Radiation Protection specific calculations

Radiation Protection Calculations – *Concepts 1/4*

- Exposure of persons and activation of components and materials are

  the core 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 has stopped

- Activation and residual radiation depend

  on the irradiation pattern/profile and the cool-down time

Radiation Protection Calculations – *Concepts 2/4*

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 into these generalized particles

- FLUKA estimate of these quantities are based on particle fluence:

  fluence-to-dose conversion coefficients are applied

  different sets are available (see following slides)

Radiation Protection Calculations – *Concepts 3/4*

Exposure of persons

- Persons can be exposed to **prompt** and **residual** radiation

  both need to be estimated!

- The prompt radiation is related to the cascade generated by the primary beam
  - E.g. radiation penetrating a shielding structure when the beam is operating
  - It is measured in pSv/primary
  - Normalization with beam intensity (e.g. primaries/h) is needed to get dose rates, e.g. (mSv/h)

- The residual radiation is related to an irradiation profile and a cool-down time
  - E.g. radiation emitted by radionuclides generated during the irradiation
  - It is measured in pSv/s

Radiation Protection Calculations – *Concepts 4/4*

Activation

- It is related to the cascade generated by the primary beam
  - Production rate: #residual nuclei / primary
  - Normalization: mass or volume

- It is related to an irradiation profile and a cool-down time
  - Activity [Bq]
  - Normalization: mass or volume

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

- Several fluence-to-dose conversion coefficients are available

    (many new coefficients added in version 4-2.0)

- Ambient dose equivalent H*(10)
    - Operational quantity for area monitoring (10mm depth in ICRU sphere)
    - "**AMB74**" coefficient set, is the default choice for dose equivalent calculation
    - i.e.: it is possible to score DOSE-EQ without an **AUXSCORE** card (see later)
    - The "**AMB74**" coefficients are based on ICRP74 recommendations and Pelliccioni data
    - M. Pelliccioni, "*Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the FLUKA code*", Radiation Protection Dosimetry 88 (2000) 279-297

Fluence-to-dose conversion coefficients

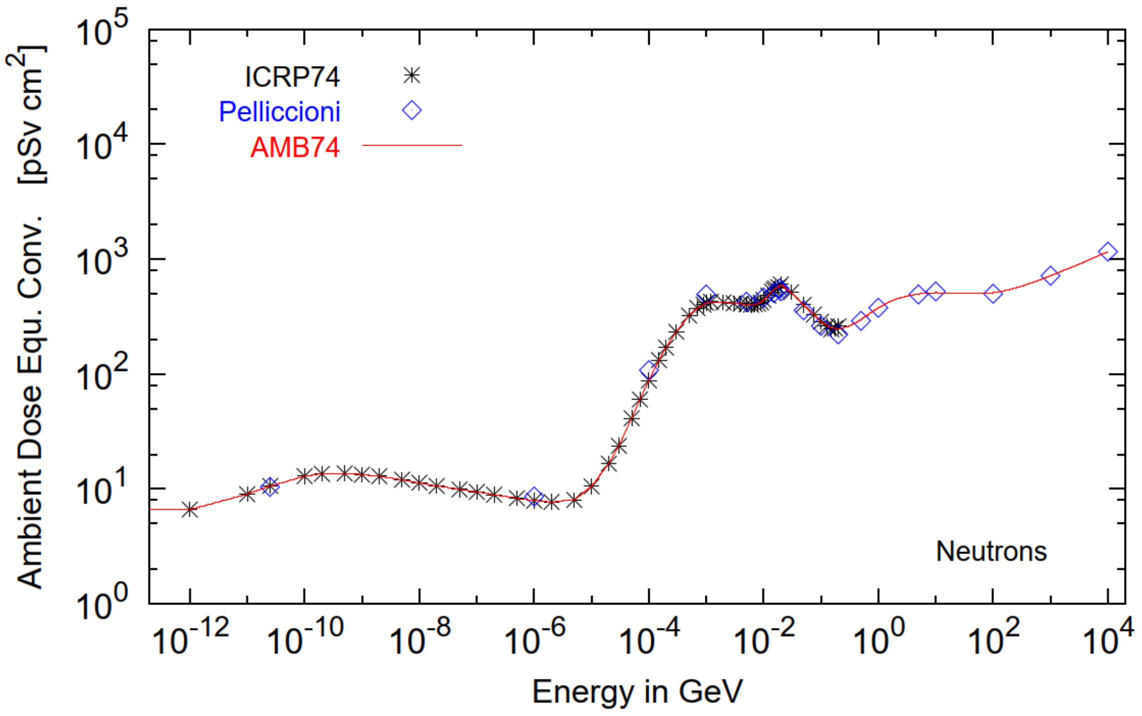
- Effective dose is based on human phantoms
  - Conversion coefficients sets depending on different recommendations and weighting factors: e.g. ICRP74, ICRP116, ICRP60, and Pelliccioni
  - Conversion coefficients sets implemented for different irradiation geometries:
    - Anterior-Posterior
    - Rotational
    - Isotropic
    - Posterior-Anterior
    - Right lateral
    - Left lateral
    - WORST (“Working Out Radiation Shielding Thicknesses”):
      It is the worst of all irradiation geometries
      It is recommended to be used for shielding design
  - 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

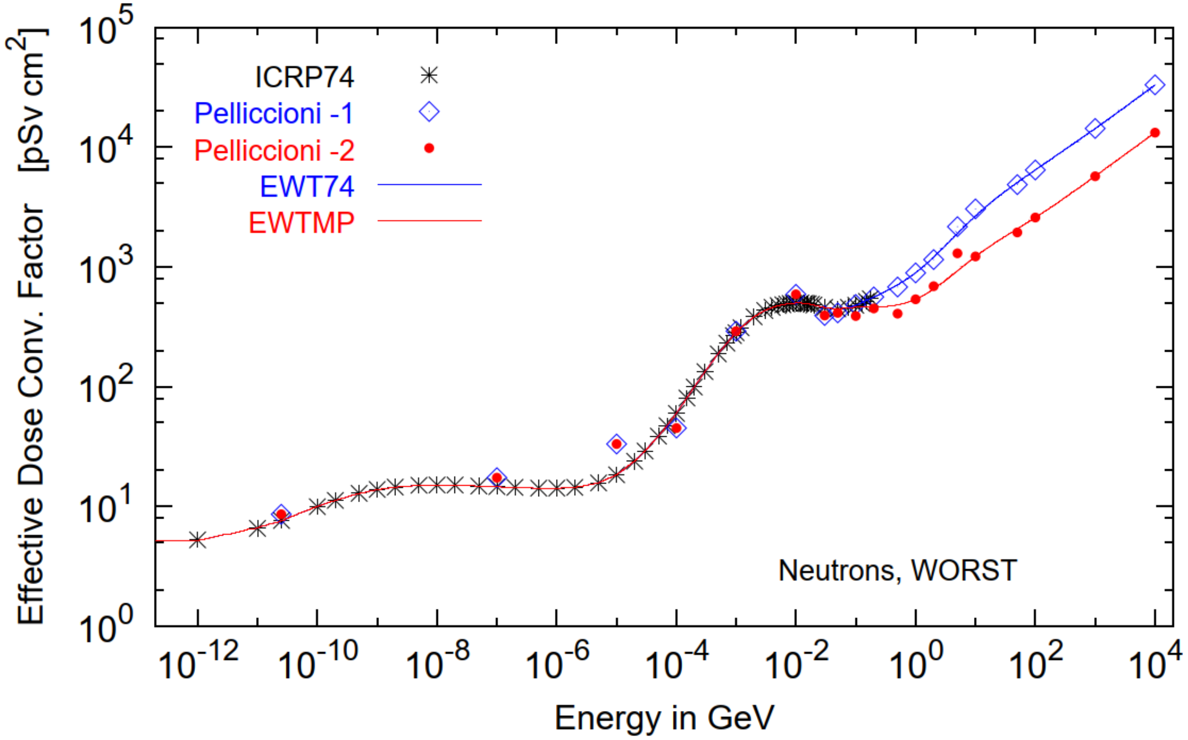
Units: pSv cm^2 (to be folded with fluence [1/(cm^2·primary)] to yield [pSv/primary])

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

Fluence-to-dose conversion coefficients

- Ambient dose
  - Conversion coefficients from ICRU95

- Personal dose
  - 12 different conversion coefficients from ICRU95
  - Depending on the irradiation geometry

- Directional and personal absorbed dose in the lens of the eyes
  - 8 different conversion coefficients from ICRU95

- Directional and personal absorbed dose in the local skin
  - 6 different conversion coefficients from ICRU95

Fluence-to-dose conversion coefficients

- For details on the different fluence-to-dose conversion coefficients sets,

  look in the FLUKA manual

SDUM

For dose equivalent (DOSE-EQ) scoring, the user can request the energy-dependent coefficients for the conversion of fluence to different dose (equivalent) quantities.

The following dose conversion coefficients sets are available:

1. Effective dose from ICRP74 and Pelliccioni data [Pel00] calculated with ICRP radiation weighting factors Wr for neutrons, protons, charged pions, muons, photons and electrons [Roe06].
   a. `EAP74` : Anterior-Posterior irradiation geometry
   b. `ERT74` : Rotational irradiation geometry
   c. `EWT74` : maximum value of all irradiation geometries (WORST), see Note 2
2. Effective dose from ICRP74 and Pelliccioni data [Pel00] calculated with the Pelliccioni radiation weighting factors Wr for neutrons, protons, charged pions, muons. For photons and electrons the sets from `EAP74` , `ERT74` and `EWT74` will be used respectively [Roe06].
   a. `EAPMP` : Anterior-Posterior irradiation
   b. `ERTMP` : Rotational irradiation geometry
   c. `EWTMP` : maximum value of all irradiation geometries (WORST), see Note 2
3. Ambient dose equivalent from ICRP74 and Pelliccioni data [Pel00] for neutrons, protons, charged pions, muons, photons and electrons [Roe06].
   a. `AMB74` : ambient dose equivalent H*(10)
4. Ambient dose equivalent with old "GRS"-conversion factors for neutrons, protons, charged pions, muons. Photons and electrons are not considered [Roe06].
   a. `AMBGS` : ambient dose equivalent H*(10)
5. Effective dose from ICRP Publication 116 [ICR116] for photons, neutrons, electrons, positrons, protons, charged muons, charged pions and alpha particles (see Note 3). The conversion coefficients have been extrapolated up to 10 TeV for all particles. For energies outside the tabulated ranges see Note 6.
   a. `EDAP` : anterior-posterior irradiation geometry
   b. `EDISO` : isotropic irradiation geometry
   c. `EDLLAT` : left lateral irradiation geometry
   d. `EDPA` : posterior-anterior irradiation geometry
   e. `EDRLAT` : right lateral irradiation geometry
   f. `EDROT` : rotational irradiation geometry
   g. `EDWORST` : maximum value of all irradiation geometries (WORST), see Note 2

   Conversion coefficients for certain irradiation geometries are available only for certain particles (see Note 4)
6. Ambient dose from ICRU Report 95 [ICRU95] for photons, neutrons, electrons, positrons, protons, charged muons, charged pions and alpha particles (see Note 3). The conversion coefficients have been extrapolated up to 10 TeV for all particles. For energies outside the tabulated ranges see Note 6.
   a. `HS` : ambient dose H*
7. Personal dose from ICRU Report 95 [ICRU95] for photons, neutrons, electrons, positrons, protons, charged muons, charged pions and alpha particles for different irradiation geometries (see Note 3). For energies outside the tabulated ranges see Note 6.
   a. `HP000` : personal dose H_p, for angle 0 degree
   b. `HP015` : personal dose H_p, for angle 15 degree
   c. `HP030` : personal dose H_p, for angle 30 degree
   d. `HP045` : personal dose H_p, for angle 45 degree
   e. `HP060` : personal dose H_p, for angle 60 degree
   f. `HP075` : personal dose H_p, for angle 75 degree
   g. `HP090` : personal dose H_p, for angle 90 degree
   h. `HP180` : personal dose H_p, for angle 180 degree
   i. `HPISI` : personal dose H_p, for IS-ISO irradiation geometry
   j. `HPISO` : personal dose H_p, for ISO irradiation geometry
   k. `HPROT` : personal dose H_p, for ROT irradiation geometry
   l. `HPSSI` : personal dose H_p, for SS-ISO irradiation geometry
8. Directional and personal absorbed dose in the lens of the eye from ICRU Report 95 [ICRU95] for electrons, positrons, neutrons and photons (see Note 3). The angle of 180 degree for neutrons is not included in the dataset. For energies outside the tabulated ranges see Note 6.
   a. `DE000` : absorbed dose d_lens for an angle of 0 degree
   b. `DE015` : absorbed dose d_lens for an angle of 15 degree
   c. `DE030` : absorbed dose d_lens for an angle of 30 degree
   d. `DE045` : absorbed dose d_lens for an angle of 45 degree
   e. `DE060` : absorbed dose d_lens for an angle of 60 degree
   f. `DE075` : absorbed dose d_lens for an angle of 75 degree
   g. `DE090` : absorbed dose d_lens for an angle of 90 degree
   h. `DEROT` : absorbed dose d_lens for rotational irradiation geometry
9. Directional and personal absorbed dose in the local skin from ICRU Report 95 [ICRU95] for photons, neutrons, electrons and positrons on the slab phantom (see Note 3). Pillar and rod phantom data sets have not been included. For energies outside the tabulated ranges see Note 6.
   a. `DS000` : absorbed dose d_skin for an angle of 0 degree
   b. `DS015` : absorbed dose d_skin for an angle of 15 degree
   c. `DS030` : absorbed dose d_skin for an angle of 30 degree
   d. `DS045` : absorbed dose d_skin for an angle of 45 degree
   e. `DS060` : absorbed dose d_skin for an angle of 60 degree
   f. `DS075` : absorbed dose d_skin for an angle of 75 degree

Activation and residual radiation – *Main features*

- The generation and transport of decay radiation (including **α**, β, γ, X-rays, and conversion electrons emissions) is possible during the same simulation which produces the radionuclides (one-step method)

- For this purpose, a dedicated database of decay emissions is used, based mostly on information obtained from NNDC, sometimes supplemented with other data and checked for consistency
  - NNDC: National Nuclear Data Center https://www.nndc.bnl.gov

- Consequently, results for production of residual nuclei, 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 ratios for each isotope/isomer
- The present isomer model roughly estimate the equal sharing among states

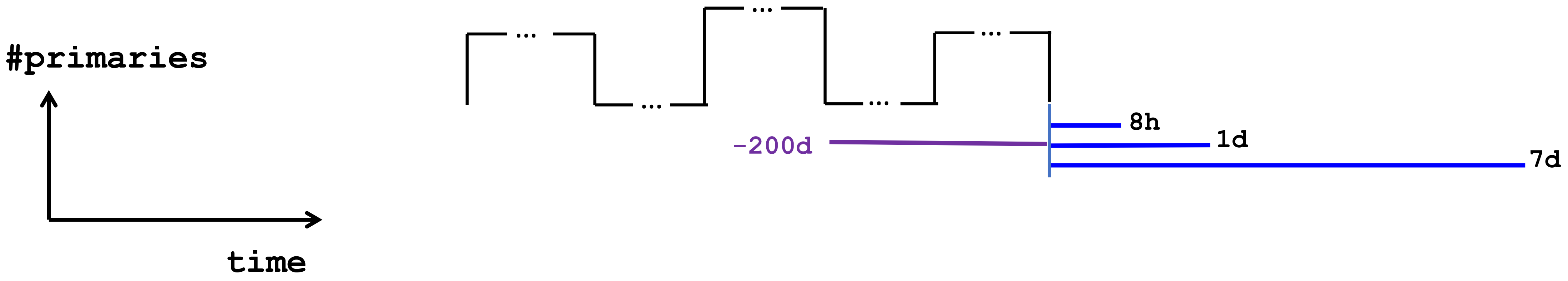
- All gamma lines down to 0.01% branching ratios
  (including X-ray lines following conversion electron emissions)
- All beta emission spectra down to 0.01% branching ratios
  (the sampling of the β spectra including screening Coulomb corrections)
- Auger and conversion electrons

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

Input options – *Overview*

- Input card: **IRRPROFI**
  - defines the irradiation profile (irradiation times and beam intensities)

- Input card: **DCYTIMES**
  - defines the decay (cooling) times measured from the end of the last irradiation period (t=0)



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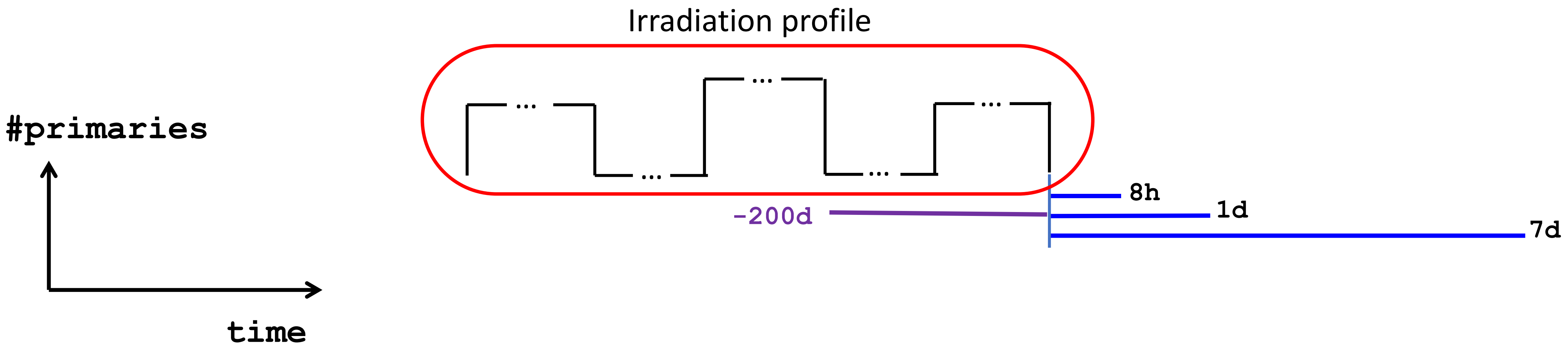

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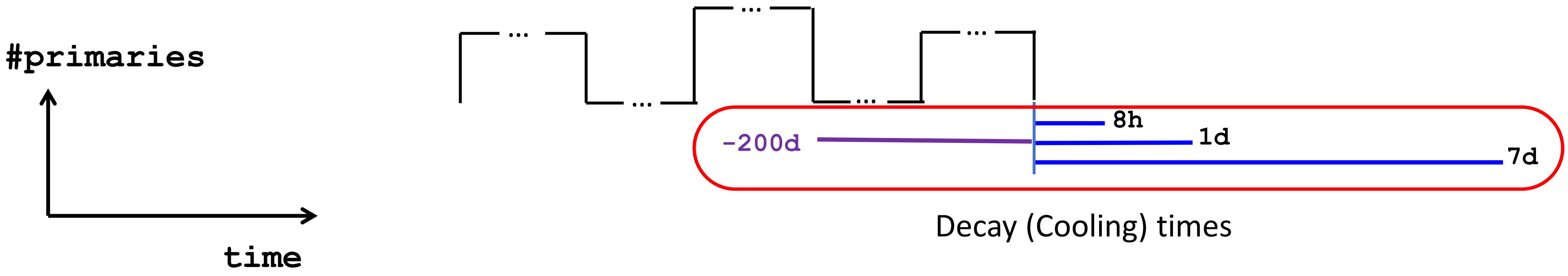


Input options – *Overview*

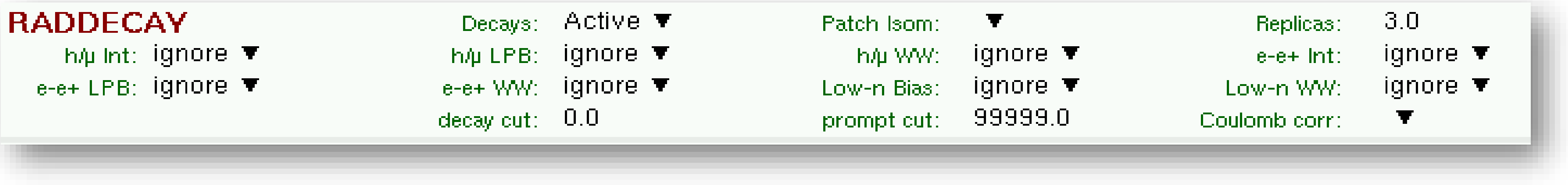
- Input card: **`RADDECAY`**
  - activates the simulation of the decay of the radioactive nuclides produced
  - allows to modify biasing and transport thresholds for the transport of decay radiation

- 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
  - allows to apply a filter within the scoring estimator for a specific generalized particle type

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

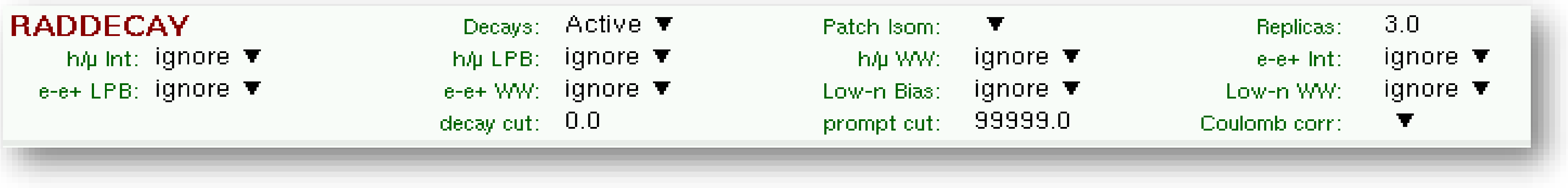
Semi-Analogue
radioactive decays activated in semi-analogue mode
each radioactive nucleus is treated like all other unstable particles (random decay time, daughters and radiation), all secondary particles/nuclei carry time stamp ("age")
Necessary to simulate radioactive sources

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 prompt 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]**

- zero intensity is accepted and can be used, e.g., to define beam-off periods
- 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	5.9×10^5 p/s
		(beam-off)	

Input option: DCYTIMES

Definition of cooling times

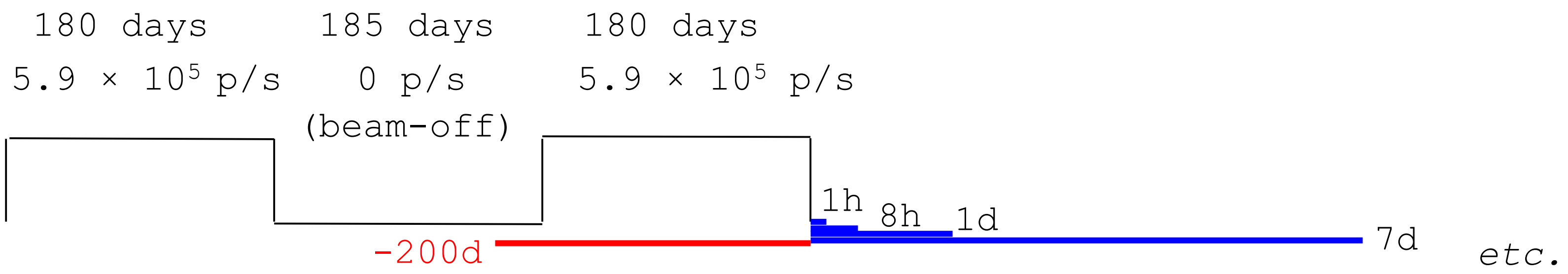
	1hour	8hours	1day	7days	1month	4months
DCYTIMES	t1: 3600.	t2: 28800.	t3: 8.64E4	t4: 6.048E5	t5: 2.592E6	t6: 1.0368E7

t1 .. t6 **cooling time (in seconds) after the end of the irradiation**

Note: Several cards can be defined.

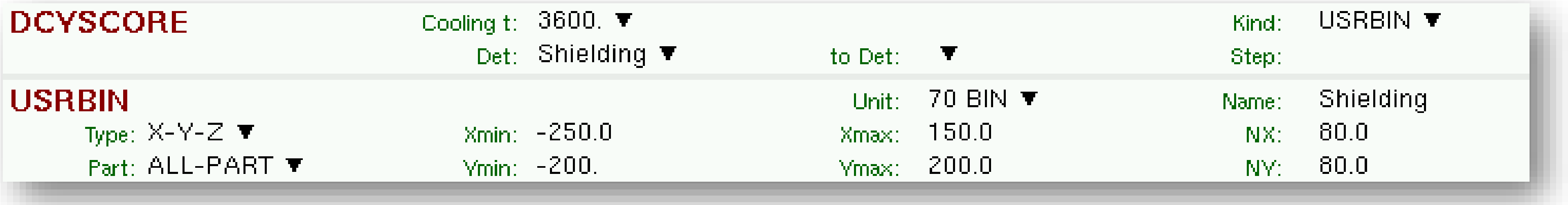
Each cooling time is assigned an index, following the order in which it has been input.
This index can be used in option **DCYSCORE** to assign that cooling time to one or more scoring detectors.
A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

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

Kind — **Type of estimator:**
RESNUCLE, **USRBIN/EVENTBIN**, **USRBDX**, **USRTRACK**...

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**

Input option: DCYSCORE [2/2]

Important note:

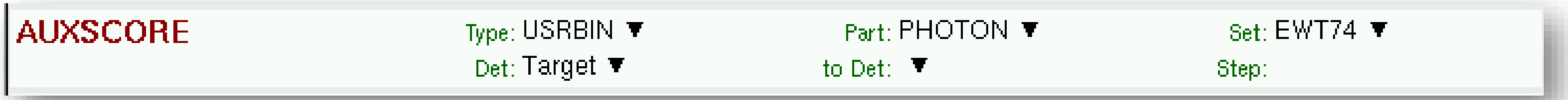
All quantities are expressed per unit time when associated to a cool-down time

- 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

Det .. to Det — **Detector range**
Drop down list to select detector range of type **Type**

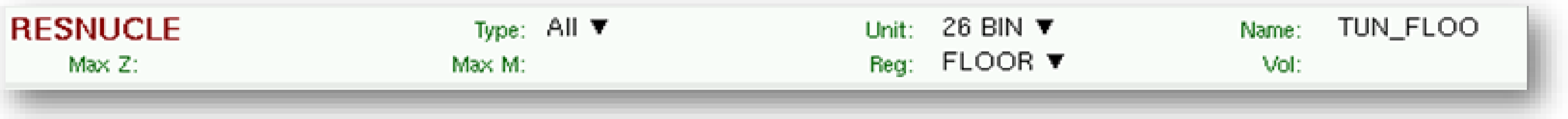
Step — **Step in assigning indices of detector range**

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)
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)

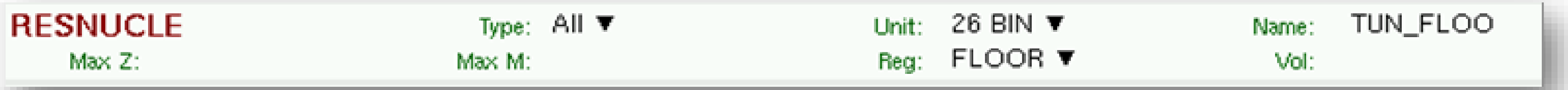
Unit — **Logical output unit**

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)

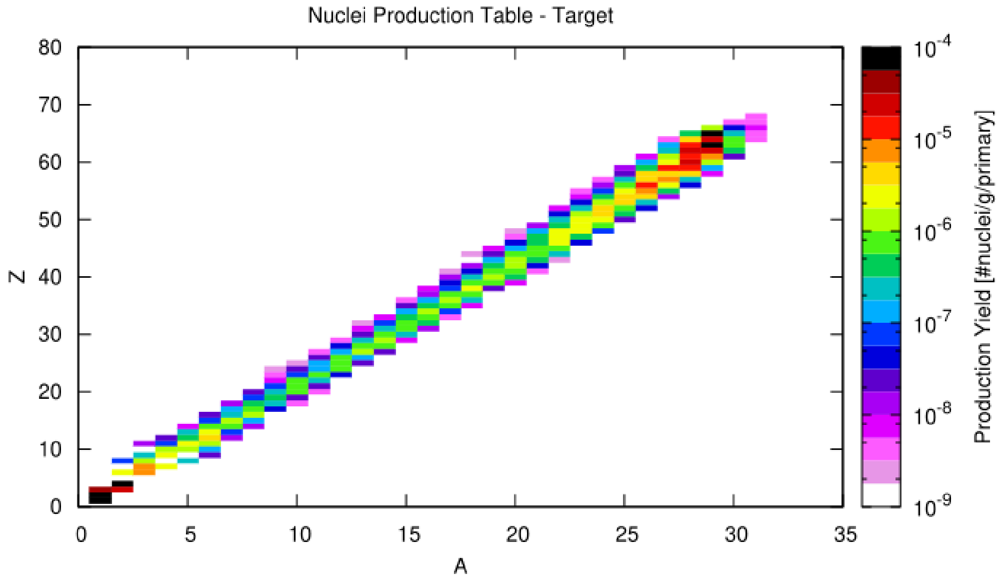
Notes:

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 ▼

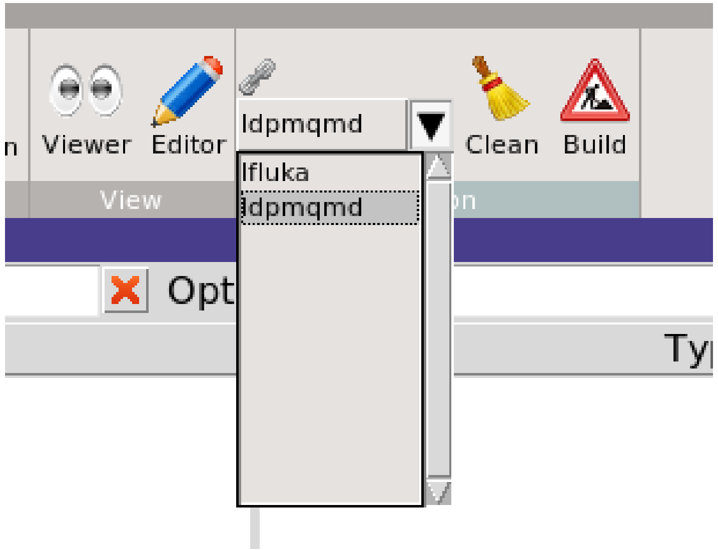
Use of **PEANUT model at all energies** (now part of default settings)

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.

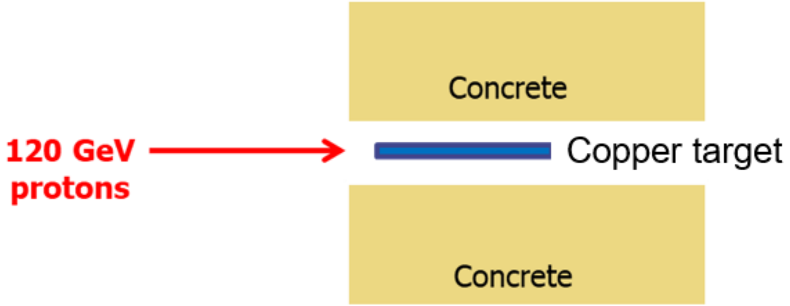


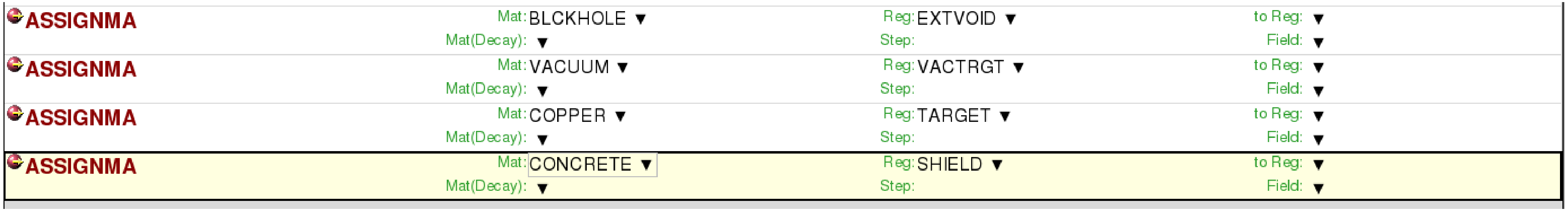
All ions (including deuterons) are treated
with RQMD (>150 MeV/n) and DPMJET (> 5 GeV/n)

All ions (excluding deuterons) < 150 MeV/n are treated with BME

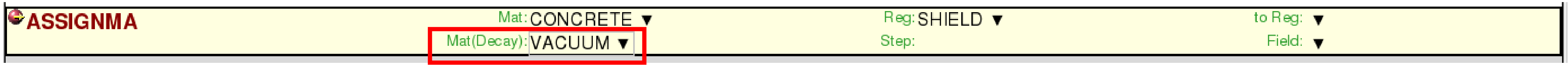
Deuterons < 150 MeV/n are treated independently with a dedicated model

Geometry modifications





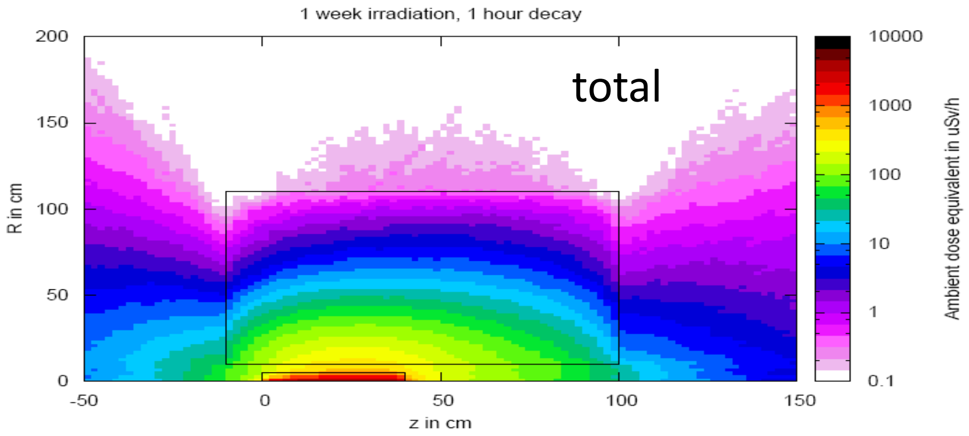
Remove concrete shield for transport of radioactive decay radiation
(e.g., for calculation of residual dose rate from target only)

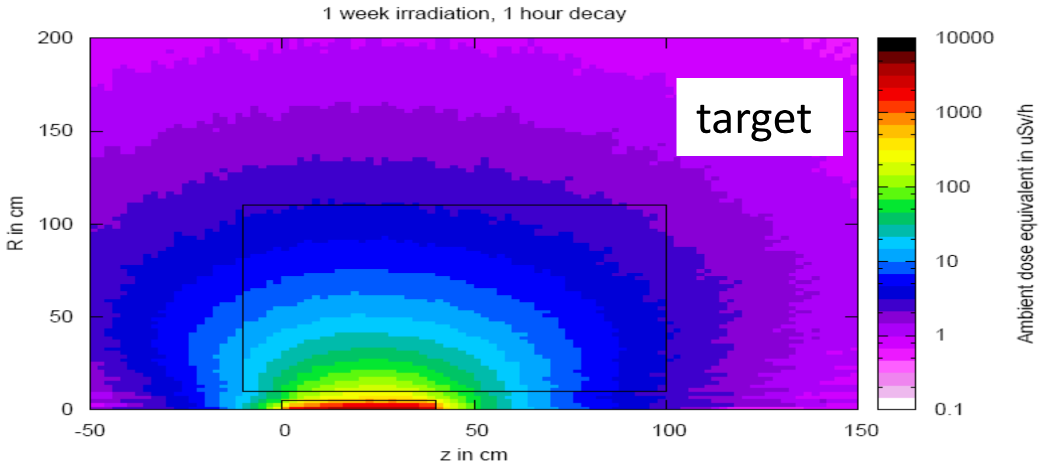


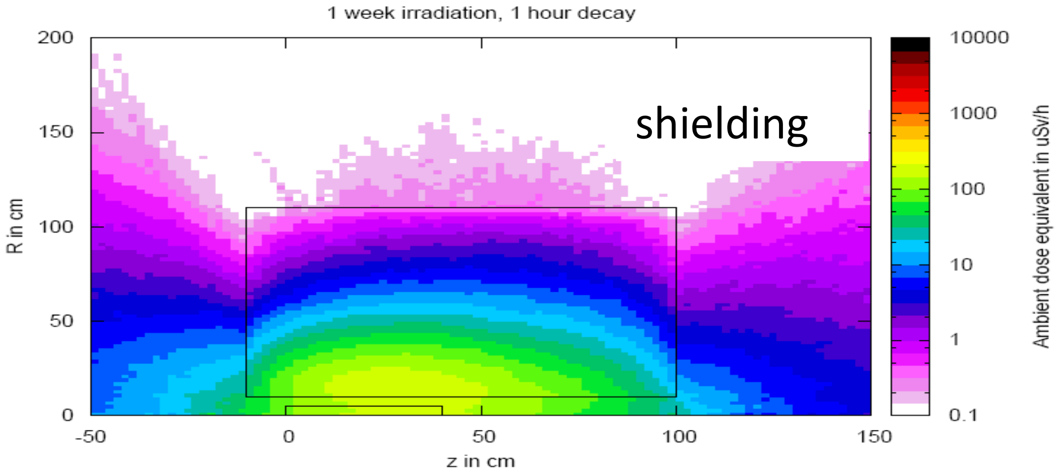
Remove target for transport of radioactive decay radiation
(e.g., for calculation of residual dose rate from concrete shield only)

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

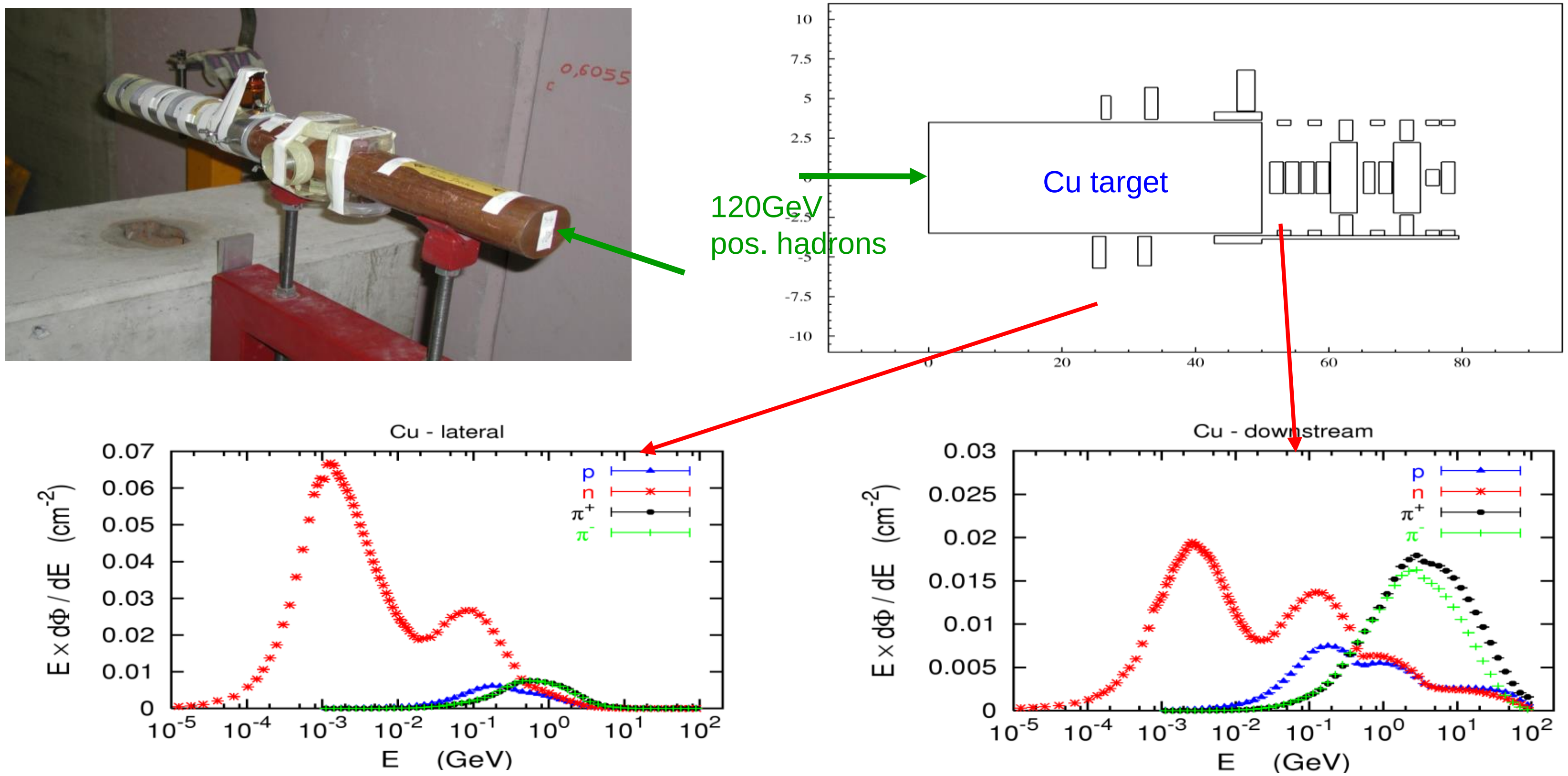
FLUKA

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



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		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

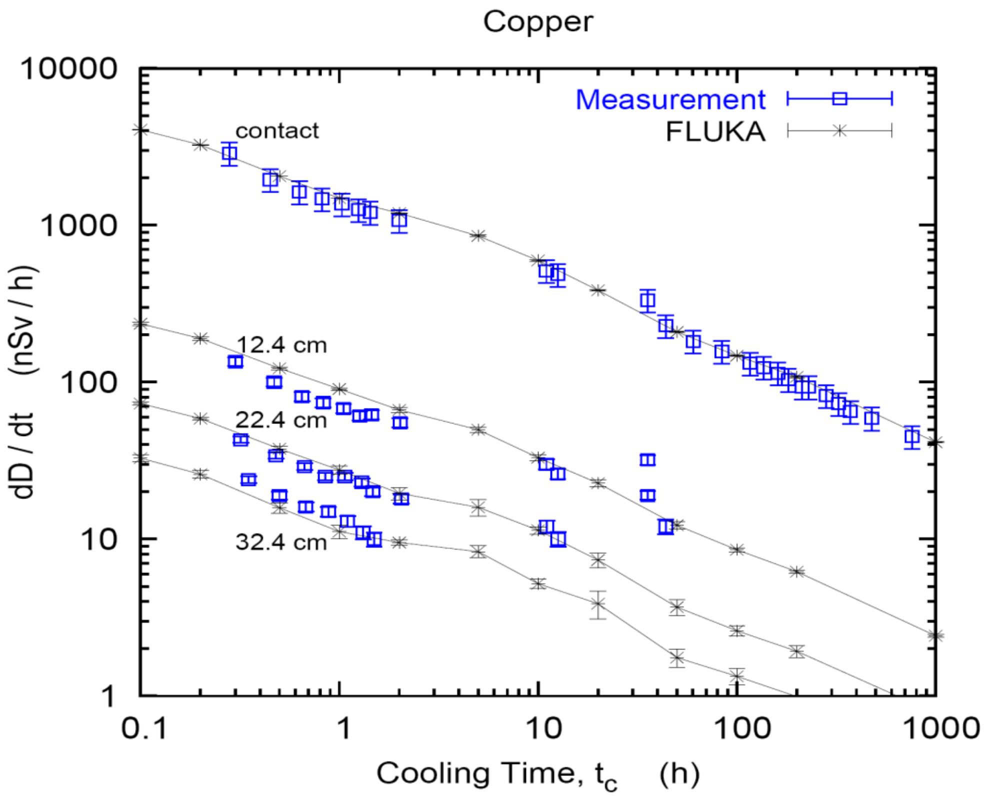
Exp/MDA < 1

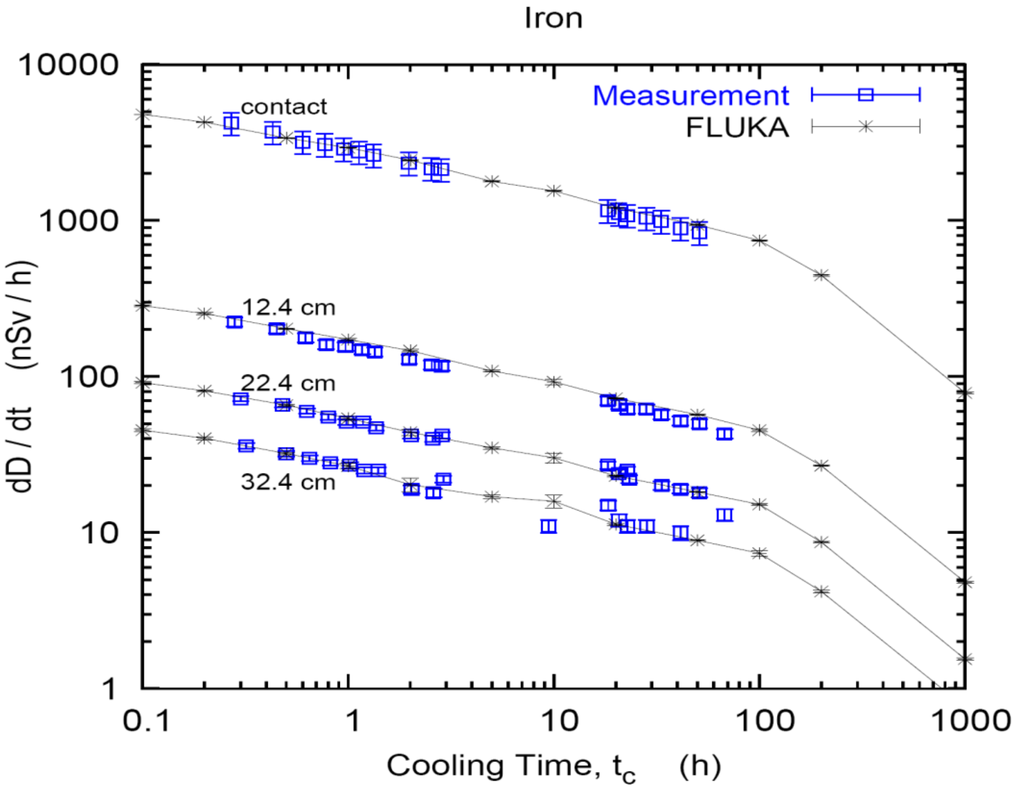
R + Error < 0.8 or
R – Error > 1.2

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*

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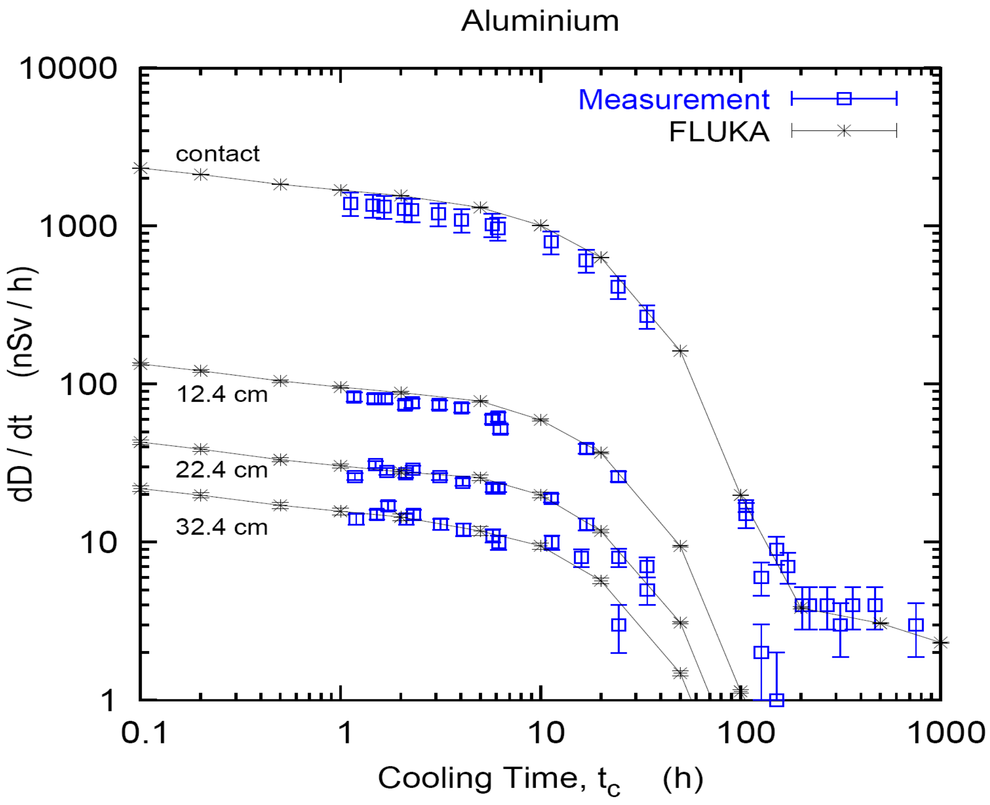

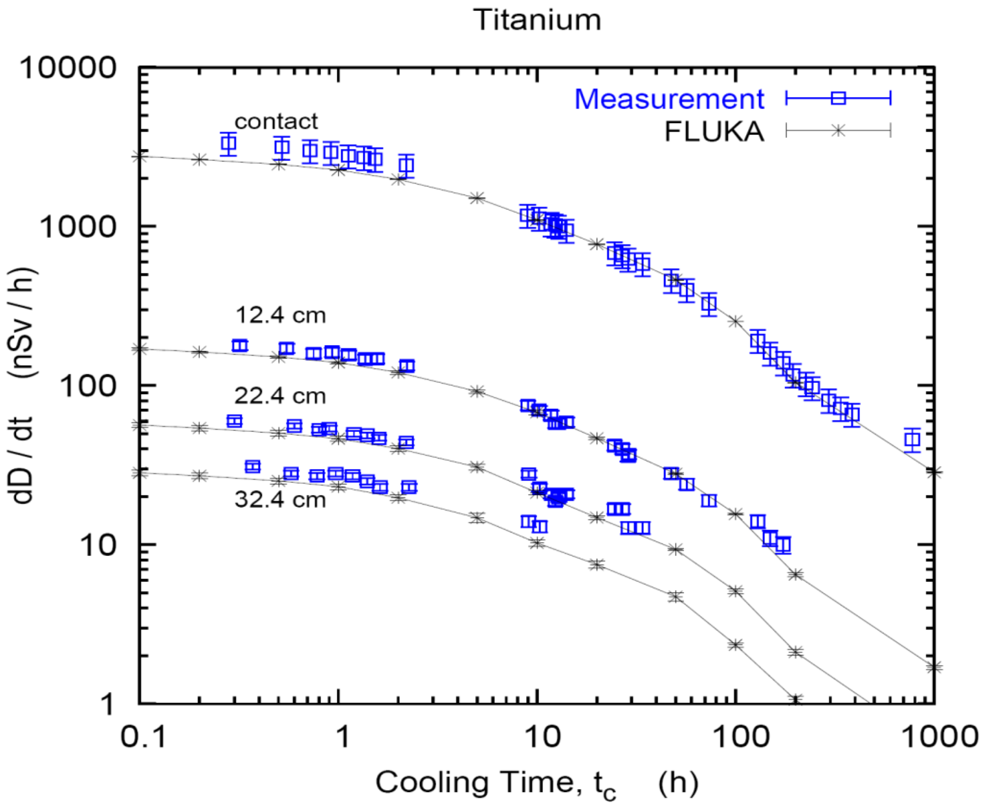

Reference: M. Brugger, S. Roesler *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

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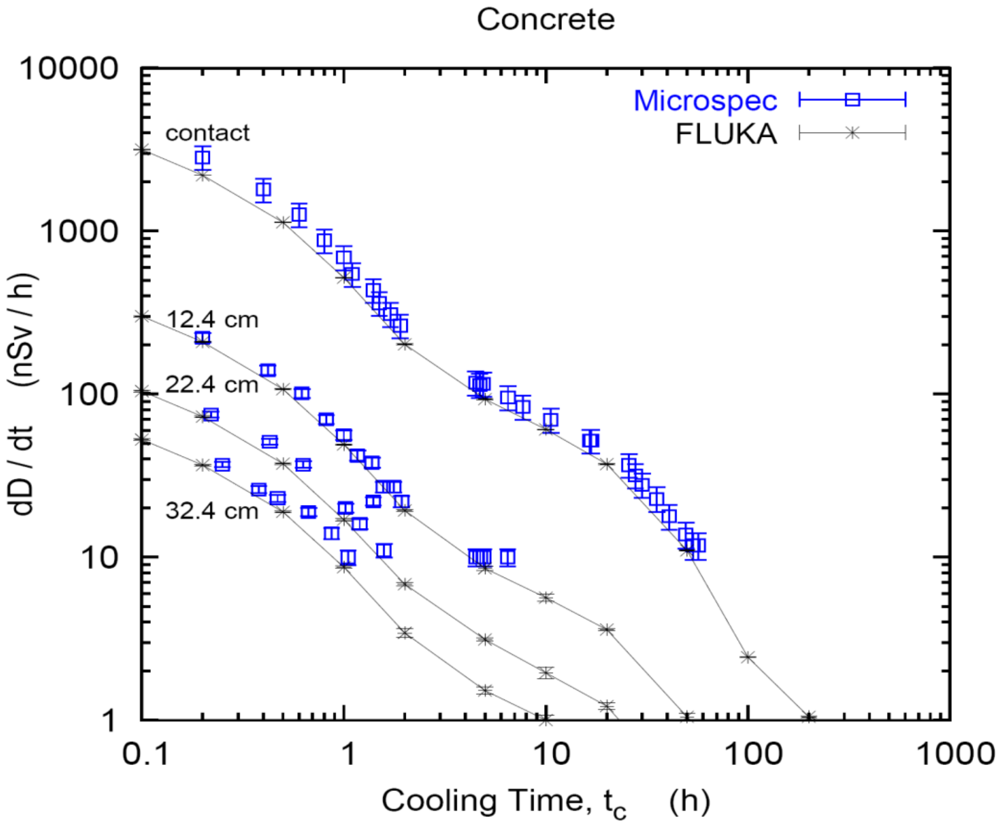


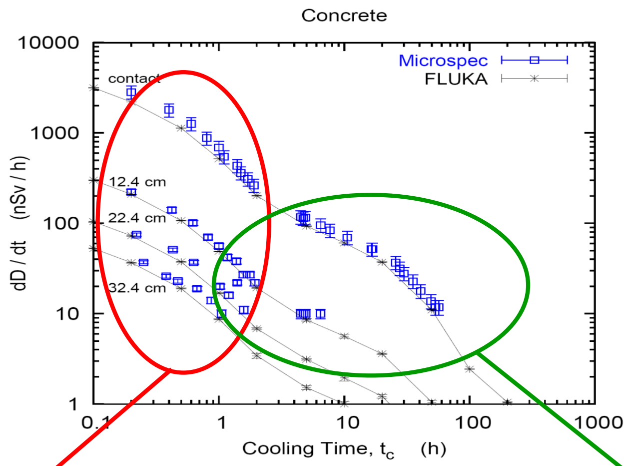
Reference: M. Brugger, S. Roesler *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

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)