Rem Meter

- Later versions replaced the lithium iodide detector with a spherical He-3 detector.

- The detector is surrounded by an inner (5.5 cm diameter) and outer (20.8 cm diameter) spherical polyethylene moderator. A 1 mm thick cadmium shell perforated with holes is located between the inner and outer moderators.

Dose Equivalent Rate Measurements

Leake Rem Meter



Dose Equivalent Rate Measurements

Leake Rem Meter

Polyethylene moderator Spherical He-3 Detector

Dose Equivalent Rate Measurements

Leake Rem Meter

- Current versions of the Leake-type neutron rem detector:
    - Berthold LB 6411

Dose Equivalent Rate Measurements

Berthold LB 6411 Leake-type Meter

- Detector: cylindrical He-3, with 25 cm spherical polyethylene moderator and perforated cadmium moderator.
- Energy range: 50 keV – 10 MeV (±30%).
- Sensitivity: 3 counts/nSv
  44 cpm per uSv/hr.
- Designed to measure H*(10) as recommended in ICRP 60.
- Lower over-response than standard Leake detector to intermediate energy neutrons, with increased sensitivity.

Dose Equivalent Rate Measurements

Problems with Typical Instruments

- The instrument's accuracy depends on the neutron spectrum.
- The manufacturer's specifications for accuracy are not always accurate.
- They can be very heavy, awkward and even dangerous to carry in areas where movement is limited, e.g., on ladders.

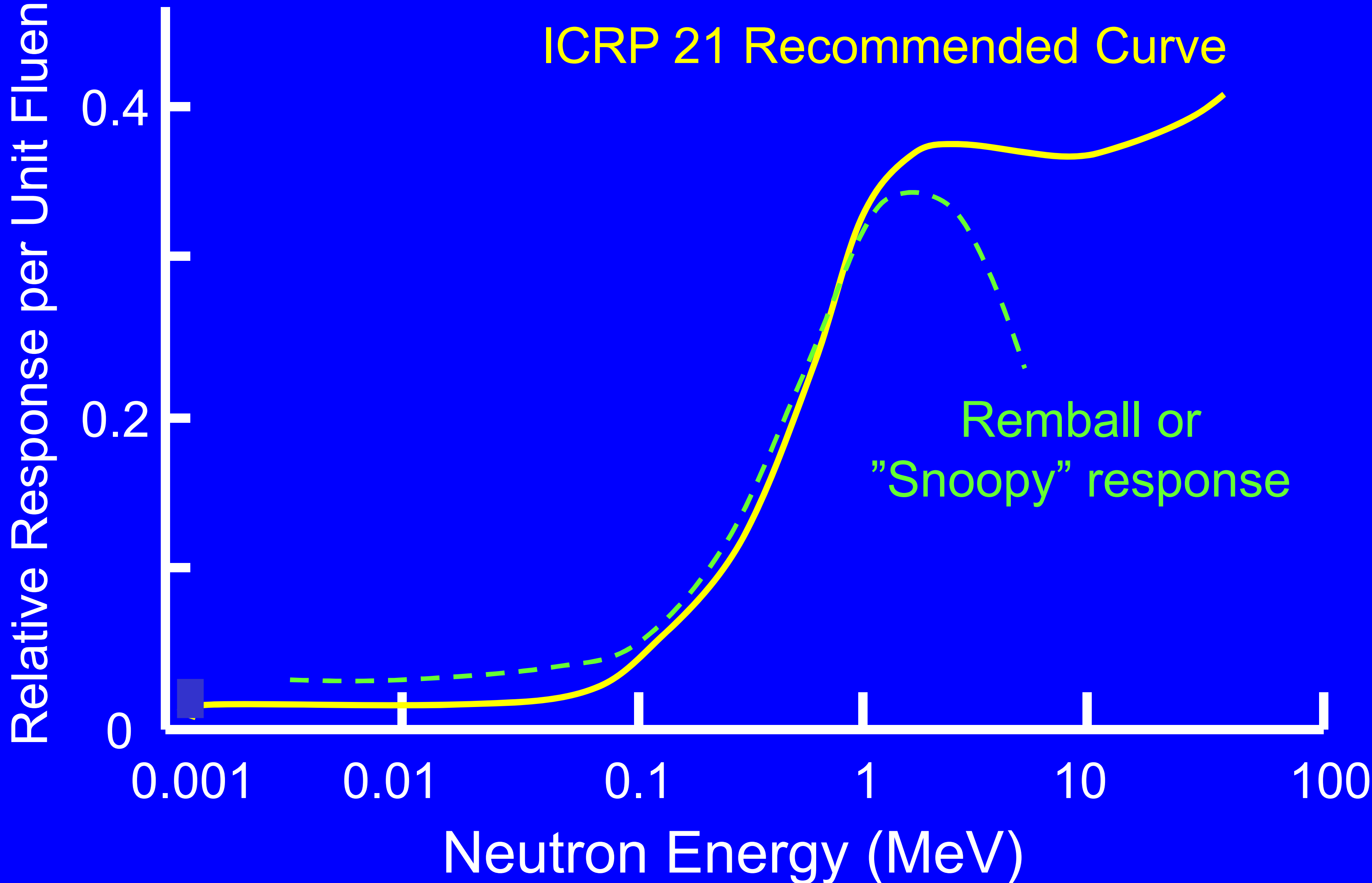
Dose Equivalent Rate Measurements

Problems with Typical Instruments

- In fields dominated by scattered neutrons, a significant component of the dose might be due to intermediate energy neutrons (10 to 100 keV) where many of these detectors over-respond.
- Maximum over-response can be expected at 10 keV. Over-responses seen by a factor of 3 for 20 to 30 keV neutrons.
- Significant under-respond to neutrons above 6 MeV (e.g., by a factor of 2 for 10 MeV neutrons).

Dose Equivalent Rate Measurements

Relative Fluence Response



Dose Equivalent Rate Measurements

Problems with Typical Instruments

Newer versions of these rem-meters (WENDI and LINUS) have largely eliminated the over-response at the lower energies and the under-response at the higher energies.

The latter was accomplished by adding a heavy metal (lead or tungsten) to the detector moderator. The high energy neutrons interact with the metal by (n,2n) and (n, 3n) reactions to produce lower energy neutrons that are detected with greater efficiency.

Dose Equivalent Rate Measurements

Problems with Typical Instruments

Prescila is a neutron scintillator rem-meter developed at Los Alamos and commercialized by Ludlum. It has better energy response (up to 20 MeV) than the standard Andersson-Braun and Hankins design and is much lighter.

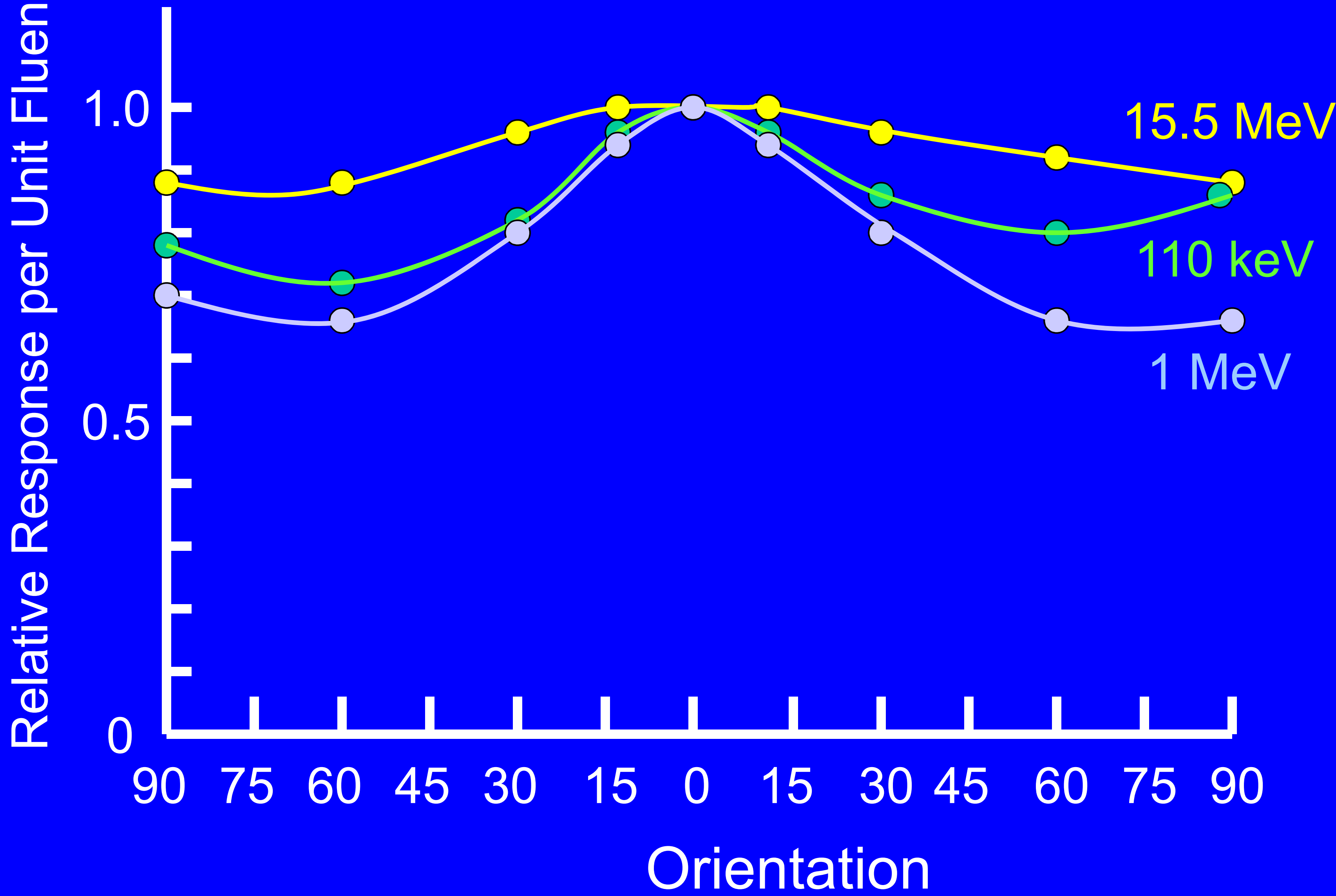
Its gamma rejection is not as good as that of a gas detector. In addition, it can have problems evaluating pulsed neutron fields.

Dose Equivalent Rate Measurements

Angular Dependence Problems with “Snoopy”

- Highest reading when irradiated from the side of the cylinder.
- Angular response is not as good as with spherical detectors (moderator-type or TEPC). In the worst case, an under-response of 35% was noted for 1 MeV neutrons.

Angular Response of a "Snoopy" Andersson-Braun Meter



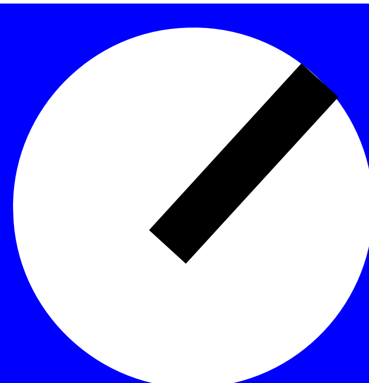
Dose Equivalent Rate Measurements

Angular Independence:

Good

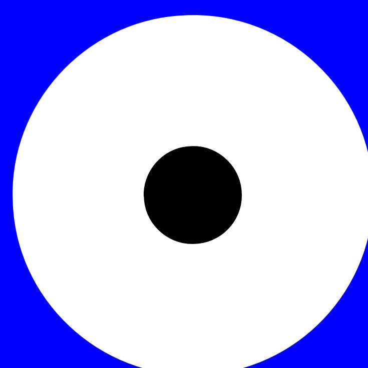
Andersson-Braun

Better



Hankins

Best



Leake

Dose Equivalent Rate Measurements

Eurisys Dineutron Meter

- The neutron energy spectrum is characterized by analyzing the ratio of the counts obtained with moderators of varying thickness.
- Once the spectrum has been characterized, an effective quality factor (radiation weighting factor) can be determined. The measured absorbed dose (D) can then be converted into the dose equivalent (H).

Dose Equivalent Rate Measurements

Eurisys Dineutron Meter

- Detector: Two He-3 detectors. One is surrounded by a spherical 2.5 inch diameter polyethylene moderator. The other is surrounded by a 4.2 inch diameter spherical moderator.
- Weight: 3.5 kg.
- Energy range: 0.025 eV – 15 MeV (±30%)
- Readout, Sv, Gy, rem, rad, also quality factor
- Dose rate: 0.01 - 9999 mrem/h
  0.1 uSv/hr - 99.99 mSv/hr
- Dose: 0.0001 - 9999 mrem
  1 nSv – 99.99 mSv
- Temperature range: -10 to +55°C
- Battery life: 25 hours

Dose Equivalent Rate Measurements

Eurisys Dineutron Meter

- The calculation of dose equivalent involves the ratio of the count rates in the two detectors.
- The ratio is referred to as the spectral index (I):

$$I = \frac{C_1}{C_2}$$

Where C_1 is the count rate from the smaller chamber
C_2 is the count rate from the larger chamber

Dose Equivalent Rate Measurements

Eurisys Dineutron Meter

- The dose equivalent (H) is calculated as follows:

$$H = \frac{C_2}{K_h}$$

- The constant K_h is a function of the spectral index:

$$K_h = a\, e^{b\, l}$$

  - The constants a and b were determined empirically by measuring the spectral index and the dose equivalent in neutron fields at nuclear power plants.

Dose Equivalent Rate Measurements

Far West Technology REM 500

Dose Equivalent Rate Measurements

Far West Technology REM 500

- Detector: Rossi-type spherical tissue equivalent proportional counter (TEPC), 2.25 inch inner diameter – it mimics a 2 um sphere of tissue.

  For details about TEPCs, see Appendix.

- Wall: A 150 TE plastic, 1.2 mm thick
- Housing: aluminum can, 0.065 inch thick
- Fill gas: propane
- Internal 0.3 uCi Cm-244 alpha source (license required)

Dose Equivalent Rate Measurements

Far West Technology REM 500

- Dose rate: 0.1 mrem/hr to 100 rem/hr
  1 uSv/hr to 1 Sv/hr
- Response: ca. 480 counts per mrem
  48 counts per uSv
- Energy response: 70 keV to 20 MeV
- Angular dependence: ± 10% through 270 degrees
- Battery life: ca. 100 hrs.
- Weight: 5 lbs, 2 oz (without batteries)
- Temperature response: ± 10% 15 to 45 °C
  ± 20% -15 to 50 °C

Dose Equivalent Rate Measurements

Far West Technology REM 500

- After a count has been performed, the pulse height distribution (a spectrum) is determined.
- Pulse height is related to the “lineal energy” (the energy deposited by a single particle in a specified volume divided by the average chord length of the particles through that volume).
- Lineal energy is related to the quality factor.
- The larger the pulse, the larger the lineal energy, the greater the quality factor and the higher the channel number into which the pulse is sorted.

Dose Equivalent Rate Measurements

Far West Technology REM 500

- Employs 256 PHA. Pulses in channels 1-4 are assumed to be due to photons or noise.
- Pulses from an internal Cm-244 alpha source are set in channel 90 to calibrate the system with lineal energy of 90 keV/um.
- 10 keV – 1 MeV neutrons have maximum lineal energy around 85 – 90 keV/um. Above 1 MeV the lineal energy decreases.

Dose Equivalent Rate Measurements

Far West Technology REM 500

- Equation used to calculate dose equivalent (H):

$$H\,(rem) = K \sum_{5}^{255} \frac{Channel\#\ x\ counts/channel\ x\ Q}{TC\ x\ 25.6}$$

Where K is the calibration factor
TC is a time constant (depends on mode of operation, e.g.,1 for 10 second integration step)
Q, the quality factor, is a function of the channel number

Dose Equivalent Rate Measurements

Far West Technology REM 500

- Examples of quality factors employed by the REM 500 to calculate dose equivalent (H):

Ch.#	Q
1	0.4
10	3.2
20	5.7
30	7.8
40	9.9
50	11.8
60	13.6

Ch.#	Q
70	15.3
80	17.0
90	18.3
100	19.6
110	20.7
120	21.5
130	22.4

Ch.#	Q
140	23.1
150	23.8
160	24.3
170	24.6
180	24.8
190	24.8
>190	24.8

Neutron Energy Spectrum Measurements

Energy Spectrum Measurements

General

- Determining the energy spectrum of the neutrons is important because the response of neutron survey instruments and dosimeters varies with the neutron energy.

- Almost all neutron spectroscopy systems involve the use of multiple detectors. The different detectors respond differently with neutron energy.

- The most common method is the use of Bonner Spheres

Energy Spectrum Measurements

Bonner Spheres

- A Bonner Sphere system consists of a LiI, He-3 or BF_3 detector in conjunction with a set of polyethylene spherical moderators.

- A typical set consists of 6 to 8 polyethylene spheres of different sizes. In some sets, one sphere (3”) is covered with cadmium.

Typical sizes: 2", 3", 5", 8", 10" and 12"

Energy Spectrum Measurements

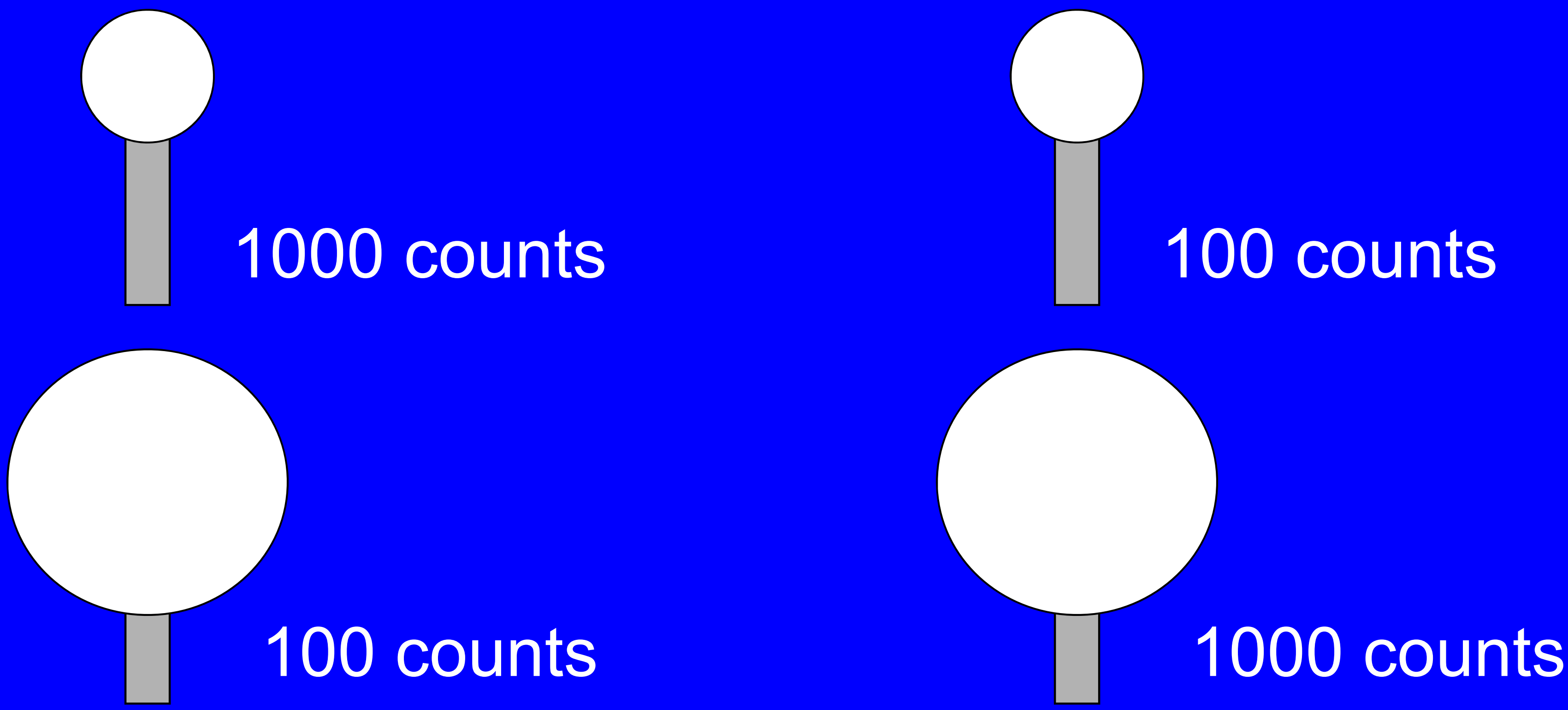
Bonner Spheres

- A count is performed with each of the spheres around the detector.

- The higher the neutron energy (the faster), the larger the sphere must be for the neutrons to be slowed down and detected.

- Larger spheres reduce the detector's response to low energy (slow) neutrons because the latter will be absorbed by the hydrogen in the sphere before reaching the detector.

Example of Detector Response to Different Energy Neutrons with Large and Small Spheres



SLOW NEUTRONS FAST NEUTRONS

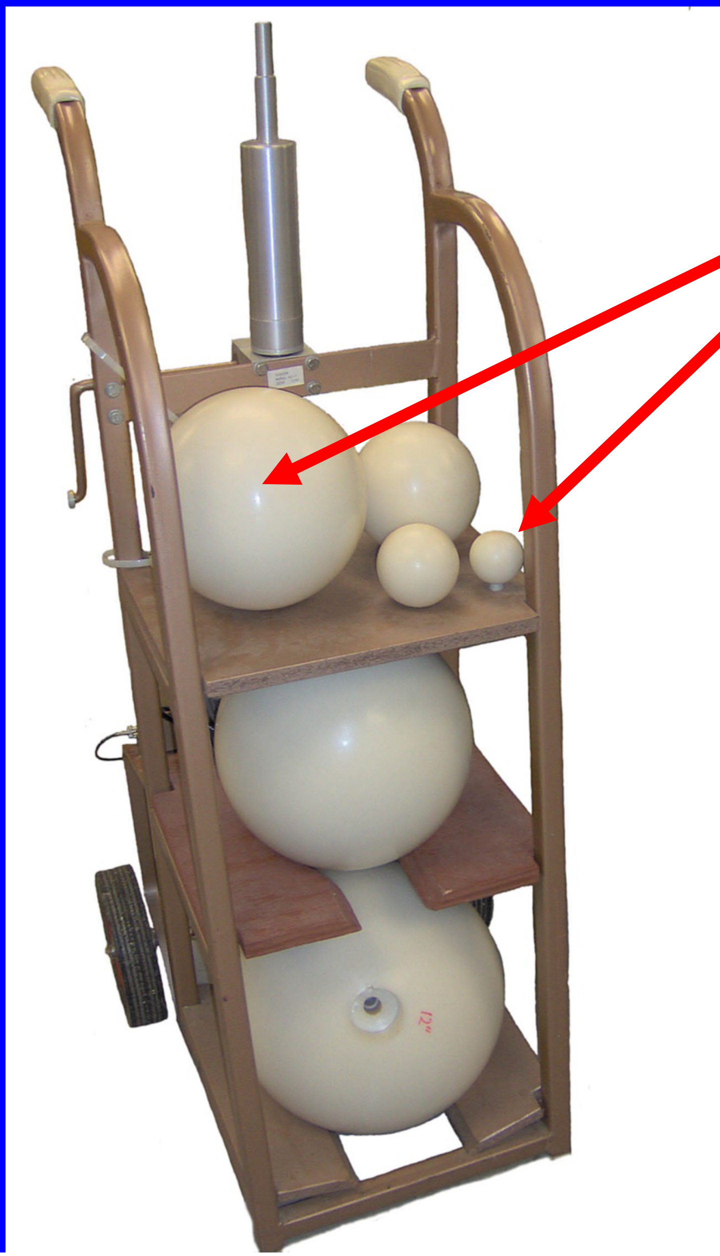
Energy Spectrum Measurements

Bonner Spheres

- The ratio of the counts obtained with the various sized Bonner Spheres carries the information about the energy of the neutrons.

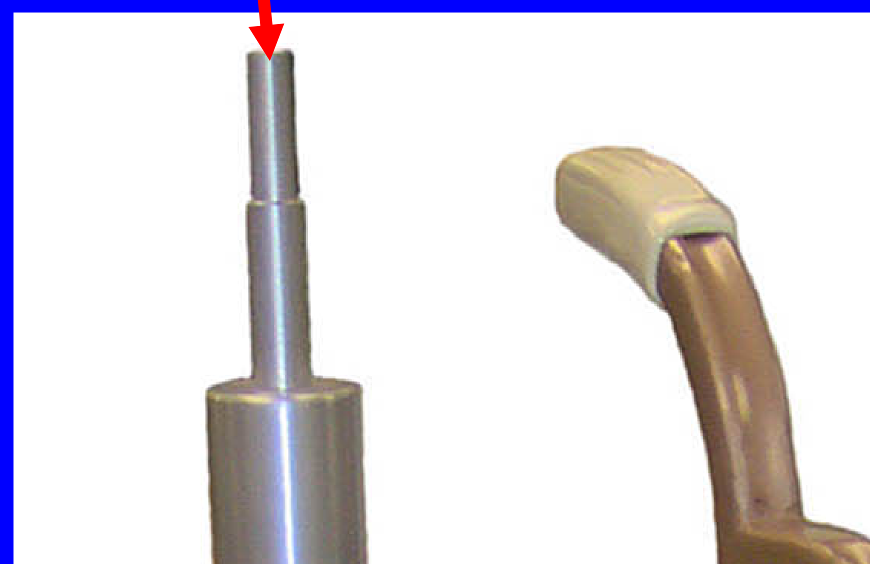
- Computer Codes such as “BON” must be used to fully interpret the results and determine the neutron spectrum. This is sometimes referred to as deconvoluting the spectrum.

Energy Spectrum Measurements



Bonner Spheres

Lithium iodide (LiI) scintillator detector.



Energy Spectrum Measurements

Activation Foils

- Threshold activation foils can be used to obtain general information about the neutron spectrum. This approach takes advantage of the fact that there can be an effective threshold, (i.e., a minimum energy) for a given neutron interaction to occur.

- After a set of different activation foils has been exposed to neutrons, they are analyzed for the activation products indicated in the following table.

Energy Spectrum Measurements

Example Activation Foils

Effective Threshold (MeV)	Target Material	Reaction
0.5	Indium	In-115 (n, n’) In-115
2.0	Zinc	Zn-64(n,p) Cu-64
3.8	Aluminum	Al-27(n,p)Mg-27
4.9	Aluminum	Al-27(n, alpha)Na-24
6.0	Magnesium	Mg-24(n,p)Na-24
8.6	Gold	Au-197(n,2n)Au-196

Energy Spectrum Measurements

ROSPEC Rotating Neutron Spectrometer

- Uses four spherical proportional counters: three 2" chambers filled with hydrogen at 3/4, 4 and 10 atmospheres, and one 6" diameter chamber filled with argon-methane at 5 atmospheres.

- The useful energy range (50 keV to 4.5 MeV) is typical of the degraded spectra encountered at nuclear power plants and other nuclear facilities.

- The detectors are rotated about a common axis in order to "average out" the field.

Energy Spectrum Measurements

ROSPEC Rotating Neutron Spectrometer

- Pulse height analysis is performed on the signals from all four detectors and the data is unfolded by the ROSPEC software to produce a neutron spectrum.

- The software also calculates the dose rate, KERMA, dose equivalent and ambient dose equivalent (H*(10)).

Neutron Dose Equivalent Measurements (dosimeters)

Dose Equivalent Measurements

General

- Most dosimeters are of the albedo type - they rely on the body to moderate and reflect neutrons.
- An albedo dosimeter should be worn close to the body. Wearing albedo dosimeters over loose clothing so that the body-dosimeter separation is too great is a common problem.
- When used as area or environmental dosimeters, they must be placed against a thick slab of hydrogenous material e.g., 8" x 8" x 4" lucite.

Dose Equivalent Measurements

Types of Neutron Dosimeters

- Thermoluminescent dosimeters (TLD)
- Track etch
- Nuclear Track Emulsions (NTA)
- Film
- Bubble dosimeters (superheated drop)
- Proton recoil detectors
- Fission track detectors
- Electronic (diode) detectors

Dose Equivalent Measurements

Thermoluminescent Dosimeters

- In the Panasonic badge employed at many nuclear power plants, the response of a calcium sulfate element (responds only to gamma rays) is subtracted from the response of a lithium borate element (responds to neutrons and gamma rays).

- The difference in their response is multiplied by a factor that accounts for the effect of the facility's neutron spectrum on the dosimeter response.

Dose Equivalent Measurements

Thermoluminescent Dosimeters

- In the Harshaw badge, the TLD-700 element (enriched in Li-7) only responds to gamma rays. The TLD-600 element (enriched in Li-6) responds to both gammas and neutrons. The response of the former is subtracted from the response of the latter to determine a net response to neutrons.

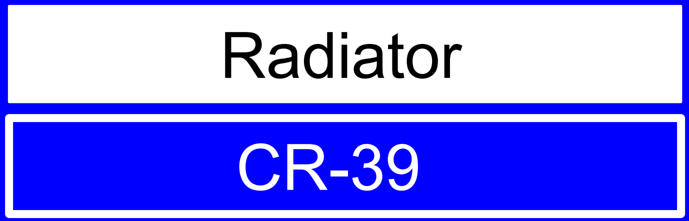
- The difference in their response is multiplied by a factor that accounts for the effect of the facility's neutron spectrum on the dosimeter response.

Dose Equivalent Measurements
Track Etch

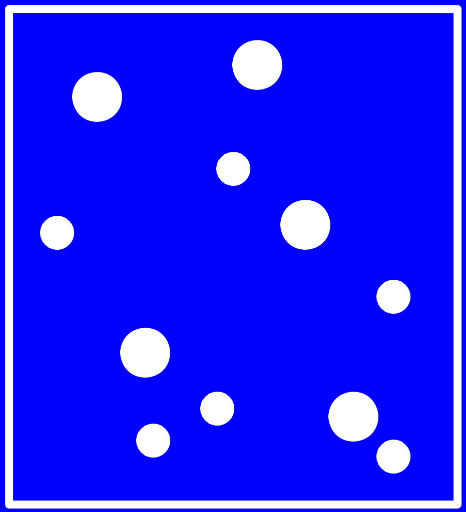
- The dosimetry method employed by Landauer.
- The dosimeter consists of CR-39 plastic (poly-allyl diglycol carbonate) in contact with a "radiator."
- Neutrons interacting in the radiator produce particles that create damage tracks in the CR-39.
- Following a neutron exposure, the CR-39 is etched in sodium hydroxide for 15 hours to make the damage tracks visible under microscope.
- The number of damage tracks produced by the neutrons in the CR-39 is related to the dose.

Dose Equivalent Measurements

Track Etch



Arrangement of radiator and Cr-39.

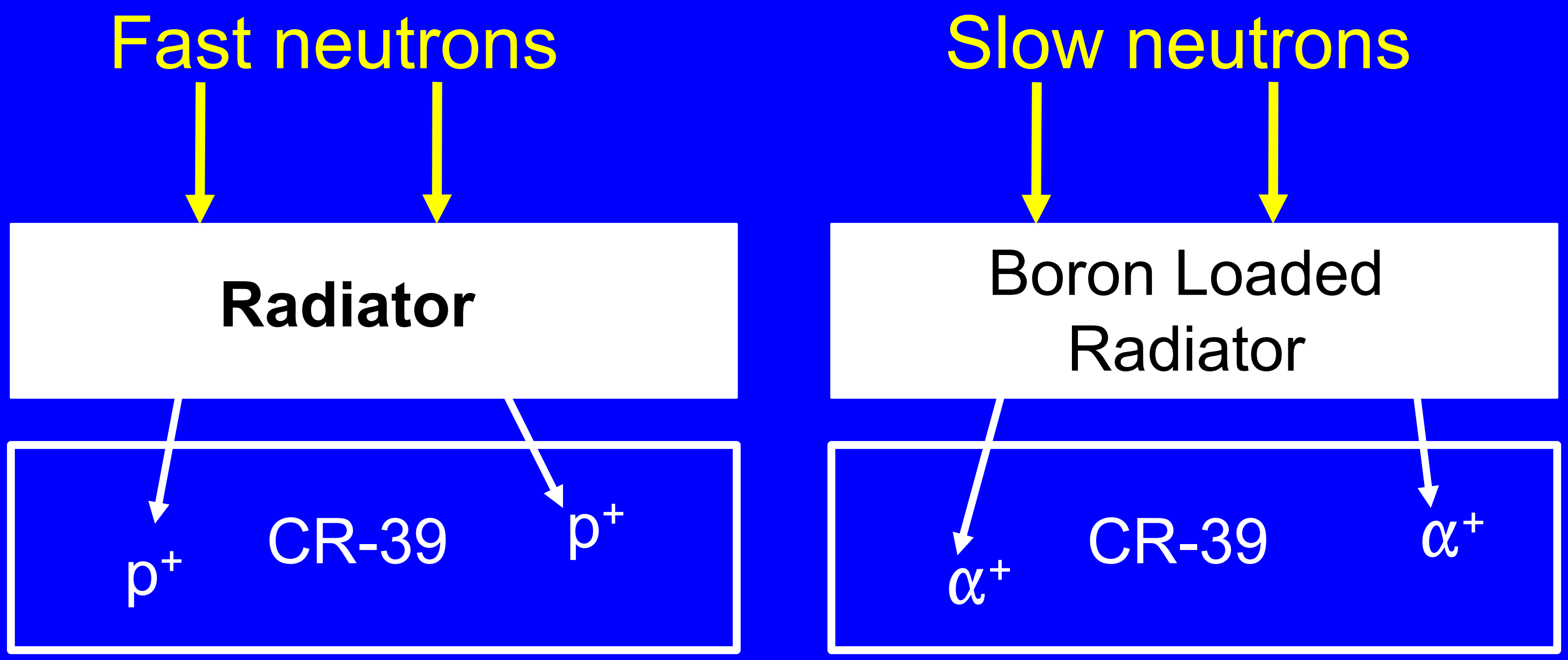


Appearance of damage tracks in the Cr-39 as seen under a microscope.

- For fast neutron dosimetry, the radiator is polyethylene. The recoil protons from the radiator produce the damage tracks in the CR-39.
- For slow neutron dosimetry, the radiator employs boron loaded Teflon. The alphas produced by interactions with boron produce the damage tracks in the CR-39.

Dose Equivalent Measurements

Track Etch



Dose Equivalent Measurements

Nuclear Track Emulsions

- Not used nearly as much today as in the past.

- The most common nuclear track emulsion (NTA) film is Kodak Type A film.

- Neutrons strike the hydrogen nuclei in the NTA film emulsion. The recoil protons (nuclei) travel through the emulsion transferring energy to the silver bromide crystals.

Dose Equivalent Measurements

Nuclear Track Emulsions

- When the film is processed, the image of the recoil tracks become visible under a microscope. The number of tracks per unit area of film is determined and related to the dose equivalent.

- Relatively insensitive to neutrons below 0.5 MeV

- They tend to over respond to neutrons above 3.5 MeV, e.g., the over response to 14 MeV neutrons can be as much as 100%!

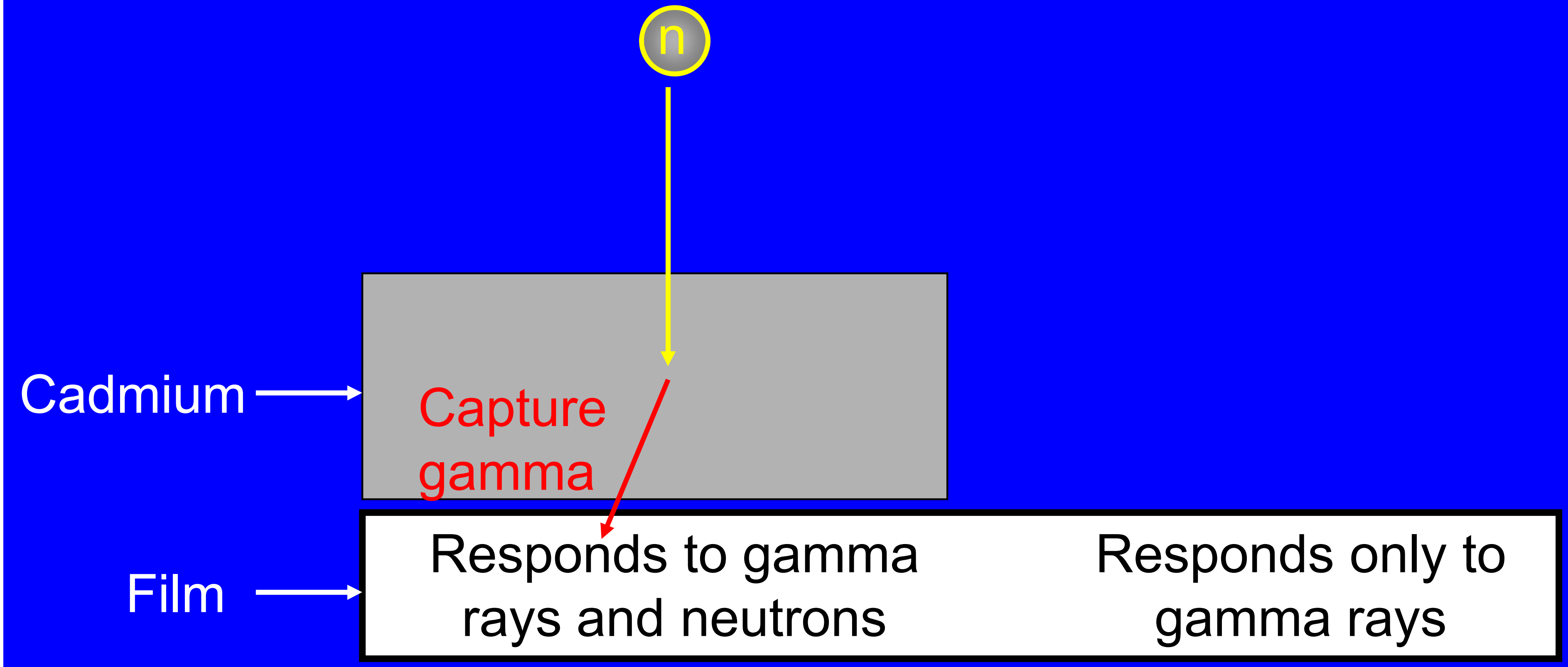
Dose Equivalent Measurements

Film

- Landauer manufactures a film dosimeter to measure the dose due to thermal neutrons. The film is partially covered with a cadmium filter. The capture of thermal neutrons by the cadmium results in the emission of prompt gamma rays that expose the film. Uncovered portions of the film are used to correct for the gamma background. A specific application of this dosimeter might be to measure personnel exposures in the vicinity of a graphite moderated neutron source.

Dose Equivalent Measurements

Film



Landauer Neutron Film Dosimeter

Dose Equivalent Measurements

Bubble Dosimeters/Superheated Drop Detectors

- Not widely used, in part due to limited shelf life
- Bubble dosimeters consist of a few mls of an inert gelatinous substance inside a plastic/glass vial.
- Thousands of tiny droplets of an organic liquid (e.g., Freon) are suspended in the gelatinous matrix. The pressure inside the vial is kept above the vaporization point of the fluid.

Dose Equivalent Measurements

Bubble Dosimeters/Superheated Drop Detectors

- High energy neutrons scatter off hydrogen nuclei to produce recoil protons which transfer their energy to the liquid droplets.
- To increase the system's sensitivity for low energy neutrons, an element (often chlorine) is added that produces a charged particle when it interacts with these low energy neutrons, e.g.,

Slow neutron + Cl-35 $\rightarrow$ p + S-35

Dose Equivalent Measurements

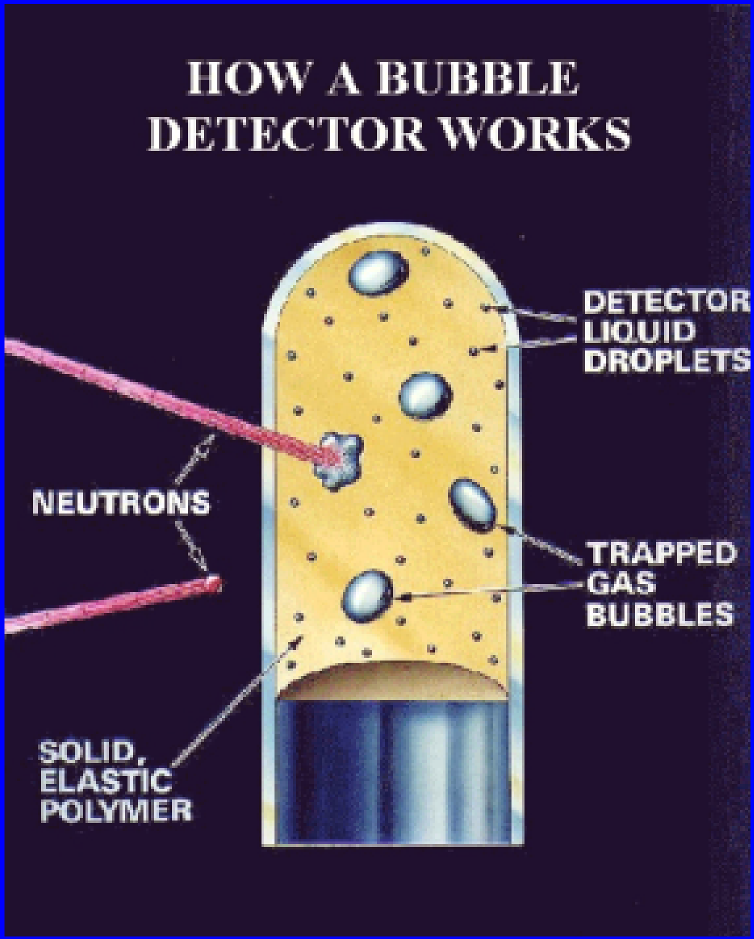
Bubble Dosimeters/Superheated Drop Detectors

- When energy is transferred to the liquid droplets, the latter are converted into a gas. This results in the formation of tiny (ca. 1 mm) bubbles in the matrix.

- The number of bubbles, which can be determined manually or with an automated counter, is related to the absorbed dose. Various sensitivities are available ranging from about 0.5 to 25 bubbles per mrem (50 to 2500 bubbles per mSv)

Dose Equivalent Measurements

Bubble Dosimeters/Superheated Drop Detectors



Using the Bonner Sphere 9” to 3” Count Ratio to Correct Dosimeter Response

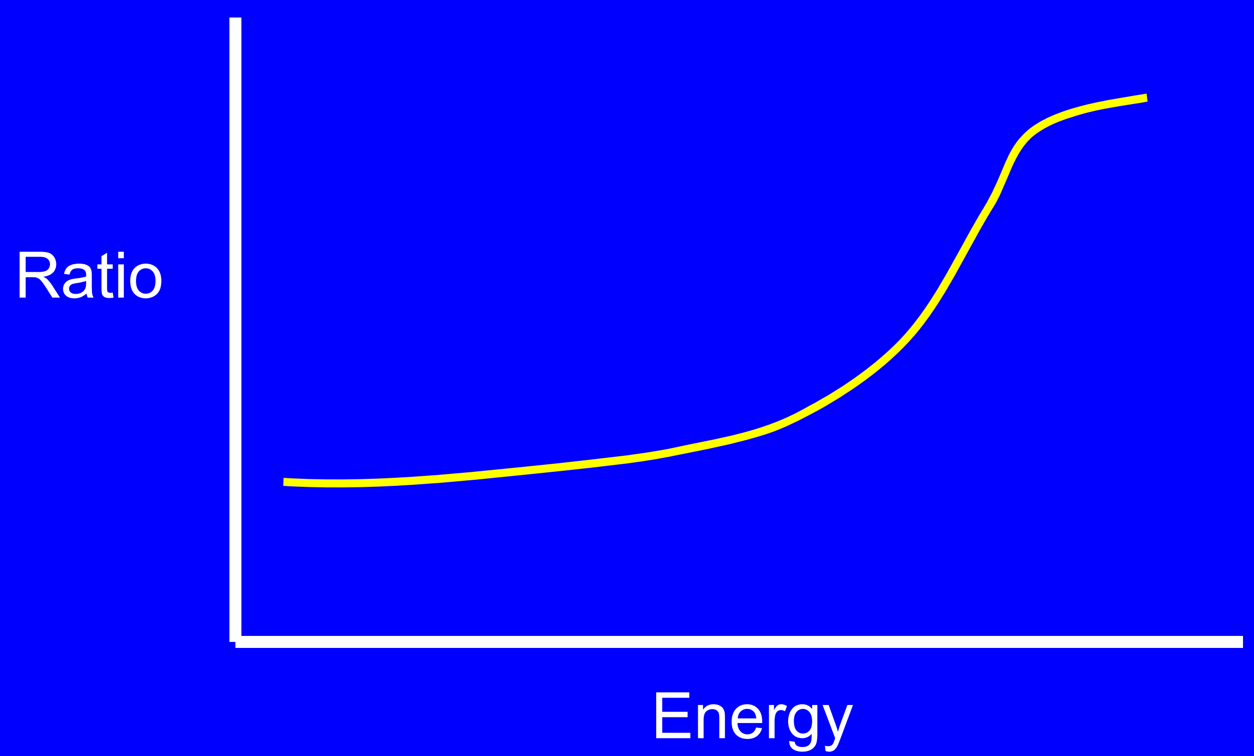
Using the Bonner Sphere 9” to 3” Ratio to Correct Dosimeter Response

- The response of many neutron dosimeters decreases as the energy of the neutrons increases.

- Some time ago, Dale Hankins suggested a relatively simple method to correct for the dependence of the dosimeter response on energy that involves performing counts with a 9 inch and 3 inch cadmium covered Bonner sphere.

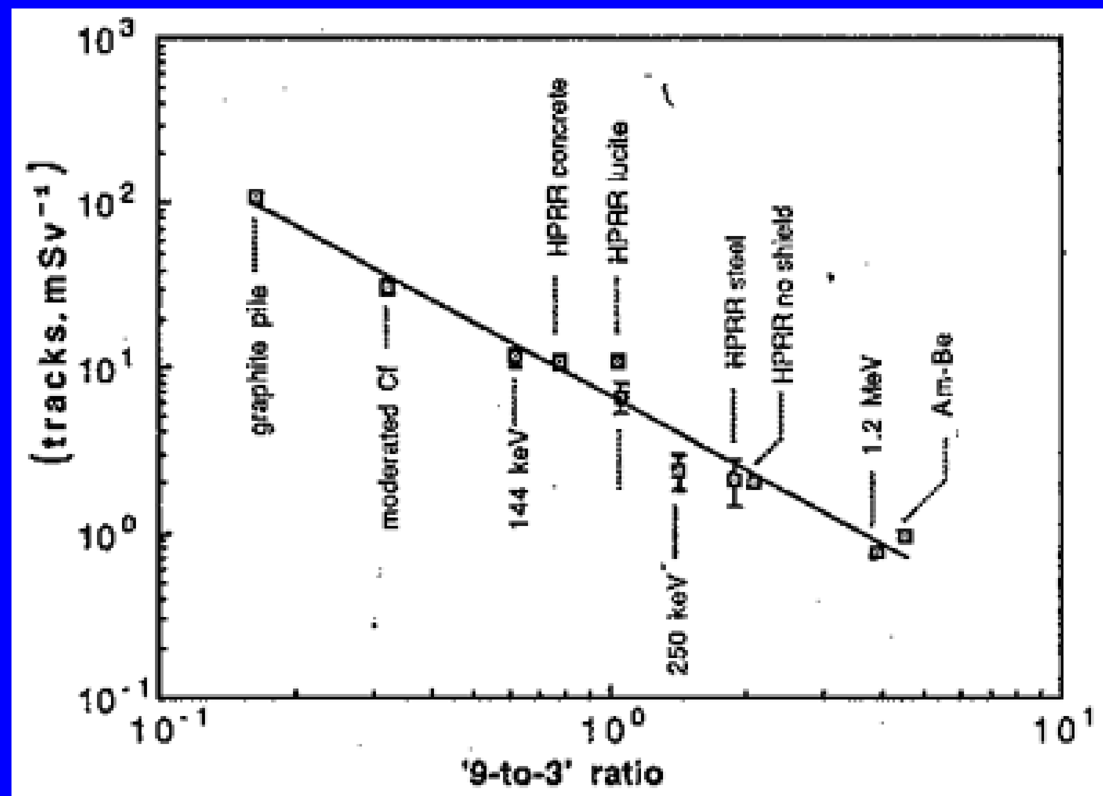
Using the Bonner Sphere 9” to 3” Ratio to Correct Dosimeter Response

- The ratio of the counts performed with the 9 inch and 3 inch spheres increases with neutron energy:



Using the Bonner Sphere 9” to 3” Ratio to Correct Dosimeter Response

- On log log paper, the dosimeter response plotted against the 9 to 3 ratio typically forms a straight line



Appendix
Tissue Equivalent Proportional Counters (TEPC)

Proportional Counter vs Ion Chamber

- A proportional counter is essentially the same as an ionization chamber except that the pulses are larger.
- In an ionization chamber, one electron reaches the anode for every primary ion pair produced in the gas. In a proportional counter, 100 to 1000 electrons reach the anode for every primary ion pair produced in the gas.

Proportional Counter vs Ion Chamber

- The pulses in an ionization chamber are usually too small to be counted. As such, an ion chamber almost always operates in the current mode, i.e., it measures the current from the chamber.
- A proportional counter typically operates in the pulse mode, i.e., it counts the number of pulses.
- It is also common to measure the size of the individual pulses.

Proportional Counter vs Ion Chamber

- By measuring the size of the pulses, the energy deposited in the detector gas by individual events (gamma ray or neutron interactions) can be determined. This is not possible with an ion chamber.

- The larger size of neutron pulses allows them to be distinguished from the smaller pulses produced by gamma rays. This is not possible with an ion chamber.

Tissue Equivalent Proportional Counters

General

- TEPCs have been used for many years in microdosimetry wherein the dose or dose equivalent to small volumes of tissue (e.g., 1 um) is measured.

- TEPC use in routine radiation protection is a more recent development.

- A big advantage is that a TEPC can separate the dose due to gamma rays and neutrons by pulse height discrimination in mixed fields.

Tissue Equivalent Proportional Counters

General

- However, pulse height discrimination for neutrons below 100 keV is not very satisfactory.
- The main reason is that the range of low energy recoil protons (hydrogen nuclei) in the detector wall is short.

Tissue Equivalent Proportional Counters

Typical Construction - Rossi Chamber

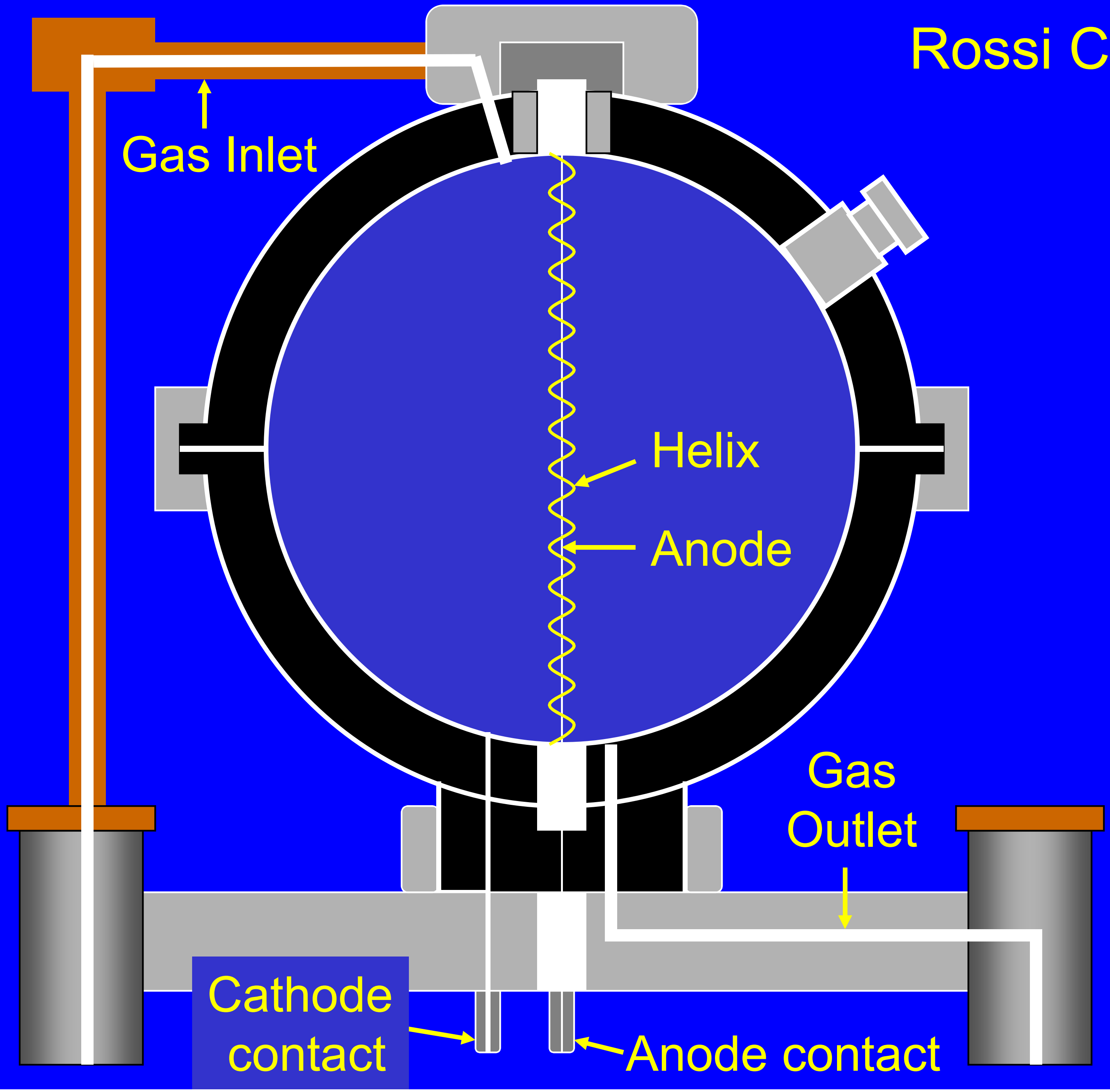
- The Rossi Chamber is a spherical chamber employing tissue equivalent walls and a tissue equivalent fill gas. It operates as a proportional counter.
- The sphere's response is more or less independent of the direction from which the radiation comes (i.e., angularly independent).
- Using a wire running along the diameter of the sphere complicates this.

Tissue Equivalent Proportional Counters

Typical Construction - Rossi Chamber

- The electric field can become distorted towards the ends of the anode where it gets close to the spherical detector wall (the cathode). Because of this distorted field, gas multiplication is decreased for the ionizing events that occur towards the ends of the anode.
- To prevent this and create a cylindrically symmetrical electric field along the length of the anode, the Rossi chamber surrounds the anode with a fine helical wire.

Rossi Chamber



Tissue Equivalent Proportional Counters

Typical Construction - Rossi Chamber

- A problem with this design is the fact that this helix is susceptible to vibration
- Such vibration results in microphonic noise, i.e., spurious counts. Since cylindrical chambers don’t require a helix, they are more rugged as well as being easier to construct.

Tissue Equivalent Proportional Counters

How They Measure Dose Equivalent

- The size of a pulse reflects the ionization produced in the gas by the particle. As such, it reflects the absorbed dose to the gas per particle (e.g., per neutron).

Tissue Equivalent Proportional Counters

How They Measure Dose Equivalent

- By measuring the size of each pulse, we can measure the absorbed dose (D) per particle in the gas. As such, we could calculate the dose equivalent (H) per particle if we could estimate the quality factor (Q).
- One way to estimate Q is to calculate the LET of the particle – Q is derived from the LET.
- Because of the following relationship, we could determine the LET of the particle if we knew its path length in the detector gas.

Tissue Equivalent Proportional Counters

How They Measure Dose Equivalent

- The energy transferred (imparted) to the gas per particle is:

$$\epsilon = LET \times l \qquad \text{or} \qquad LET = \epsilon / l$$

ϵ is the energy imparted to the detector gas per particle (e.g., keV).

LET is the average linear energy transfer of the particle over the path length (e.g., keV/um).

l is the particle path length (um).

Tissue Equivalent Proportional Counters

How They Measure Dose Equivalent

- While the energy transferred (imparted) to the gas per particle (ϵ) can be measured, we don't know the path length (l) so we can't determine the LET.
- However, if the detector chamber has a known geometry, we can calculate the average path length of the particles traversing the chamber.
- The average path (chord) length of particles traversing a sphere is easy to determine.

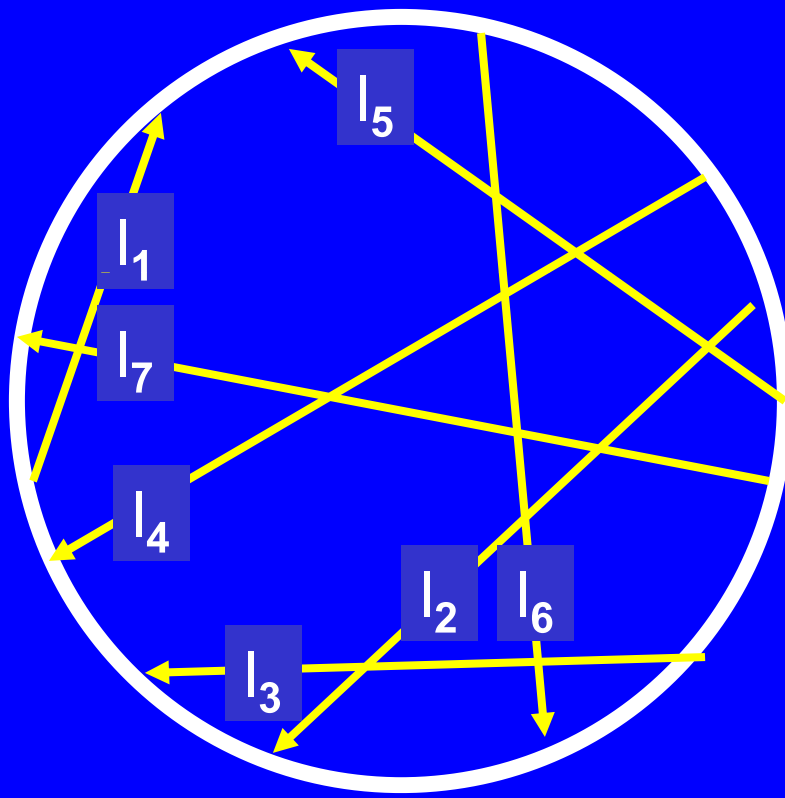
Tissue Equivalent Proportional Counters

How They Measure Dose Equivalent

The average path (chord) length for a sphere is:

$$l_{ave} = (4/3)\ R$$

Where R is the sphere radius



Tissue Equivalent Proportional Counters

How They Measure Dose Equivalent

- Knowing the average path length of particles traversing a spherical detector chamber, and knowing the energy transferred to the gas per particle, allows us to calculate a quantity closely related to the LET: the lineal energy.

- The lineal energy (y) is: $$y = \frac{\varepsilon}{I_{ave}}$$

- The lineal energy (y), unlike the LET, can be measured easily.

Tissue Equivalent Proportional Counters

How They Measure Dose Equivalent

- According to ICRU 40, "the lineal energy is the quotient of ϵ by l_{ave}, where ϵ is the energy imparted to matter in a volume by a single energy-deposition event and l_{ave} is the mean chord length in that volume"

$$y = \frac{\varepsilon}{I_{ave}}$$

- Unlike LET, lineal energy (y) is a stochastic quantity – for a given type of particle and a given energy, the lineal energy varies (due to varying path lengths).

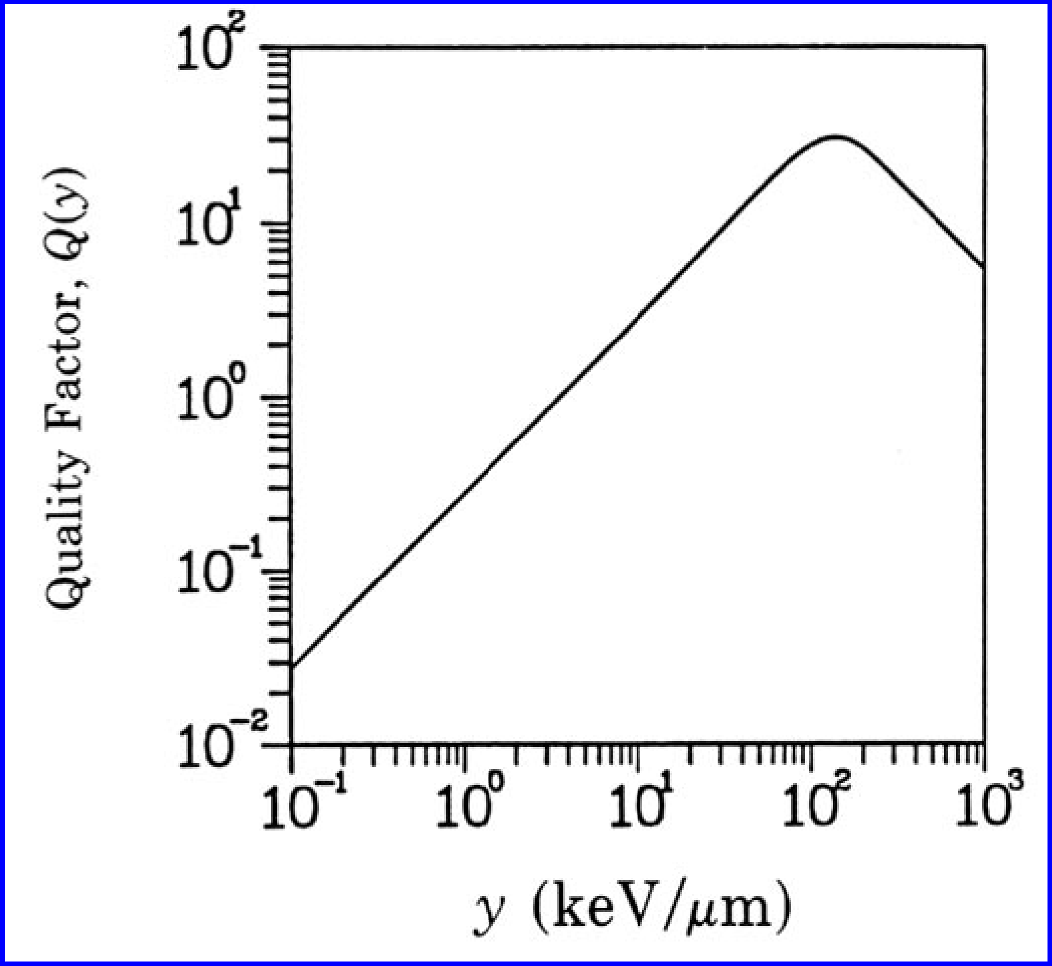
Tissue Equivalent Proportional Counters

How They Measure Dose Equivalent

- Even though the value assigned to Q is conventionally based on the LET, it is recognized that there is good reason to employ the lineal energy to calculate Q.

- According to ICRU 40, lineal energy "should thus be more closely related to the biological effect of radiation [than the LET]" and "for purposes of radiation protection, radiation quality [i.e., Q] should be based on lineal energy in a 1 um diameter sphere of ICRU tissue."

Relationship Between the Quality Factor and the Lineal Energy (ICRU 40)



Tissue Equivalent Proportional Counters

How They Measure Dose Equivalent

- Since the energy deposited in the gas by a particle (ϵ) is directly related to lineal energy (y), the pulse size is also directly related to y.
- Pulse height analysis on the TEPC output generates a lineal energy spectrum: the higher the lineal energy, the higher the channel number the pulse is sorted into.
- By using the ICRU or ICRP recommendations regarding the relationship between the lineal energy and the quality factor (Q), a value for Q can be assigned to each channel number.