Techniques

of

Proton Radiotherapy

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Harvard University,

the

Physics Department,

and the

Lab for Particle Physics and Cosmology

(**LPPC**)

made this course possible by their support.

Neutron Detectors

fluence meters:

moderated detector (Bonner sphere, Snoopy, REM Meter)

(detour: radiation protection basics)

bubble counter

gross physical dose meter:

ionization chamber

microdosimeters:

track-etch plate (CR-39)

tissue-equivalent proportional chamber (Rossi counter)

solid-state array

Moderated Detectors

This is your basic area monitor. A neutron *moderator* which slows neutrons to thermal energy (0.025 eV, 2 km/s) surrounds a small *detecting element* which has a very high cross section for thermal neutrons. The simplest moderator is a polyethylene (CH_2) sphere. Three possible detecting reactions are:

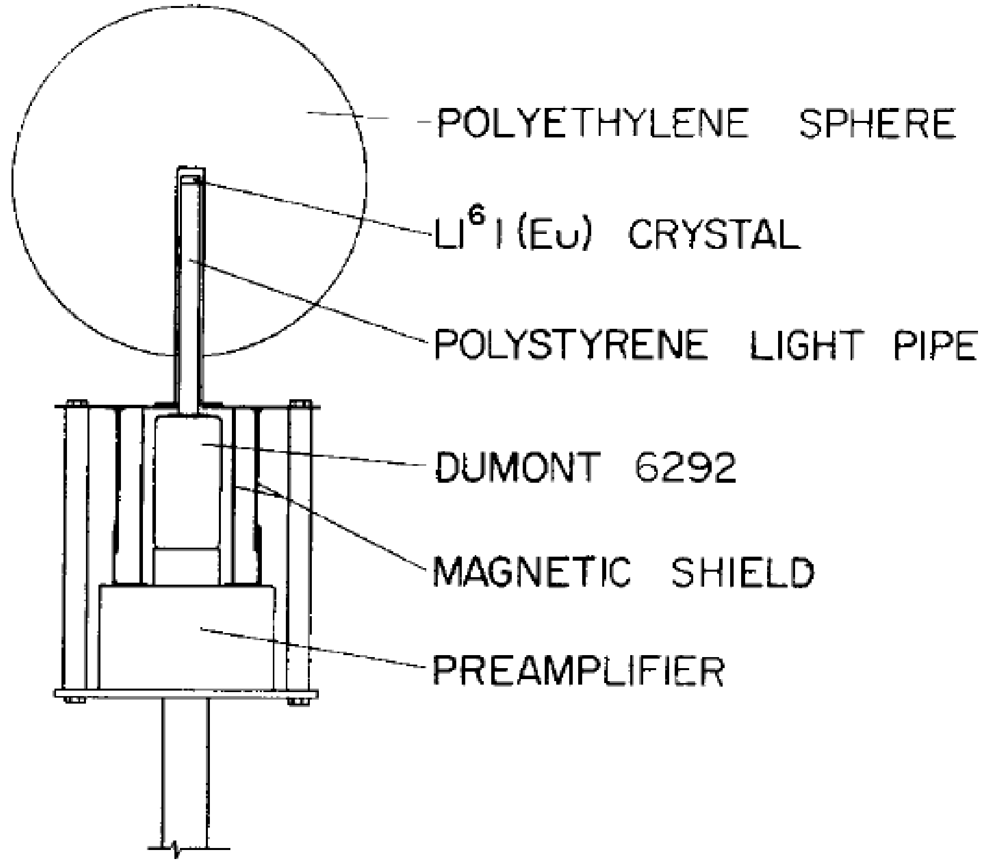
${}_3Li^6$ (n,α) ${}_1H^3$ (4.787 MeV) Li^6 I(Eu) scintillator (somewhat obsolete)

${}_5B^{10}$(n,α)${}_3Li^7$ (2.78 MeV) BF_3 gas proportional counter

${}_2He^3$(n,p)${}_1H^3$ (0.764 MeV) He^3 gas proportional counter

High efficiency and good γ rejection are desirable. Basically this detector is a neutron *fluence* meter but if the moderator is properly designed the detector's response can approximate the biologically equivalent dose to the human body. In that case the detector is called a REM (Roentgen Equivalent Man) meter.

In general, moderated detectors are quite sensitive. A typical 10" Bonner sphere yields 14,000 counts/mrem as calibrated with a moderated Am-Be source (4.86×10^{-5} mrem/sec at 1 m). A 'Snoopy' BF_3 detector (Andersson-Braun moderator, somewhat directional) is only slightly less sensitive (9,000 cts/mrem). Indeed, when moderated detectors are used to measure neutron dose to the patient the beam intensity must be reduced well below the therapy value.



From Bramblett et al., 'A new type of neutron spectrometer,' Nucl. Instr. Meth. 9 (1960) 1-12 . They first noted that a series of 'Bonner spheres' of different sizes exposed at the same point could measure (crudely) the neutron energy distribution at that point, and that a 12" diameter sphere had a relative response at each neutron energy proportional (within a factor 2) to the neutron effective dose at that energy (total counts = total eff. dose to a person standing there).

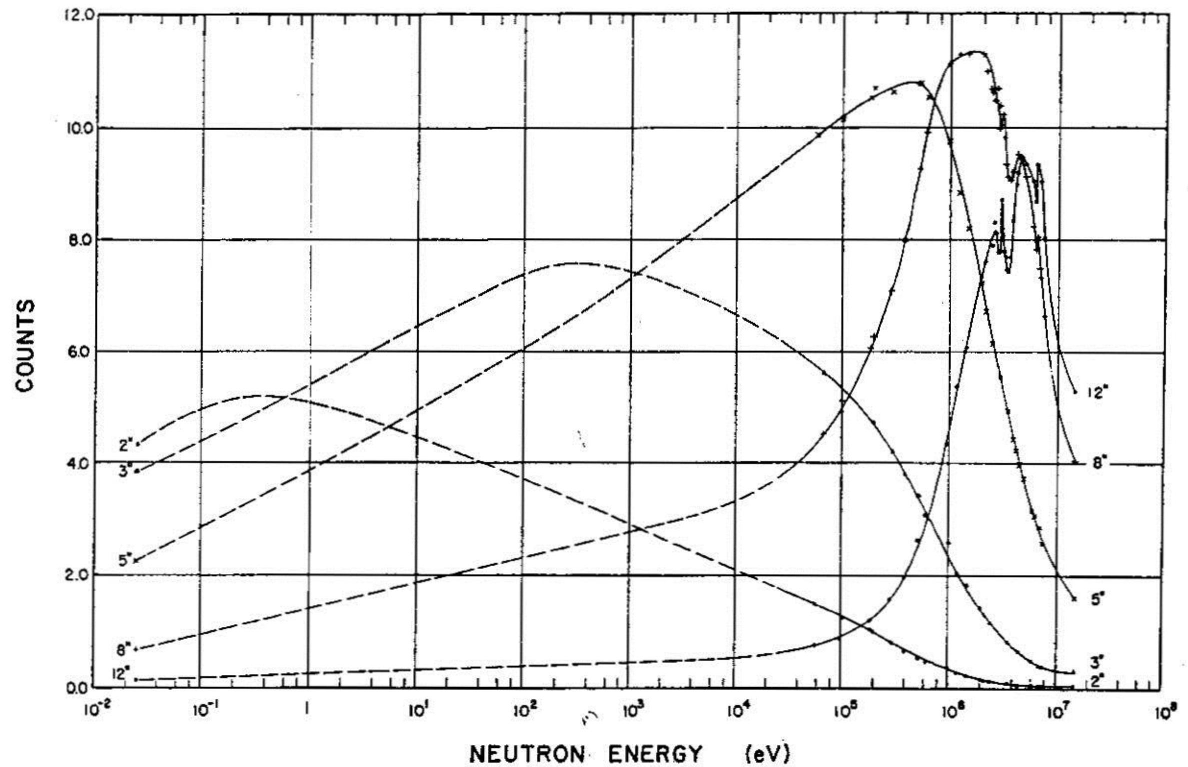


Fig. 8. Results with all counters giving the counts per 10^6 neutrons emitted from an isotropic point source 40 cm away.

From Bramblett et al. : measured response of Bonner spheres of various diameters to monoenergetic neutrons of different energies. The smaller spheres slow the neutrons down less so their response peaks at lower energy. In the large spheres, low energy neutrons are apt to be captured by H before reaching the detector, accounting for the low response. Since this paper, more accurate response curves have been computed with the aid of Monte-Carlo programs.

Basic Problems for Neutron Dosimetry

Radiation protection is concerned with setting limits on unwanted dose for the patient, the staff ('radiation workers') of the facility, and the general public (Yawkey Center and Liberty Hotel).

Assuming we are concerned with the long-term ('stochastic') effects of very low doses, we don't know what those are, and it is in principle almost impossible to find out. Most existing numbers are from Hiroshima survivors ('Health Risks from Exposure to Low Levels of Ionizing Radiation,' BEIR VII Phase 2, Nat'l Research Council (2006) (406 pp))

It is usually *assumed* that the dose-response curve for such doses is *linear*. Some ballpark risk values (BEIR VII), averaged over male/female and age: incidence of cancer (all causes) 41%; mortality from cancer 20%; lifetime attributable risk of mortality from solid cancer from radiation ≈ 5%/Sv.

Even if we knew how bad neutron dose is for you (RBE, Q, weight factors) the next problem is that it is very hard to measure. Neutron fluences generated by proton accelerators depend in a complicated way on direction and neutron energy, and both factors affect the sensitivity of neutron detectors. The size, composition and orientation of the detector and/or phantom can have a strong effect on the number of counts recorded.

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The 2007 Recommendations of the International Commission on Radiological Protection

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J. VALENTIN

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Annals of the ICRP

ICRP PUBLICATION 92

Relative Biological Effectiveness (RBE), Quality Factor (Q), and Radiation Weighting Factor (w_R)

Editor
J. VALENTIN

PUBLISHED FOR

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by

PERGAMON

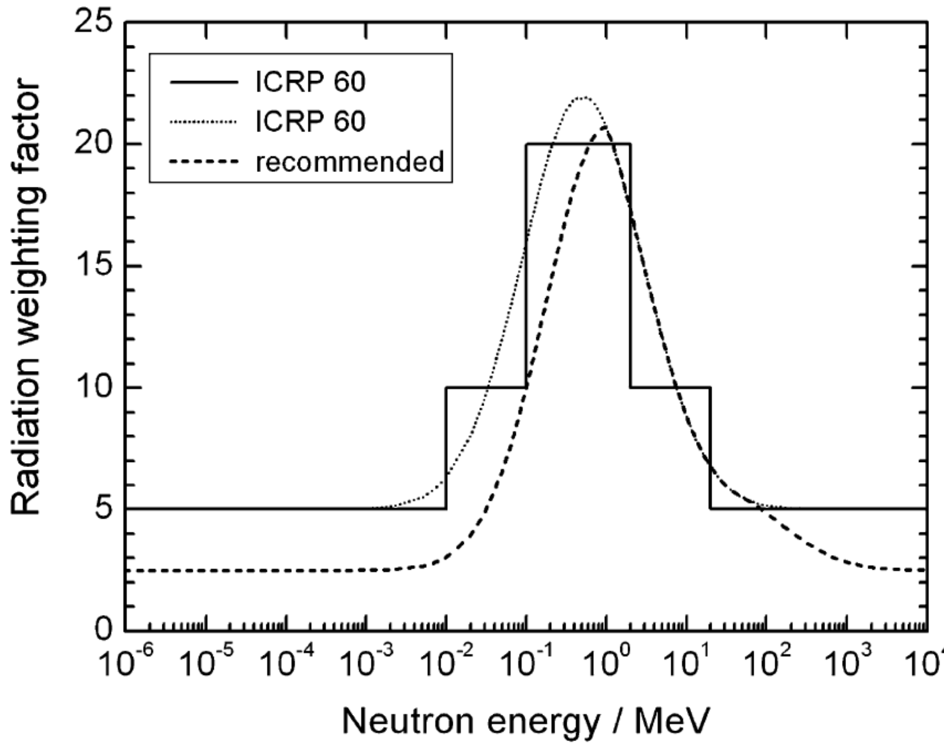
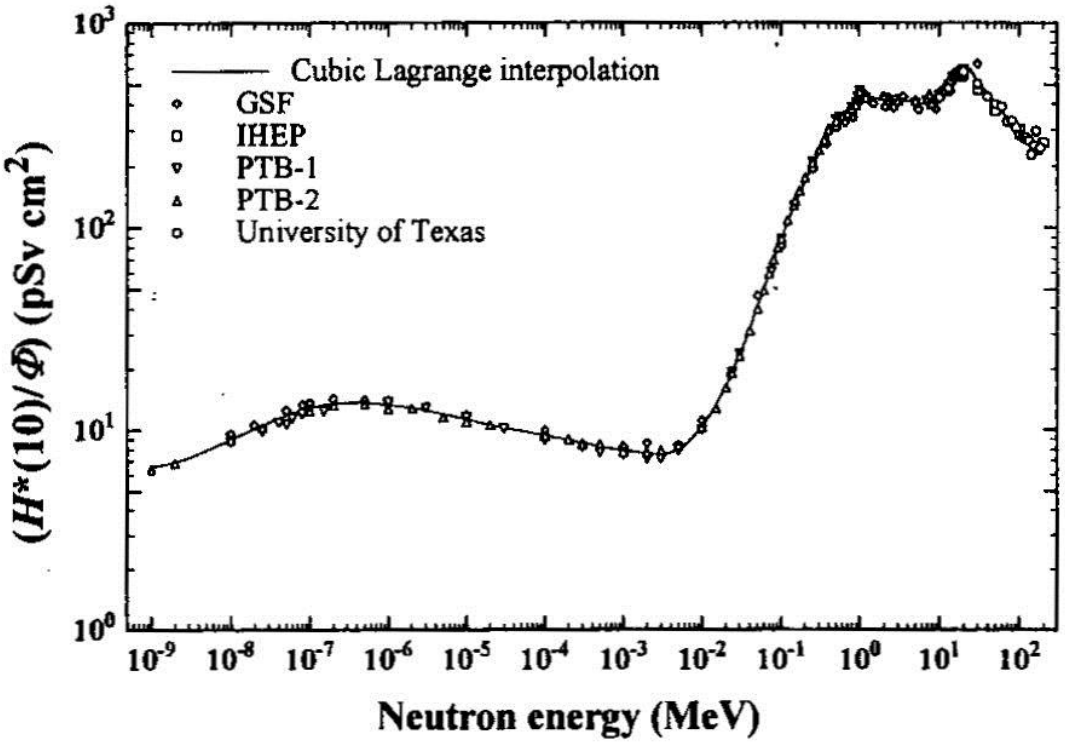


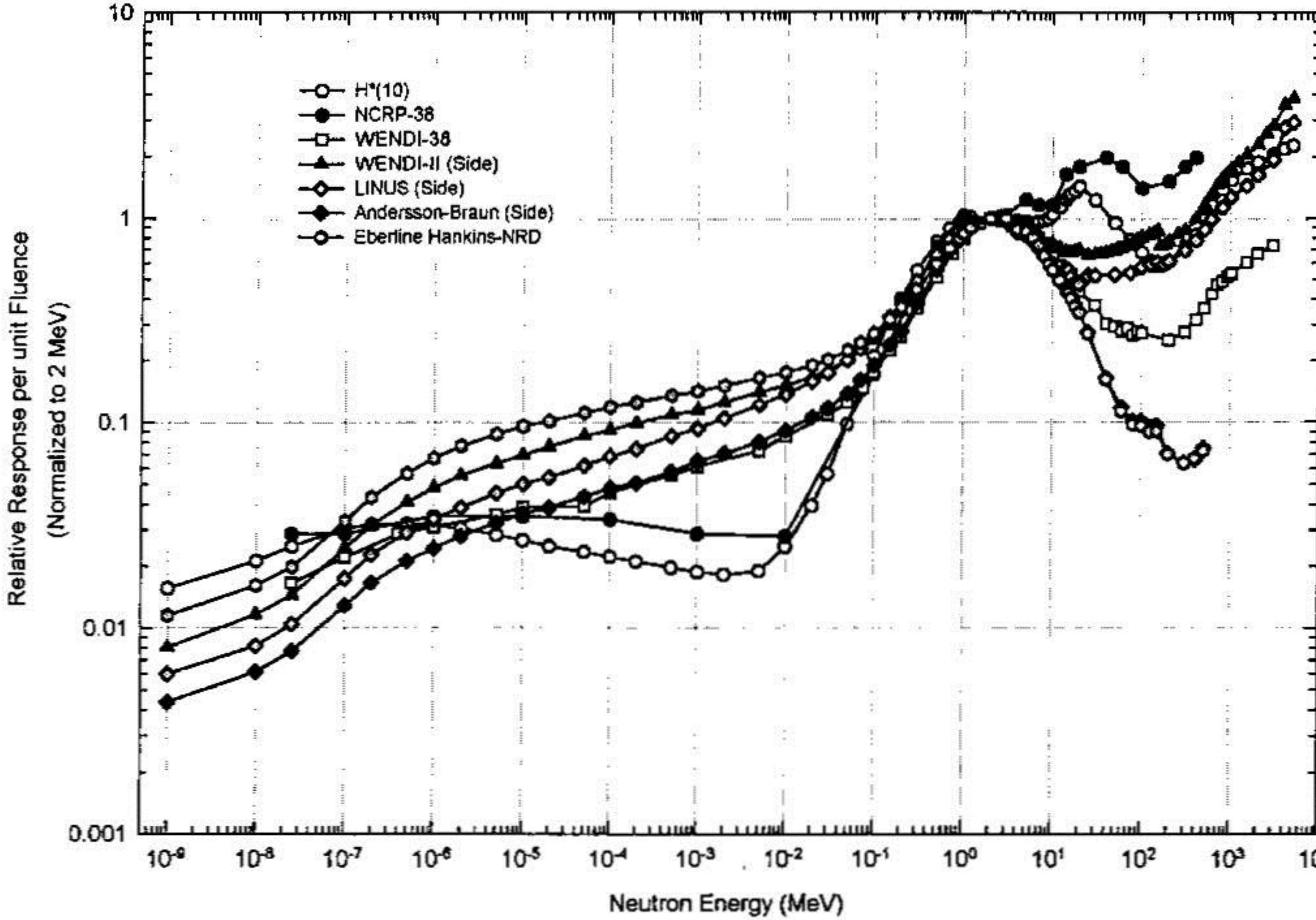
Fig. B.4. Radiation weighting factor, w_R, for neutrons versus neutron energy. Step function and continuous function given in *Publication 60* (ICRP 1991b) and function adopted in the 2007 Recommendations.

From the 2007 recommendations of the ICRP (Publ. 103). Absorbed dose weighting factor for neutrons when computing *equivalent dose* in a tissue or organ.

Neutrons are considered most deleterious at ~1 MeV where the RBE for low-dose stochastic effects (cancer induction) is around 20. Opinions change with time, but there is considerable bias against large changes in recommendations because of regulatory consequences.



A neutron detector is considered to be an ideal area monitor if it responds to neutrons according to this curve (ICRP Publ. 74, Figure 31). It is then deemed to measure H*(10), the ambient dose equivalent at a depth of 10 mm in the ICRU sphere (a standard phantom). Simple Bonner spheres, even large ones, have trouble at the high end. They under-respond to the high energy neutrons prevalent in proton therapy. Most of the literature and developmental work in moderated counters is devoted to fixing this problem by means of more sophisticated moderators (Andersson-Braun, WENDI ...) Unfortunately, most of the fixes yield a non-isotropic detector response (and a heavy detector).



This graph (Olsher et al. Health Physics 79(2) (2000) 170-181 shows how well the WENDI moderator design performs against the standard (H*(10), NCRP 38) and against several other moderator designs. Some moderators achieve a better result at the expense of isotropic response.

A modern neutron survey meter (Ludlum Model 12-4). The moderator is a 9" diameter cadmium-loaded polyethylene sphere and the detector is a He^3 gas proportional counter.

In a modern proton therapy center a number of such meters will be mounted at various locations, feeding data to a central point where it is recorded, to monitor neutron dose to staff and the general public.

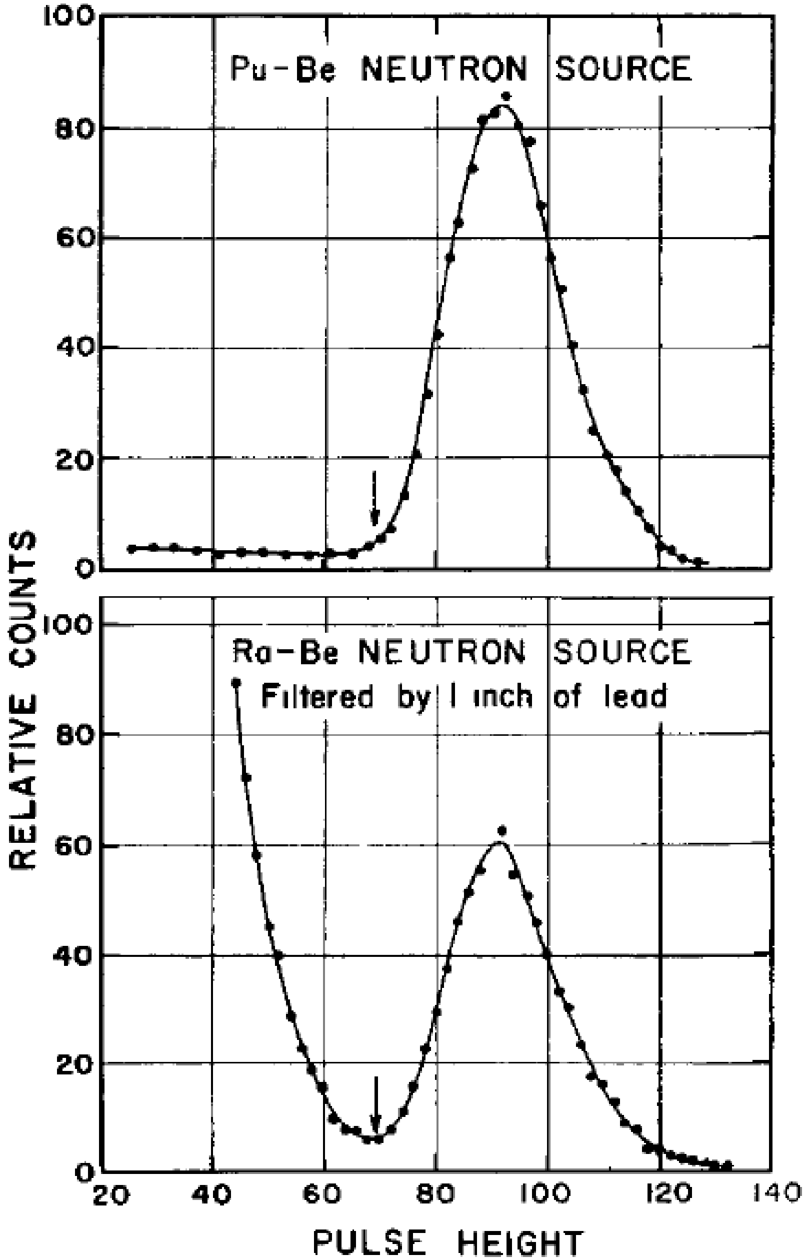
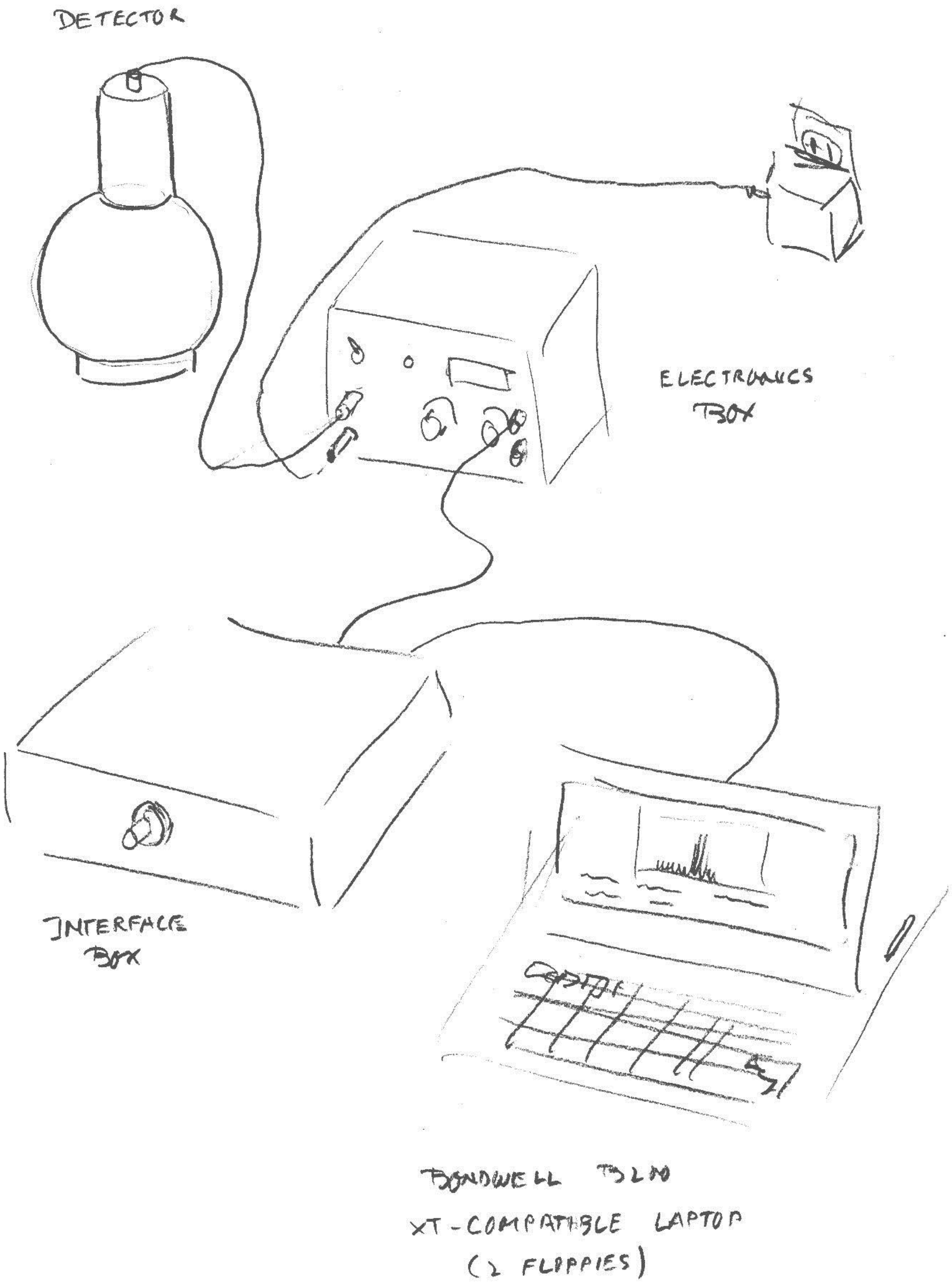


Fig. 2. Pulse spectra obtained with 8 inch counter showing the effect of a large number of γ rays

From Bramblett et al. This pulse-height spectrum tells us nothing about the neutron energy spectrum! It is merely the scintillator response to the monoenergetic capture of a thermal neutron. Pu-Be puts out very few γ rays, so there is almost no background.

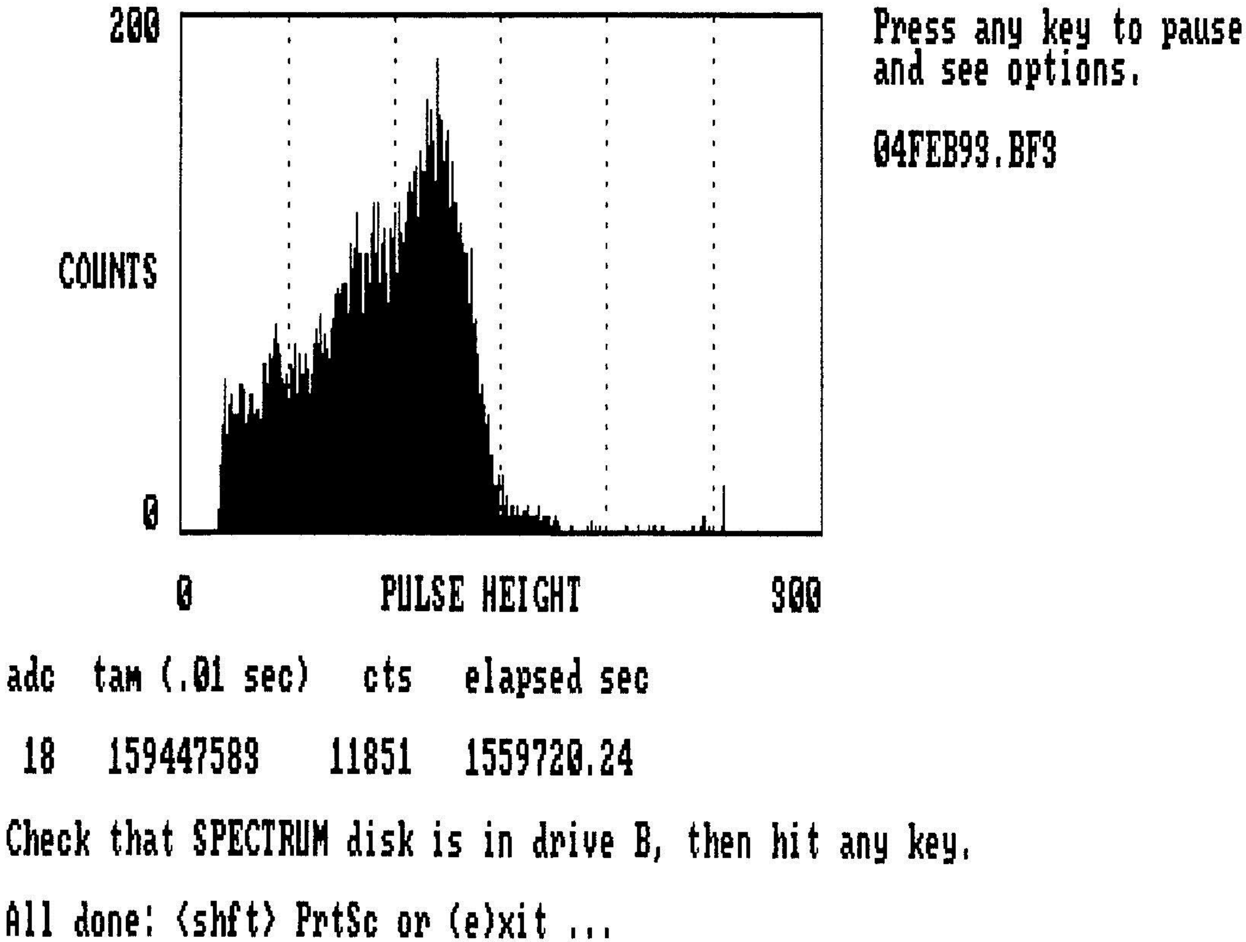
Ra-Be has far more γ rays giving the rising background. This would be nearly absent if a BF_3 or He^3 gas counter were used instead of the Li^6I scintillator. Even so, a pulse-height discriminator set at the arrow will eliminate most of the γ-ray counts.



Around 1990 we were charged with monitoring neutron dose in buildings adjacent to HCL for compliance with Harvard's safety standards. We placed a detector, electronics and computer on a cart. This 'roving neutron monitor' was left at various locations for a week at a time.

The counting rate was very low so the computer could record total charge and time of arrival for each pulse. Later, these data could be correlated with the date/time stamped cyclotron log to see which of the four beams was in use.

Roving neutron monitor. The detector was a moderated BF_3 counter calibrated with an AmBe neutron source. The data-logging system was a homemade HV supply, preamp and 8-bit pulse digitizer with an RS-232 serial interface to a Bondwell laptop computer with two floppy drives (no hard drive) and an early version of DOS. Because of the very low counting rate the computer was easily able to record each pulse height with a time stamp. The monitor was left at remote locations for a week or so after suitable reassurances to the occupants.



This integrated pulse height spectrum from the cylindrical BF_3 proportional counter confirms that the neutron detector was working properly and that the discriminator threshold was reasonable. The shape is due both to the pulse height resolution and the fact that tracks traverse different lengths in the gas tube.

18:30	0	0	113	0	0	0	0	8057	22222222222222222222222222222222222222222222222222222222	
19:30	11	0	35	0	0	0	0	8103	22222222222222222NNNNN	
20:30	60	0	0	0	2	5	0	8170	00SNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN	
21:30	0	0	0	0	0	14	0	8184	0000000	20[23] shut down
22:30	0	0	0	0	0	18	0	8202	000000000	
23:30	0	0	0	0	0	15	0	8217	0000000	71 - 1 bg = 58 (1)
									Wednesday 17FEB93	
0:30	0	0	0	0	0	15	0	8232	0000000	
1:30	0	0	0	0	0	13	0	8245	000000	0/1/7
2:30	0	0	0	0	0	13	0	8258	000000	
3:30	0	0	0	0	0	21	0	8279	0000000000	
4:30	0	0	0	0	0	15	0	8294	0000000	27/bg
5:30	0	0	0	0	0	20	0	8314	0000000000	
6:30	0	0	0	0	0	17	0	8331	00000000	
7:30	0	3	0	2	0	6	0	8342	000TE	
8:30	0	40	6	5	0	0	0	8393	TT222EEEEEEEEEEEEEEEEEEEE	215 - 5 × 13.49 = 148 (2)
9:30	0	0	43	0	0	0	0	8436	222222222222222222222	
10:30	0	0	10	0	10	0	0	8456	SSSSS22222	21.1/pt ± 1.4
11:30	0	0	84	0	2	0	0	8542	S222222222222222222222222222222222222222222	
12:30	0	0	59	0	1	0	0	8602	22222222222222222222222222222	
13:30	0	0	19	0	11	0	0	8632	SSSSS222222222	← 13[30] end treatments
14:30	0	0	0	8	8	0	0	8648	SSSSTTTT	
15:30	0	0	57	0	27	0	0	8732	SSSSSSSSSSSSS2222222222222222222222222222	
16:30	0	0	0	0	10	0	0	8742	SSSSS	
17:30	0	0	53	0	11	0	0	8806	SSSSS22222222222222222222222222	← 17[00] unit check
18:30	0	0	72	0	0	0	0	8878	222222222222222222222222222222222222	
19:30	79	0	21	0	1	0	0	8979	2222222222NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN	N#1 cals 18[37]
20:30	36	0	78	0	0	0	0	9093	222222222222222222222222222222222222222NNNNNNNNNNNNNNNNNN	N#2 cals 20[10]
21:30	0	0	96	0	0	4	0	9193	00222222222222222222222222222222222222222222222222	
22:30	0	0	0	0	0	10	0	9203	00000	
23:30	0	0	0	0	0	16	0	9219	00000000	115 - 1 bg = 101 (1)
									Thursday 18FEB93	
0:30	0	0	0	0	0	12	0	9231	000000	0/0/10
1:30	0	0	0	0	0	12	0	9243	000000	
2:30	0	0	0	0	0	17	0	9260	00000000	
3:30	0	0	0	0	0	12	0	9272	000000	
4:30	0	0	0	0	0	10	0	9282	00000	
5:30	0	0	0	0	0	16	0	9298	00000000	
6:30	0	0	0	0	0	12	0	9310	000000	
7:30	0	0	0	0	0	15	0	9325	0000000	
8:30	0	0	2	14	1	0	0	9342	TTTTTTT2	
9:30	0	0	66	0	3	0	0	9411	S222222222222222222222222222222222	
10:30	0	0	10	0	14	0	0	9435	SSSSSSS22222	
11:30	0	0	31	0	8	0	0	9474	SSSS222222222222222	
12:30	0	0	47	0	7	0	0	9528	SSS22222222222222222222222	605 - 12 × 13.49 = 443 (2)
13:30	0	0	35	0	11	0	0	9574	SSSSS22222222222222222	
14:30	0	0	65	0	13	0	0	9652	SSSSSS22222222222222222222222222222222	44.3/pt. ± 2
15:30	0	0	40	0	6	0	0	9698	SSS22222222222222222222	
16:30	0	0	0	0	11	0	0	9709	SSSSS	
17:30	0	0	47	0	6	0	0	9762	SSS22222222222222222222222	
18:30	0	0	51	0	6	0	0	9819	SSS2222222222222222222222222	
19:30	0	0	107	0	0	0	0	9926	22222222222222222222222222222222222222222222222222222	
20:30	0	0	106	0	0	0	0	10032	22222222222222222222222222222222222222222222222222222	
21:30	0	0	20	0	1	4	0	10057	002222222222	
22:30	0	0	0	0	0	14	0	10071	0000000	(no cals)
23:30	0	0	0	0	0	12	0	10083	000000	
									Friday 19FEB93	
0:30	0	0	0	0	0	20	0	10103	0000000000	
1:30	0	0	0	0	0	11	0	10114	00000	0/1/11
2:30	0	0	0	0	0	18	0	10132	000000000	
3:30	0	0	0	0	0	13	0	10145	000000	
4:30	0	0	0	0	0	22	0	10167	00000000000	
5:30	0	0	0	0	0	11	0	10178	00000	86 - 1 × 13.49 = 72.5 cts (1.5)
6:30	0	0	0	0	0	11	0	10189	00000	
7:30	2	0	0	3	0	13	0	10207	000000TN	72.5/bg
8:30	0	56	6	0	0	0	0	10269	222EEEEEEEEEEEEEEEEEEEEEEEEEEEE	
9:30	0	30	44	0	1	0	0	10344	2222222222222222222222EEEEEEEEEEEEEEE	
10:30	0	0	42	0	8	0	0	10394	SSSS222222222222222222222	555 - 13 × 13.49
11:30	0	0	7	0	16	0	0	10417	SSSSSSSS222	
12:30	0	0	80	0	2	0	0	10499	S2222222222222222222222222222222222222222	= 380 cts (2)
13:30	0	0	43	0	9	0	0	10551	SSSS222222222222222222222	
14:30	0	0	48	0	9	0	0	10608	SSSS222222222222222222222222	
15:30	0	0	79	0	0	0	0	10687	222222222222222222222222222222222222222	34.5/pt ± 1.5
16:30	0	0	47	0	2	0	0	10736	S22222222222222222222222	
17:30	0	0	15	0	8	0	0	10759	SSSS2222222	
18:30	0	0	30	0	8	0	0	10797	SSSS222222222222222	
19:30	0	0	20	0	4	0	0	10821	SS2222222222	
20:30	0	0	76	0	0	0	0	10897	22222222222222222222222222222222222222	
21:30	0	0	24	0	0	4	0	10925	00222222222222	
22:30	0	0	0	0	0	17	0	10942	00000000	(no cals)
BEAM	1	1.5	2	TUNE	S'BY	OFF	?			
	N	E	2	T	S	O				

FIG. 2

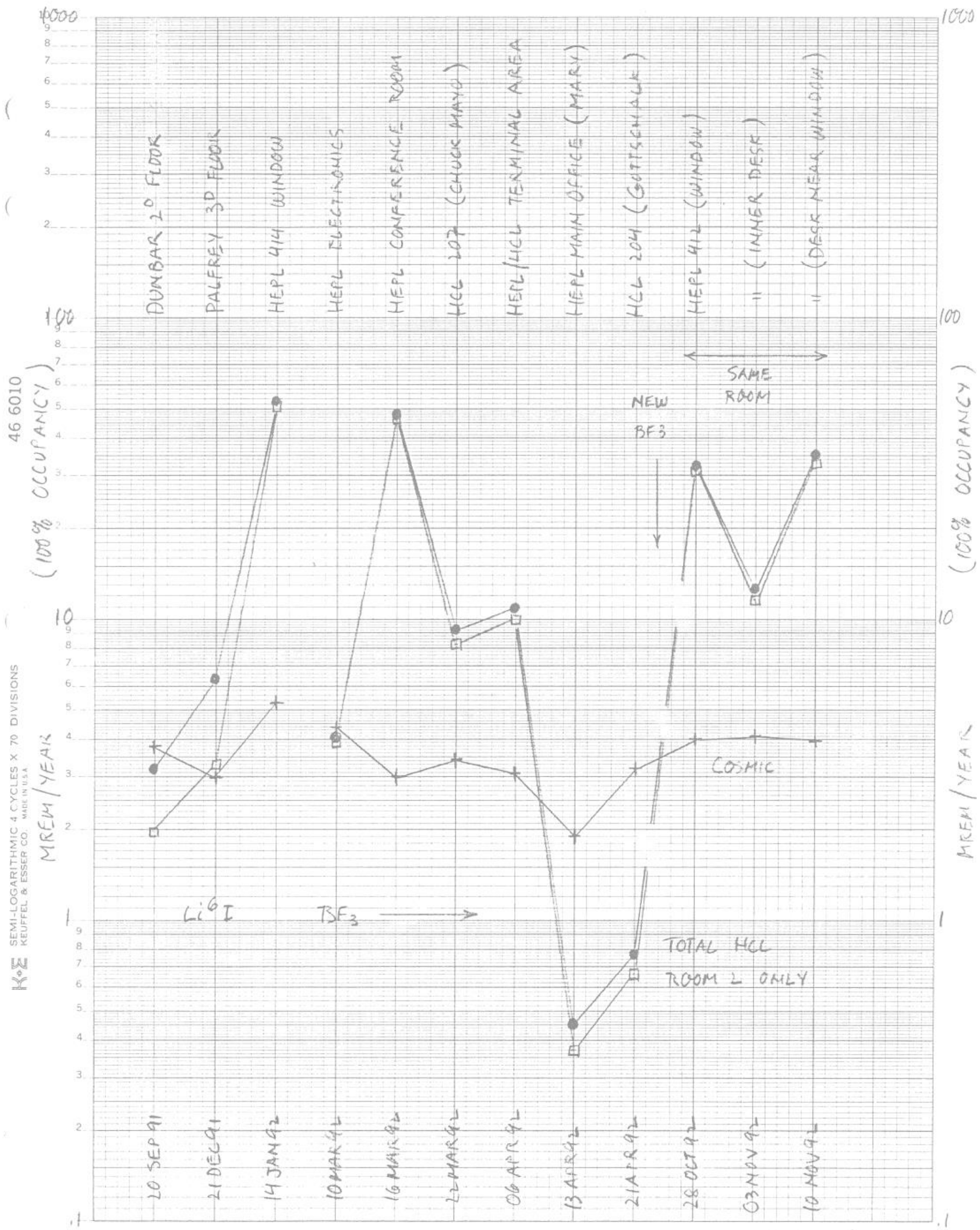


FIG. 4/1

The previous slide shows neutron dose at a single location correlated with various HCL beams. The treatment day is clearly visible as is cosmic ray neutron background while the machine is off.

These data, combined with the mrem/ct obtained with a known neutron source, could be used to draw a dose map for typical HCL operations at various distant locations. Thereafter, it was only necessary to monitor four fixed locations.

The cosmic n background (2-4 mrem/yr) agrees with the accepted value. It is lower on the lower floors of a building because of shielding by intervening concrete.

Ionization Chamber

Neutrons ultimately produce ionizing radiation which can be detected with something as simple as a large plane-parallel ion chamber (PPIC). Of course this will detect total ionization from protons, neutrons, γ's and ions, but if one is reasonably certain (say from a Monte Carlo) that the radiation is mostly neutrons (for instance, on the beam axis just downstream of the Bragg peak) this is a simple technique.

A PPIC measures physical dose (*D*, not *H*) to the extent that W (energy per ion pair) is independent of energy. One needs a large PPIC because the physical dose rate is $\sim 10^4$ smaller than the proton dose rate. Thus, one might use an active volume ~ 30 cm^3 (e.g. PTW 233612) rather than the 0.02 cm^3 (Markus chamber) that might be used to scan the Bragg peak itself.

Some calibration uncertainty results from the variation of W in air for various particle species that might be produced but W = 34 eV/ion pair = 34 J/C (protons) is a reasonable compromise. The water/air stopping power ratio also varies with particle species and energy but overall, the calibration error is about ±5%, very good for neutron work, and the calibration is *absolute* because the active volume of a large PPIC is well determined by its dimensions.

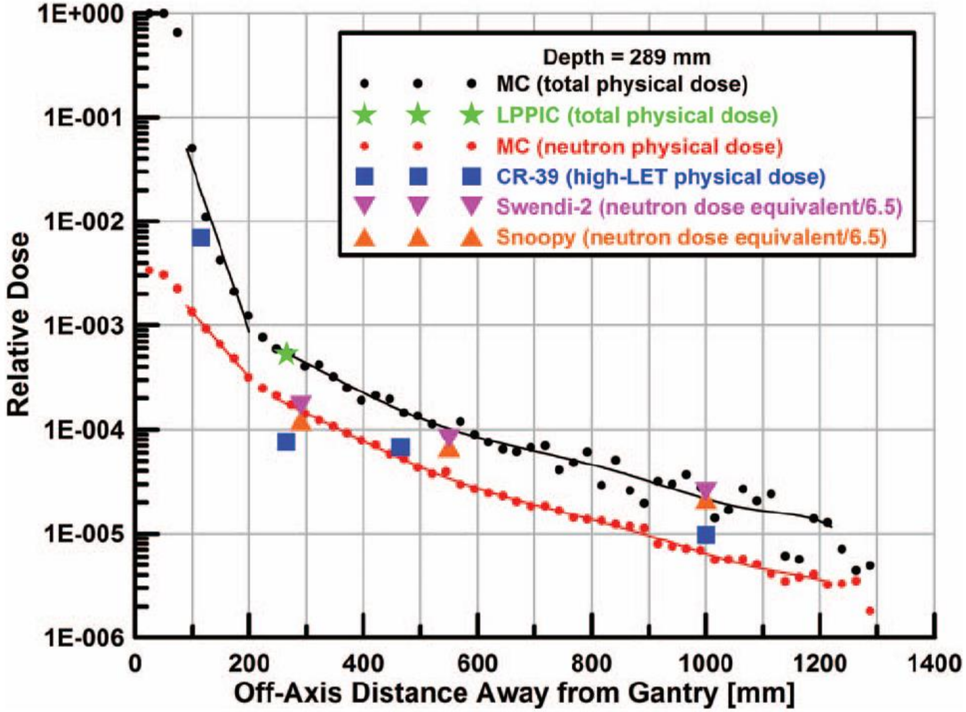


FIG. 7. Dose relative to the prescribed dose at a depth of 289 mm in the phantom patient. Black circles represent the total physical dose calculated by MCNPX. Between 90 and 200 mm off-axis the values were fit with an exponential curve. Between 200 and 1400 mm off-axis the data were fit with a fifth-order polynomial. The green star represents the total dose measured with the LPPIC. Red circles represent the neutron only physical dose calculated by MCNPX. Blue squares represent the high-LET physical dose measured with CR-39. Inverted magenta triangles represent the neutron only physical dose derived from the SWENDI-2 dose equivalent measurements by dividing by an average quality factor of 6.5. Orange triangles represent the neutron only physical dose derived from the Snoopy dose equivalent measurements by dividing by an average quality factor of 6.5.

Moyers et al. 'Leakage and scatter radiation from a double-scattering based proton beamline,' Med. Phys. 35 (2008) 128-144. This figure compares *physical* neutron and total doses measured and inferred from various detectors to Monte Carlo calculations. The ion chamber point (LPPIC, green) agrees well with the MC prediction of total dose.

BTI BUBBLE Technology Industries

BUBBLE DETECTORS
Neutron Dosimeters

- Accurate, sensitive, real-time neutron dosimeters
- Immediate visible response to neutron radiation
- Ideal for ALARA programs and rapid measurements of neutron radiation fields
- Tissue-equivalent, energy-independent, neutron dose measurements
- Zero sensitivity to gamma radiation, providing accurate neutron dosimetry in mixed fields
- Lightweight, rugged, and compact
- Low cost and reusable hundreds of times
- Simple to use, maintenance-free, no power required
- Fully temperature-compensated
- Proven, patented, reliable technology
- Meets ICRP-60 sensitivity requirements

Bubble Detectors are the most sensitive, accurate, neutron dosimeters available. Used for over 15 years by nuclear facilities, research institutes, military personnel, and the medical community, Bubble Detectors provide instant visible detection and measurement of neutron dose. Inside the detector, tiny droplets of superheated liquid are dispersed throughout a clear polymer. When a neutron strikes a droplet, the droplet immediately vaporizes, forming a visible gas bubble trapped in the gel. The number of droplets provides a direct measurement of the tissue-equivalent neutron dose.

The Bubble Detector is the only neutron dosimeter where the response is independent of dose rate and energy, with zero sensitivity to gamma radiation. Bubble Detectors are so compact, lightweight, and rugged, that they can be clipped to a coat or shirt pocket, placed in areas with limited access, or used in close proximity to a neutron source for a quick assessment. With an isotropic angular response, neutron dose can be accurately measured regardless of the direction of neutrons relative to the detector. Bubble Detectors are ideal for ALARA programs, providing the user with an immediate measurement of neutron hazards.

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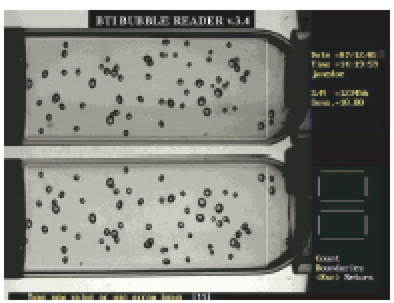
The **BDR-III™ Automatic Bubble Reader** is an affordable solution for automatic counting of large numbers of detectors. The BDR-III provides bar code-ready, fully automated counting with machine vision technology that generates database compatible files in a compact, simple-to-use instrument.



- Affordable solution for routine bubble detector reading
- Fully automated counting
- Database compatible file generation
- Bar code-ready
- Compact, simple to use
- Image storage for audit and archiving

Applications:

Bubble detectors are ideal for rapid and accurate measurements in a broad range of applications:

- Nuclear power stations and nuclear research laboratories (neutron dosimetry and shielding verification)
- Hospitals involved in radiation therapy/nuclear diagnostics (neutron dosimetry and LINAC shielding verification)
- Airline crew dosimetry and space applications (high altitude neutron dosimetry)
- Military personnel (neutron dosimetry and hazard detection)

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BUBBLE DETECTORS
Technical Specifications
(Visit www.bubbletech.ca for more information)

	BD-PND™	BD100R™	BDT™	BDS™
Energy Range	< 200 keV to > 15 MeV	< 200 keV to > 15 MeV	Thermal (~ 1/V for epithermals)	Six thresholds: 10, 100, 600, 1000, 2500 and 10000 keV
Dose Range	0.1 - 500 mrem 1 - 5000 µSv	0.1 - 500 mrem 1 - 5000 µSv	0.1 - 10 mrem 1 - 100 µSv	~ 50 mrem ~500 µSv
Sensitivity (User Selectable)	0.33 - 33 bub/mrem 0.033 - 3.3 bub/µSv	0.33 - 33 bub/mrem 0.033 - 3.3 bub/µSv	~ 30 bub/mrem 3.0 bub/µSv	1 - 2 bub/mrem 0.1 - 0.2 bub/µSv
Automatic Temperature Compensation	Yes	No	Yes	No
Optimum Temperature Range	20 - 37 °C	10 - 35 °C	20 - 37 °C	20 °C
Size	145 mm length x 19 mm diameter	120 mm length x 16 mm diameter	145 mm length x 19 mm diameter	80 mm length x 16 mm diameter
Weight	58 g	33 g	58 g	20 g
Re-use	Yes	Yes	Yes	> 10 cycles
Recompression Method	Integrated assembly	Integrated assembly	Integrated assembly	External recompression chamber required
Notes	Recommended for personal neutron dosimetry	Temperature response curve provided	Thermal:fast neutron sensitivity > 10:1	Ideal for neutron spectral characterization

All bubble detectors offer:

- Zero gamma sensitivity
- Energy-independent above threshold, dose rate-independent, tissue-equivalent dose measurements
- Isotropic angular response
- 90 day warranty

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BD-PND:

The BD-PND is the recommended detector for personal neutron dosimetry. Its sensitivity exceeds the ICRP-60 requirements for neutron dosimetry. It incorporates automatic compensation for sensitivity change with temperature over the operational range of 20 - 37 °C. Nuclear laboratories, utilities, and military personnel have found that the BD-PND's immediate visual response and high sensitivity, coupled with its small size, light weight and rugged construction, make it the ideal device for ALARA programs.

BD100R:

Similar in performance to the BD-PND, but without temperature compensation. A temperature response curve is provided.

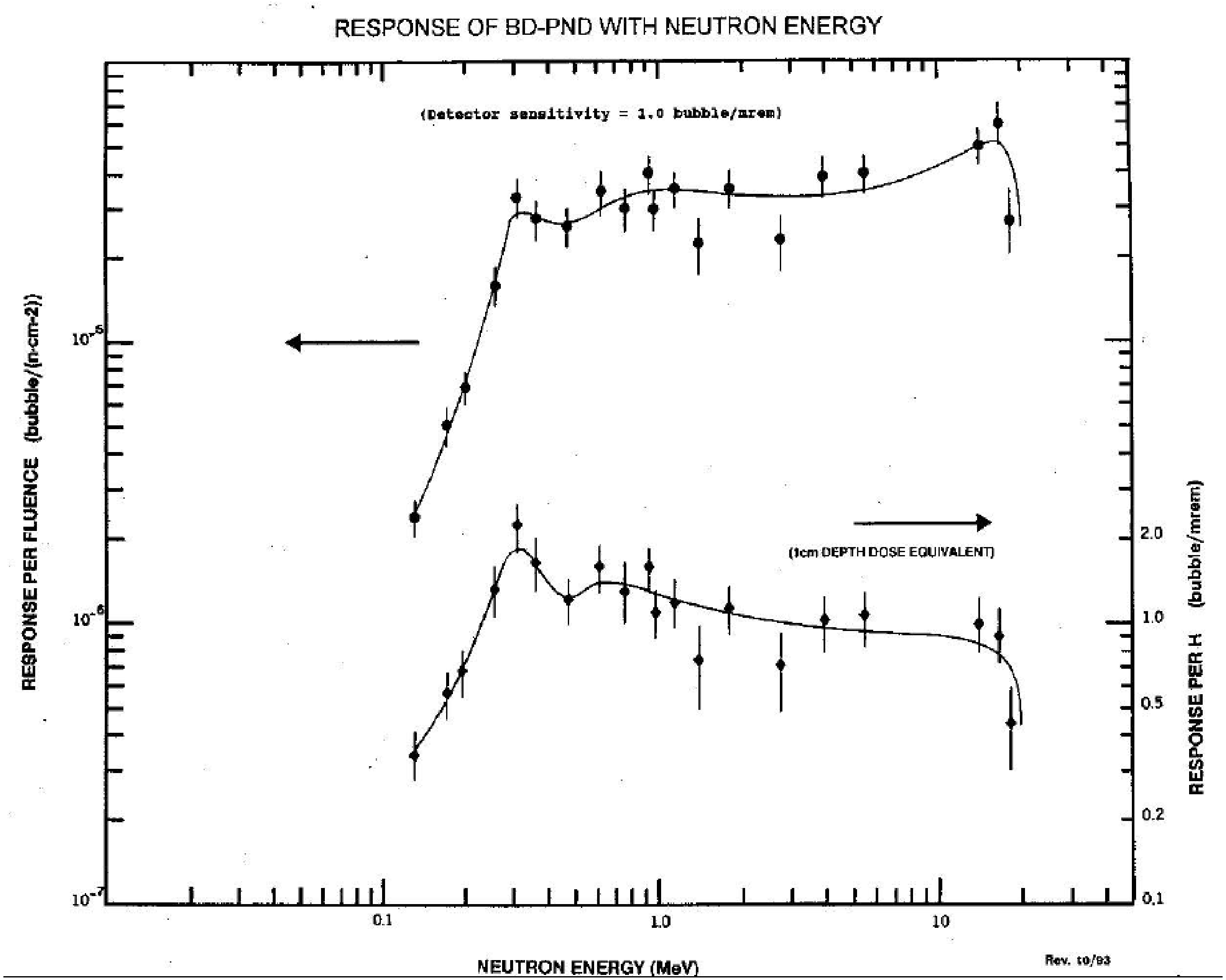
BDT:

Health physicists and others who are especially concerned with **thermal** neutron dose can take advantage of the simplicity and low cost of thermal Bubble Detectors. The BDT Bubble Detector is preferentially sensitive to thermalized neutrons, with an exclusion ratio of thermal-to-fast neutron response exceeding 10:1.

BDS:

The BDS is a complete low-cost neutron spectrometer package consisting of 36 Bubble Detectors that have been specifically formulated with six different energy thresholds. Each spectral measurement can be made with 18 detectors (3 of each threshold supplied – 10, 100, 600, 1000, 2500, 10000 keV). A simple algorithm is included for "unfolding" the neutron measurement data. Detectors can be re-used through recompression in a pressure chamber (available from BTI).

Bubble Technology Industries ▪ 31278 Highway 17 ▪ Chalk River, Ontario ▪ K0J 1J0 ▪ Canada
Phone: 613-589-2456 ▪ Fax: 613-589-2763 ▪ www.bubbletech.ca



Curve courtesy of Bubble Technology Industries, Chalk River, Ontario, 2007. Shows that BD-PND is a rem meter between 0.2 and ~20 MeV.

CR-39 Track Etch Detectors

(description courtesy George Coutrakon, LLUMC)

CR-39 is a near tissue-equivalent thermosetting polymer sensitive to charged particles of LET $\geq$ 5 keV/μm (50 MeV/cm, corresponding to a ~10 MeV proton in water). An ion traversing the CR-39 breaks chemical bonds in the polymer, producing latent damage along the trajectory. After exposure, the detector is etched in 6.25 *N* NaOH at 50°C, converting the damage trails to conical pits which can be measured with an optical microscope. The size of the elliptical opening of each track is proportional to the LET of the charged particle that produced it. By measuring many tracks one can infer an LET spectrum and therefore, dose and dose equivalent.

CR-39 is used in commercial dosimetry systems or, sometimes, by experts in in-house experiments. Commercial dosimeters use a polyethylene converter to produce proton recoils from fast neutrons and/or a borated converter to produce α's from thermal neutrons.

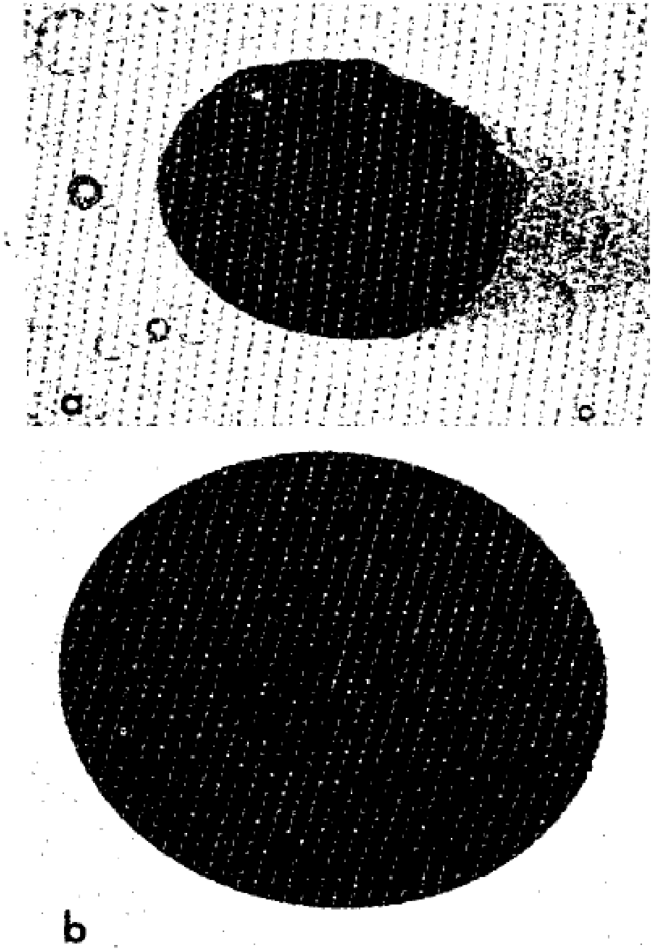


Fig. 1. Comparison of surfaces of (a) Lexan and (b) CR-39 etched in NaOH solution. The thickness of material removed by etching was 25 μm for Lexan and 45 μm for CR-39. The elliptical holes are the mouths of track etch pits that intersected the surface at an angle. For CR-39 the particle that produced the track was ^{40}Ar; for Lexan it was an ultraheavy cosmic ray with $Z > 75$. The minor axis of the ellipse for CR-39 is 80 μm. The greater homogeneity of CR-39 than of Lexan results in a far smoother etched surface, far more uniform etched track lengths and diameters, and less variability of response to particles of a given ionization rate.

From Cartwright et al. 'A nuclear track recording polymer of unique sensitivity and resolution,' Nucl. Instr. Meth. 153 (1978) 457-460, evidently the first paper to tout CR-39.

Track-etch techniques *per se* had been used for some time, but the uniform response, high sensitivity and 'superb optical quality' made CR-39 superior.

Track-etch techniques are widely used outside neutron detection: cosmic ray studies, free quark searches, monopole searches ... There is an extensive literature.

LANDAUER®

Neutrak® Dosimeter for Neutron Radiation

Neutrak dosimetry service provides neutron radiation monitoring with CR-39® and Track Etch® technology. The Neutrak 144 detector is a CR-39 (allyl diglycol carbonate) based, solid-state nuclear track detector that is not sensitive to x, beta or gamma radiation, and can be packaged specifically for neutron detection only, or as a component of another dosimeter such as Luxel®+ or InLight™ to include x, gamma and beta radiation monitoring. The CR-39 is laser engraved for permanent identification, and wrapped with a 2-D bar code to assure efficient chain-of-custody.

Landauer's comprehensive full service includes automatic exchange out of dosimeters for each wear period, processing and analysis, data management, reporting of exposure results, direct computer access via the Internet to Landauer's database for shipment tracking, and customer service and technical support programs.

CR-39 Fast Neutron

CR-39 Fast/Intermediate/ Thermal Neutron

Design

Neutrak dosimeters span the full spectrum of energies found in neutron environments. Landauer offers two neutron dosimeters, a fast neutron dosimeter and a combination fast, intermediate, thermal neutron dosimeter. Neutrak's fast neutron dosimeter uses a polyethylene radiator for fast neutrons that records recoil protons resulting from neutron interactions in the dosimeter. Neutrak's thermal/intermediate neutron dosimeter has a design intended for fast, intermediate, and thermal neutrons. The left area of the chip uses a polyethylene radiator for fast neutrons while the right area uses a boron loaded Teflon® radiator for fast, intermediate, and thermal neutrons that records alpha particles resulting from neutron interactions in the dosimeter.

Track Etch Technology

The CR-39 is processed with Track Etch technology. During analysis in our laboratory, the CR-39 is etched for 15 hours in a chemical bath to enlarge exposure tracks. The fast neutron dose is measured by counting the tracks generated as a result of the proton recoil with the polyethylene radiator, while the thermal/ intermediate dose is measured by counting the alpha tracks generated with the boron radiator.

Neutrak Dosimeter Selection Guide

	Fast Neutron	Fast, Intermediate, and Thermal Neutron
Typical Applications	Monitoring personnel working with unmoderated or moderately shielded fast neutron sources such as	Monitoring radiation near graphite-moderated neutron sources or monitoring requirements that involve

interactions in the dosimeter. Neutrak's thermal/intermediate neutron dosimeter has a design intended for fast, intermediate, and thermal neutrons. The left area of the chip uses a polyethylene radiator for fast neutrons while the right area uses a boron loaded Teflon® radiator for fast, intermediate, and thermal neutrons that records alpha particles resulting from neutron interactions in the dosimeter.

chemical bath to enlarge exposure tracks. The fast neutron dose is measured by counting the tracks generated as a result of the proton recoil with the polyethylene radiator, while the thermal/ intermediate dose is measured by counting the alpha tracks generated with the boron radiator.

Neutrak Dosimeter Selection Guide

	Fast Neutron	Fast, Intermediate, and Thermal Neutron
Typical Applications	Monitoring personnel working with unmoderated or moderately shielded fast neutron sources such as Californium-252 and Americium-241 Beryllium.	Monitoring radiation near graphite-moderated neutron sources or monitoring requirements that involve exposure to low, high or varying mixtures of neutron energies such as those occurring in nuclear power plants, shielded high-energy accelerators, etc.
Technical Specifications	Energy range: 40 keV to 40 MeV Dose Measurement Range: 20 mrem to 25 rem (200 µSv to 250 mSv)	Energy range: 0.25 eV to 40 MeV Dose Measurement Range: 10 mrem to 25 rem (100 µSv to 250 mSv)
Accreditations Approvals Licenses	**NVLAP** (National Voluntary Laboratory Accreditation Program) accredited (NVLAP Lab Code 100518-0) in category VIA when combined with Luxel+ or InLight. **HSE** (Health and Safety Executive) United Kingdom, External: Whole Body Neutrons. **DOELAP** (Department of Energy Laboratory Accreditation Program) accredited. **CNSC** (Canadian Nuclear Safety Commission) authorized for use.	

The Neutrak 144 packaged in a vinyl pouch specifically for neutron detection only.

The Neutrak 144 dosimeter can be sealed inside the Luxel+ plastic blister pack.

The Neutrak 144 dosimeter can be enclosed inside the InLight holder.

LET Counters (Rossi counters)

The pattern of energy (dose) deposition by a particle, not just the total energy deposited, is very important in determining the biological effect. Low LET particles (γ's, protons) produce single hits in many cells. Neutrons (via low energy protons from glancing collisions) produce multiple hits in fewer cells. These are difficult for the cell to repair, leading to a larger biological effect.

Microdosimetry is the art of measuring not just average dose but the pattern of dose deposition at the cellular scale. Macroscopic counters mimic the cellular scale by using tissue-equivalent gas as the detection medium. One detects single events (beam intensity must be reduced) and logs the energy deposited in each event using a pulse-height analyzer.

Unlike moderated counters and ionization chambers, which are relatively easy to use, LET counters and their associated data logging and analysis require considerable care and are best left to experts. If you are seriously interested in microdosimetry, ICRU Report 36 is required reading. Our description is very abridged and meant only to allow one to read the literature on unwanted neutron dose with some understanding.

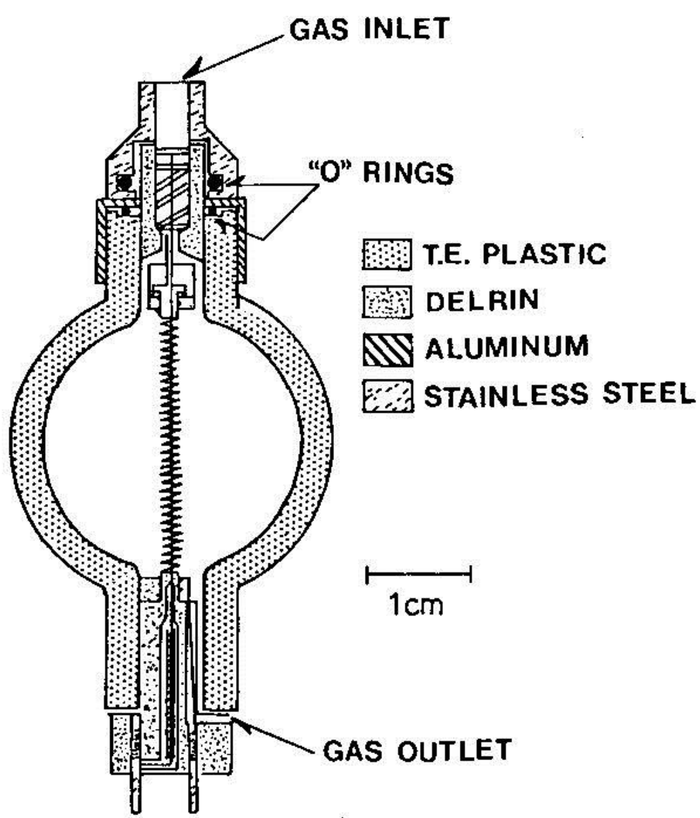
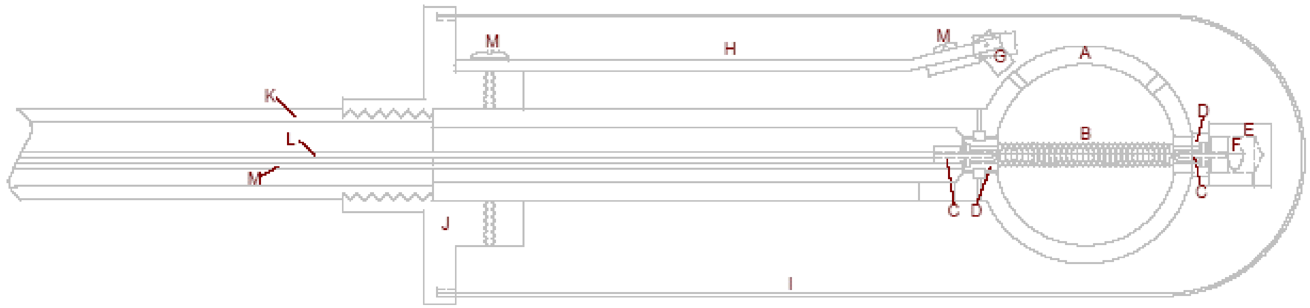


Fig. D.1. This solid-wall counter is an example of the type most frequently used in microdosimetry. The helix is maintained at positive potential with respect to the outer shell, so electrons are collected throughout the spherical region. The center wire is, of course, positive with respect to the helix. Tension is maintained in the center wire by means of a spring at the top. A gas inlet and outlet are provided for a gas-flow system.

'Rossi' counter, from ICRU 36. Both the spherical shell and the fill gas are tissue equivalent. A track crosses the sphere, secondary electrons (the final product of any ionizing particle) drift towards the helix/wire assembly, and are multiplied by the avalanche process between the helix and the wire. The resulting charge pulse, further amplified and filtered, has a height proportional to the charge (therefore energy) deposited by that single event.

Many such pulses are accumulated in a pulse-height analyzer. Because of the large dynamic range, data are taken at several overlapping electronic gain settings and those spectra need to be matched (combined) into a single one, with checks to make sure the gas gain was constant throughout.



A. Sphere, 0.050" thick A-150 TE Plactic wall
B. Central Electrode, 0.0018" dia. SS wire,
Helix, 0.0018" dia. SS wire, 0.031" ID x 20 truns (in sphere dia)
C. Insulator, Electrode, Polycarbonate
D. Insulator, Helix, Teflon
E. Spring Cover, Lucite
F. Spring, SS, 0.002" thick, 0.020" wide x 0.125" long
G. Source Rod, 0.062" dia x 0.115" long, points up when off
H. Source Support, Aluminun, 0.032" thick x 0.175" wide x 1.45" long
I. Cover, Aluminum, 0.007" thick wall, 0.76" ID
J. Header, Aluminum
K. Stem, Aluminum, 0.035" wall
L. Signal Wire, Copper, 0.016" dia
M. Helix Wire, Copper, 0.016" dia
N. Screw & Lock Wahser, Steel, 2-56 x 3/16

UNLESS OTHERWISE SPECIFIED
INTERPRET DRAWING PER ANSI Y 14
DIMENSIONS ARE IN INCHES AND APPLY AFTER PLATING
BREAK ALL SHARP EDGES

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MATERIAL

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Far West Technology, Inc.
330 D South Kellogg Ave. Goleta, CA 93117 (805) 964-3615

LET 1/2 SPHERE ASSEMBLY

A | DRAWING NUMBER LET1-029 | REV
SCALE | SHEET 1 OF 1

Commercial Rossi counter, drawing courtesy Far West Technology Inc., www.fwt.com This counter, which costs $3800 (2007), has a built-in calibration source which can be aimed at or away from the active volume.

Microdosimetric Data Analysis

Microdosimetry reveals a great deal about the unknown radiation field and has its own analysis methods. See ICRU 36 for details.

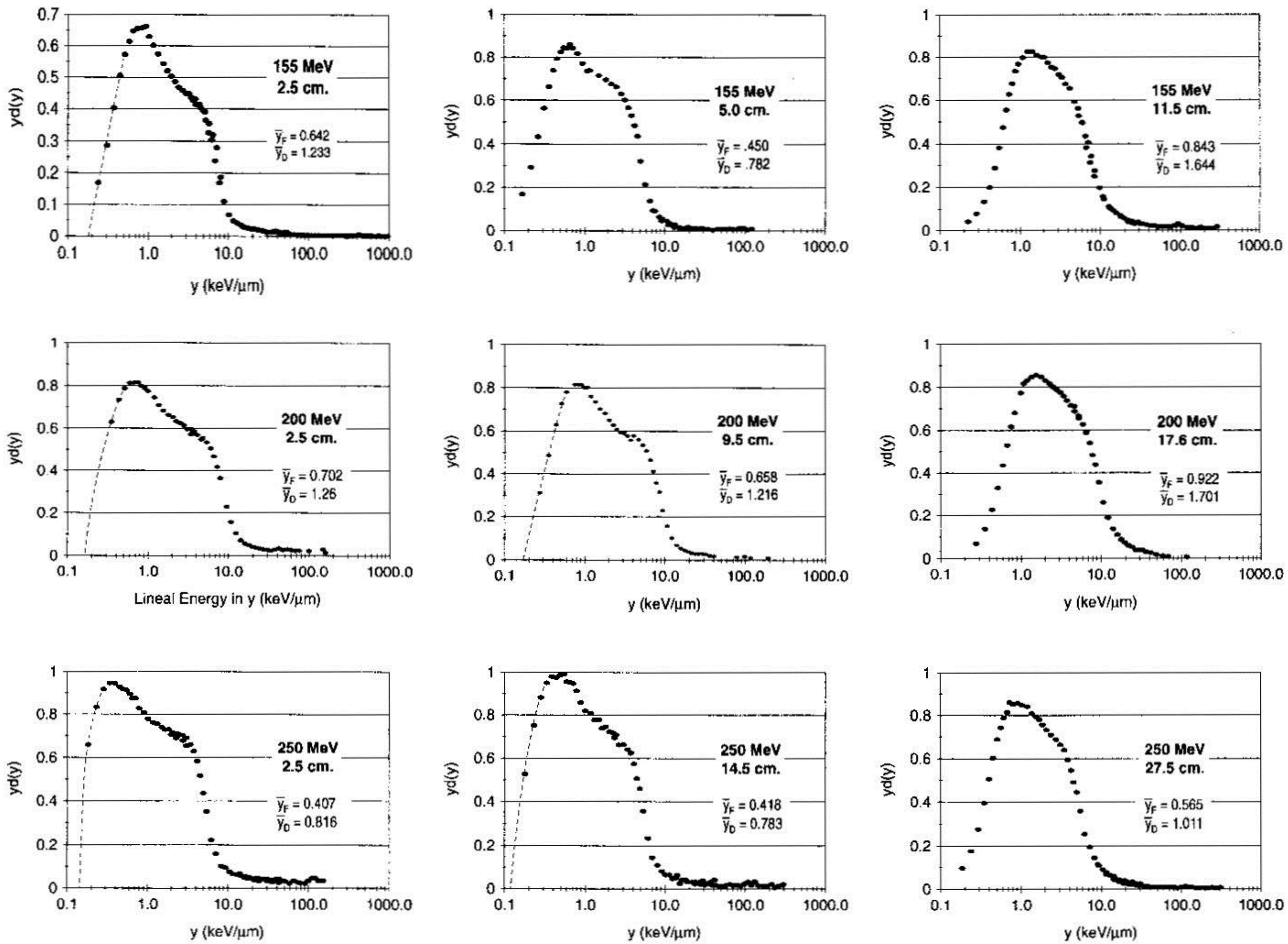
The *lineal energy*, $y \equiv \varepsilon / l$ (dimension keV/μm) is the stochastic equivalent of dE/dx or LET. ε is the *energy imparted* to the volume by a *single event* and l is the *mean chord length* in that volume. For a sphere of radius r, l = (4/3)r.

The *specific energy*, $z \equiv \varepsilon / m$ (dimension Gy) is the stochastic equivalent of dose *D*. m is the total mass contained in the fiducial volume.

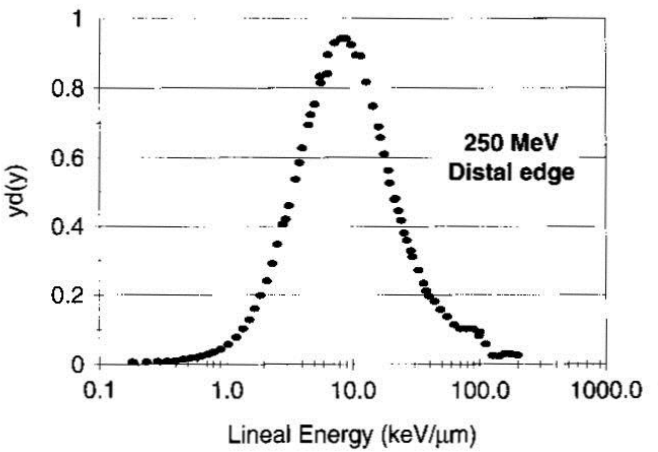
d(y) is the dose probability density of y. d(y) dy is the fraction of absorbed dose associated with y in dy. Because y ranges over many decades, it must be plotted logarithmically. So that equal areas on a log plot will still correspond to equal doses, one uses

$$dy = y\, d(\ln y) = (\ln 10)\, y\, d(\log y)$$

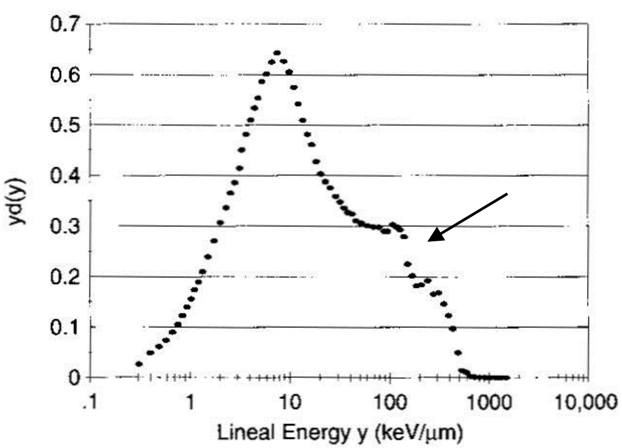
and plots *y* d(y) on a log plot. Log plots of y d(y) or z *f*(z) allow the expert to identify the kind of radiation involved and its typical energy and to compute RBE and total dose. A few examples follow.



These *y d*(*y*) plots (Coutrakon et al. (Med. Phys. 24 (1997) 1499) show the lineal energy distribution in a range modulated proton therapy beam at various proton energies and locations in the SOBP. The single low-*y* group shows that almost all the dose is from protons. Its width is due to the proton energy spread from range modulation.



This spectrum taken on the distal edge of the SOBP is still mostly protons but the average lineal energy is much higher because the protons are low energy (mix of 0-10 MeV). Coutrakon et al. show that the proton RBE in this region is ≈ 1.6 as opposed to ≈ 1 elsewhere.



This spectrum is taken 5 cm *beyond* the SOBP where the dose is mostly from very low energy recoil protons coming from a mix of *neutrons*. It is qualitatively different from the previous one. The characteristic 'proton edge' at 140 keV/µm is from low energy protons that have the maximum possible stopping power.

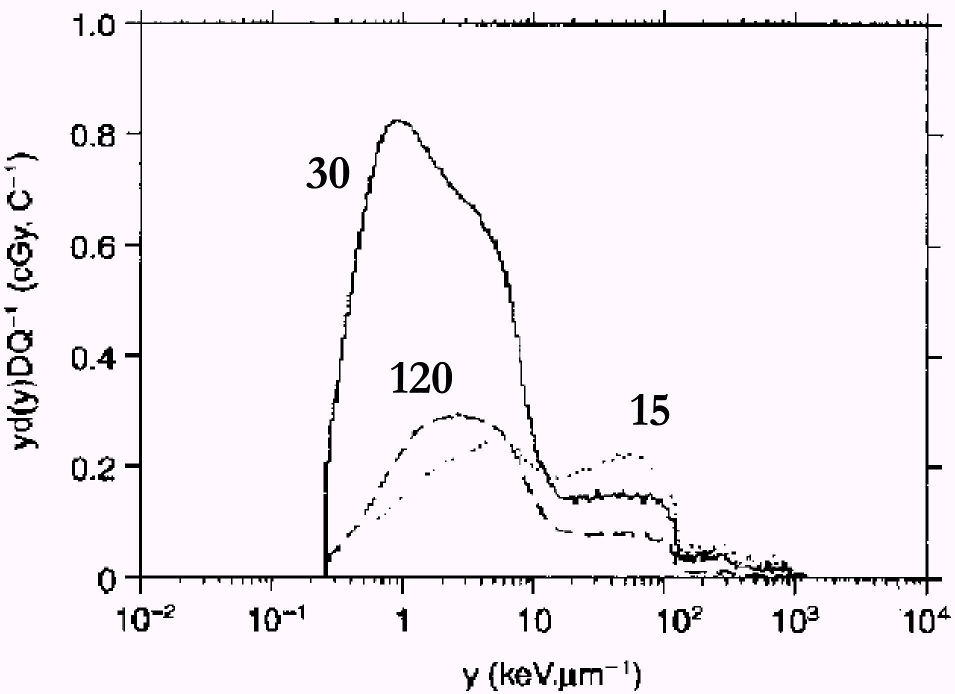
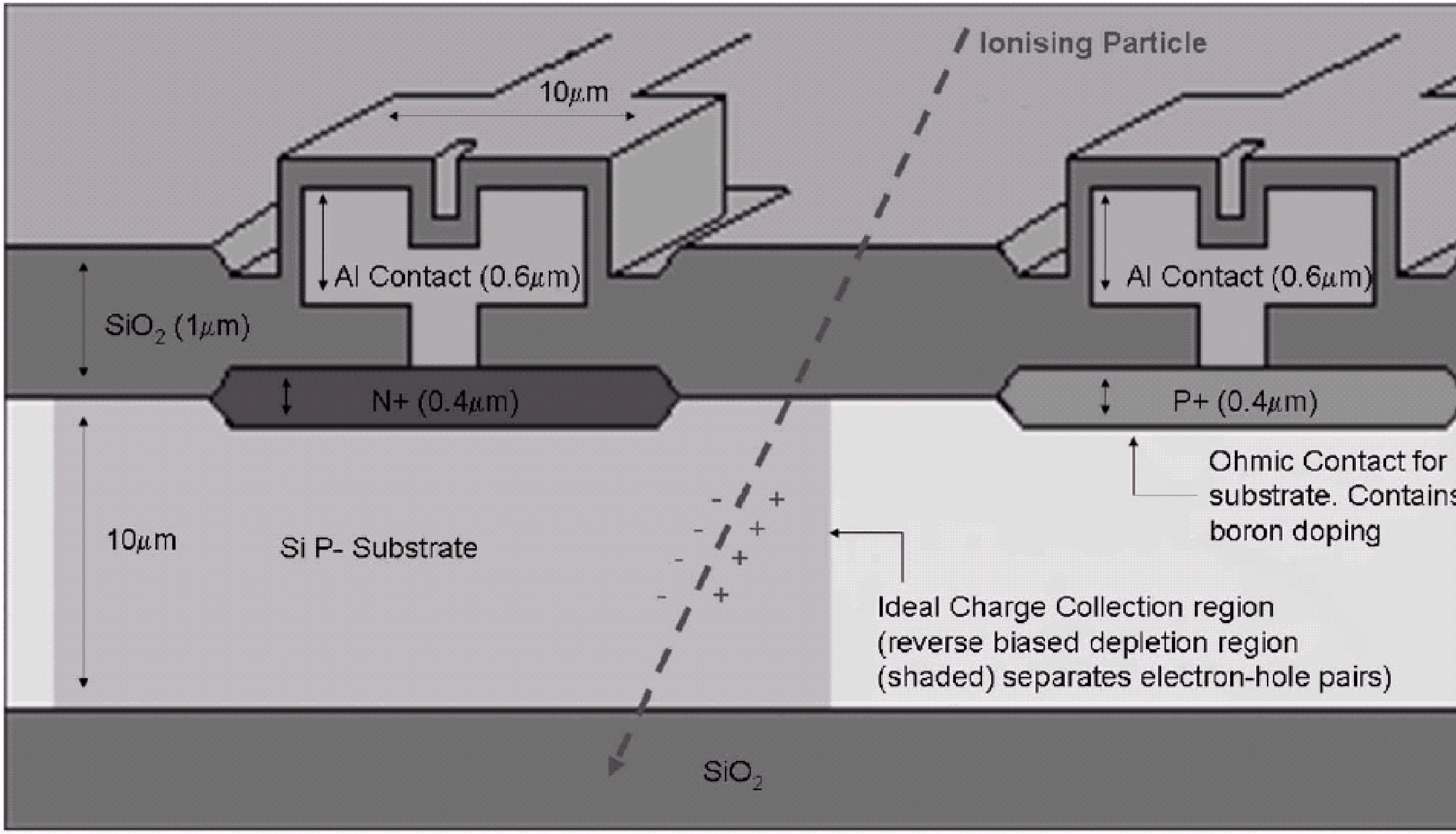
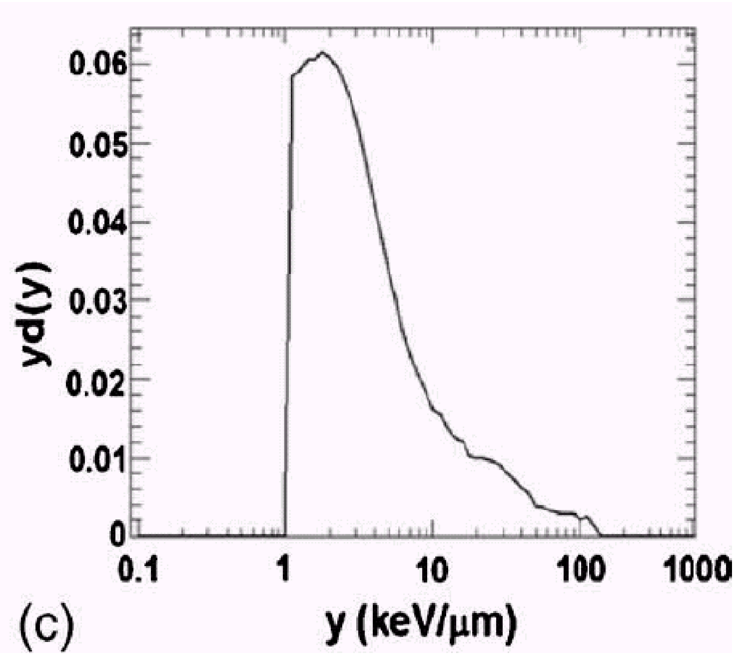


Figure 4. Single-event spectra measured in air 15 cm behind the patient collimator (No 4 in Figure 1) and at lateral displacements of 15 (···), 30 (—) and 120 cm (·--) from the central axis of a circular treatment field 4 cm in diameter. Spectra are normalised per treatment gray at the isocentre.

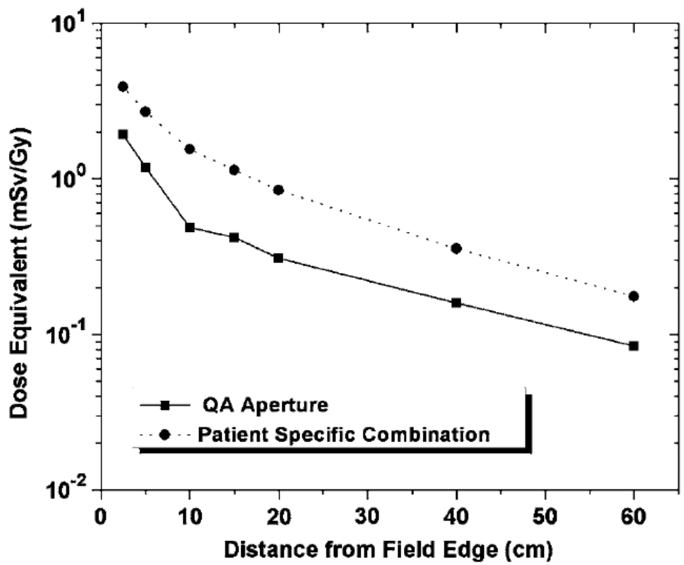
This figure from Binns and Hough (Rad. Prot. Dosim. 70 (1997) 441) illustrates the full power of microdosimetry. The neutron component (10-100 keV/μm) falls steadily with increasing distance (15, 30, 120 cm) from the beam axis. The low LET component has a strong flare at 30 cm, just outside the shadow of the patient collimator, attributed to unblocked protons from the beam window and scattering system. Because of their low LET this has relatively little effect on the *equivalent* dose (mSv) to the patient. Nevertheless, this proton leakage was blocked later by additional shielding.



The SOI (Silicon-On-Insulator) microdosimeter is a relatively new, not yet commercial technique (Wroe et al., Med. Phys. 34 (2007) 3449 and references therein). Here the fiducial volume actually *is* of μm dimensions. A large array (4800 30×30×10 μm cells) is used to get enough signal. Even so, the whole detector is small enough to be embedded in a phantom. A ½ mm polyethylene converter in front of the array converts neutrons to recoil protons.



y d(*y*) spectrum measured in a proton radiotherapy beam with the SOI detector. The analysis follows standard microdosimetry practice. The edge at 1 keV/µm is non- physical and comes from the electronic cutoff of sensitivity. The radiation is almost all protons with just a hint of neutrons and the 'proton edge'.



Neutron dose measured just outside the proton field with the SOI detector. As usual, the dose near the field edge is of order mSv/Gy. This graph shows that, as the patient collimator is closed down, the neutron dose goes up. Fewer protons stop in the patient but more stop in the collimator and these are more spread out by the time they reach the patient.

Neutron Detector Summary

Moderated neutron counters are easy to use, sensitive, and measure dose equivalent (*H*) with reasonable accuracy. However, they are bulky and difficult to incorporate into a patient phantom. They are generally used to measure *H* near the target volume or to monitor the low dose in radiation-worker or public areas.

Bubble counters are small, inexpensive, reusable and real-time. They can be inserted into a phantom and measure *H* reasonably well. They are sensitive enough to measure dose to the patient and radiation workers.

Large plane-parallel ion chambers can be used to measure *D* if it is known *a priori* that it is mostly from neutrons. In that case, they are simple and absolute.

Track-etch detectors are the most common commercial monitor for radiation protection. They are not very sensitive, but can give some information on RBE.

Tissue-equivalent proportional counters (TEPC's) used with microdosimetry techniques give by far the most information about the radiation field. The equipment is commercially available. However, data collection and interpretation are relatively complicated and best left to the experts. Silicon-on-insulator (SOI) microdosimetry arrays are compact but not yet commercially available. The relatively high charge threshold should not be a problem for neutrons.