## LINAC RADIATION MONITORING AND SURVEYS: INSTRUMENTS AND METHODS

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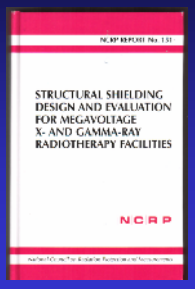
"Doing the right thing, doing it right"



## NCRP Report No. 151:Chapter 6

1. Radiation survey required for:
   - New facilities
   - 0ld installations that have been modified
   - New procedures
2. Preliminary survey immediately after accelerator is operational
3. Complete survey once accelerator is completely operational
4. Provides guidelines for surveys






## Impact of Pulsed Operation on Linac Monitoring

- Repetition rates vary from ~ 100 to 400 pulses per second
- Pulse widths range from ~ 1 to 10 microseconds
- Duty factor (DF) = pulse width x repetition rate
  - For e.g., DF =100 pulses/s x 1 x$10^{-6}$ s = 1 x $10^{-4}$
- Very small DF imposes severe restrictions on instruments
- Peak Intensity = Average Intensity/DF
  - $I_{peak}$ = 10,000 x $I_{av}$



## Impact of Pulsed Operation on Instrument Response

- Intense photon pulse overwhelms active detector that detects particles electronically
- Instruments with long dead times (GM tubes and proportional counters) saturate and count repetition rate
- Scintillation survey meters may become non-linear at high dose rates because of PM tubes
- Ionization chambers are less influenced but must be operated with adequate voltage to overcome recombination losses

## Photon Monitoring Outside Room

- Use ionization chamber with rate and integrate modes
- Integrate mode is handy for measurements outside maze
- Range up to 50 mGy/h
- Several commercial instruments are available

Inovision 451B-RYR

Fluke Biomedical Radiation Management Services, Cleveland, Ohio



## NIMBY = Neutrons In My Back Yard

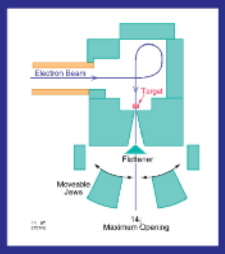
- Photoneutron production occurs at photon energies above ~ 6.2 MeV
- Monitor the neutrons
- Neutron monitoring discussed in Appendix C, NCRP 151

http://www.varian.com/orad/prd171.html



## Photoneutron Production In Accelerator Head

- Photoneutrons produced by interaction of photon beam with accelerator components
- Produced mainly in the target, primary collimator, flattener and jaws /collimators, etc.
- Typical materials are copper, iron, gold, lead and tungsten
- Neutron production in electron mode is lower than in photon mode
  - Direct production of neutrons by electrons is at least 2 orders of magnitude lower
  - Lower electron current






## Photoneutron Production

- Photoneutrons consist of direct emission and evaporation neutrons
- <u>Direct Emission</u>
  - Average energy of direct neutrons is ~ few MeV
  - Angular distribution of direct neutrons follows a $\sin^2\theta$ distribution
  - Contributes about 10-20% of neutron yield for bremsstrahlung with upper energies of 15 to 30 MV

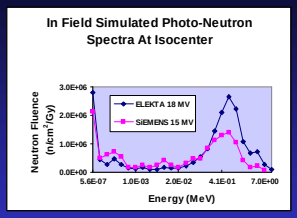
## Photoneutron Production

- **Evaporation Neutrons**
  - Dominant process in heavy nuclei
  - Emitted isotropically
  - Spectral distribution is independent of photon energy for energies that are a few MeV above neutron production threshold
  - Average energy is ~ 1 -2 MeV
  - Evaporation spectra closely resemble fission spectra



## Photoneutron Spectra Inside Primary Beam

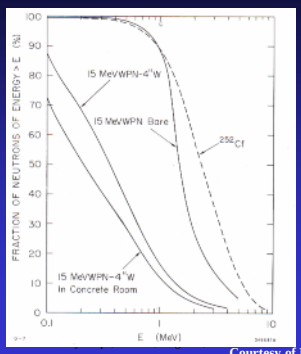
- C. Ongara et al, Phys. Med. Biol. 45 (2000) L55-L61
- Simulations in patient plane with Monte Carlo Code MCNP-GN
- Field size =10 cm x 10 cm
- Isocenter = 100 cm from target
- Neutron fluence includes room scattered neutrons and direct neutrons from accelerator head




ELEKTA-18 MV , $E_{av}$= 0.71 MeV
SIEMENS 15 MV, $E_{av}$= 0.34 MeV



## Integral Photoneutron Spectra for 15 MeV Electrons Striking a Tungsten Target (NCRP 79)




Courtesy of R.C. McCall



## Photoneutron Spectrum

- Photoneutron spectrum from accelerator head resembles a fission spectrum
- Spectrum changes after penetration though head shielding
- Since linac is in concrete vault, room scattered neutrons will further soften the spectrum
- Spectrum outside the concrete shielding resembles that of a heavily shielded fission spectrum
  - Average energy is significantly less than inside room
  - Most neutrons are < 0.5 MeV in energy

## Neutron Energy Classification

- Thermal: $\bar{E}_n$ = 0.025 eV at 20°C
  Typically $E_n \leq 0.5$ eV (Cd resonance)
- Intermediate: 0.5 eV $< E_n \leq 10$ keV
- Fast: $E_n > 10$ keV
- Epithermal $E_n > 0.5$ eV

For therapy linacs neutron spectrum can be divided into two energy regions:

- Thermal (0 – 0.5 eV)
- Epithermal (> 0.5 eV)



## Neutron Detector Calibration

- Calibration Sources
  - PuBe , $E_{av}$ = 4.2 MeV, AmBe, $E_{av}$ = 4.5 MeV
  - $^{252}$Cf, $E_{av}$ = 2.2 MeV
  - PuF, $E_{av}$ = 0.9 MeV, PuLi, $E_{av}$ = 0.5 MeV
- Use of PuBe and AmBe can lead to systematic uncertainties because of higher energies
- Spectrum of fission neutrons from $^{252}$Cf is in general similar to a typical photoneutron spectrum
- Detector calibrated with $^{252}$Cf may be adequate for neutrons in primary beam
- Spectrum outside primary beam and outside room shielding is a heavily shielded photoneutron spectrum
- Thus assumption of fission spectrum may lead to errors in the above case



## Neutron Monitoring

- Measurement of fluence (n cm$^{-2}$)
- Measurement of dose equivalent (ambient dose equivalent) or dose equivalent rate
- Measurement of neutron spectrum

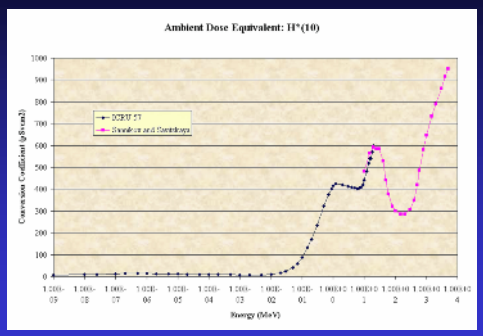


## Determination of Neutron Dose Equivalent (H)

- Radiation protection quantities defined in human body
- Not amenable to measurement
- ICRU developed operational quantities (ambient, directional, personal dose equivalent)
- Numerical value determined
  - Measuring a physical quantity, fluence ($\Phi(E)$ ) which characterizes field
  - Converting to dose equivalent using conversion coefficients ($h_\Phi(E)$ )
  - $H^*(10) = \int h_\Phi(E)\, \Phi(E)\, dE$

J.C. McDonald et al., Rad. Prot. Dosim. Vol. 78, pp. 147-148, 1998

## Conversion Coefficients



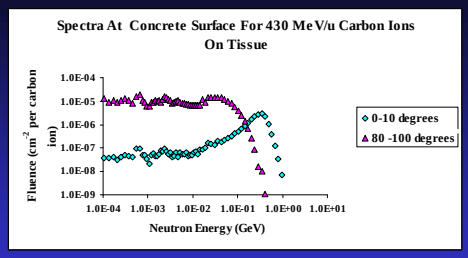

- Higher neutron energies encountered at particle therapy facilities
- Proton ~ 250 MeV
- Carbon Ions ~ 1 Gev

Courtesy of R.H. OLsher

Sannikov & Savitskaya, Radiat. Prot.Dosim. 70, Nos 1-4, 383-386, 1997



## Neutron Spectra From Carbon Ions On Tissue




Spectra at 0-10 ° extends to ~ 1 GeV

Spectra at 80-100 ° extends to ~ 400 MeV

N. Ipe & A. Fasso, Proceedings of SATIF8, Shielding Aspects of Targets, Accelerators and Irradiation Facilities, Eighth Meeting, 22-24 May 2006, Pohang, Korea, In Press.



## Difficulties With Neutron Monitoring Inside Treatment Room

- Photon interference from primary and leakage photons
  - Photon fluence inside beam is 1000 - 4000 x higher than neutron fluence
  - Photon fluence outside beam is 10 - 100 x higher than neutron fluence
  - Intense photon pulse overwhelms active detector
  - Photon pulse pile up
  - Photon induced responses in passive detectors from primary beam



## Difficulties With Neutron Monitoring Inside Treatment Room

- For moderated detectors measured neutron readings are higher than the repetition rate because
  - Scattered radiation in room
  - Neutron moderation time allows an event to be detected after pulse has ended
- Neutron detection spread over decades of energy (0.025 eV – several MeV)
  - No single detector can accurately measure fluence or dose equivalent over entire range
- Only passive detectors can be used, except at the outer maze area

## Neutron Monitoring Outside Room

- Neutron pulse spread over several 100 μs because of moderation
- Neutron spectrum resembles heavily shielded fission source- many low energy neutrons (100's of keV and less)
- Most neutrons have energies less than 0.5 MeV outside well shielded room
- Average neutron energy at outer maze area ~ 100 keV
- Active and passive detectors can be used



## Neutron Monitoring Techniques

- Active
  - Relies on slowing down or moderating fast neutrons until they reach thermal energies
  - Thermal detector used to detect thermal neutrons
  - Instrument is designed to measure dose equivalent (rem-meters) or fluence (fluence meters)
  - Can be used for measurements outside room
- Passive
  - Relies on similar principle or direct interactions
  - Method of choice for measurements inside room



## Thermal Detectors

1. BF3 Proportional counter

- $^{10}B\ (n_{th},\alpha)^{7}Li$, $E_Q$ = 2.31 MeV, σ = 3840 barns
- α and recoil $^{7}Li$ nucleus produce large pulse, orders of magnitude higher than photon pulse
- Excellent photon rejection, low cost
- Most commonly used outside shielded therapy rooms

$E_Q$ = kinetic energy released
σ = thermal neutron cross section
Cross sections drop roughly as $E_n^{-1/2}$
Detectors without moderators are sensitive only to thermal neutrons



## Thermal Detectors

2. $^{3}He$ Proportional Counter

- $^{3}He(n_{th}, p)^{3}H$, $E_Q$ = 0.76 MeV, σ = 5330 barns
- More sensitive, more stable, much more expensive

3. LiI(Eu) scintillator:

- $^{6}Li(n_{th}, \alpha)^{3}H$, $E_Q$ = 4.78 MeV, σ = 940 barns
- Very high sensitivity, poor photon rejection
- Difficult to use in mixed photon-neutron fields

## Active Detectors

- Rem-meters (outside room, and outer maze entrance, NOT inside room)
- Moderated BF3 Detectors (outside room, and outer maze entrance, NOT inside)

BF3




## Rem-Meters

- Consist of a neutron moderator (hydrogenous like material e.g. polyethylene) surrounding a thermal detector
- Moderator slows down fast and intermediate neutrons which are then detected by the thermal detector
- Useful in radiation fields for which spectrum is not well characterized
- Important to have a rough idea of the spectrum

Studsvik 2202D

Berthold LB 6411



## Rem-Meters

- Energy response is determined by size and geometry
- Response is shaped to fit an appropriate fluence to dose-equivalent conversion coefficient over a particular energy range
- Most rem-meters over respond in intermediate energy range
- <u>Provide adequate measure of dose equivalent between 100 keV and 6 MeV</u>
- Pulse pile up at high photon dose rates
- Dead time corrections at high neutron dose rates

Eberline NRD – PRESCILA - WENDI

Courtesy of R.H. Olsher



## Rem-Meter Response

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

where

$h_\Phi(E)$ is the fluence to ambient dose equivalent conversion coefiicient

$\Phi(E)$ is the neutron fluence as a function of energy for a given neutron field.

Rem meter response, R, is given by:

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

where

$r_\Phi(E)$ 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.

## Rem-Meter Response

- As long as $r_{\Phi}(E)$ has a similar energy response to that of $h_{\Phi}(E)$, the rem meter measurement can be said to be accurate
- The ratio $r_{\Phi}(E)/ h_{\Phi}(E)$ defines the traditional energy response of the rem meter in terms of counts per unit dose equivalent



## Victoreen Portable Neutron Survey Meter Model 190n

- Andersson Braun remmeter
- Polyethylene cylinder 24 cm long, 21.6 cm in diameter containing BF3 tube
- Fill gas is 96% enriched $^{10}B$
- Range: 0 µSv/h to 0.75 Sv/h
- Integrate: 0 µSv to 10 Sv
- Gamma rejection: up to 500 R/h for $^{137}Cs$
- Directionality: Less than 20% in orthogonal directions
- Weighs 9.52 kg

Courtesy of Fluke Biomedical Radiation Management Services, Cleveland, Ohio



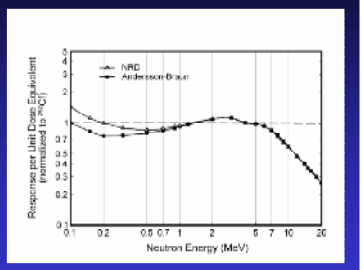
## Thermo Electron Corporation ASP/2e NRD Neutron Survey Meter

- Portable, battery operated
- BF3 tube in 22.9 cm diameter cadmium-covered polyethylene sphere
- Tissue equivalent from thermal to ~ 10 MeV
- Dose equivalent range: 1 - 100 mSv/h
- Background gamma rejection : up to ~ 5 Gy/h

http://www.thermo.com/com/cda/product/detail/1,1055,16071,00.html



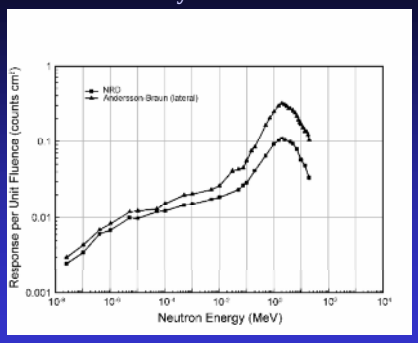
## Thermo Electron Corporation ASP/2e NRD Neutron Survey Meter




- Dead Time: 10 µs nominal
- Directional response: within 10%
- Response time: Slow, Medium, Fast (programmable from 0 - 255 µs)
- Dual Analog/Digital display
- Ratemeter: integrate and scalar
- Count range: 1 – 1.3 million cpm

http://www.thermo.com/com/cda/product/detail/1,1055,16071,00.html

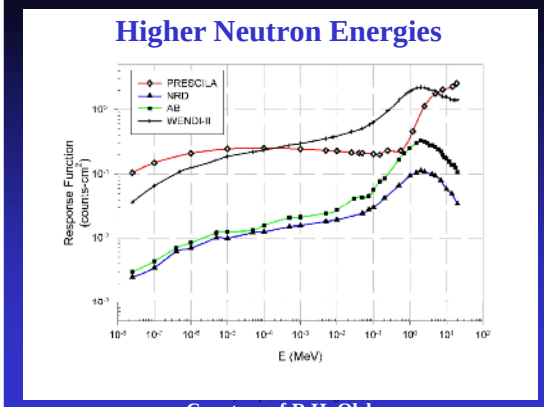
## Response of Thermo Electron Corporation NRD Neutron Survey Meter and AB rem-meter




Courtesy of R.H. Olsher



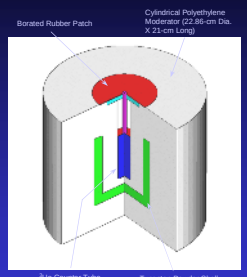
## Higher Neutron Energies




Courtesy of R.H. Olsher



## WENDI-II – Extended Energy to 5 GeV




WENDI-II REM Meter: Cutaway View



http://www.thermo.com/com/cda/product/detail/1,1055,10121729,00.html

## Fluence Meters -Moderated BF3 Detector

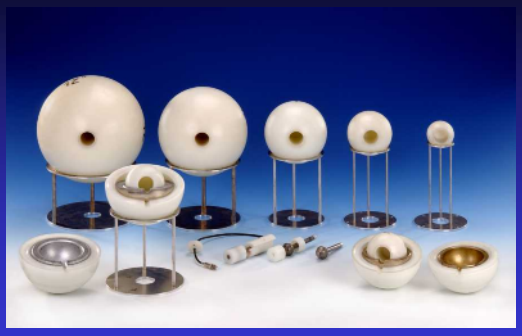
- Bare BF3 detector measures thermal neutron fluence rate
- Moderator enclosed in 0.5 mm cadmium eliminates incident thermal neutrons
- Moderated BF3 measures epithermal neutron fluence rate
- Fluence converted with appropriate coefficients to obtain dose equivalent
- Use requires knowledge of spectrum
- Moderated BF3 is useful to monitor relative variations of neutron field with time (e.g. IMRT)
- Ratio of rem-meter and moderated BF3 detector readings provides rough estimate of neutron spectrum

## Neutron Spectrometer - Bonner Spheres

- Series of hydrogenous spheres with varying diameters surrounding a thermal detector
- Amount of moderation varies in each sphere
- Calculate spectrum by folding responses into a series of equations
- Requires computer program, large number of spheres and long measurement times
- Process is laborious
- Can be used with active and passice detectors



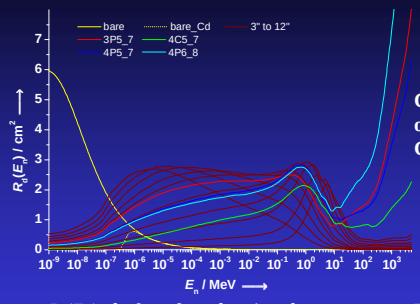
## Bonner Spheres -The PTB NEMUS



Courtesy of PTB, Germany



## Bonner Spheres -The PTB NEMUS




Courtesy of PTB, Germany

The response $R_d(En)$ of sphere $d$ as a function of neutron energy $E_n$ for the bare and cadmium shielded SP9 counter (yellow), for the regular polyethylene spheres (brown) and for the modified spheres with embedded copper (green) and lead shells (cyan, red and blue)



## Passive Detectors

- Activation Detectors (inside room, and in primary beam)
- Bubble Detectors (inside and outside room, NOT in primary beam)
- Solid State Track Detectors (inside room, NOT in primary beam)

## Photon Induced Effects in Bubble and Track Detectors*

1. $^{2}D(\gamma,n)p$ , $E_{th}$ = 2.23 MeV,
   ($E_{th}$ = threshold energy, 0.02% of hydrogen is deuterium)
2. $^{16}O(\gamma, \alpha)^{12}C$, $E_{th}$ = 7.2 MeV
3. $^{12}C(\gamma, \alpha)^{8}Be \rightarrow 2\alpha$, $E_{th}$ = 7.4 MeV

*Ipe et al, Radiat. Prot. Dosim. 23:135,1988



## Activation Detectors

- Stable and reproducible
- Photon interference must be considered
- Thermal neutron detectors
  - Gold (thermal)
  - Indium (thermal)
- Threshold detectors
  - Phosphorus (thermal and fast)

http://www.thermo.com/com/cda/product/detail/1,1055,114807,00.html



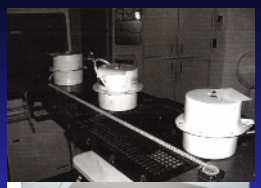
## Thermal Neutron Detectors

- Bare foil and cadmium covered foil can be used for thermal neutron fluences
- Moderated foil for fast neutrons
- Neutron absorption by foil results in production of radioactive nucleus
- Radioactivity can be correlated with incident thermal neutron fluence
- Gold and Indium foils counted with thin window GM, proportional counter, scintillation counter or GeLi detector



## Moderated Activation Foils

- Moderator consists of a cylinder of polyethylene, 15.2 cm in diameter, 15.2 cm in height
- Covered with 0.5 mm of cadmium (or with boron shield)
- Moderator provides an energy independent thermal neutron fluence, proportional to incident fast fluence
- For in beam exposures:
  - Use only at energies ≤ 20 MV because of photon induced response in cadmium and moderator lining
  - Field size wide enough to irradiate entire moderator
- Distance between moderators should be 2X diameter of the moderator



## More moderators, and then some! Some more effective than others!



## Threshold detectors

- Radioactivity produced by fast neutron interaction when neutron energy is above some threshold
- Phosphorous counted with liquid-scintillation counter



## Activation Detectors (AAPM Report No. 19)

| Reaction | Cross Section (b) | Percent Abundance | Product Half Life | Decay Radiation (MeV) | Branching Intensity |
|---|---|---|---|---|---|
| $^{115}In\ (n_{th},\gamma)\ ^{116m}In$ | 194 | 95.7 | 54 m | β-: 1.00<br>γ: 0.138 to 2.111 | 1.00 |
| $^{197}Au\ (n_{th},\gamma)\ ^{198}Au$ | 99 | 100 | 2.698 d | β-: 0.962<br>γ: 0.412 | 0.99<br>0.99 |
| $^{31}P(n,p)^{31}S$ Threshold=0.7 MeV | Varies with energy | 100 | 2.62 h | β-: 1.48<br>γ: 1.26 | 0.99<br>0.07 |
| $^{31}P\ (n_{th},\gamma)\ ^{32}P$ | 0.190 | 100 | 14.28 d | β-: 1.71 | 1.00 |

## Bubble Detectors, Bubble Technology Industries, Canada

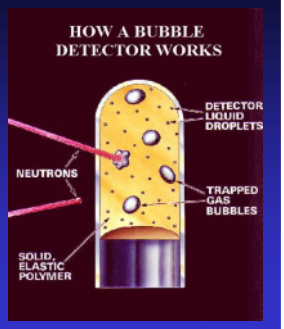
- Easy to use
- High sensitivity
- Reusable
- Integrating
- Allow instant visible detection of neutrons
- Isotropic response
- Variations in sensitivity within a batch

http://www.bubbletech.ca/b_info.htm

*Ipe et al, SLAC PUB 4398, 1987

## Bubble Detectors, BTI, Canada

- Consist of minute droplets of a superheated liquid dispersed throughout an elastic polymer
- Detector sensitized by unscrewing the cap
- Neutrons strike droplets producing secondary charged particles
- Charged particles cause droplets to vaporize, producing bubbles
- Bubbles remain fixed in polymer
- Bubbles can be counted by eye or in automatic reader
- Dose is proportional to the number of bubbles




http://www.bubbletech.ca/b_page2.htm



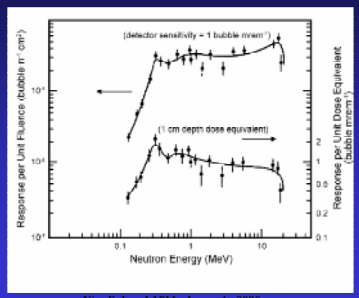
## Bubble Detectors (BTI , Canada)

| Characteristics | BDPND | BD100R | BDT | BDS |
|---|---|---|---|---|
| Energy Range | <200 keV->15MeV | <200 KeV->15MeV | Thermal ~1/V for epithermals | 6 distinct thresholds: 10, 100, 600, 1000,2500, 10 000 keV |
| Dose range | 0.1 – 500 mrem | 0.1 - 500 mrem | 0.1 - 10 mrem | ~50 mrem |
| Sensitivity (Typical) | 0.33 - 33 bub/mrem 0.033-3.3 bub/µSv | 0.33 - 33 bub/mrem .033 – 3.3 bub/ µSv | ~30 bub/mrem 3.0 bub/µSv | 1-2 bub/mrem 0.1-0.2 bub/µSv |
| Gamma Sensitivity | None but photon induced effect | None but photon induced effect | None but photon induced effect | None but photon induced effect |
| Tissue Equivalence | Yes | Yes | Yes | Yes |
| Temperature Compensation | Yes | No | Yes | No |

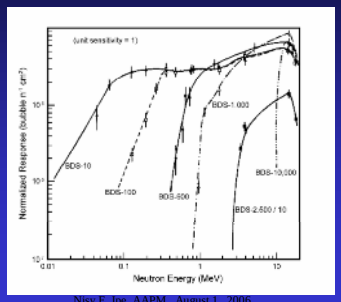
## Bubble Detectors (BTI , Canada)

| Characteristics | BDPND | BD100R | BDT | BDS |
|---|---|---|---|---|
| Optimum Temp. Range | 20-37°C | 10-35°C | 20-37°C | 20°C |
| Angular Response | Isotropic | Isotropic | Isotropic | Isotropic |
| Size | 145mm x 19mm dia | 120mm x 16mm dia | 145mm x1 9mm dia | 80mm x 16mm dia |
| Weight | 58g | 33g | 58g | 20g |
| Re-use | Yes | Yes | Yes | >10 cycles |
| Warranty | 90 days | 90 days | 90 days | 90 days |
| Other | | T Response Curve Provided | Thermal/fast Sensitivity 10/1 | Special Recompression Chamber Available |

## Response of BD-PND as a Function of Energy



## Normalized Response of BDS as a Function of Energy






## Solid State Nuclear Track Detector Neutrak® 144, Landauer, Inc.

- CR-39 (di allyl glycol carbonate) solid state track detector
- Fast neutron option: polyethylene radiator
  - Recoil proton from fast neutron interaction leaves sub microscopic damage trails
- Thermal neutron option: boron loaded teflon radiator + polyethylene radiator
  - $^{10}B(n_{th}, \alpha)^{6}Li$
- Detector is chemicially etched to reveal tracks
- Tracks are counted in an automatic counter
- Neutron dose is proportional to number of tracks
- Fast: 40 keV to 30 MeV, 20 mrem minimum
- Thermal : < 0.5 eV, 10 mrem minimum


http://www.landauerinc.com/neutron.htm



## Neutrak® ER

- Neutrak® 144 + TLD albedo
- Fast: 40 keV to 30 Mev
- TLD Albedo : 0.5 eV -100 keV
- Minimum dose: 20 mrem

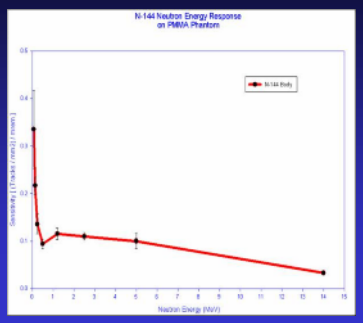
Note: Track etch detectors suffer from directional dependence


http://www.landauerinc.com/neutron.htm

*Ipe et al, Radiat. Prot. Dosim. 23:135,1988

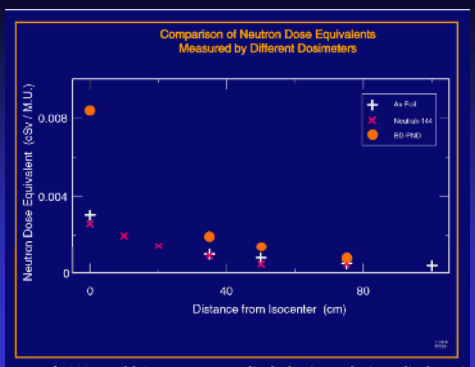


## Sensitivity of Neutrak 144® as a Function of Neutron Energy




Courtesy of Landauer, Inc.

NEUTRON DOSE EQUIVALENT IN PATIENT PLANE FOR 15 MV VARIAN CLINAC 2300 C/D




Ipe et al, Proc. of 2000 World Congress on Medical Physics and Biomedical Engineering, July 2000, Chicago

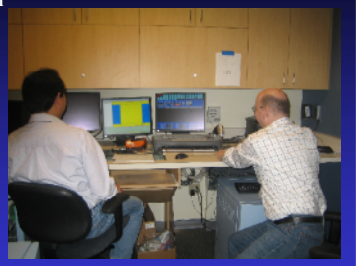
## Neutron Monitoring

- Neutron monitoring inside treatment room may be performed to determine
  - Neutron leakage from accelerator head
  - Neutron dose equivalent in patient plane, inside and outside primary beam
- Prudent to perform spot checks outside treatment room with hydrogenous barriers
- Laminated barriers shall be monitored for neutrons
- Neutrons shall be monitored at door, maze entrance and any opening through shielding



## Radiation Surveys For Shielding Evaluation

1. Record name of individual performing surveys
2. Record facility name and linac information
3. Record survey instrument manufacturer, model no., and date of calibration
4. Set machine to desired energy
5. Use maximum field size
6. Set machine to highest dose rate
7. Remove phantom
8. Record linac parameters





## Radiation Surveys For Shielding Evaluation

9. Set gantry angle at 0º
10. Perform photon and neutron measurements at 30 cm from the primary barrier
11. Record readings on plans and sections
12. Repeat with gantry angles at 90, 180 and 270 degrees and oblique angles as necessary (laminated barriers, wall floor intersections etc.)
13. Repeat all the above measurements for secondary barriers with phantom in beam

## Accelerator Head Leakage

- Wrap film around accelerator head to identify hot spots
- Measure with ion chamber at 1 m from source for locations -M(L)
- Measure 10 cm x 10 cm open field at isocenter with ion chamber - M(IC)
- % Leakage = M(L)/M(IC) x 100

Courtesy of C. Ma