NEUTRON SHIELDING DESIGN AND EVALUATIONS

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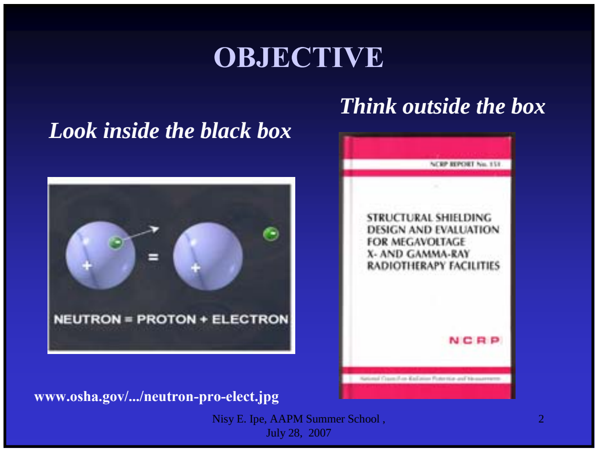
"Doing the right thing, doing it right"

www.osha.gov/.../neutron-pro-elect.jpg



OBJECTIVE

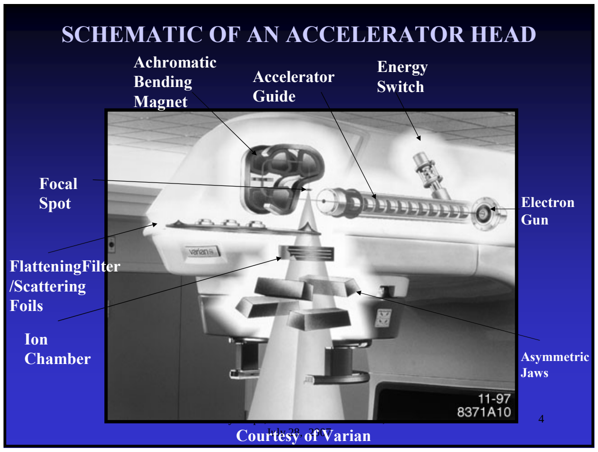
Look inside the black box

Think outside the box

www.osha.gov/.../neutron-pro-elect.jpg

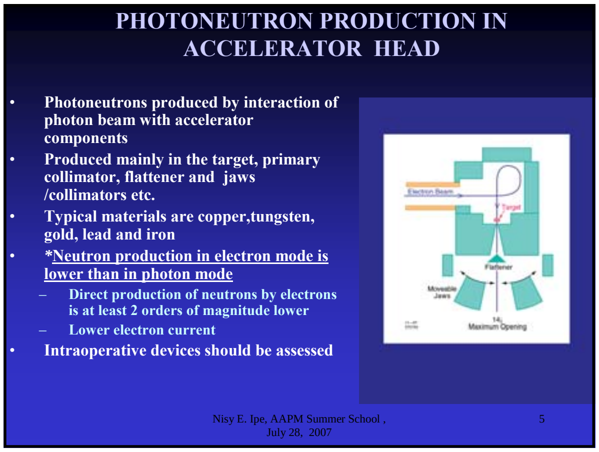
OUTLINE

- Photoneutron Production
- Photoneutron Spectra
- Neutron Interactions
- Transport in Accelerator Head
- Neutron Yields
- Neutron Shielding Materials & TVLS
- Neutron Monitoring
- Not covered
  - *Mazes*
  - *Laminated Barriers*
  - *Skyshine*



SCHEMATIC OF AN ACCELERATOR HEAD

Courtesy of Varian



PHOTONEUTRON PRODUCTION IN ACCELERATOR HEAD

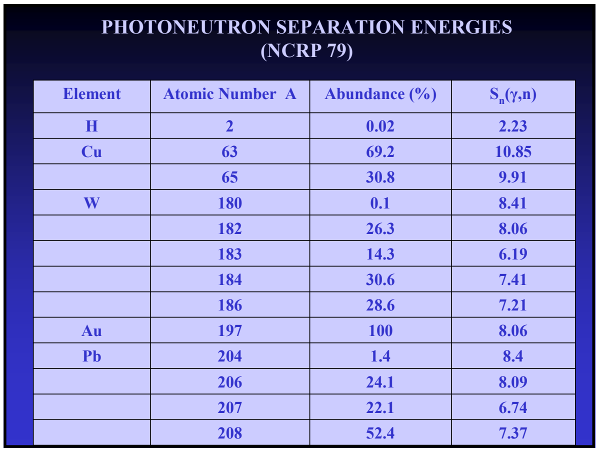
- Photoneutrons produced by interaction of photon beam with accelerator components
- Produced mainly in the target, primary collimator, flattener and jaws /collimators etc.
- Typical materials are copper,tungsten, gold, lead and iron
- *<u>Neutron production in electron mode is lower than in photon mode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

PHOTONEUTRON PRODUCTION

- Photon must have energy greater than binding energy of nucleus in atom
- S_n =Separation Energy

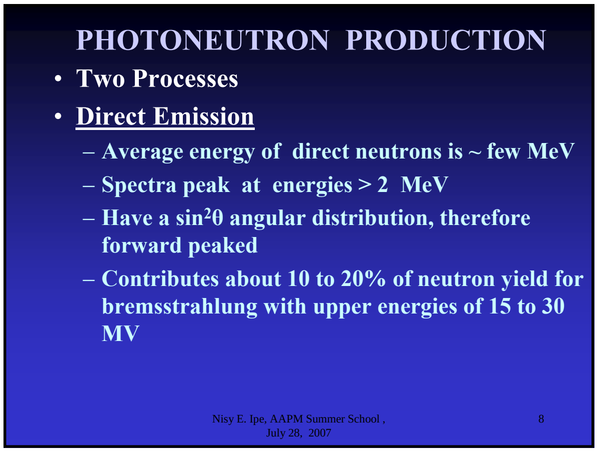
<u>Neutron production in primary laminated barrier</u>

- Lead has lower S_n than Iron
  - Lead
    - Pb-207 (22.1%): S_n =6.74 MeV (NCRP 79)
    - Pb-208 (52.4%) : S_n = 7.37 MeV
  - Iron
    - Fe-57 (2.1%): S_n= 7.65 MeV
    - Fe-56 (91.7%): S_n =11.19 MeV
- Lead has a higher neutron yield than iron
- Steel is a better choice for reducing neutron production



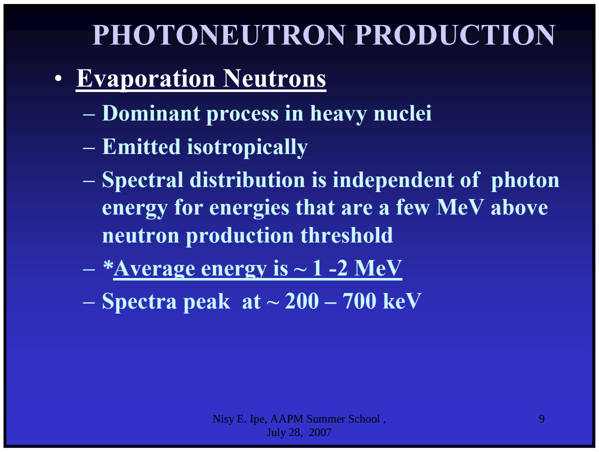
PHOTONEUTRON SEPARATION ENERGIES (NCRP 79)

Element	Atomic Number A	Abundance (%)	$S_n(\gamma,n)$
H	2	0.02	2.23
Cu	63	69.2	10.85
	65	30.8	9.91
W	180	0.1	8.41
	182	26.3	8.06
	183	14.3	6.19
	184	30.6	7.41
	186	28.6	7.21
Au	197	100	8.06
Pb	204	1.4	8.4
	206	24.1	8.09
	207	22.1	6.74
	208	52.4	7.37



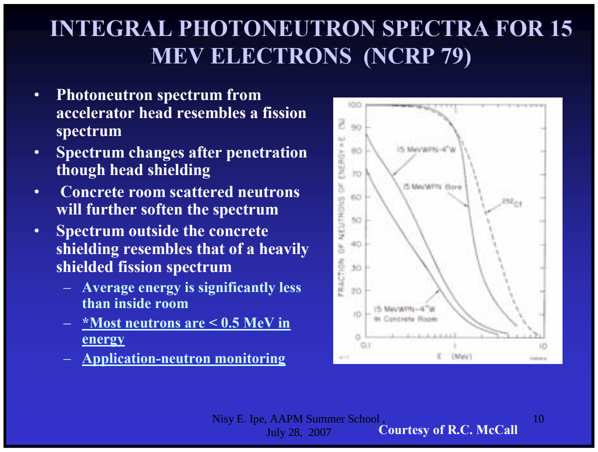
PHOTONEUTRON PRODUCTION

- Two Processes
- **Direct Emission**
  - Average energy of direct neutrons is ~ few MeV
  - Spectra peak at energies > 2 MeV
  - Have a $\sin^2\theta$ angular distribution, therefore forward peaked
  - Contributes about 10 to 20% of neutron yield for bremsstrahlung with upper energies of 15 to 30 MV



PHOTONEUTRON PRODUCTION

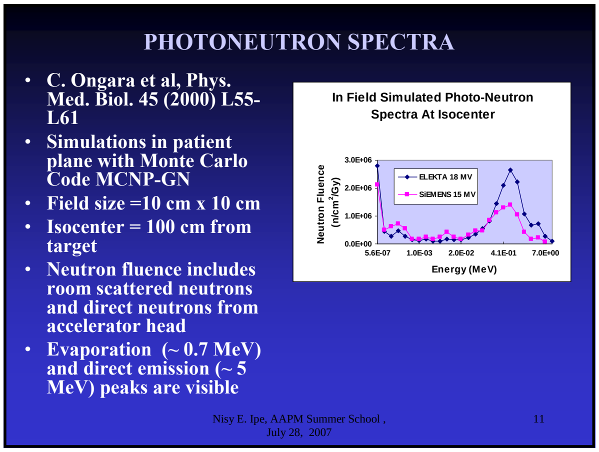
- **Evaporation Neutrons**
  - Dominant process in heavy nuclei
  - Emitted isotropically
  - Spectral distribution is independent of photon energy for energies that are a few MeV above neutron production threshold
  - *Average energy is ~ 1 -2 MeV
  - Spectra peak at ~ 200 – 700 keV



INTEGRAL PHOTONEUTRON SPECTRA FOR 15 MEV ELECTRONS (NCRP 79)

- Photoneutron spectrum from accelerator head resembles a fission spectrum
- Spectrum changes after penetration though head shielding
- Concrete 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
  - Application-neutron monitoring

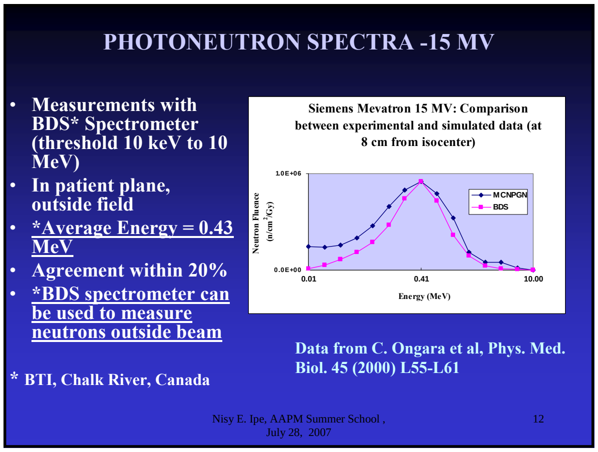
Courtesy of R.C. McCall



PHOTONEUTRON SPECTRA

- 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
- Evaporation (~ 0.7 MeV) and direct emission (~ 5 MeV) peaks are visible

In Field Simulated Photo-Neutron Spectra At Isocenter



PHOTONEUTRON SPECTRA -15 MV

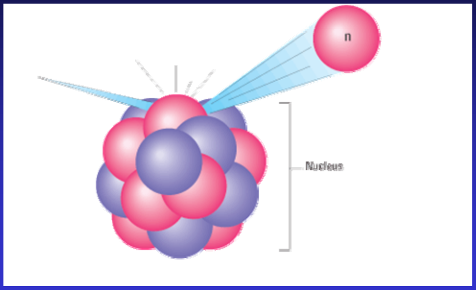
- Measurements with BDS* Spectrometer (threshold 10 keV to 10 MeV)
- In patient plane, outside field
- *Average Energy = 0.43 MeV
- Agreement within 20%
- *BDS spectrometer can be used to measure neutrons outside beam

Siemens Mevatron 15 MV: Comparison between experimental and simulated data (at 8 cm from isocenter)

Data from C. Ongara et al, Phys. Med. Biol. 45 (2000) L55-L61

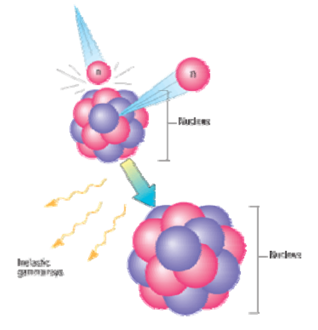
* BTI, Chalk River, Canada

ELASTIC SCATTERING



http://www.glossary.oilfield.slb.com/Display.cfm?Term=elastic%20neutron%20scattering

INELASTIC SCATTERING



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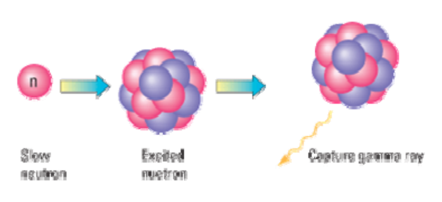
NEUTRON CAPTURE

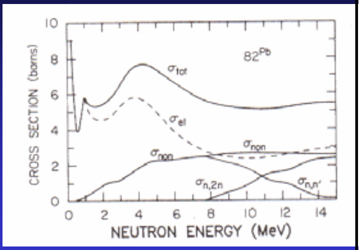


NEUTRON INTERACTIONS

- Almost all interactions are scatters (elastic or inelastic)
- In light materials (hydrogenous) elastic scatter helps thermalize neutrons
- Interaction with hydrogen is like a billiard ball collision
- In heavy materials only inelastic scattering reduces neutron energy
- Absorption important only at thermal energies and in a few resonances in keV region

NEUTRON INTERACTION CROSS-SECTIONS IN LEAD (NCRP 79)

- **Non elastic cross section (σ_{non}) is the sum of inelastic ($\sigma_{n\ \acute{n}}$) and (n, 2n) cross sections**
- **Inelastic scattering dominates at lower energies and (n, 2n) dominates at higher energies**
- ***Pb is transparent to neutrons below 0.57 MeV**
  - *Application: Lead sills should not be used under linac vault doors at higher energies*



TRANSPORT IN ACCELERATOR HEAD

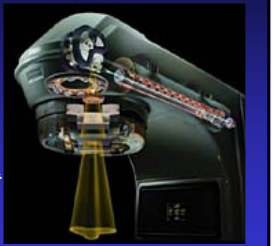
- High-Z shielding material not very effective in attenuating neutrons
- Neutrons lose energy by non-elastic, i.e. inelastic scattering and (n, 2n) reactions (which result in build up of fluence)
- Neutrons undergo elastic scattering in head shielding resulting in increased path length and therefore more opportunities for non-elastic reactions
- High Z shielding degrades neutron energy
- Absorbed dose or dose equivalent is therefore reduced.

*High-Z material in placed front of hydrogenous shielding makes latter more effective because of degradation of neutron energy

Application: laminated barriers and door

TRANSPORT IN ACCELERATOR HEAD

- *Maximum amount of neutrons are produced inside head when collimators are completely closed
  - Application: Include small fields for neutron radiation survey
- Neutrons are nearly isotropic and penetrate head in all directions
- *Leakage neutron yield at 1 m from target in target plane should be used for shielding calculations for secondary barriers



http://www.varian.com/orad/prd160.html

Neutron Energy Classification

- Thermal: $\bar{E}_n = 0.025$ eV at 20ºC
  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

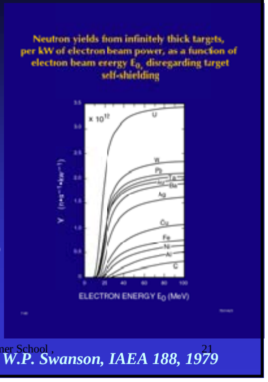
For therapy linacs neutron spectrum can be divided into two energy regions:

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

PHOTONEUTRON YIELD

- Yield depends on primary electron energy and target material
  - *Siemens 18 MV has lower neutron yield than Varian 18 MV because of differing end point energies and target material**
- Rapid rise in neutron production
- as primary electron energy is varied through the range of 10 -20 MeV
- Slower rise above 25-30 MeV
- Neutron yields are summarized in NCRP 151, Appendix B: Table B-9

**O. Chibani & C.M.Ma, Med. Phys. 30(8)



W.P. Swanson, IAEA 188, 1979

OUTSIDE-BEAM NEUTRON YIELD AT 1 M FROM TARGET FOR ELEKTA LINACS*

Energy (MV)	Neutron Yield (%Gy/Gy)	Neutron Yield (mSv/Gy with QF =10)
10	0.003	0.3
15	0.007	0.7
18	0.015	1.5
20	0.020	2.0
25	0.030	3.0

Use these values for secondary barriers

*Elekta Site Planning Guide 4513 370 1526 06

OUT-BEAM NEUTRON YIELD AT 1 M FROM TARGET (HEAD) FOR SIEMENS LINACS*

Energy (MV)	Field Size (cm x cm)	Max. Neutron Yield (%Gy/Gy)	Neutron Yield (mSv/Gy with QF =10)
10	0 x 0	0.001	0.1
15	0 x 0	0.004	0.4
18	0 x 0	0.007	0.7
20	0 x 0	0.014	1.4
23	0 x 0	0.012	1.2

Use these values for secondary barriers

*Courtesy of Siemens Medical Solutions, U.S.A.

IN-BEAM NEUTRON YIELD AT ISOCENTER FOR SIEMENS LINACS*

Energy (MV)	Field Size (cm x cm)	Neutron Yield (%Gy/Gy)	Neutron Yield (mSv/Gy with QF =10)
10	20 x 20	0.002	0.2
	0 x 0	0.001	0.1
15	20 x 20	0.014	1.4
	0 x 0	0.003	0.3
18	20 x20	0.022	2.2
	0 x 0	0.007	0.7
20	20 x 20	0.033	3.3
	0 x 0	0.012	1.2
23	20 x20	0.049	4.9
	0 x 0	0.015	1.5

Use 20 cm x 20 cm values for primary

barriers

*Courtesy of Siemens Medical Solutions, U.S.A.

NEUTRON YIELD FOR VARIAN LINACS *

Energy (MV)	Neutron Yield ***	Neutron Yield ***
BJR** 11 (BJR 16)	(% Sv/Gy)	(mSv/Gy)
10 (10)	0.004	0.04
15 (16)	0.07	0.7
18 (23)	0.15	1.5
20 (25)	0.18	1.8

*Varian Installation Data Package June 2006

*British Journal of Radiology

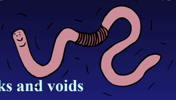
** Jaws closed

NEUTRON SHIELDING MATERIALS

- Hydrogenous materials are most effective for neutrons
- Concrete (ρ = 2.35 g/cm^3)
  - Water content is important, at least 5.5% by weight
  - 2.2 MeV γ from thermal neutron capture in H
  - Average γ energy from neutron capture= 3 MeV
  - Maximum γ energy from neutron capture = 10 MeV
  - TVL ~ 8.3”
- Heavy Concrete
  - Higher densities due to high-Z aggregates
  - TVLs for photons lower than concrete (inverse ratio of densities)
  - Typically TVLs for neutrons about the same as concrete except Ledite®* with TVL of ~ 6.4”

* Atomic International, Frederick, PA

NEUTRON SHIELDING MATERIALS



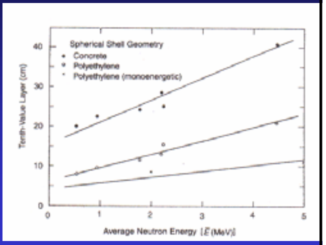
- Earth (ρ = 1.1 -1.5 g/cm^3)
  - “Dirt cheap”
  - Conpacted earth is free from cracks and voids
  - Considerable variation in composition, density and water content
  - Unlike Europe no U.S. regulations regarding protection of fauna
- Polyethylene (ρ = 0.92 g/cm^3)
  - Very effective because of H content
  - 2.2 MeV γ from thermal neutron capture in H
- Borated Polyethylene (ρ ~ 0.92 g/cm^3)
  - Typically 5% boron by weight
  - High thermal neutron capture cross section for boron (3840 b/atom)
  - 0.478 MeV γ from thermal neutron capture in boron

DOSE EQUIVALENT TENTH VALUE LAYERS FOR WALL SHIELDING (NCRP 79)

At 1 MeV,

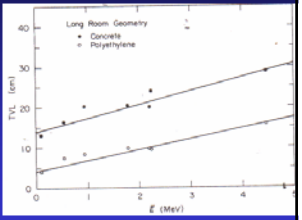
- Concrete TVL = 21 cm (8.3”)
- Polyethylene TVL = 9.6 cm (3.8”)
- NCRP 151 suggests 25 cm of concrete or 3.8” of borated polyethylene

**Note typo on page 46 3.8 cm should be 3.8”*



DOSE EQUIVALENT TENTH VALUE LAYERS FOR MAZE DOOR (NCRP 79)

- Fast neutrons at 100 keV,
  - Concrete TVL = 15 cm (5.9”)
  - Polyethylene TVL = 4.5 cm (1.8”)
  - NCRP 151 suggests 4.5 cm of borated polyethylene
- Thermal neutrons:
  - Polyethylene TVL = 1.2 cm (0.47”)
- Capture gamma rays
  - Lead TVL= 6.1 cm (2.4”)
  - Steel TVL = 13.5 cm (5.31”)
  - Concrete TVL = 46 cm (18”)



SECONDARY BARRIER NEUTRON TRANSMISSION

B_{Ln} = Neutron transmission of barrier

P = Design dose limit at point of interest

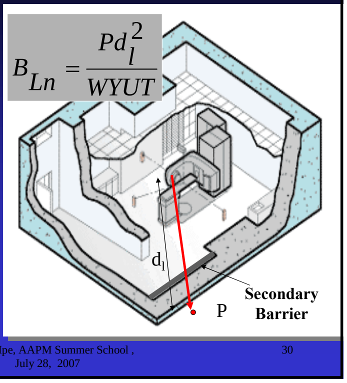
W = Workload (dose at 1 m from target)

U = Use Factor

T = Occupancy Factor

d_l = Distance from the target to point of interest

Y = Leakage neutron yield at 1 m from target (Sv/Gy)



$$B_{Ln} = \frac{Pd_l^2}{WYUT}$$

SECONDARY BARRIER NEUTRON CALCULATION

15 MV Varian Linac
W = 600 Gy/wk
Y = 0.7 x 10^{-3} Sv/Gy
P = 20 μSv/wk
U =1
T = 1
d_{sec} = 5.49 m
TVL (concrete) = 9.84” (25 cm)

$$B_L = \frac{\left(20\,x10^{-6}\right)\left(5.49\right)^2}{600\,x0.7\,x10^{-3}\left(1\right)\left(1\right)} = 1.43\,x10^{-3}$$

N = log B_x^{-1} = 2.84 TVLs
Thickness of concrete = 2.84 x 9.84” ~ 28”

SECONDARY BARRIER –PHOTON CALCULATION

15 MV Linac
W = 600 Gy/wk
Leakage = 1 /1000
P = 20 μSv/wk
U =1
T = 1
d_l = 5.49 m
TVL (concrete) = 14” (36 cm) , 13” (33 cm)

$$B_L = \frac{1000\left(20\,x10^{-6}\right)\left(5.49\right)^2}{600\left(1\right)\left(1\right)} = 1.0\,x10^{-3}$$

N = log B_x^{-1} = 3 TVLs
Thickness of concrete = 14 + 2 x 13 = 40”
Photons dominate!

CAVEAT

- Photoneutrons are produced for linacs operating above 6.2 MeV
- Normally if such facilities are adequately shielded for photons *with concrete* they will be adequately shielded for neutrons
- If shielded with lead or steel, will require concrete (or polyethylene) after the high-z material
- Order of shielding is important especially for primary barriers because of neutron production in lead or steel

NIMBY = Neutrons In My Back Yard

- Neutron monitoring discussed extensively in Appendix C, NCRP 151
- Performed inside treatment room to determine
  - Neutron leakage from accelerator head
  - Neutron dose equivalent in patient plane, inside and outside primary beam
- Prudent to perform spot checks outside concrete treatment room
- Laminated barriers shall be monitored
- Door, maze entrance and any opening through shielding shall be monitored

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

Neutron Monitoring

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

Fluence-to-Dose Equivalent Conversion Coefficients for Neutrons Derived over Past 40 Years

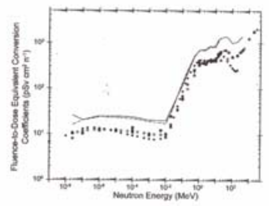


Fig. 1.1. Fluence-to-dose equivalent conversion coefficients (McDonald et al., 1998). [● (ICRP, 1996; ICRU, 1998), ▼ (DOE, 1993; NRC, 1996), — (NCRP, 1991), – – and ■ (before Paris) (ICRP, 1987), △ (ICRP, 1973), ⧫ (Patterson and Thomas, 1973), ○ (NCRP, 1971), □ (ICRP, 1964), and ● (NBS, 1957).

- Below 20 MeV differences in calculated values are negligible compared to uncertainties in estimated risk
- Two curves sit above data points because of increase in Quality Factor

With permission from NCRP Report No. 151

Instrument 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
- 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
- Assumption of fission spectrum may lead to errors in the above case

Difficulties With Neutron Monitoring Inside Treatment Room

- Photon interference from primary and leakage photons
  - Intense photon pulse overwhelms active detector
  - Photon induced responses in detectors from primary beam
- Neutron detection spread over many 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 DETECTORS

- Active
  - Moderated BF3 Detectors (outside room)
  - Rem-meters (outside room)
- Passive
  - Bubble Detectors (inside and outside room, NOT in primary beam)
  - Solid State Track Detectors (inside room, NOT in primary beam)
  - Activation Foils (inside room, and in primary beam)
    - Phosphorus (thermal and fast)
    - Gold (thermal)
    - Indium (thermal)

ACTIVE: FLUENCE DETECTOR

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
- 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

MODERATED BF3 DETECTOR

- Bare BF3 detector measures thermal neutron fluence rate
- Moderated BF3 measures epithermal neutron fluence rate
- Moderator is a hydrogenous material enclosed in 0.5 mm cadmium eliminates incident thermal neutrons
- Fluence converted with appropriate coefficients to obtain dose equivalent
- Use requires knowledge of spectrum
- Useful to monitor relative variations of neutron field with time (e.g. IMRT)

ACTIVE: REM-METER

- Consists 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

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 in intermediate energy range
- Pulse pile up at high photon dose rates
- Dead time corrections at high neutron dose rates
- Provide adequate measure of dose equivalent between 100 keV and 6 MeV

COMMERCIAL REM-METERS

Victoreen Portable Neutron Survey Meter Model 190n

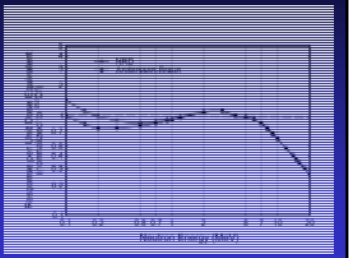
Courtesy of Fluke Biomedical Radiation Management Services, Cleveland, Ohio

Thermo Electron Corporation ASP/2e NRD Neutron Survey Meter

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

Thermo Electron Corporation ASP/2e NRD Neutron Survey Meter

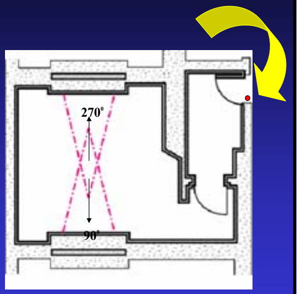
- Portable, battery operated
- Dead Time: 10 µs nominal
- Directional response: within 10%
- Ratemeter: integrate and scalar
- Tissue equivalent from thermal to ~ 10 MeV
- Dose equivalent range: 1 - 100 mSv/h
- Background gamma rejection : up to ~ 5 Gy/h



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

NEUTRON RADIATION SURVEYS

1. Record
    - Name of individual and facility
    - Linac parameters
    - Survey instrument manufacturer, model no., and date of calibration
    - Measurements on plans and sections
2. Set machine to desired energy
3. Use smallest field size and largest field size
4. Set machine to highest dose rate
5. Remove phantom and repeat with phantom
6. Measure at maze entrance and outside barriers for different gantry angles
7. Use active detector on integrate mode
8. Measure photons also



PASSIVE: ACTIVATION DETECTORS

- Neutron absorption by detector results in production of radioactive nucleus
- Radioactivity can be correlated with incident neutron fluence
- Stable and reproducible
- Photon interference must be considered
- Thermal neutron detectors
    - Gold
    - Indium
- Threshold detectors
    - Phosphorus (thermal and fast)
- Described extensively in AAPM Report No. 19

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

Activation Detectors -Thermal Neutron Detectors

- Bare foil and cadmium covered foil can be used for thermal neutron fluences
- Moderated foil for fast neutrons
- 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!

ACTIVATION DETECTORS - THRESHOLD DETECTORS

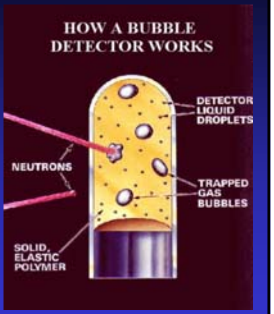
- Radioactivity produced by fast neutron interaction when neutron energy is above some threshold
- Phosphorous counted with liquid-scintillation counter
- Tedious process

Activation Foils (AAPM Report No. 19)

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

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



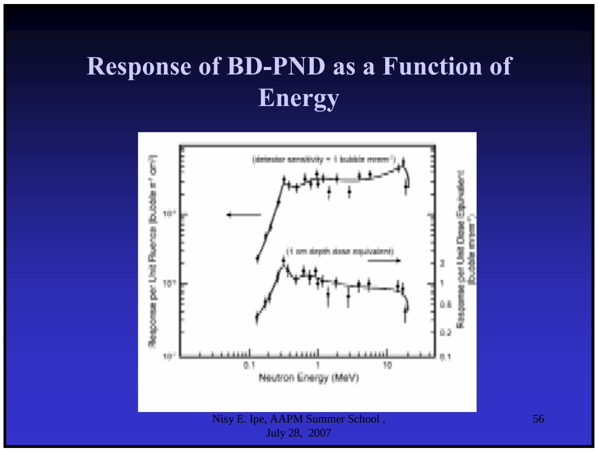
http://www.bubbletech.ca/b_page2.htm

BUBBLE DETECTORS, BUBBLE TECHNOLOGY INDUSTRIES, CANADA

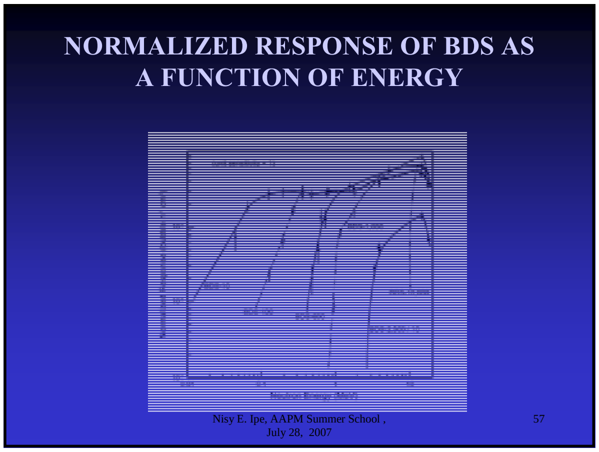
- Easy to use
- High sensitivity
- Reusable
- Integrating
- Allow instant visible detection of neutrons
- Isotropic response
- Variations in sensitivity within a batch
- Photon induced effects

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

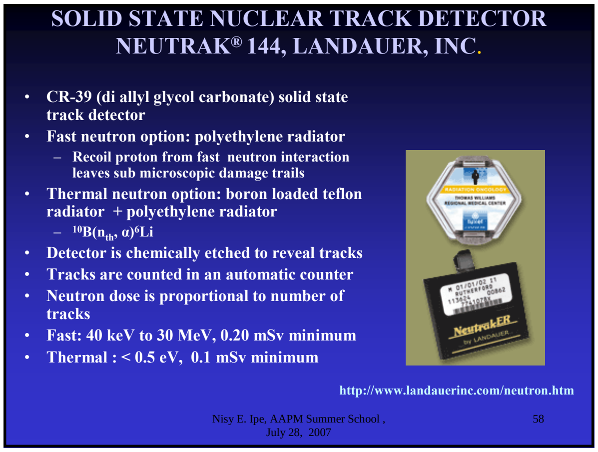
*Ipe et al, SLAC PUB 4398, 1987



Response of BD-PND as a Function of Energy



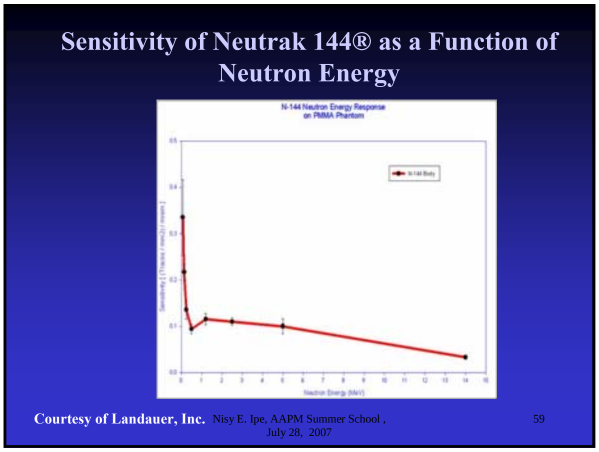
NORMALIZED RESPONSE OF BDS AS A FUNCTION OF ENERGY



SOLID STATE NUCLEAR TRACK DETECTOR NEUTRAK® 144, LANDAUER, INC.

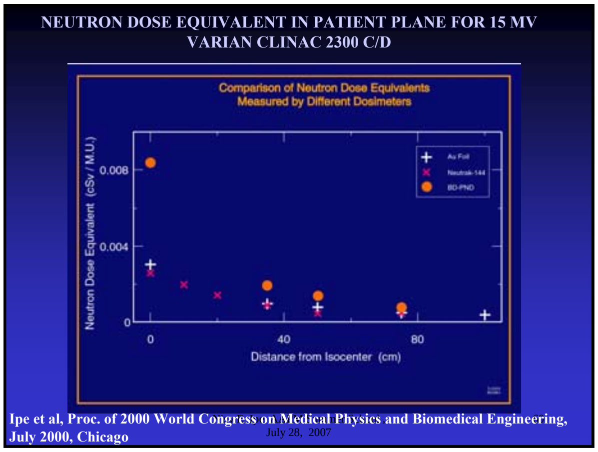
- CR-39 (di allyl glycol carbonate) solid state track detector
- Fast neutron option: polyethylene radiator
  - Recoil proton from fast neutron interaction leaves sub microscopic damage trails
- Thermal neutron option: boron loaded teflon radiator + polyethylene radiator
  - $^{10}B(n_{th}, \alpha)^{6}Li$
- Detector is chemically 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, 0.20 mSv minimum
- Thermal : < 0.5 eV, 0.1 mSv minimum

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



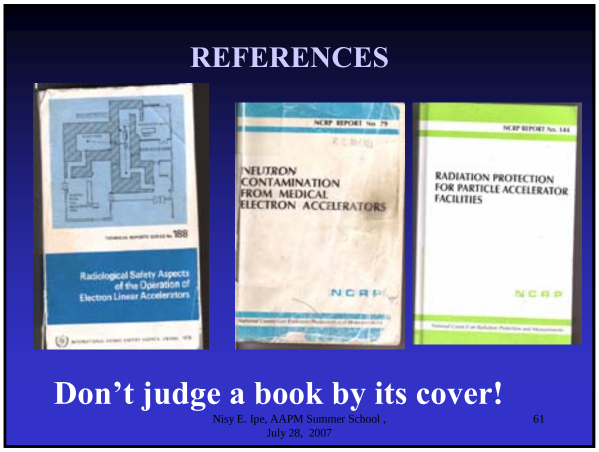
Sensitivity of Neutrak 144® as a Function of Neutron Energy

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



REFERENCES

Don’t judge a book by its cover!