Radiation Protection specific calculations

Radiation Protection Calculations – *Concepts*

- Exposure of persons and activation of components and materials are the principal considerations for Radiation Protection (RP) related simulations.

- The particle cascades induced by the beam particle (prompt radiation) may trigger nuclear reactions that result in unstable radionuclides (activation).
- The decay of these radionuclides leads to residual radiation; even when the beam (particle) has stopped.
- Activation and residual radiation depend on an irradiation pattern/profile and the cool-down time.

Radiation Protection Calculations – *Concepts*

Exposure of persons:

- RP quantities (ambient dose equivalent or effective dose [pSv]) are not physical quantities directly simulated. Conversion coefficients are needed to translate radiation fields to these generalized particles → fluence based: fluence-to-dose conversion coefficients [different sets available]
- Persons can be exposed to [need to be able to score both]
  - Related to a single primary particle cascade: Prompt radiation (e.g. neutrons penetrating the shielding structure of a target area when the beam is operating) -> pSv/primary
    Normalization with beam intensity [primaries/s or primaries/h] needed to get dose rates, e.g. [mSv/h]!
  - Related to an irradiation profile and the cool-down time: Residual radiation (e.g. beta and gamma radiation inside the target area due to the radioactive decays inside the target) -> pSv/s

Activation can be scored (event based)

- Related to a single primary particle cascade: Production rate [#residual nuclei / primary] & normalization [volume, mass]
- Related to an irradiation profile and the cool-down time: Activity [Bq] & normalization [volume, mass]

Relevant Generalized Particle Types

Name	Units	Description
DOSE	GeV/g	Dose (energy deposited per unit mass)
DOSE-EQ	pSv	Dose Equivalent (**AUXSCORE**) Based on ICRU sphere or human phantom (see next slides)
ACTIVITY	Bq/cm^3	Activity per unit volume
ACTOMASS	Bq/g	Activity per unit mass

Fluence-to-dose conversion coefficients

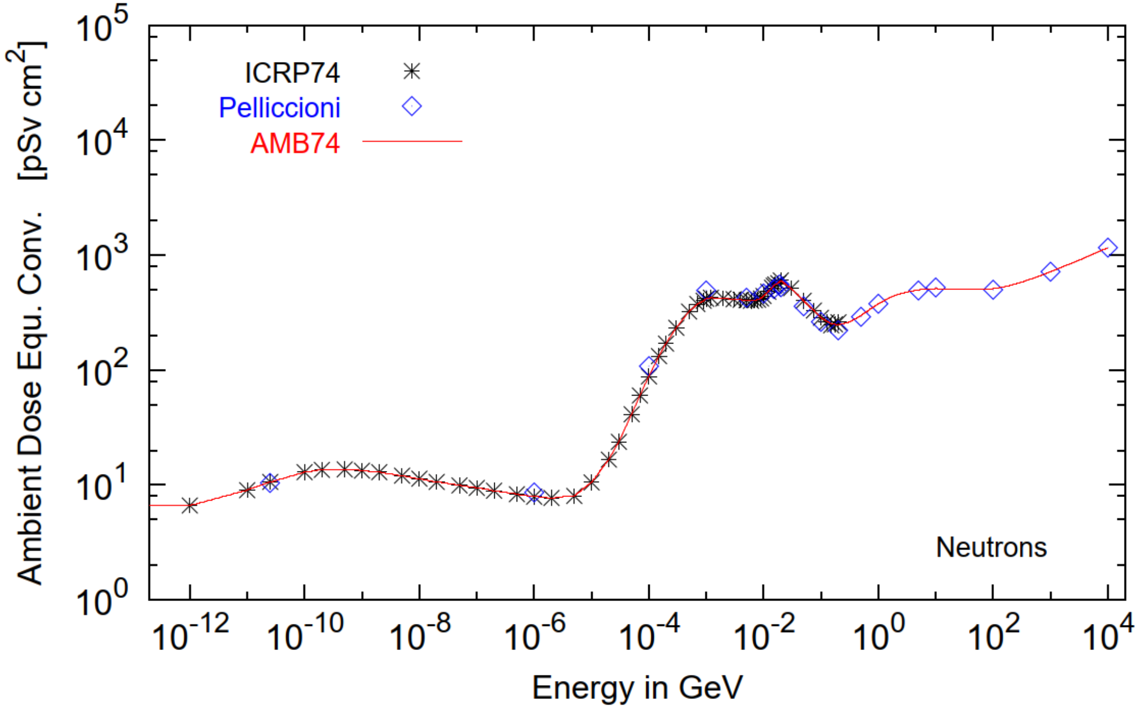
- Ambient dose equivalent H*(10)
  - operational quantity for area monitoring (10mm depth in ICRU sphere)
  - AMB74 is the default choice for dose equivalent calculation (scoring DOSE-EQ without **AUXSCORE** card)
- Effective dose is based on human phantoms
  - Conversion coefficients from fluence to effective dose are implemented for three different irradiation geometries:
    - Anterior-Posterior
    - Rotational
    - WORST (“Working Out Radiation Shielding Thicknesses”) is the maximum coefficient of anterior-posterior, posterior-anterior, right-lateral and left-lateral geometries. It is recommended to be used for shielding design.
- Implemented for radiation weighting factors recommended by ICRP60 (e.g., EWT74) and recommended by M. Pelliccioni (e.g., EWTMP).
- Implemented for protons, neutrons, charged pions, muons, photons, electrons (conversion coefficients for other particles are approximated by these)
- Zero coefficient is applied to all heavy ions

Fluence-to-dose conversion coefficients

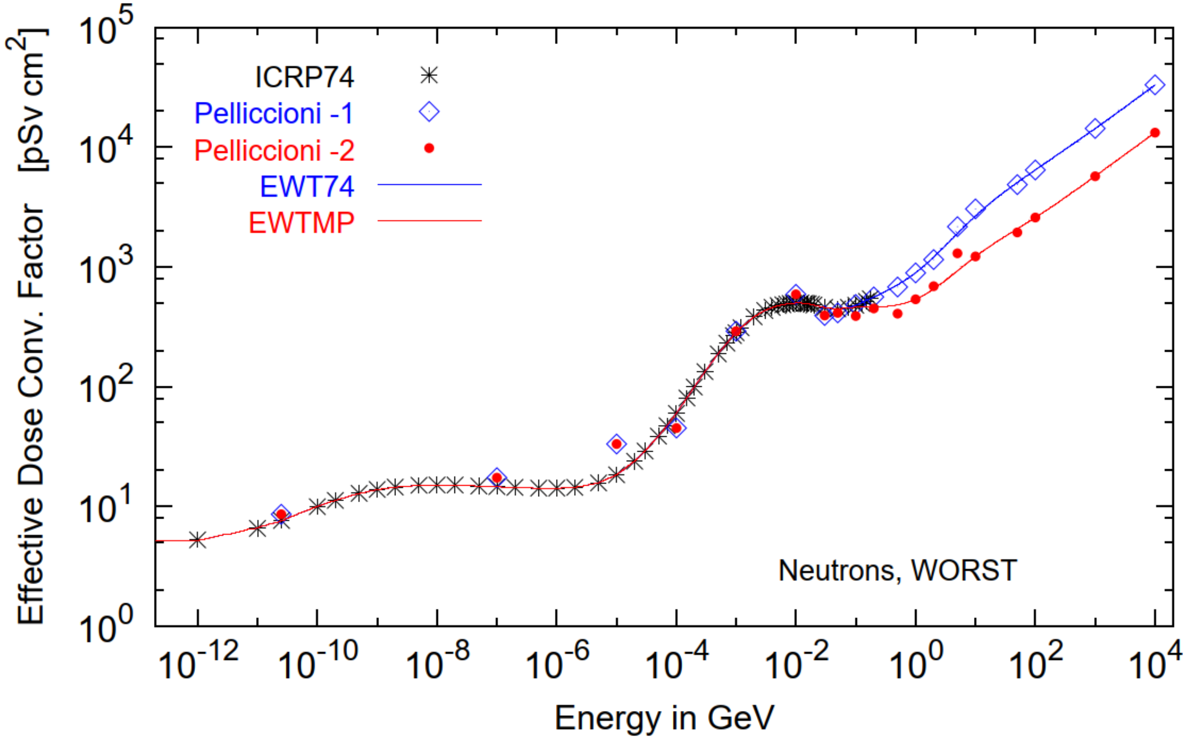
Units: pSv cm^2 (to be folded with fluence [1/(cm^2·primary)] to yield [pSv/primary])

Examples:

Ambient dose equivalent for neutrons



Effective dose for WORST irradiation geometry



For more information please see: https://flukafiles.web.cern.ch/flukafiles/documents/deq2.pdf

Activation and residual radiation – *Main features*

The generation and transport of decay radiation (limited to γ, β-, β+, X-rays, and Conversion Electrons emissions for the time being) is possible during the same simulation which produces the radionuclides (one-step method). For that, a dedicated database of decay emissions is used, based mostly on information obtained from NNDC, sometimes supplemented with other data and checked for consistency.

Consequently, results for production of residuals, their time evolution and residual doses due to their decays can be obtained in the same run, for arbitrary decay times and for a given irradiation profile.

Activation and residual radiation – *Main features*

- up to 4 different decay branching for each isotope/isomer

- all gamma lines down to 0.1-0.01% branching, including X-ray lines following conversion electron emissions
- all beta emission spectra down to 0.1-0.01% branching: the sampling of the β+/- spectra including screening Coulomb corrections
- Auger and conversion electrons

- Isomers: the present models do not distinguish among ground state and isomeric states (it would require spin/parity dependent calculations in evaporation). A rough estimate (equal sharing among states) of isomer production can be activated in the **RADDECAY** option. In future release, branching ratio for isomers produced by neutrons <20 MeV will be based on JEFF

- Different transport thresholds can be set for the prompt and decay radiation parts, as well as some (limited) biasing differentiation (see later)

Input options – *Overview*

Input card: **RADDECAY**

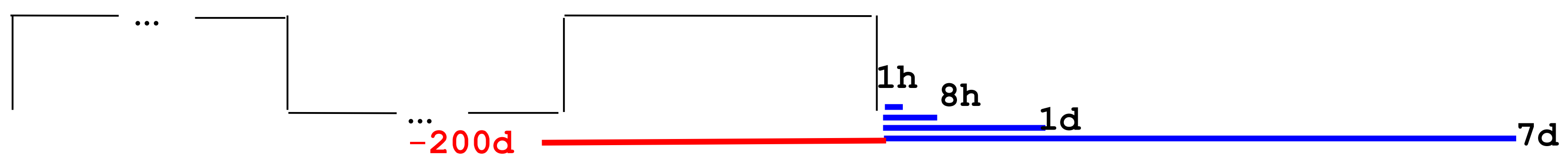
requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

Input card: **IRRPROFI**

definition of an irradiation profile (irradiation times and intensities)

Input card: **DCYTIMES**

definition of decay (cooling) times measured from the end of irradiation cycle (t=0)



Input card: **DCYSCORE**

associates scoring detectors (radio-nuclides, fluence, dose) with different cooling times (and the irradiation profile)

Input card: **AUXSCORE**

allows to associate scoring estimators with dose equivalent conversion factors or/and to filter them according to (generalized) particle identity

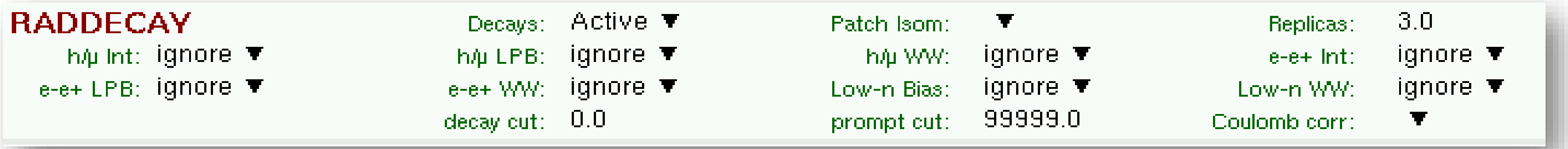
Input option: RADDECAY [1/2]

Requests the calculation of radioactive decays

Decays	Active	**radioactive decays activated for requested cooling times** “activation study case”: time evolution calculated analytically for *fixed* (cooling) times. Daughter nuclei as well as associated radiation is considered at these (fixed) times
	Semi-Analogue	**radioactive decays activated in semi-analogue mode** each radioactive nucleus is treated like all other unstable particles (random decay time, daughters and radiation), all secondary particles/nuclei carry time stamp (“age”)
Patch Isom	On	**isomer “production” activated**
Replicas	#	**number of “replicas” of the decay of each individual nucleus**

Input option: **RADDECAY** [2/2]

Requests the calculation of radioactive decays



h/μ Int .. Low-n WW — **switch for applying various biasing features only to prompt radiation or only to particles from radioactive decays**

decay cut, prompt cut — 0.1 x input value is used as **multiplication factors to be applied to e+/e-/gamma transport energy cutoffs** (defined with **EMF-CUT** cards)

Examples:

input value for decay cut = 10	decay radiation production and transport thresholds are not modified (0.1 x 10)
input value for decay cut = 200	prompt radiation threshold increased by factor of 20 (0.1 x 200)

Special cases:

decay cut = 99999	kill EM cascade for residual radiation
prompt cut = 99999	kill EM cascade for prompt radiation

Input option: IRRPROFI

Definition of irradiation pattern

IRRPROFI	Δt: =180* day	p/s: 5.9e5
	Δt: = 185 * 86400	p/s: 0
	Δt: =1.553e7	p/s: 5.9e5

Δt # **irradiation time (second)**

p/s # **beam intensity (particles per second)**
Note: zero intensity is accepted and can be used, e.g., to define beam-off periods

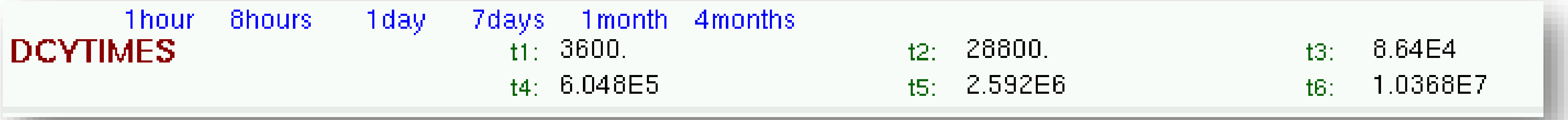
Notes: Each card has 6 inputs with 3 durations / intensities (intercalated).
Several cards can be combined. Sequence order is assumed from first card (top) to last (bottom)

Example (see above):

180 days	185 days	180 days
5.9×10^5 p/s	0 p/s (beam-off)	5.9×10^5 p/s

Input option: `DCYTIMES`

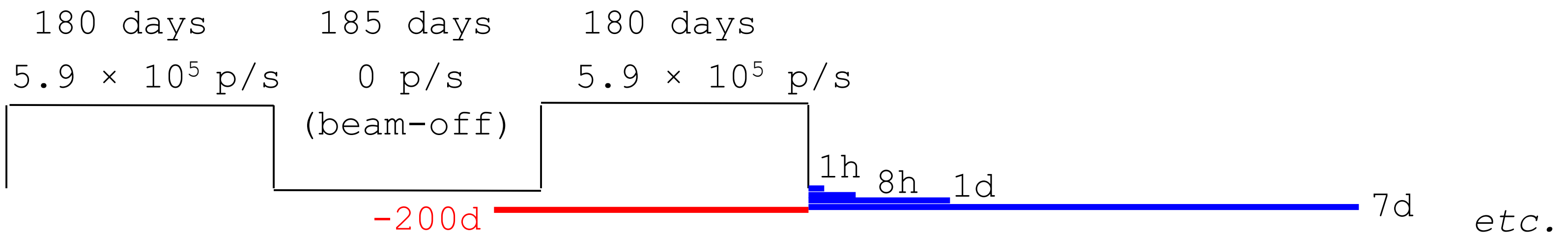
Definition of cooling times



t1 .. t6	**cooling time (in seconds) after the end of the irradiation** Note: Several cards can be defined.

Each cooling time is assigned an index, following the order in which it has been input. This index can be used in option **`DCYSCORE`** to assign that cooling time to one or more scoring detectors. A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

Example:



Input option: DCYSCORE [1/2]

Association of scoring with different cooling times

Cooling t	#	**Cooling time index to be associated with the detectors** Drop down list of available cooling times
Det .. to Det		**Detector index/name of kind (SDUM/Kind)** Drop down list of available detectors of kind (**Kind**)
Step	#	**step lengths in assigning indices**
Kind		**Type of estimator:** **RESNUCLE**, **USRBIN/EVENTBIN**, **USRBDX**, **USRTRACK**...

Input option: DCYSCORE [2/2]

Notes:

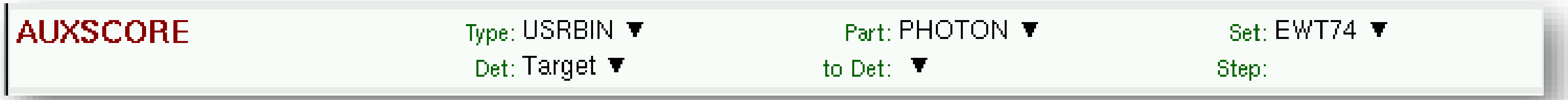
- **All quantities are expressed per unit time when associated to a cool-down time.**
  - For example:

RESNUCLE	Bq
USRBIN	fluence rate / dose rate

In the semi-analogue decay mode, estimators can include the decay contribution (on top of the prompt one) if associated to DCYSCORE with a cooling time index -1.0

Input option: AUXSCORE

Association of scoring with scoring with dose equivalent conversion factors

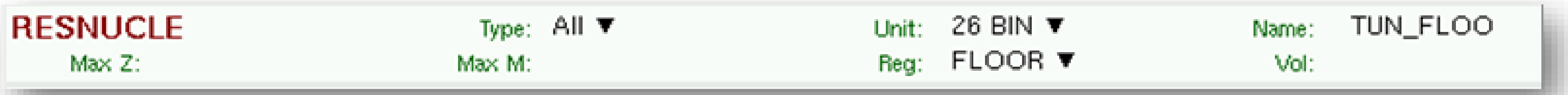


Type		**Type of estimator to associate with** drop down list of estimator types (**USRBIN**, **USRBDX**…)
Part	#	**Particle or isotope to filter for scoring** Particle or particle family list. If empty then flair will prompt for Z, A, and State for filtering on specific isotopes
Det .. to Det		**Detector range** Drop down list to select detector range of type **Type**
Step	#	**Step in assigning indices of detector range**
Set		**Conversion factor set for dose equivalent (DOSE-EQ) scoring** Drop down list of available dose conversion sets

Note: This card is NOT just for activation-type scorings. It can be used for prompt radiation.

Input option for Activation: RESNUCLE[1/3]

Scoring of residual nuclei or activity on a region basis



Type — **Type of products to be scored**

1.0	spallation products (all inelastic interactions except for low-energy neutron interactions, i.e. with multigroup treatment)
2.0	products from low-energy neutron interactions (provided the information is available)
3.0	all residual nuclei are scored (if available, see above)
<= 0.0	resets the default (= 1.0)

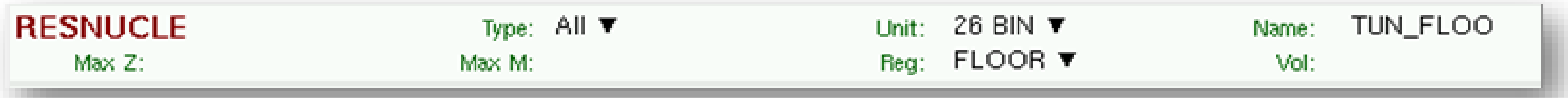
Unit — **Logical output unit** (Default = 11.0)

Max Z — **Maximum atomic number Z** of the residual nuclei distribution
Default: according to the Z of the element(s) of the material assigned to the scoring region

Max M — **Maximum $M = N - Z - NMZ_{min}$** of the residual nuclei distribution ($NMZ_{min} = -5$)
Default: maximum value according to the A, Z of the element(s) of the material assigned to the scoring region.

Input option for Activation: RESNUCLE [2/3]

Scoring of residual nuclei or activity on a region basis



Reg — **Scoring region name**
Default = 1.0; if set to -1.0 or @ALLREGS scoring will include all regions)

Vol — **Volume of the region** in cm^3
Default = 1.0 cm^3
The scored quantity is normalized by this number.
In case mass specific quantity is needed, i.e. [Bq/g], the mass shall be entered.

Name — **Character string identifying the detector** (max. 10 characters)

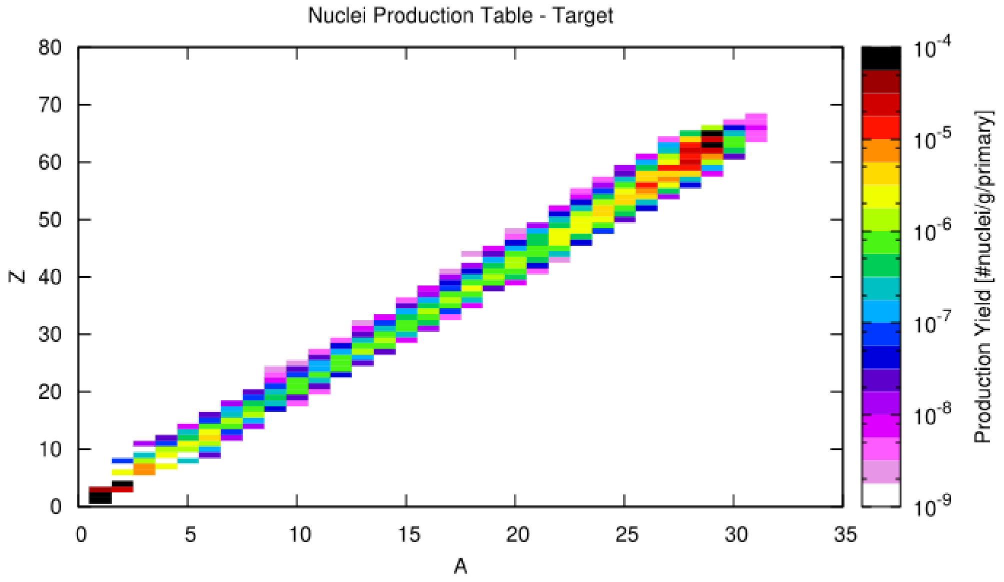
Notes:

1. In the case of heavy ion projectiles, the default **Max M**, based on the region material, is not necessarily sufficient to score all the residual nuclei, which could include possible ion fragments
2. Residual nuclei from low-energy neutron interactions are only scored if that information is available in the low-energy neutron data set (see Manual)
3. Also, protons are scored (at the end of their path)

Input option for Activation: RESNUCLE[3/3]

Output example (…tab.lis format)

```
# Detector n:      1
ProdTarg
# A_min-A_max     1    78
   78    0.000        0.000
...
   70    0.000        0.000
   69    0.000        0.000
   68  5.2866E-09    58.88
   67  8.4585E-09    35.36
   66  1.1567E-06    3.919
   65  9.0705E-05   0.2184
   64  2.4312E-05   0.6704
...
 # Z_min-Z_max              1           33
   33    0.000        0.000
   32    0.000        0.000
   31  2.1146E-08    26.93
   30  2.0290E-06    2.901
   29  3.7067E-04   0.2059
   28  9.8531E-05   0.3745
   27  3.9925E-05   0.4396
...
# A/Z Isotopes:
   68    23    0.000        0.000
...
   68    30   1.0573E-09    99.00
   68    31   4.2292E-09    75.00
...
   67    30   4.2292E-09    35.36
   67    31   4.2292E-09    35.36
...
   66    29   1.1070E-06    4.374
   66    30   4.3350E-08    21.22
   66    31   6.3439E-09    39.67
...
   65    28   5.4874E-07    3.121
   65    29   8.9877E-05   0.2307
   65    30   2.7596E-07    6.742
   65    31   3.1719E-09    69.39
...
   64    27   4.2292E-09    52.04
   64    28   4.3730E-06    1.471
   64    29   1.9291E-05   0.8280
   64    30   6.4073E-07    5.916
   64    31   3.1719E-09    69.39
...
   63    27   1.1313E-07    10.85
   63    28   1.0566E-05   0.7723
   63    29   2.2026E-04   0.3408
   63    30   6.8937E-07    3.173
...
# A/Z/m Isomers:
   24    11     1   1.5490E-07    4.344
....
   58    27     1   5.2770E-06   0.6021
   60    25     1   5.2866E-10    99.00
   60    27     1   2.1416E-06    1.697
   62    27     1   2.0723E-07    4.304
```



Input option: PHYSICS

Please activate the following cards if scoring of residual nuclei is of interest:

Evaporation of heavy fragments

PHYSICS Type: EVAPORAT ▼ Model: New Evap with heavy frag ▼

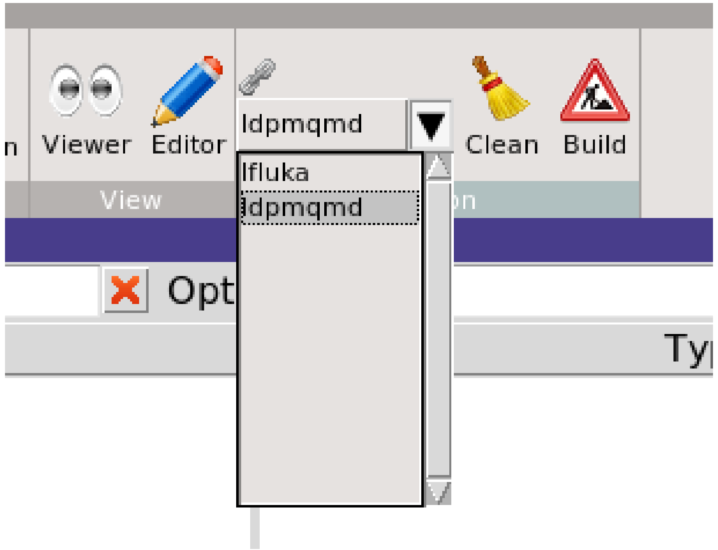
Activation of **coalescence** treatment

PHYSICS Type: COALESCE ▼ Activate On ▼

Use of **PEANUT model at all energies** (now part of default settings)

PHYSICS	Type: PEATHRES ▼	Nucleons: 1000.	Pions: 1000.
Kaons: 1000.	Kaonbars: 1000.	AntiNucleon: 1000.	AntiHyperons: 1000.

Input option: PHYSICS



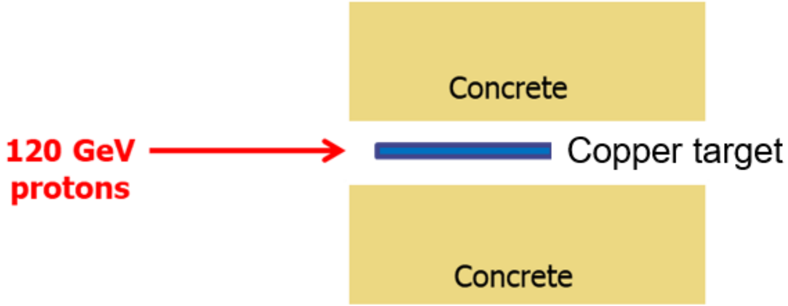
The evaporation of heavy fragments produces deuterons, which need to be transported!

Please activate the RQMD and DPMJET packages.

All ions (including deuterons) are treated with RQMD (>150 MeV/n) and DPMJET (> 5 GeV/n);
All ions (excluding deuterons) < 150 MeV/n are treated with BME;
Deuterons < 150 MeV/n need to be treated as individual nucleons with IONSPLIT option of the PHYSICS card.

Activation of **ion splitting** of (only!) deuterons into p+n, from 5 to 150 MeV/n.
[this card is already included in the example inp file]

Geometry modifications



ASSIGNMA	Mat: BLCKHOLE ▼	Reg: EXTVOID ▼	to Reg: ▼
	Mat(Decay): ▼	Step:	Field: ▼
ASSIGNMA	Mat: VACUUM ▼	Reg: VACTRGT ▼	to Reg: ▼
	Mat(Decay): ▼	Step:	Field: ▼
ASSIGNMA	Mat: COPPER ▼	Reg: TARGET ▼	to Reg: ▼
	Mat(Decay): ▼	Step:	Field: ▼
ASSIGNMA	Mat: CONCRETE ▼	Reg: SHIELD ▼	to Reg: ▼
	Mat(Decay): ▼	Step:	Field: ▼

Remove concrete shield for transport of radioactive decay radiation
(e.g., for calculation of residual dose rate from target only)

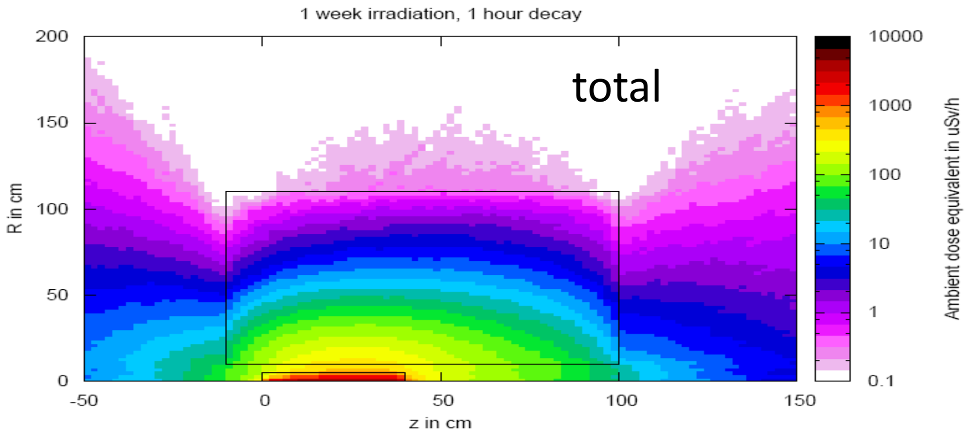
ASSIGNMA	Mat: CONCRETE ▼	Reg: SHIELD ▼	to Reg: ▼
	Mat(Decay): VACUUM ▼	Step:	Field: ▼

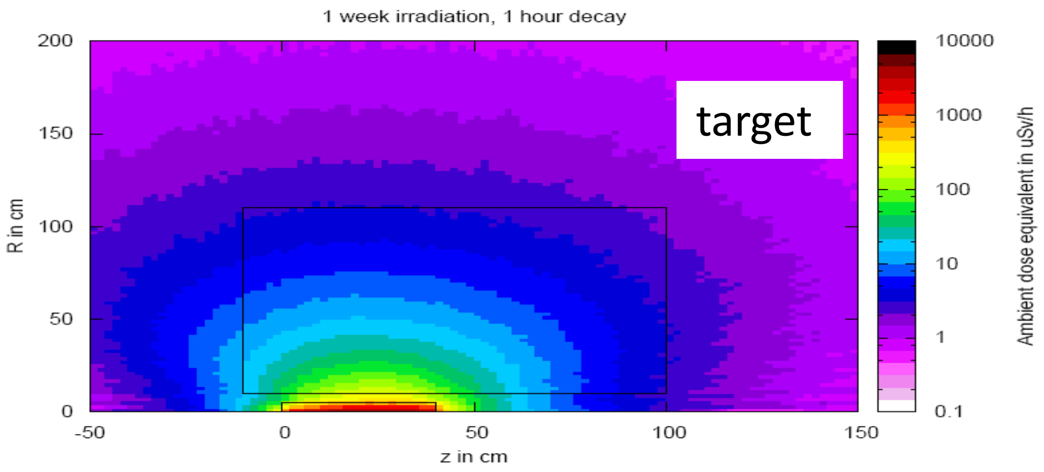
Remove target for transport of radioactive decay radiation
(e.g., for calculation of residual dose rate from concrete shield only)

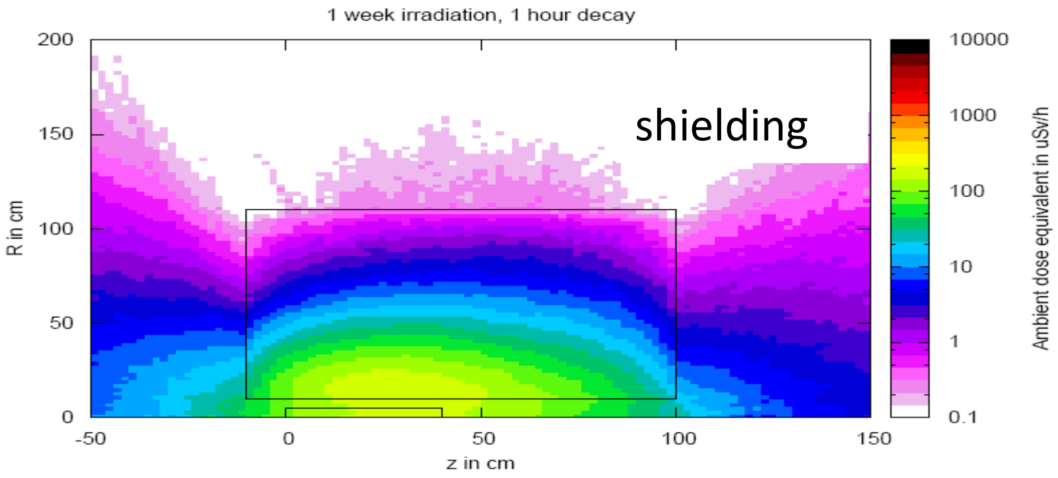
ASSIGNMA	Mat: COPPER ▼	Reg: TARGET ▼	to Reg: ▼
	Mat(Decay): VACUUM ▼	Step:	Field: ▼

Note: Radioactive decay products originating from regions switched to a different material are ignored.

Geometry modifications







Input option: **BEAM/HI-PROPE**

Simulation of a radioactive source

Example:

Radioactive source of ^{60}Co (two main γ-emissions: 1332.5 keV and 1173.2 keV)
cylindrical shape, 2cm diameter, 2mm height along z, centre of cylinder at origin

BEAM		Beam: Momentum ▼	p:	Part: ISOTOPE ▼
	Δp: Flat ▼	Δp:	Δϕ: Flat ▼	Δϕ:
	Shape(X): Rectangular ▼	Δx:	Shape(Y): Rectangular ▼	Δy:
HI-PROPE		Z: 27.	A: 60.	Isom:
BEAMPOS		x:	y:	z:
		cosx:	cosy:	Type: POSITIVE ▼
BEAMPOS		Rin:	Rout: 1.	Type: CYLI-VOL ▼
		Hin:	Hout: 0.2	

Notes:

- Do not forget switching on radioactive decays with the **RADDECAY** card in semi-analogue mode and to associate the scoring detectors with **DCYSCORE** to semi-analogue decay mode!
- Also a point source is perfectly valid for ISOTOPE beam cards!

Summary of main input cards

RADDECAY

requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

IRRPROFI

definition of an irradiation profile (irradiation times and intensities)

DCYTIMES

definition of decay (cooling) times

DCYSCORE

associates scoring detectors (radio-nuclides, fluence, dose equivalent) with different cooling times

Summary of main input cards

AUXSCORE

allows to associate scoring estimators with dose equivalent conversion factors or/and to filter them according to (generalized) particle identity

RESNUCLE

allows to score residual nuclei production or activity on a region basis

PHYSICS

switch to activate the evaporation of heavy fragments (up to A=24) and the simulation of coalescence

FLUKA

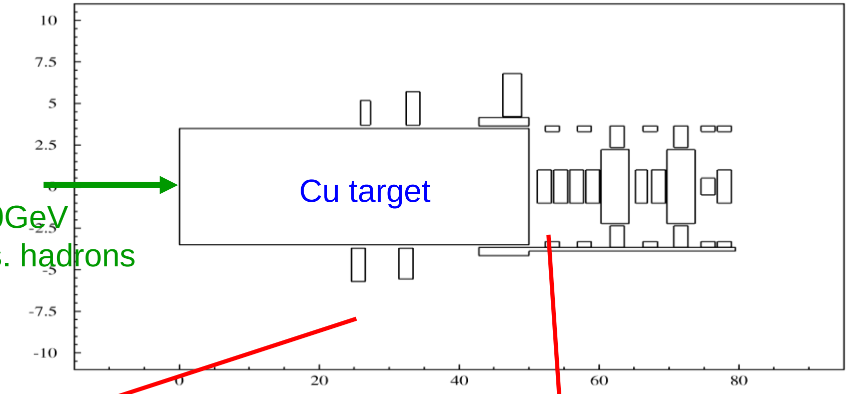
Benchmarks

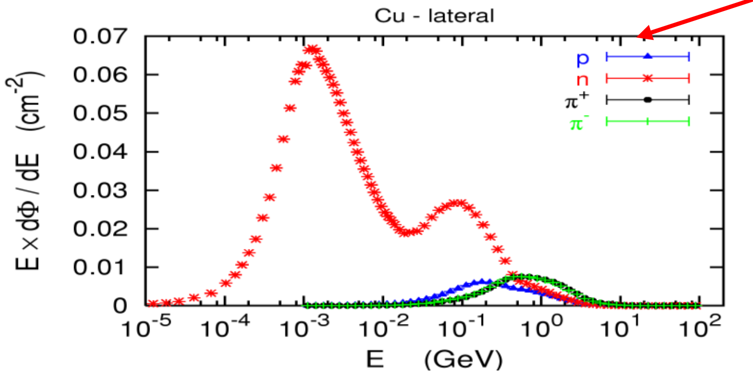
Benchmark experiment

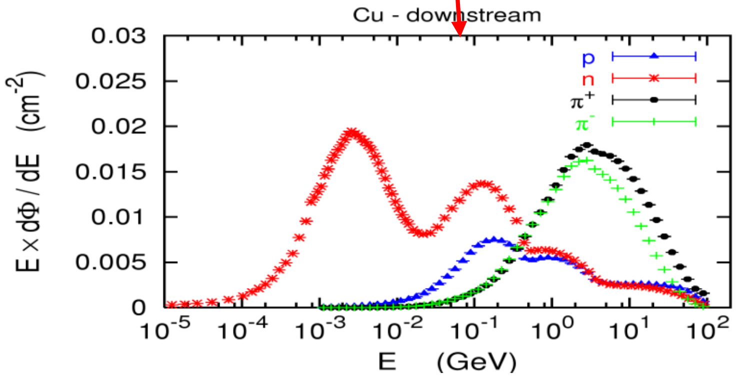
Irradiation of samples of different materials to the stray radiation field created by the interaction of a 120 GeV positively charged hadron beam in a copper target

Reference: M. Brugger, S. Roesler, *et al.*, Nuclear Instruments and Methods A 562 (2006) 814-818

120GeV
pos. hadrons







Benchmark experiment - *Instrumentation*

Low-background coaxial High Precision Germanium detector (Canberra)

- use of two different detectors (90 cm^3 sensitive volume, 60% and 40% relative efficiency)

Genie-2000 (Ver. 2.0/2.1) spectroscopy software by Canberra and PROcount-2000 counting procedure software

- include a set of advanced spectrum analysis algorithms, *e.g.,* nuclide identification, interference correction, weighted mean activity, background subtraction and efficiency correction
- comprise well-developed methods for peak identification using standard or user-generated nuclide libraries. HERE: use of user-generated nuclide libraries, based on nuclides expected from the simulation and material composition

Efficiency calibration with LABSOCS

- allows the creation of a corrected efficiency calibration by modelling the sample taking into account self-absorption inside the sample and the correct detector geometry

Portable spectrometer Microspec

- NaI detector, cylindrical shape, 5 x 5 cm
- folds spectrum with detector response ("calibrated" with ^{22}Na source)
- physical centre of detector determined with additional measurements with known sources (^{60}Co, ^{137}Cs, ^{22}Na) to be 2.4 cm

Isotope	Half-life	Copper		Iron		Titanium		Stainless Steel			Aluminum			Concrete		
^{7}Be	53.29d	1.47 ± 0.19	M	1.65 ± 0.22		1.50 ± 0.19		0.98 ± 0.24	M	C,N	0.71 ± 0.09		Al	1.17 ± 0.14		O, C
		0.84 ± 0.25		0.90 ± 0.15												
^{22}Na	2.60y	0.72 ± 0.11		0.70 ± 0.13	M	0.85 ± 0.11		———			0.76 ± 0.07		Al	0.86 ± 0.09		Ca,(Si,Mg)
^{24}Na	14.96h	0.42 ± 0.03		0.48 ± 0.02		0.63 ± 0.02		0.37 ± 0.02		Fe,(Cr,Si)	0.81 ± 0.03		Al,Mg	0.62 ± 0.02		Ca,(Si,Al)
^{27}Mg	9.46m					0.79 ± 0.14	M				1.52 ± 0.25		Al,Mg			
^{28}Mg	20.91h	0.25 ± 0.04	-	0.23 ± 0.03	-	0.31 ± 0.02	-	0.29 ± 0.10	M-	Fe,Ni,Si)				0.29 ± 0.02	-	Ca,(Si)
^{28}Al	2.24m	0.25 ± 0.03	-	0.21 ± 0.02	-	0.31 ± 0.02	-	0.29 ± 0.10	M-	Fe,Ni,Si)				0.29 ± 0.03	-	Ca,(Si)
^{29}Al	6.56m			———		0.93 ± 0.25	M									
^{38}S	2.84h	———		———		0.60 ± 0.12	-	———								
^{m34}Cl	32.00m			0.91 ± 0.19	M	1.19 ± 0.16		0.77 ± 0.15		Fe,Cr,(Mn)				1.25 ± 0.07		Ca
^{38}Cl	37.24m	———		0.61 ± 0.08		0.60 ± 0.01		0.58 ± 0.07		Fe,Cr,(Mn)						
^{39}Cl	55.60m			0.64 ± 0.11	M	0.73 ± 0.08		0.66 ± 0.12		Fe,Cr,(Mn)						
^{41}Ar	1.82h	0.39 ± 0.06		0.46 ± 0.05		0.47 ± 0.04	-	0.38 ± 0.05		Fe,Cr,(Mn)				0.98 ± 0.14		Ca
^{38}K	7.64m	———		———				———						1.76 ± 0.20	-	Ca
^{42}K	12.36h	0.66 ± 0.10		0.83 ± 0.06		0.95 ± 0.05		0.76 ± 0.09		Fe,Cr,(Mn)				1.21 ± 0.08		Ca
^{43}K	22.30h	0.81 ± 0.10	-	0.77 ± 0.05		0.85 ± 0.03		0.74 ± 0.04		Fe,Cr,(Mn)	———			1.16 ± 0.05		Ca
^{44}K	22.13m					———										
^{45}K	17.30m					———										
^{47}Ca	4.54d	0.59 ± 0.16		0.56 ± 0.17	M	0.73 ± 0.12		0.51 ± 0.15	M	Fe,Cr,(Mn)				0.79 ± 0.12		Ca
^{43}Sc	3.89h	0.40 ± 0.07	-	1.01 ± 0.14		1.28 ± 0.28	-	0.93 ± 0.15		Fe,Cr,(Mn)						
^{44}Sc	3.93h	0.89 ± 0.07		1.06 ± 0.06		0.88 ± 0.05		0.96 ± 0.08		Fe,Cr,(Mn)	———			0.83 ± 0.06		Fe,(Ti)
^{m44}Sc	58.60h	0.95 ± 0.12		1.20 ± 0.09		2.13 ± 0.12		1.24 ± 0.09		Fe,Cr,(Mn)	1.08 ± 0.17		Fe,Mn	1.67 ± 0.22		Fe,(Ti)
^{46}Sc	83.79d	0.81 ± 0.07		0.86 ± 0.07		0.93 ± 0.08		0.89 ± 0.08		Fe,Cr,(Mn)	0.79 ± 0.18		Mn,(Ti,Fe)	0.88 ± 0.10		Fe,(Ti)
^{47}Sc	80.28h	1.09 ± 0.14		1.17 ± 0.10	-	0.87 ± 0.07		1.06 ± 0.09		Fe,Cr,(Mn)	1.04 ± 0.15		Mn,(Ti,Fe)	1.00 ± 0.09		Fe,Ti,(Ca)
^{48}Sc	43.67h	1.39 ± 0.16		1.47 ± 0.10		1.10 ± 0.04		1.42 ± 0.08		Fe,Cr,(Mn)				1.36 ± 0.25		Fe,Ti,(Ca)
^{48}V	15.97d	1.16 ± 0.08		1.45 ± 0.06		1.11 ± 0.07		1.44 ± 0.11		Fe,Cr,(Mn)	1.07 ± 0.13		Fe,Mn	1.63 ± 0.16		Fe
^{48}Cr	21.56h	0.92 ± 0.14		0.97 ± 0.07				1.02 ± 0.08		Fe,(Cr)				1.06 ± 0.23	M	Fe
^{49}Cr	42.30m	1.00 ± 0.22	M	1.24 ± 0.12	-			1.06 ± 0.12		Fe,(Cr)						
^{51}Cr	27.70d	1.06 ± 0.13		1.15 ± 0.12		0.64 ± 0.24	M	1.24 ± 0.16		Fe,Cr	0.86 ± 0.16		Fe,Mn	1.33 ± 0.22		Fe
^{52}Mn	5.59d	0.68 ± 0.05		1.15 ± 0.04				1.09 ± 0.03		Fe,(Mn)	0.88 ± 0.07		Fe,Mn	1.39 ± 0.07		Fe
^{m52}Mn	21.10m	1.68 ± 0.35		1.24 ± 0.09				1.12 ± 0.10		Fe,(Mn)				1.75 ± 0.79	M	Fe
^{54}Mn	312.12d	1.13 ± 0.12		1.01 ± 0.10				1.08 ± 0.11		Fe,(Mn)	0.96 ± 0.12		Mn,Fe	1.06 ± 0.13		Fe
^{56}Mn	2.58h	0.81 ± 0.06		0.99 ± 0.05				1.33 ± 0.10		Fe	1.53 ± 0.25		Mn	1.03 ± 0.25		Mn,Fe
^{52}Fe	8.28h	———		1.09 ± 0.13				0.99 ± 0.19	M	Fe,(Mn)						
^{53}Fe	8.51m			———												
^{59}Fe	44.50d	0.82 ± 0.09														
^{55}Co	17.53h	0.66 ± 0.09		0.76 ± 0.04				1.03 ± 0.05		Fe,Ni				———		
				1.13 ± 0.10												
^{56}Co	77.27d	1.04 ± 0.08		1.15 ± 0.10				1.37 ± 0.11		Fe,Ni	———			0.80 ± 0.20	M	Fe
				1.79 ± 0.15												
^{57}Co	271.79d	0.85 ± 0.09		0.38 ± 0.09	M			1.16 ± 0.13		Ni	0.66 ± 0.24	M	Cu,Zn,Ni			
^{58}Co	70.82d	0.91 ± 0.09		0.31 ± 0.08	M			0.98 ± 0.10		Ni	0.82 ± 0.19		Cu,Zn,Ni	———		
^{60}Co	5.27y	0.90 ± 0.08														
^{61}Co	99.00m	0.68 ± 0.08														
^{62}Co	90.00s	———														
^{57}Ni	35.60h	0.76 ± 0.11		———				1.44 ± 0.07		Ni				———		
^{65}Ni	2.52h	1.46 ± 0.29														
^{60}Cu	23.70m	0.78 ± 0.08														
^{61}Cu	3.33h	0.87 ± 0.25														
^{64}Cu	12.70h	0.63 ± 0.10														
^{62}Zn	9.19h	1.05 ± 0.23														
^{63}Zn	38.47m	———														
^{65}Zn	244.26d	0.62 ± 0.08														
		0.97 ± 0.20														

R = Ratio FLUKA/Exp

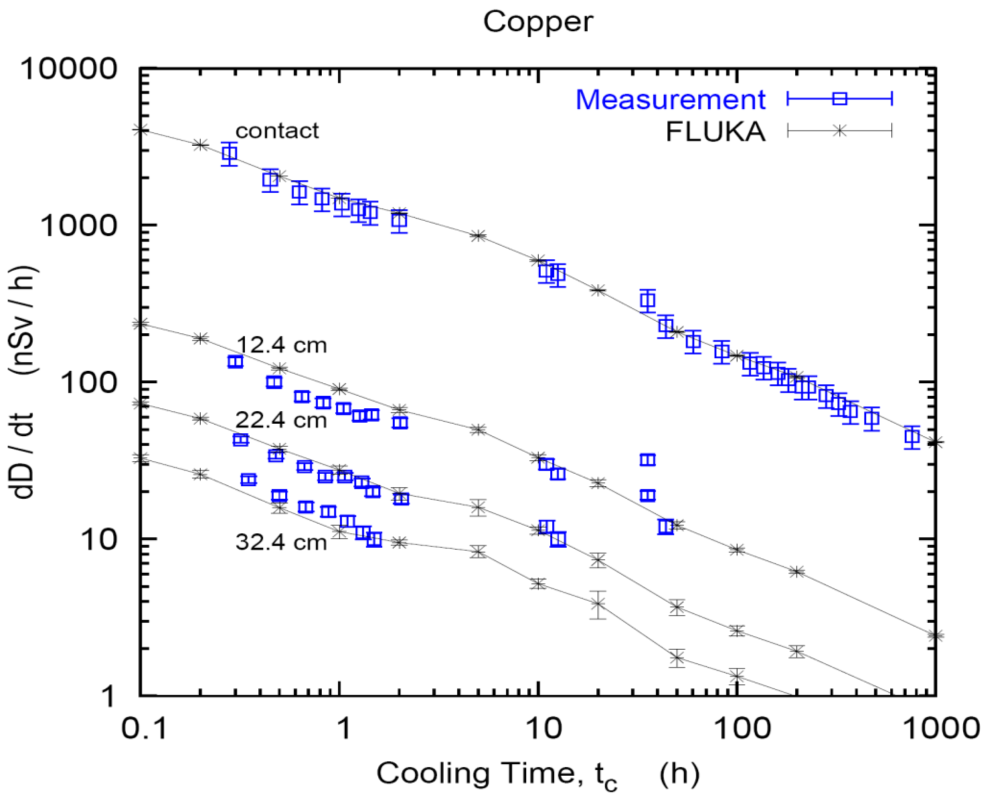
- 0.8 < R < 1.2
- 0.8 < R ± Error < 1.2
- Exp/MDA < 1
- R + Error < 0.8 or R – Error > 1.2

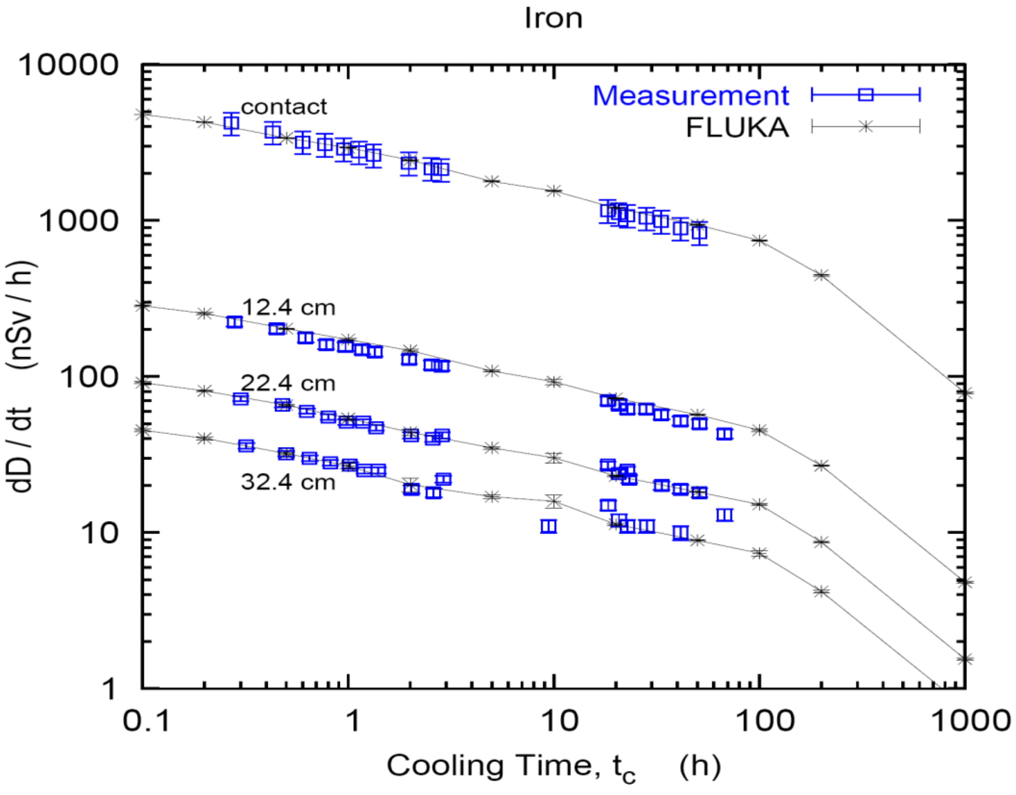
Reference:

M. Brugger, S. Roesler *et al.*, Nuclear Instruments and Methods A 562 (2006) 814-818

Benchmark experiment - *Results*

Dose rate as function of cooling time for different distances between sample and detector

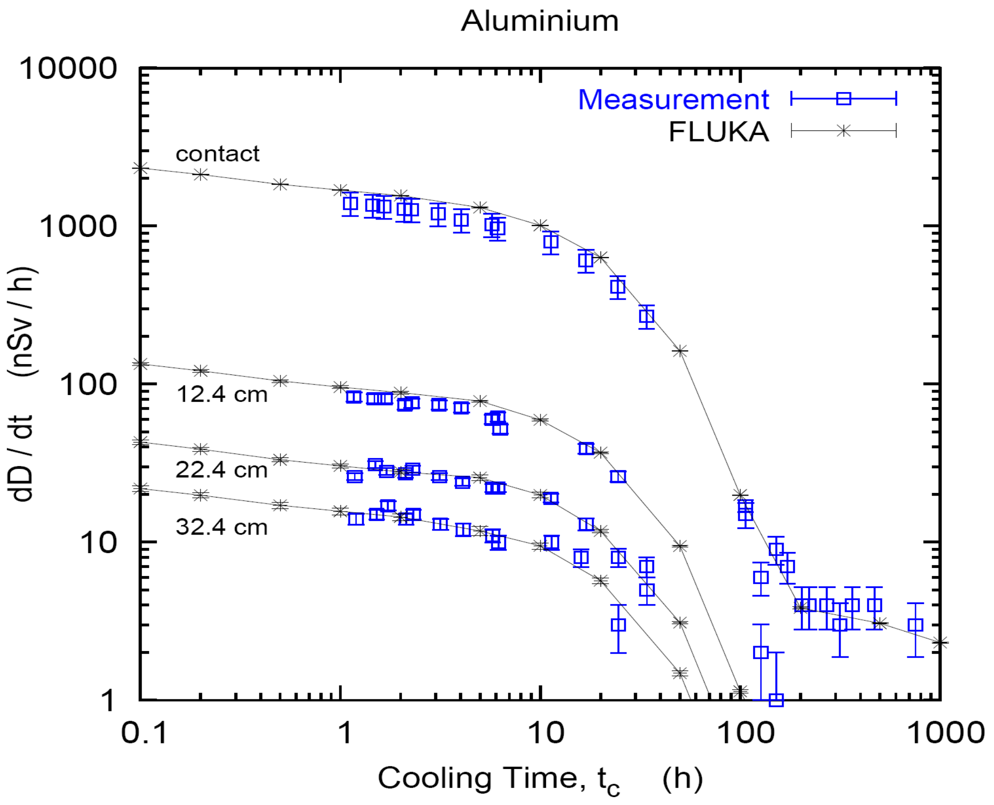


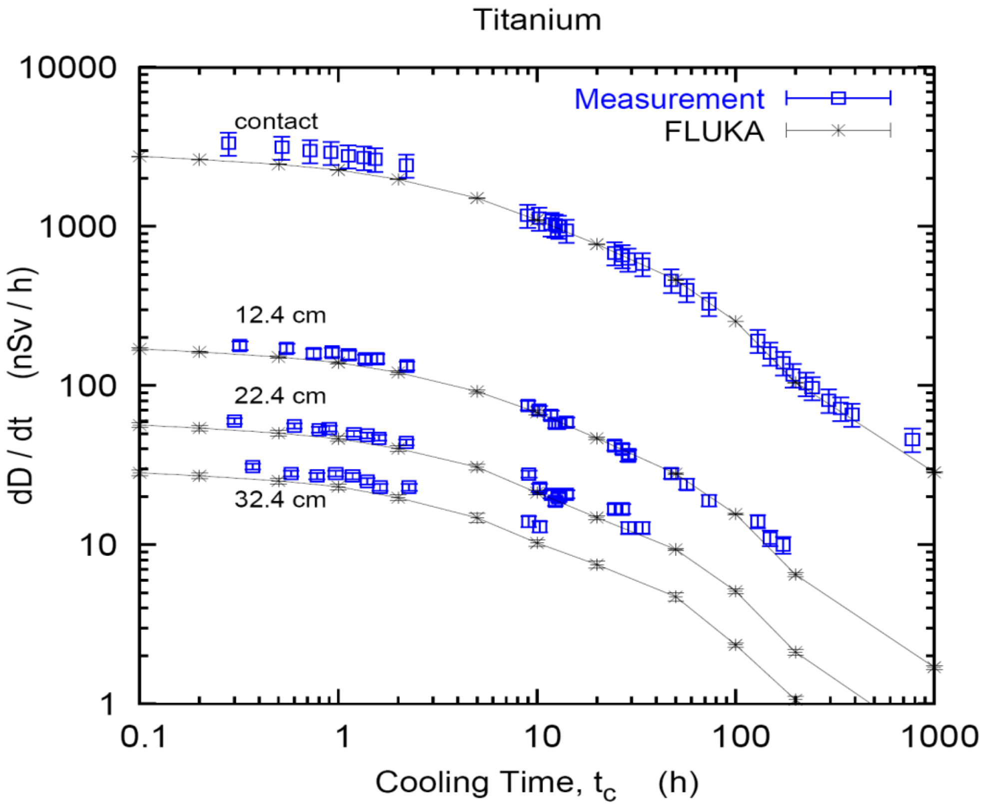


Reference: M. Brugger, S. Roesler *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

Benchmark experiment - *Results*

Dose rate as function of cooling time for different distances between sample and detector

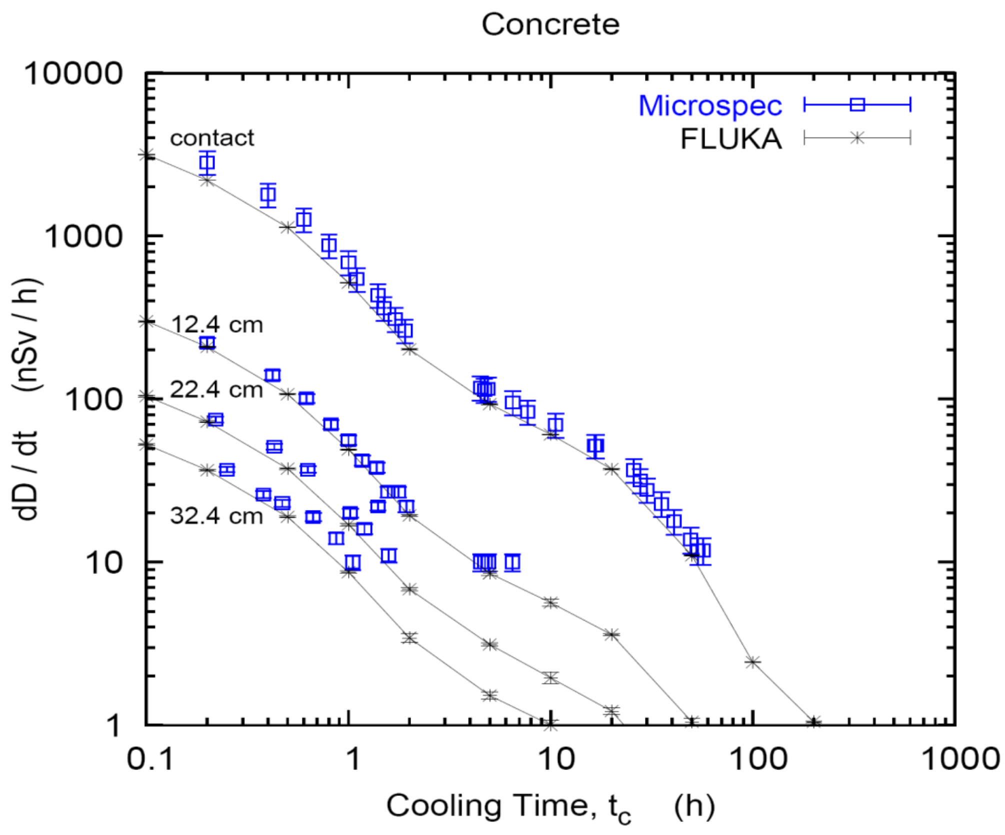




Reference: M. Brugger, S. Roesler *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

Benchmark experiment - *Results*

Dose rate as function of cooling time for different distances between sample and detector

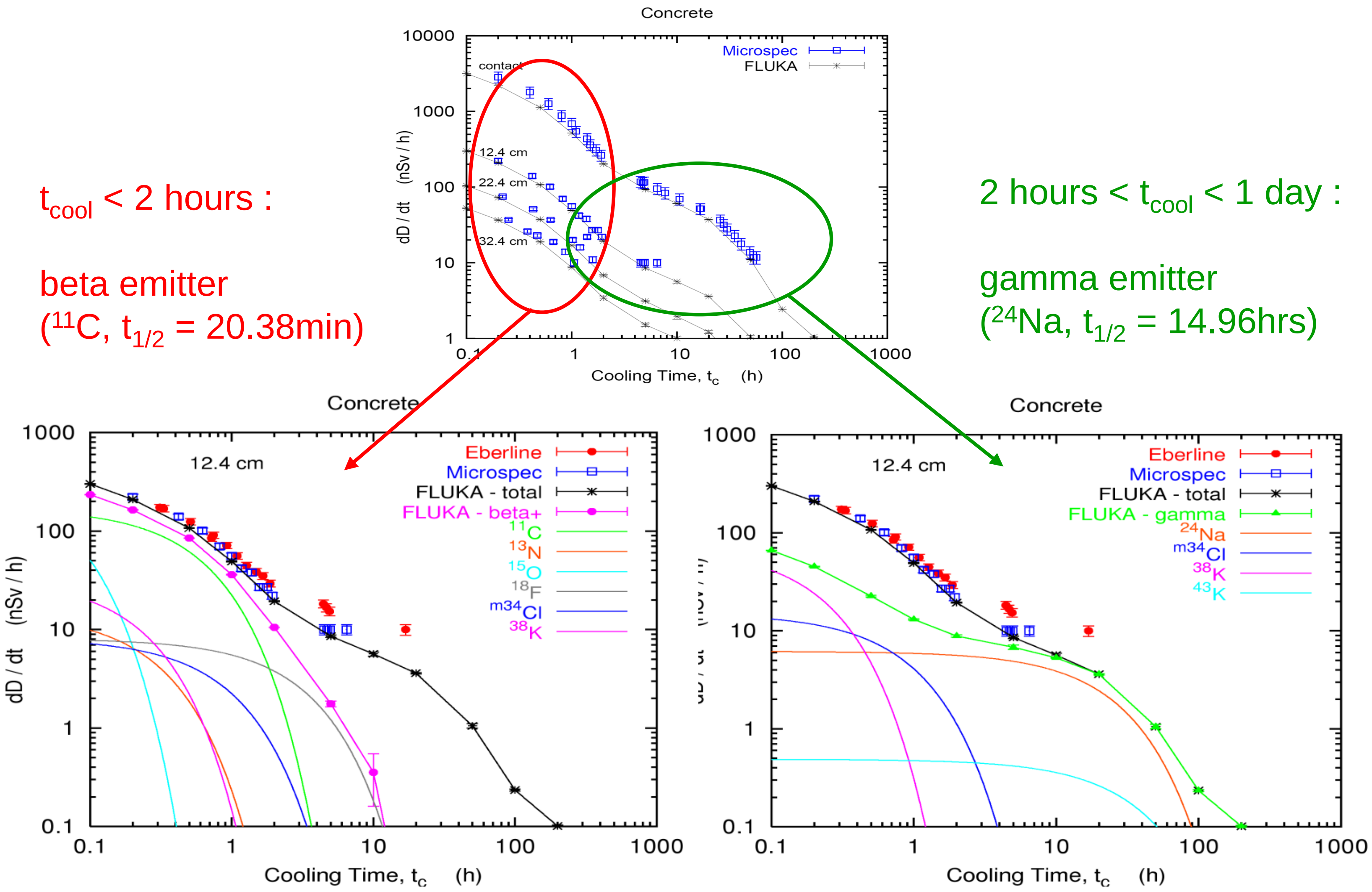


Reference: M. Brugger, S. Roesler *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

Benchmark experiment - *Results*

t_{cool} < 2 hours :

beta emitter
(^{11}C, $t_{1/2}$ = 20.38min)



2 hours < t_{cool} < 1 day :

gamma emitter
(^{24}Na, $t_{1/2}$ = 14.96hrs)