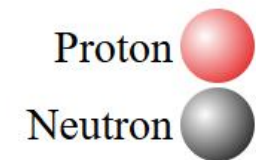
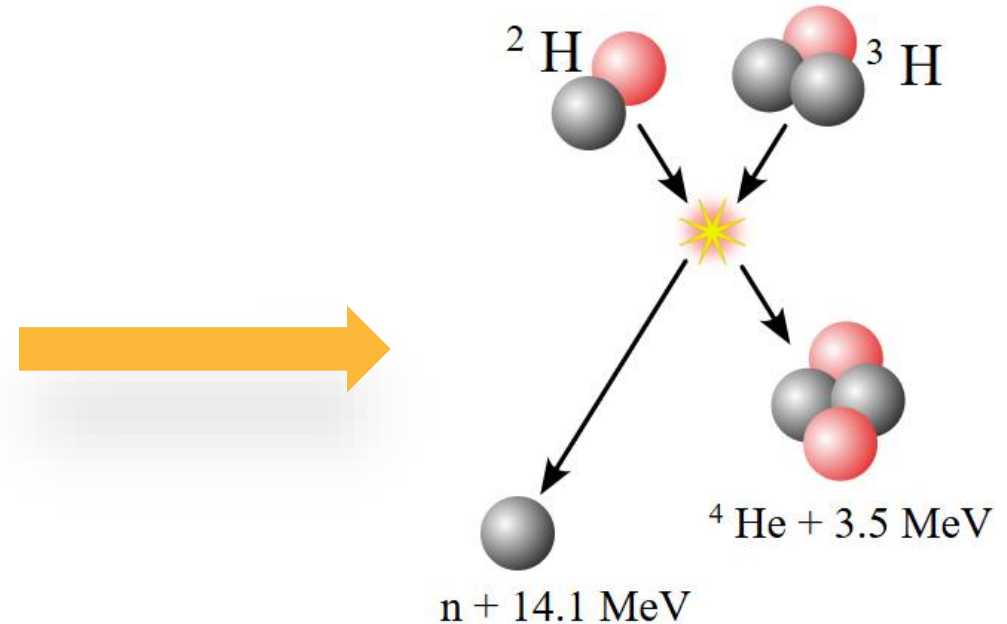


# 14 MeV Neutron Detection Using Track-Etch Dosimetry

Nathan Duff, MHP, CHP, CLSO

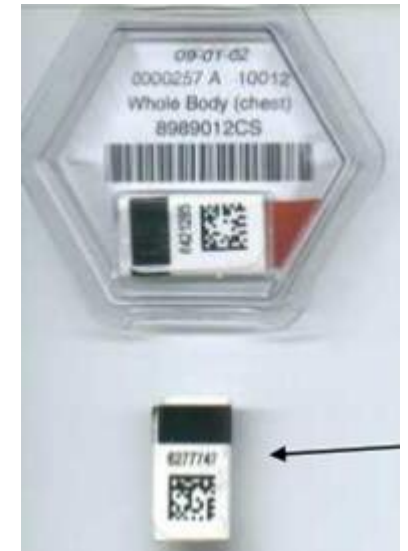
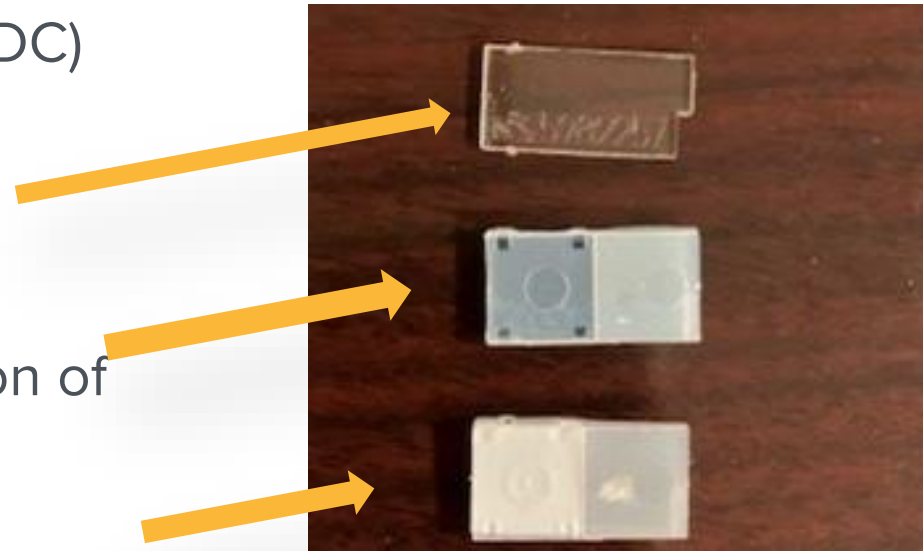
- D-<sup>3</sup>He has no neutron emission component
- D-D Fusion Reactions
  - Two <sup>2</sup>H (1 proton+1 neutron) nuclei fuse
  - Output is <sup>3</sup>He (2 protons+1 neutron) and a 2.45 MeV neutron, OR
  - <sup>3</sup>H (1 proton+2 neutrons) and a 3.02 MeV proton
- D-T Fusion Reactions
  - One <sup>2</sup>H (1 proton+1 neutron) and one <sup>3</sup>H (1 proton +2 neutrons) nuclei fuse
  - Output is <sup>4</sup>He (2 protons+2 neutrons) and a **14.1 MeV neutron**
- External Dosimetry Implications
  - D-D
    - 2.45 MeV neutron energy is within well-known response range, similar to Cf-252 (2.13 MeV)
  - D-T
    - 14.1 MeV neutron is at the outer limit of common testing range
    - ANSI N13.11 does not extend beyond AmBe (4.16 MeV) – No Accreditation category for D-T neutrons



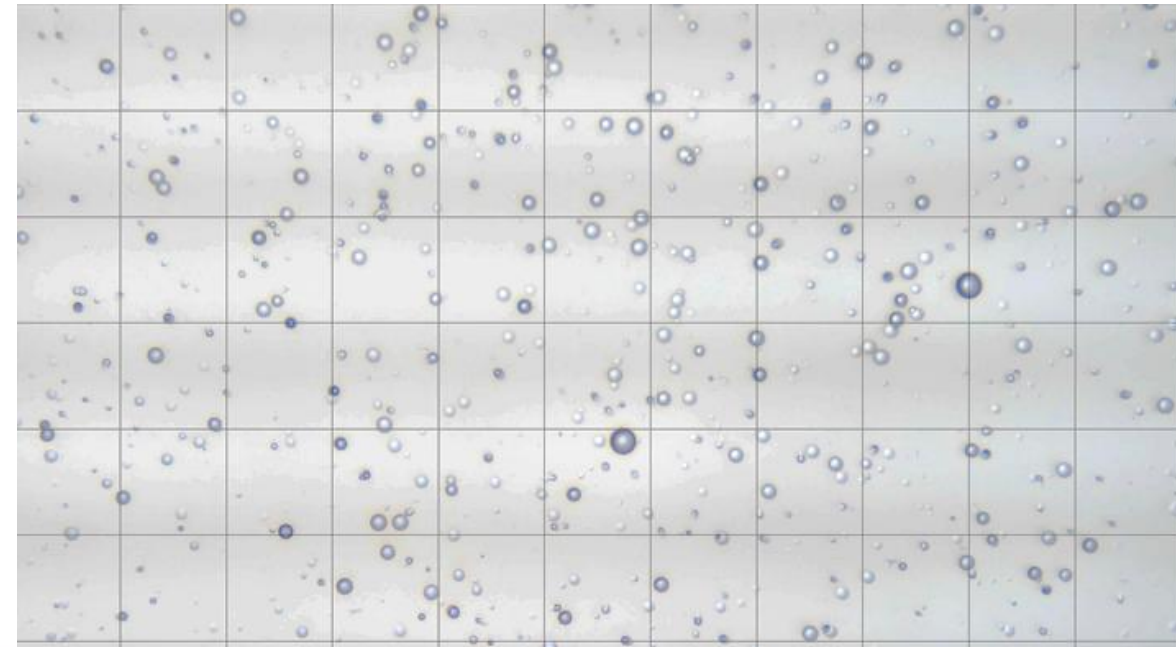
## Track-Etch Neutron Dosimetry

Commercially Available Currently

- Polyallyl diglycol carbonate (PADDC)
- Commercial name: CR-39®
- Plastic polymer in which HCPs leave damage tracks
- Polyethylene radiator for creation of protons using (n,p)
- Can also utilize a boron-Teflon radiator to detect thermal neutrons via (n, $\alpha$ )
- Chips are etched in NaOH to enlarge molecular tracks



- After etching, the tracks from the neutron reaction are now visible under a microscope
  - 200x Magnification
- Chips must be viewed manually or by a counting camera
- Small tracks are proton from fast neutrons
- Large tracks are alpha from thermal neutrons
- Track density correlates to neutron dose
- Correction Factors applied for known-energy
- Correction Factors may be provided by the customer for specific use cases



- Bare response is 1/4 the AmBe response
- 1mm Polyethylene response is 1/4.5 the AmBe Response
- This means the Neutron Correction Factor would need to be at least 4
- An NCF of 4 is considered very large and results in many false positives at low doses

#### Sensitivity

Source (MeV)	1 mm Plastic		Bare CR39		Thermal Neutron Component			
	Fast Sensitivity (tracks/mm2/mrem)	Std	Fast Sensitivity (tracks/mm2/mrem)	Std	Fast Sensitivity (tracks/mm2/mrem)	Std	Thermal Sensitivity (tracks/mm2/mrem)	Std
0.07	0.336	0.038	0.366	0.042	0.350	0.035	0.268	0.130
0.144	0.220	0.016	0.236	0.011	0.234	0.020	0.220	0.021
0.25	0.128	0.005	0.163	0.023	0.124	0.003	0.141	0.021
0.5	0.085	0.007	0.085	0.005	0.092	0.011	0.070	0.012
1.2	0.104	0.014	0.114	0.011	0.098	0.015	0.049	0.007
2.5	0.121	0.008	0.108	0.014	0.124	0.020	0.054	0.013
5	0.140	0.008	0.097	0.006	0.167	0.024	0.020	0.005
14	0.032	0.009	0.024	0.006	0.049	0.009	0.053	0.013

- 16.5 MeV neutron test performed at the National Physical Laboratory (NPL) in the United Kingdom
- 16.5 MeV is expected to be even lower response than 14.1 MeV, but gives a decent estimate
- Mean response ranges from 0.314 to 0.565

Neutron energy, $E$ (MeV)	Average $H_p(10)$ exposure, $H^0$ (mSv)	Relative unc. in reference dose, $U_{rel,k,j}^0$	Mean response, $R_{k,j}$	Standard deviation of the readings/response, $S$	$U$ value for the response, $U_{k,j}$	$1+r_{min} - U_{rel,k,j}^0$	$R_{k,j} - U_{k,j}$	$R_{k,j} + U_{k,j}$	$1+r_{max} + U_{rel,k,j}^0$
Tests at $H_{min}+0.1$ mSv, taken to be 0.2 mSv, where $r_{min} = -55\%$ and $r_{max} = +120\%$ for $0^\circ$ irradiations									
16.5	0.207	0.050	0.565	0.125	0.093	0.400	0.472	0.659	2.250
16.5	0.208	0.050	0.522	0.088	0.068	0.400	0.454	0.590	2.250
Tests for $H^0 > 0.5$ mSv; irradiations at 1.0 mSv where $r_{min} = -40\%$ and $r_{max} = +70\%$ for $0^\circ$ irradiations									
16.5	0.978	0.050	0.355	0.030	0.028	0.550	0.327	0.383	1.750
16.5	0.984	0.050	0.314	0.040	0.033	0.550	0.281	0.347	1.750

## So What's the Problem?

Response to D-T Neutrons is low

- D-T Fusion neutrons are detectable using PADC+PE, but at low sensitivities
- Correction Factors up to 4 are undesirable

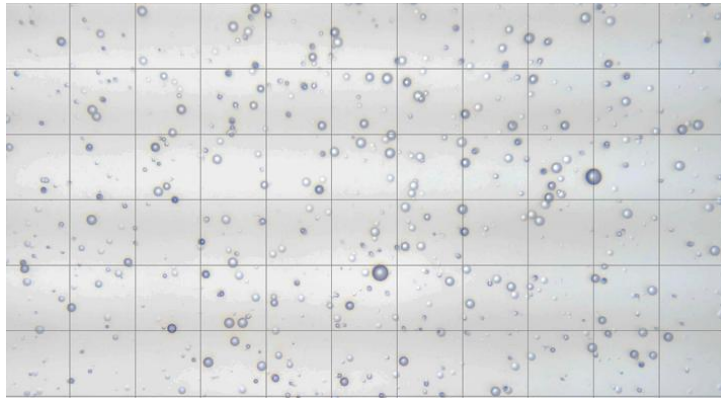
## What should we do?

3 Clear Options Currently

- Do nothing
- Develop energy-specific algorithm
- Modify radiator

It's not really nothing...

- Utilize current methodology and apply a Neutron Correction Factor
- NCFs are available for dosimetry accounts with known neutron fields.



- Pros:
  - It's easy; We can do this now
  - NCF = 4.5 is justifiable with current studies
  - No accreditation category, so it's "good enough"
- Cons
  - Correction Factors up to 4 are undesirable
  - Counting errors are magnified
  - This can result in false positives at lower doses.
  - Spectrum may be more complicated

### Radiation Weighting Factors

- NRC Table 1004(b).2 lists a Q value of 7.5 for 14 MeV.
- ICRP60  $W_r$  for 14.1 MeV falls into the 10 step, along with AmBe.
- ICRP103  $W_r$  calculation puts AmBe at 13 and 14.1 MeV at 7.
- Depending on the necessary regulation, this can require a different NCF

$$w_R = \begin{cases} 2.5 + 18.2e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leq E_n \leq 50 \text{ MeV} \\ 2.5 + 3.25e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases} \quad (4.3)$$

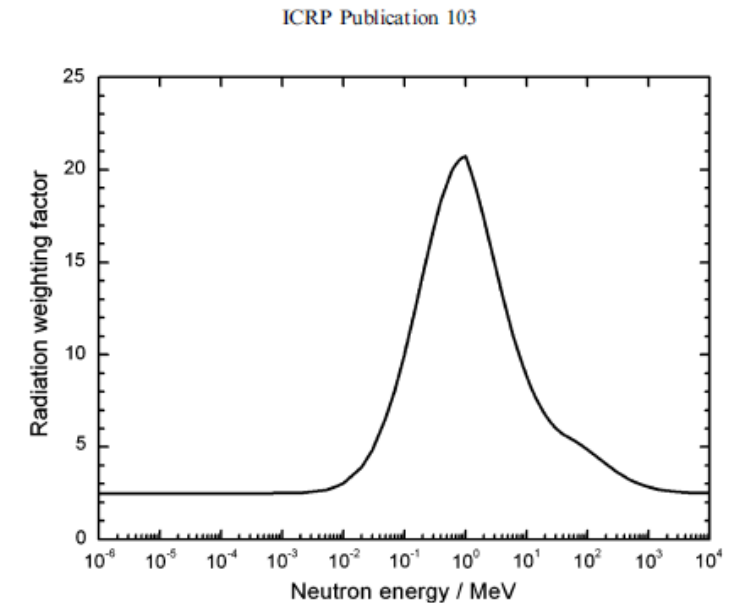
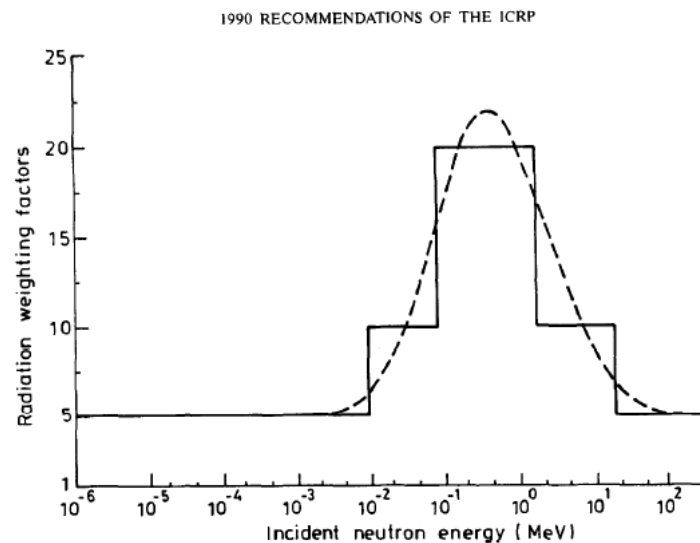


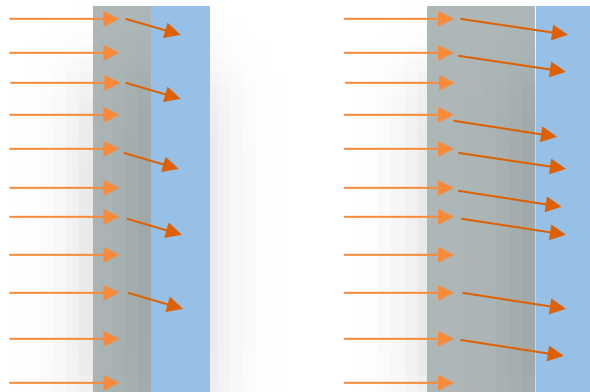
Fig. 1. Radiation weighting factor,  $w_R$ , for neutrons versus neutron energy.

- Digital microscope scans CR39 and records image
- Track morphology is evaluated by the algorithm to estimate the energy of incident neutron

- Pros:
  - Already in progress at LDRE, with improved results
  - Independent of varying energy spectra
  - Meets ISO/IEC requirements
- Cons
  - Requires advanced equipment
  - Track morphology is hard
  - Algorithm development continues and may require AI in perpetuity

Neutron energy, $E$ (MeV)	Average $H_p(10)$ exposure, $H^0$ (mSv)	Relative unc. in reference dose, $U_{rel,k,j}^0$	Mean response, $R_{k,j}$	Standard deviation of readings/response, $S$	$U$ value for response, $U_{k,j}$	$1+r_{min}$ $-U_{rel,k,j}^0$	$R_{k,j}-U_{k,j}$	$R_{k,j}+U_{k,j}$	$1+r_{max}$ $+U_{rel,k,j}^0$
Tests at $H_{min}+0.1$ mSv, taken to be 0.2 mSv, where $r_{min} = -55\%$ and $r_{max} = +120\%$ for $0^\circ$ irradiations									
16.5	0.207	0.050	0.641	0.138	0.104	0.400	0.537	0.745	2.250
16.5	0.208	0.050	0.596	0.098	0.076	0.400	0.521	0.672	2.250
Tests for $H^0 > 0.5$ mSv; irradiations at 1.0 mSv where $r_{min} = -40\%$ and $r_{max} = +70\%$ for $0^\circ$ irradiations									
16.5	0.978	0.050	0.727	0.060	0.056	0.550	0.671	0.783	1.750
16.5	0.984	0.050	0.659	0.081	0.066	0.550	0.593	0.725	1.750

- Good studies evaluating other radiator types exist
- These are currently disadvantageous, operationally
- What if we increase PE radiator thickness?
- (Presumably) will increase higher energy response



- Pros:
  - Analysis is easy to model
  - Requires adjustment only in one dimension
  - Material is inexpensive compared to other radiator types (i.e. cadmium, zirconium)
- Cons
  - Thickness for 1:1 AmBe ratio may be unrealistic
  - Self-shielding of protons may plateau the effect
  - Two different models is operationally cumbersome

Keep your options open

- Prepare the current system for immediate application of NCFs
- Continue Neutron Track Morphology Algorithm development
- Model radiator thickness effects

# Thank You

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