Neutron Spectra and Dosimetric Quantities Outside Typical Concrete Shielding of Synchrotron Light Sources

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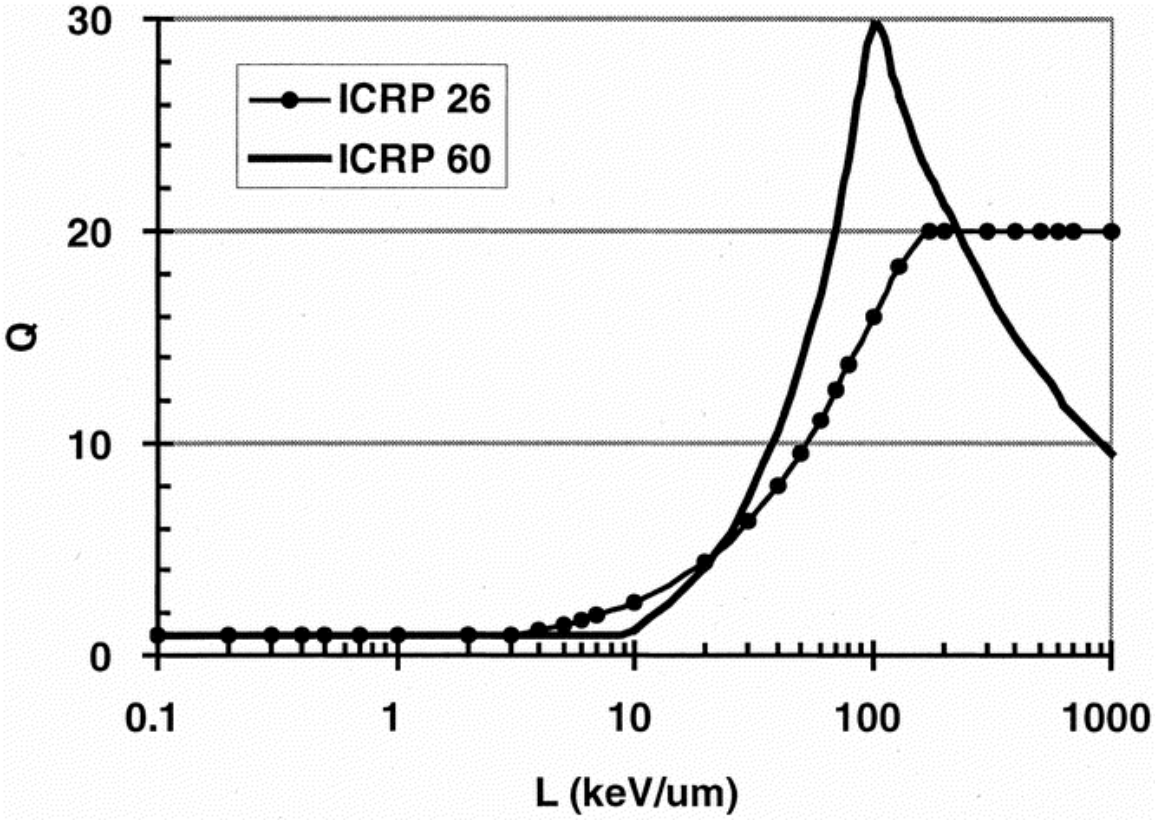
Outline

- Background information for changes of dosimetric quantities
- Answer some questions:
  - What are the neutron spectra outside concrete shielding?
  - How do the operational quantities compare to the limiting protection quantity *E*?
  - What are the dose fractions of neutrons > 20 MeV?
  - What are the attenuation lengths in concrete?
  - How about the SHIELD11 neutron dose results?
- FLUKA results examined particularly for typical concrete shielding (60 – 150 cm) at light sources.

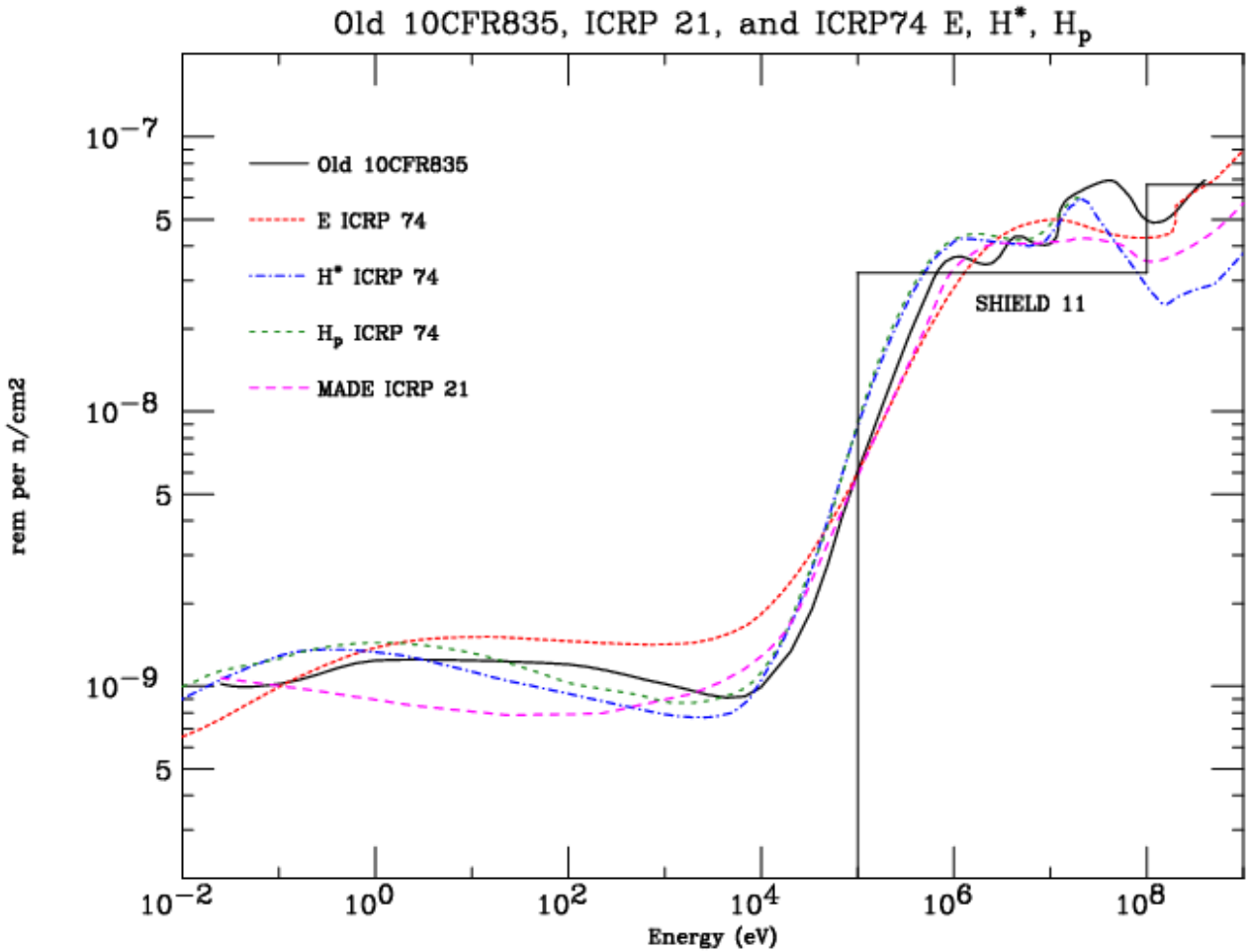
US Regulation	International Recommendation	Protection Quantity	Operational Quantity	Comments
Old 10CFR835 (1998)	ICRP21 (1973) NCRP38 (1971)		**MADE** from ICRU20 (1971)	
	ICRP26 (1977)	**H_E** Effective Dose Equivalent	MADE	**Old Q(L)** (maximum 20 at >150 keV/um)
	ICRU39 (1985)		**H*, H', H_p**	ANSI N13.11 (1983) DOELAP
New 10CFR835 (2007)	ICRP60 (1991)	**Effective Dose** $E = \sum W_T H_T$ $= \sum W_T \sum W_R D_T$		W_R (E) (max. 20), New Q(L) for H* H', H_p (maximum 30 at 100 keV/um)
	ICRU51 (1993)		**H*, H', H_p**	**New Q(L)** **(max. 30)**
	ICRP74 (1997)	*E*	**H*, H', H_p**	ANSI N13.11 (2009) DOELAP

New Q(L) – ICRP60 (1991)



Increase up to a factor 2 for LET around ~100 keV/μm (0.1-2 MeV neutrons).

Fluence to “Dose” Conversion Coefficients for Neutron Spectrum



Red curve: E(worst)

Blue curve: H*(10)

Small Changes between New Quantities and MADE for Neutron Sources

Source spectra from *Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes*, IAEA Technical Reports Series No. 403.

Ratio	^{252}Cf	AmBe
E(AP) / MADE	0.98	1.09
$H^*(10)$ / MADE	1.15	1.06
$H_p(10)$ / MADE	1.20	1.12

But How About Spectra with Neutrons > 20 MeV?

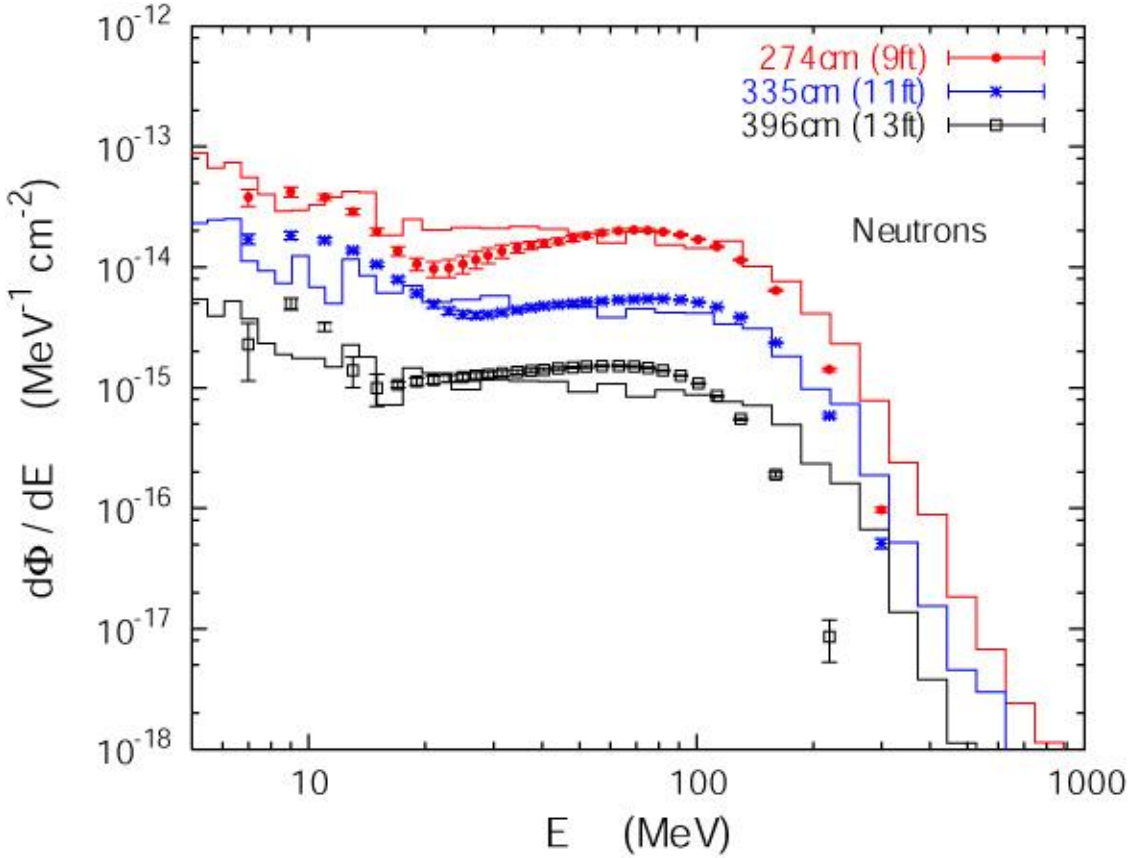
FLUKA Calculations

- FLUKA Monte Carlo code version 2008.3.5
- Three electron energies (100 MeV, 1 and 10 GeV)
- Electrons incident on an “optimum” copper target (30.48 cm long, 5.08 cm in radius; EM cascade fully developed)
- Cylindrical concrete shield surrounding the target at 2 m
- ANSI NBS04 ordinary concrete (30.5 to 244 cm thick)
- Scoring neutron spectrum at 5 m from the target, independent of shielding thickness (to allow comparisons of attenuation lengths without corrections for $1/r^2$ attenuation)
- Scoring in three angular intervals: 65º–75º, 75º–85º and 85º–95º (experience has shown that the maximum dose is found generally at angles slightly smaller than 90º)

FLUKA Calculations

- Separate calculations for each thickness to avoid correcting for backscattering inside the shielding.
- Neutron fluence folded with conversion coefficients for Effective Dose (***E***), Ambient Dose Equivalent ***H*(10)***, and with the Andersson-Braun remmeter response curve.
  - Coefficients of ***E*** and ***H*(10)*** from ICRP 74, extended to higher energies by Pelliccioni.
  - Andersson-Braun (AB) rememter response from *Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes*, IAEA Technical Report #403 (2001).

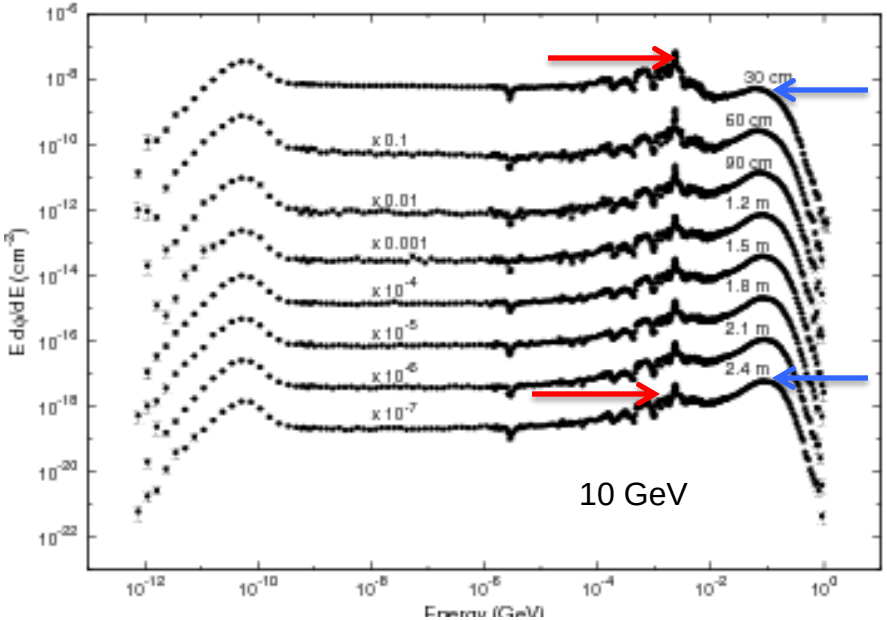
Benchmark Measurements and FLUKA Calculations for Equilibrium Neutron Spectra

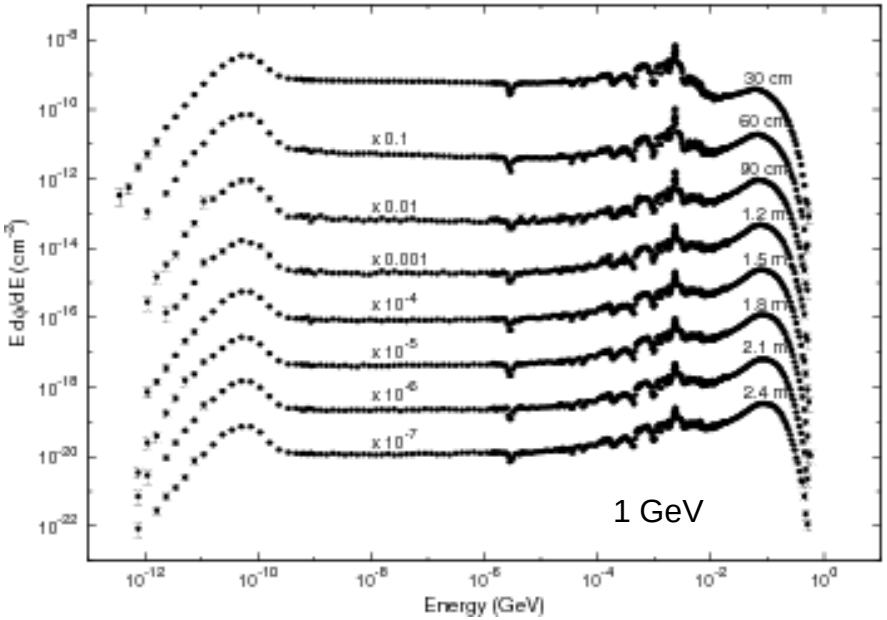


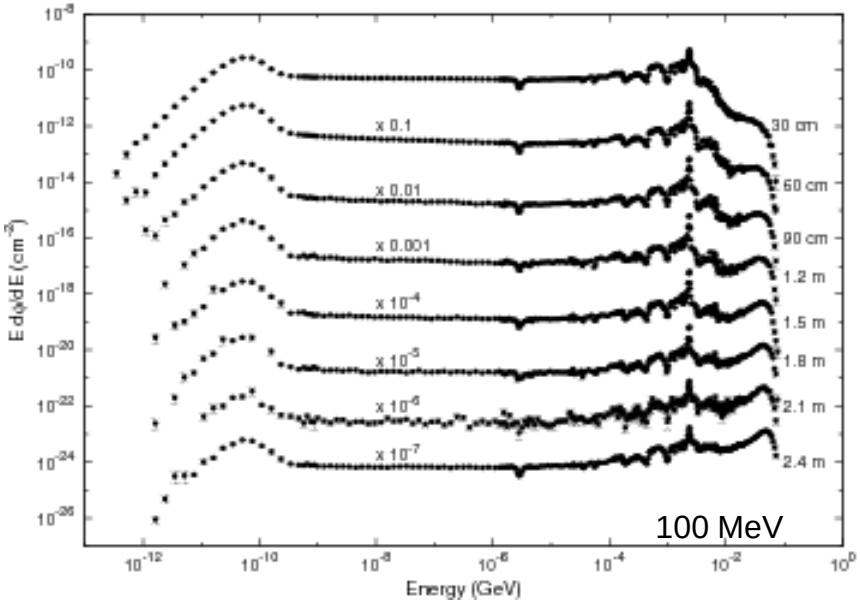
Points: NE213

Histograms: FLUKA

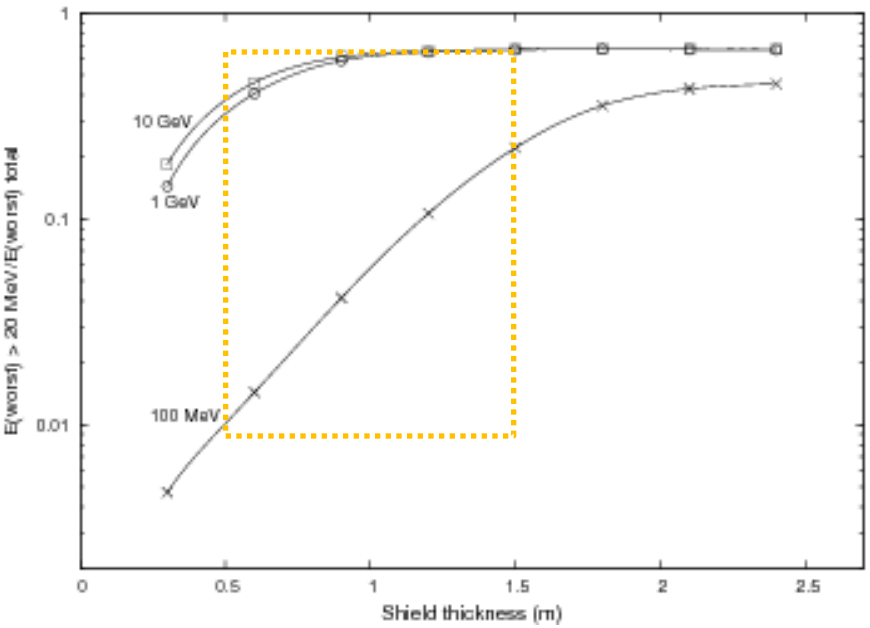
Nuclear Instrument Method, A503, 606-616 (2003). SLAC-PUB-9210 (SLAC/Tohoku/CERN)

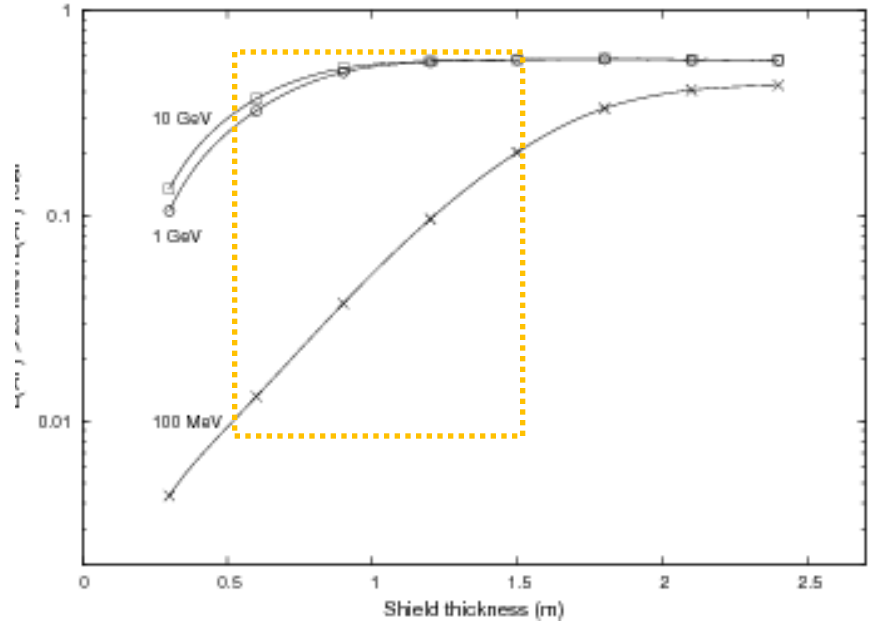


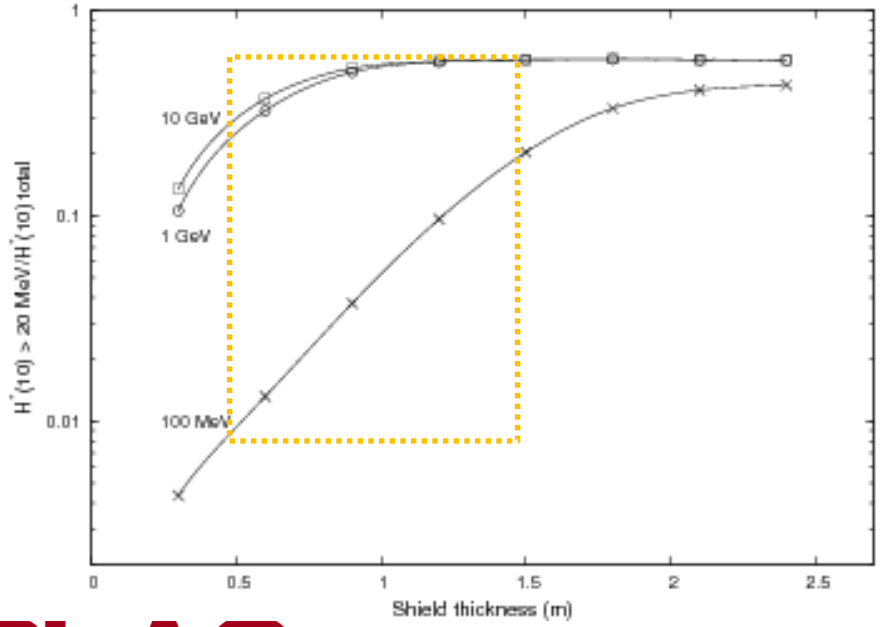




- Peaks at about 1 and 80 MeV
- Neutron spectral shape becomes nearly constant for concrete > 1.2 m thick at 1 and 10 GeV, confirming the existence of an **equilibrium spectrum** beyond such thickness for GeV accelerators.





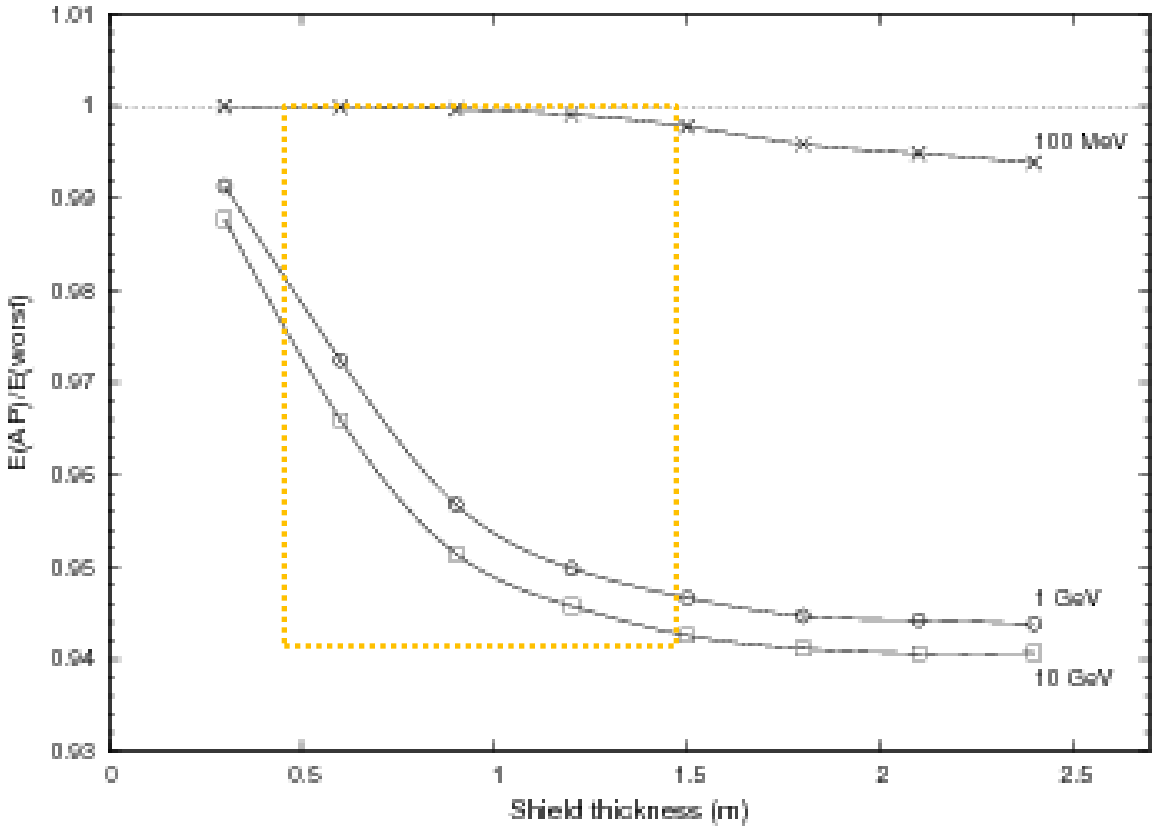


For 1 and 10 GeV, dose fraction due to neutrons > 20 MeV is gradually increasing with concrete thickness (from 15% to 65%).

For 100 MeV, dose fraction increases from about 5% to 50%.

Two sets of conversion coefficients for Effective Dose *E*:

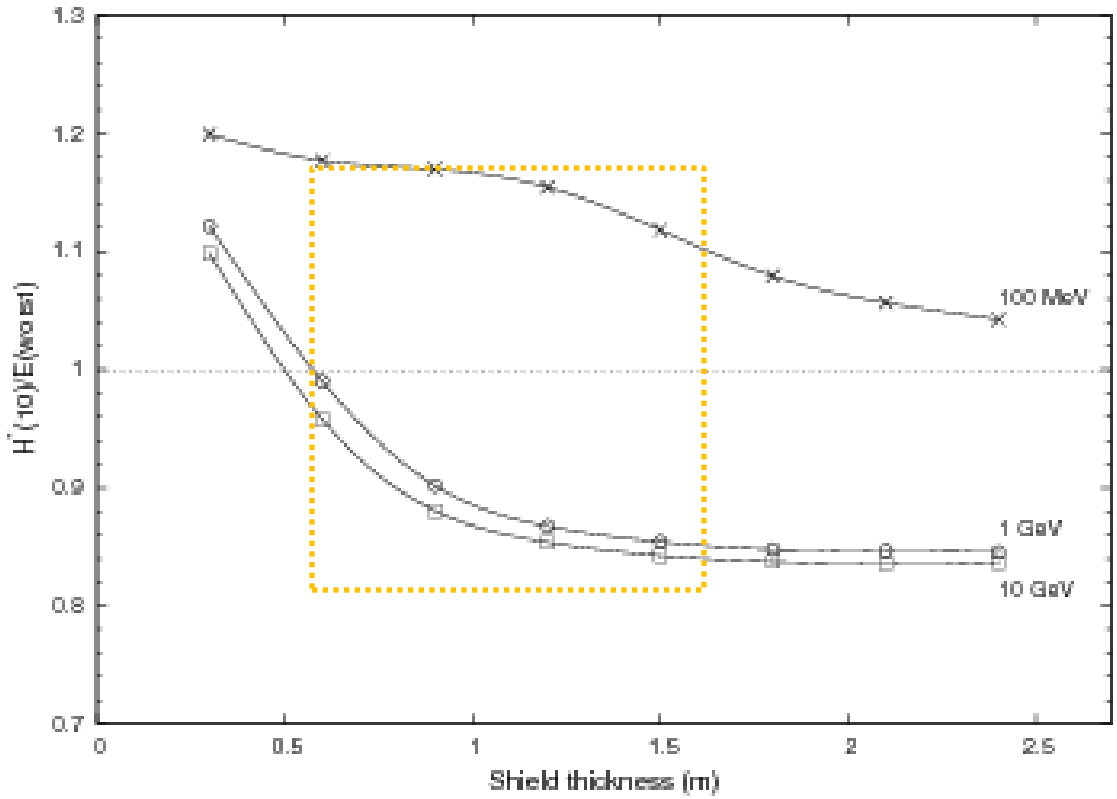
- **AP (Anterior-Posterior)**
- **"Worst" (at any neutron energy, the highest value among the different available irradiation geometries)**



For 100 MeV, *E(AP)* ≅ *E(worst)* at all thicknesses.

For 1 and 10 GeV, *E(AP)* < *E(worst)* by a maximum of 6% at concrete > 1 m!

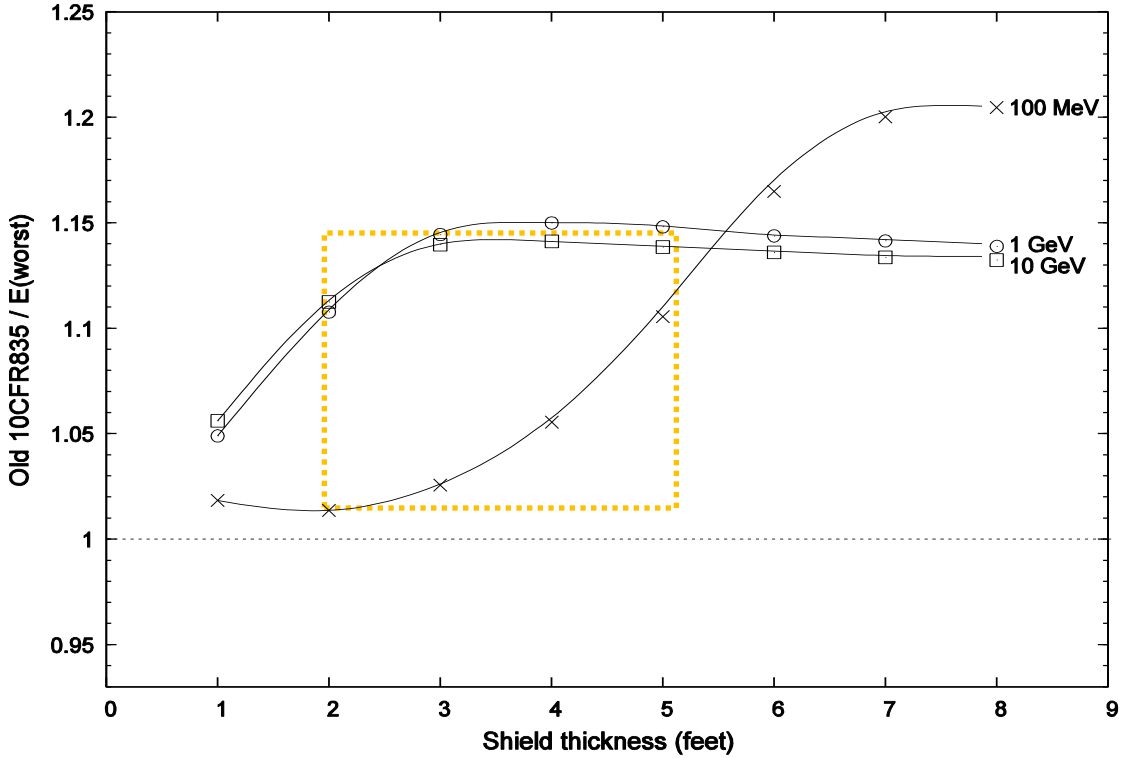
Ratio between *H*(10)* and *E(worst)*



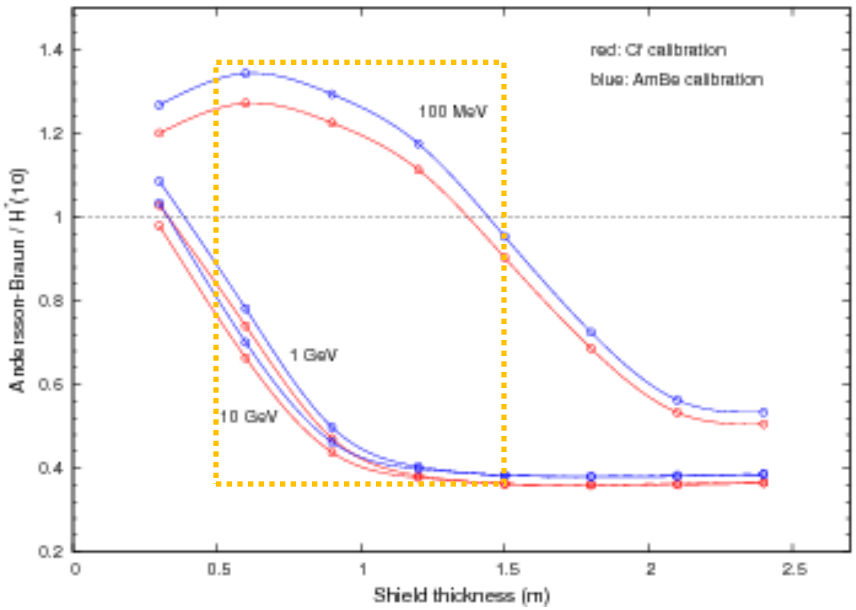
For 100 MeV,
H(10)* **>** *E(worst)* by ~15%

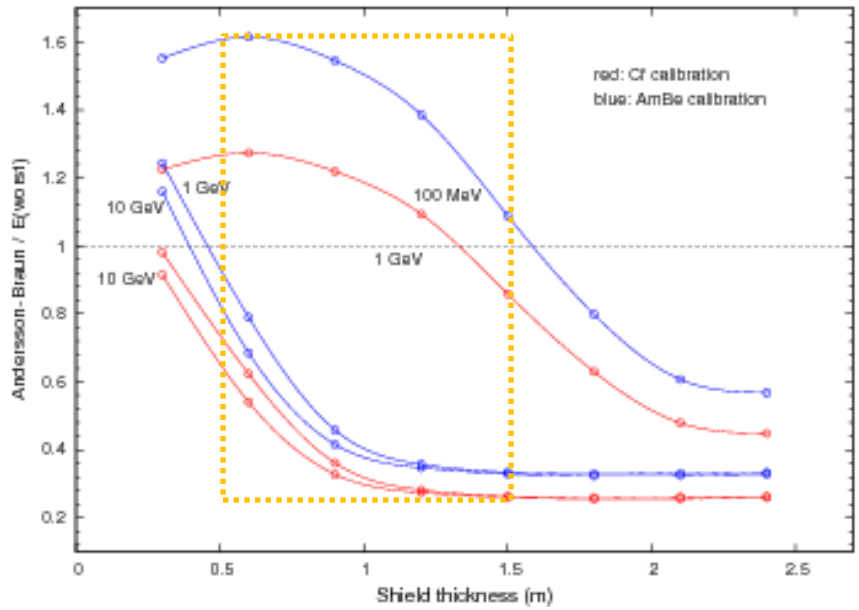
For 1 and 10 GeV,
H(10)* **<** *E(worst)* by 15% maximum for concrete > 60 cm!

Ratio between *MADE (old 10CR835)* and *E(worst)*



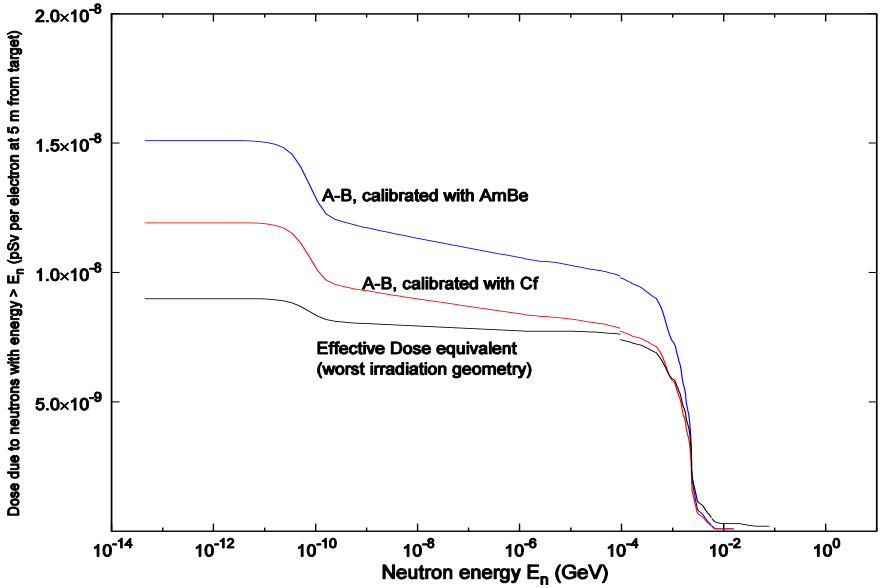
For 0.1, 1 and 10 GeV, *MADE* > *E(worst)* up to 20% max.

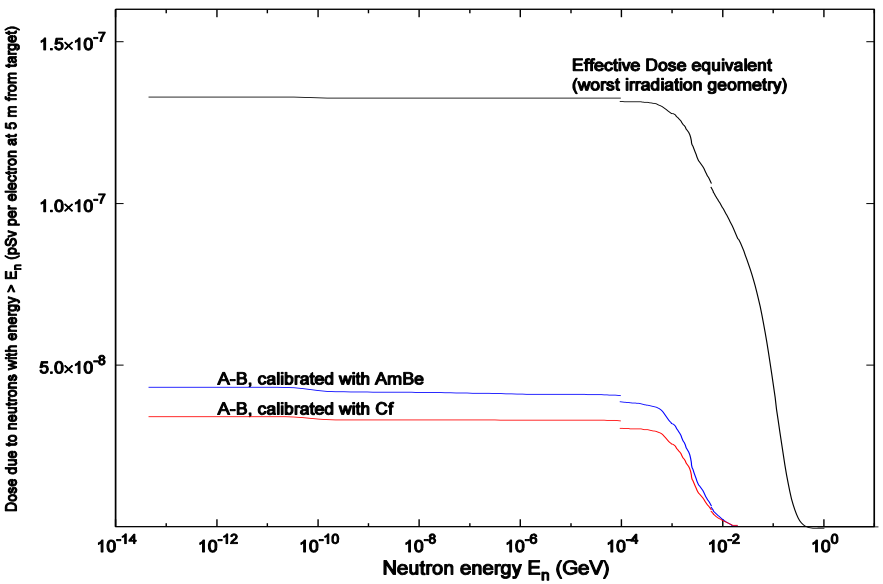




- For 1 and 10 GeV, the **AB remmeter** underestimates ***H*(10) and E***:
  - -20% to -70% for concrete ≥ 60 cm.
  - Underestimation is worse for ^{252}Cf than for AmBe calibration, and worse for ***E*** (–74%) than for ***H*(10)*** (–64%).
- The practice to double (or more) the AB readings outside the shielding of a GeV accelerator is thus justified!
- For 100 MeV and concrete < 150 cm, AB remmeter overestimates ***H*(10)*** and ***E***

Comparison of Cumulative Remmeter Response and Cumulative *E*





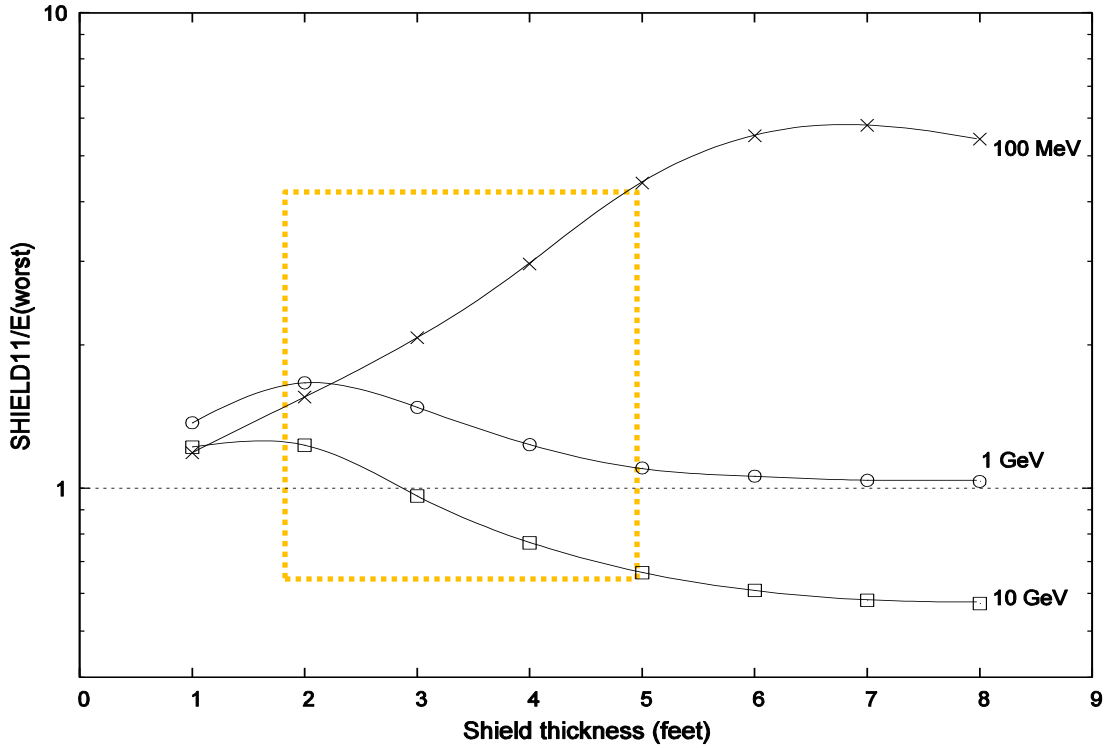
100 MeV, 60-cm concrete

AB overestimate (due to low-E neutrons)

10 GeV, 2.1-m concrete

AB underestimate (due to high-E neutrons)

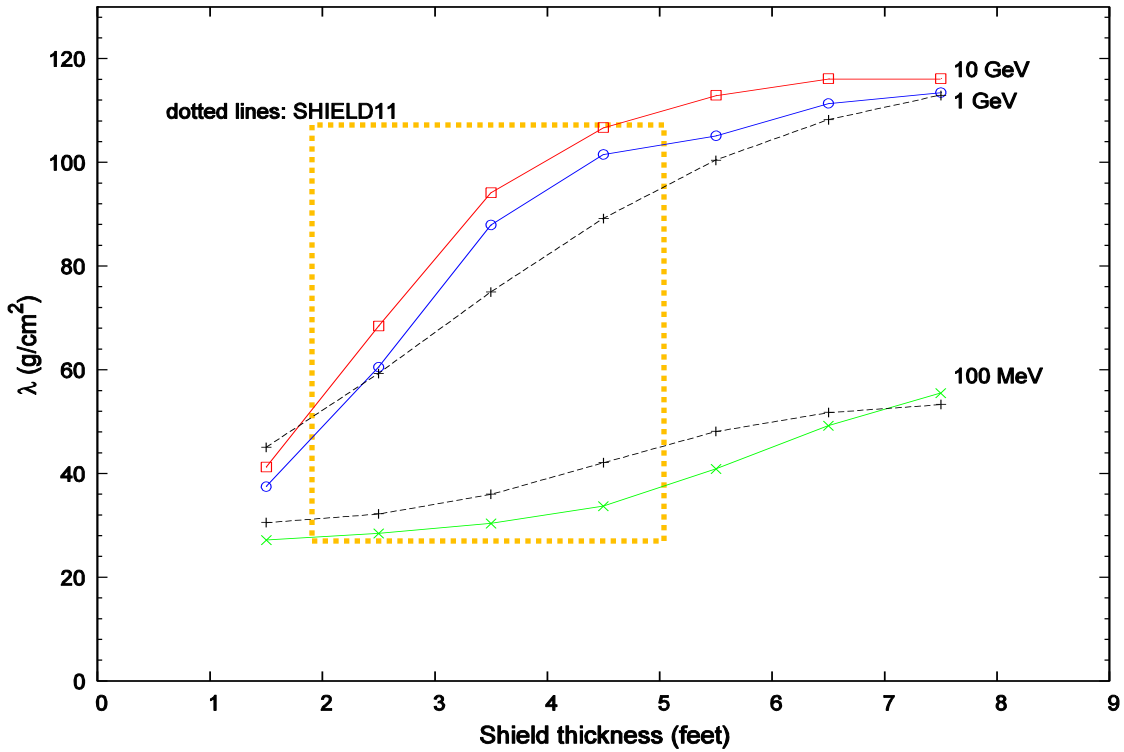
Ratio between *SHIELD11 Dose* and *E(worst)*



For 10 GeV, *SHIELD11* ≈ *E(worst) within 40%*.
For 1 GeV, *SHIELD11* > *E(worst)* by 45% max.
For 100 MeV, *SHIELD11* **>** *E(worst)* by 600% max.

SHIELD11 Shielding Calculations

- SHIELD11 code has 3 neutron components:
  - GRN ($0.1 < E_n < 20$ MeV), 3.2×10^{-8} rem·cm^2
  - MID (20 MeV $< E_n < 100$ MeV), 3.2×10^{-8} rem·cm^2
  - HEN ($E_n > 100$ MeV), 6.7×10^{-8} rem·cm^2
- SHIELD11 GRN and MID conversion coefficients are lower than the average values of most curves, and the HEN coefficient is higher. (*these are now changed*).
- SHIELD11 neutron yields and attenuation lengths are not changed.



1) Equilibrium attenuation length for electron and proton accelerators are similar, 117 ± 2 g/cm^2 (Thomas and Stevenson, Tech. Rep. 283, IAEA, Vienna,1987)
2) For 1 and 10 GeV, equilibrium attenuation length reached for concrete ≥ 1.5 m

- Maximum λ calculated in this work:

10 GeV: 116 g/cm^2
1 GeV: 114 g/cm^2
100 MeV: 56 g/cm^2 (no-equilibrium)

- Consistent with that for proton accelerators

Reported Attenuation Lengths for Neutron Spectra in Concrete at about 90º

Reference	Electron energy (GeV)	λ (g/cm^2)
Teterev, Atomic Energy 62, 396-400 (1987)	0.027	28
Alsmiller, Jr. and Barish, Part. Accel. 5, 155-159 (1973)	0.4	35
Gabriel, Lillie and Bishop, ORNL/TM-10036 (1986)	0.75	96
Liu et al., SLAC RP-Note 02-20 (2002)	3.0	110
Bathow et al., Nucl. Phys. B2, 669-689 (1967)	6.3	91
O'Brien, HASL-203 (1968)	10	105
Jenkins, Nucl. Instrum. Meth. 159, 265-288 (1979)	15	104
DeStaebler, SLAC Report No. 9 (1962)	20	120
Swanson, Tech. Rep. 188, IAEA, Vienna (1979)	20	120
Roesler et al., Nucl. Instrum. Meth. A503, 606-616 (2003) Taniguchi et al., Nucl. Instrum. Meth. A503, 595-605 (2003)	28.7	116
Dinter et al., Nucl. Instrum. Meth. A455, 460-469 (2000)	30	94
Goebel et al., CERN LEP Note 538 (1985)	100	115

Summary: Neutron Spectra and Attenuation Lengths

- Spectral shape becomes nearly constant for concrete > 1.2 m, confirming the existence of an equilibrium spectrum.
  - *Non-equilibrium spectra with typical light source concrete shielding.*
- For 1 and 10 GeV, the dose fraction due to neutrons with energy > 20 MeV increases with shielding thickness from 15% to 65%. For 100 MeV, the dose fraction increases from 5% to 50%.
- Attenuation length in concrete for equilibrium spectrum is 115 g/cm^2.

Summary of Dosimetric Quantities and SHIELD11

- For 0.1, 1 and 10 GeV, *MADE* **>** *E(worst)* up to 20% max.
- For 1 and 10 GeV, *E(AP)* **<** *E(worst)* up to 6% for concrete > 1 m. For 100 MeV, *E(AP)* ≅ *E(worst)* at all thicknesses.
- For 1 and 10 GeV, *H*(10)* **<** *E(worst)* by 15% maximum for concrete > 60 cm. For 100 MeV, $H^*(10)$ > *E(worst)* by 15%.
- AB remmeter underestimates *E and* $H^*(10)$ by up to 70%. For 100 MeV and concrete < 150 cm, AB remmeter overestimates $H^*(10)$ and *E*
- SHIELD11 is conservative, except for 10 GeV and > 90 cm concrete, where it underestimates doses by about 40%.

- Given that for neutrons:
  - Both *E* and *H*(10*) can neither be measured nor be calculated
  - Both are derived from calculated fluences using conversion coefficients
  - Both can be measured with some approximation using a calibrated instrument with a suitable energy response (the Andersson-Braun response can be adjusted to fit either *H*(10)* or *E*)
  - In addition, for neutrons > a few tens of MeV, which constitute an important dose fraction outside the shield at high energies, $H^*(10)$ is not conservative with respect to *E*
- Why use *H*(10),* an approximation which is not even conservative, when with the same techniques one can obtain directly *E*?
- *E(worst)* is a better choice: always conservative by definition!