

How to Use DeTra in MARS15 and Calculate Residual Dose around Small Objects

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MARS15 Tutorial
Fermilab

Two Ways to Calculate Residual Dose at a Distance from a Small Object

- MARS15 provides contact dose for relatively large objects ($\gg \lambda_{1 \text{ MeV } \gamma}$). For practical applications: 1) dose at a distance; 2) Dose from relatively small objects.
- **First method (with DeTra):**
 - (1) MARS15 calculation of the production rates of individual residual nuclei, (2) calculation of activities of the isotopes in the target with the DeTra code after certain irradiation and cooling times, and (3) conversion of activities to individual doses at a distance using specific gamma-ray constants
- **Second method:**
 - (1) MARS15 calculation of the residual dose on contact with the target, (2) correction for a small target size, and (3) Monte-Carlo based distance correction.

Calculation of Isotope Production Rates

- Production rates of the residual nuclides in the gold target are calculated using **MARS15**.
- Production rates are used as initial data for the **DeTra** (built-in) code for definite irradiation and cooling times (**NCLD, IMNC**).
- **CEM** generator (**ICEM 4=2, PHOT 8=-1**). **FERMILAB-CONF-08-322-APC**
- The **Cascade-Exciton Model (CEM)** of nuclear reactions was proposed at the Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, **Dubna**, by **Gudima, Mashnik, and Toneev**.
- Calculates nuclear reactions induced by **nucleons, pions, and photons**.
- A three-stage process: 1) **IntraNuclear Cascade (INC)** (re-scattered and produces secondary particles several times before the escape from a nucleus), 2) **preequilibrium emission** of particles during the equilibration of the excited residual nuclei formed after the INC, subsequent relaxation of nuclear excitation is treated in terms of a modified version of **exciton model** 3) **evaporation** of particles from or **fission** of the compound nuclei.

Calculation of Activities of Isotopes with DeTra (1)

- DeTra solves the Bateman equations governing the decay and transmutation of nuclides using transmutation trajectory analysis (TTA).
- The core of the method is that a complex web of decay and transmutation reactions can be decomposed into a set of linear chains consisting of all possible routes, or trajectories, through the web.
- A set of linear chains is constructed for each nuclide and following all the possible reaction and decay modes leading to it. The concentrations of nuclides encountered in each chain are calculated by assuming that only the first nuclide of the chain has non-zero initial atomic density.
- Doing this for each nuclide in the initial composition and superposing the results yields the solution of the original problem. However, some chains may become very long and are thus cut when the contribution falls below a given threshold. In the case considered here, the chains are not very long and not cyclic.

Calculation of activities of the isotopes with DeTra (2)

```
TITLE Mu2e Au target decay heat
SIZE 20 100 5000 5000
LIMIT 1.0
LIBRARY nudat.bin
OUTPUT 20011.0 activation.res
POWER 0.0 0.0 2.E13
SELECTOR 1.0 1.0 0.0 0.0 1.0
IRRADIATE 365.0
SELECTOR 0.0 0.0 0.0 0.0 1.0
IRRADIATE 30.0
TIME 30.0
TIME 395.0
```

```
INIT 0.0
Au 183 0.000E+00 1.190E-04
Au 184 0.000E+00 2.880E-04
Au 185 0.000E+00 1.628E-03
Au 186 0.000E+00 2.598E-03
Au 187 0.000E+00 5.967E-03
Au 188 0.000E+00 8.064E-03
Au 189 0.000E+00 1.478E-02
Au 190 0.000E+00 1.820E-02
Au 191 0.000E+00 3.345E-02
Au 192 0.000E+00 2.696E-02
Au 193 0.000E+00 5.335E-02
Au 194 0.000E+00 4.041E-02
Au 195 0.000E+00 5.729E-02
Au 196 0.000E+00 8.437E-02
END
CALCULATE
```

- P. Aarnio, CMS-NOTE-1998/086, CERN (1998).

Conversion of Activities to Individual Doses (3)

$\Gamma = 6 * E_{\gamma} * I_{\gamma}$, where E_{γ} – gamma-ray energy (MeV), and I_{γ} – gamma-ray activity per decay (Ci).

Specific γ -ray constants to estimate the dose at 1 meter.

Γ [mSv/(hr-MBq)].

Inverse square law for other distances.

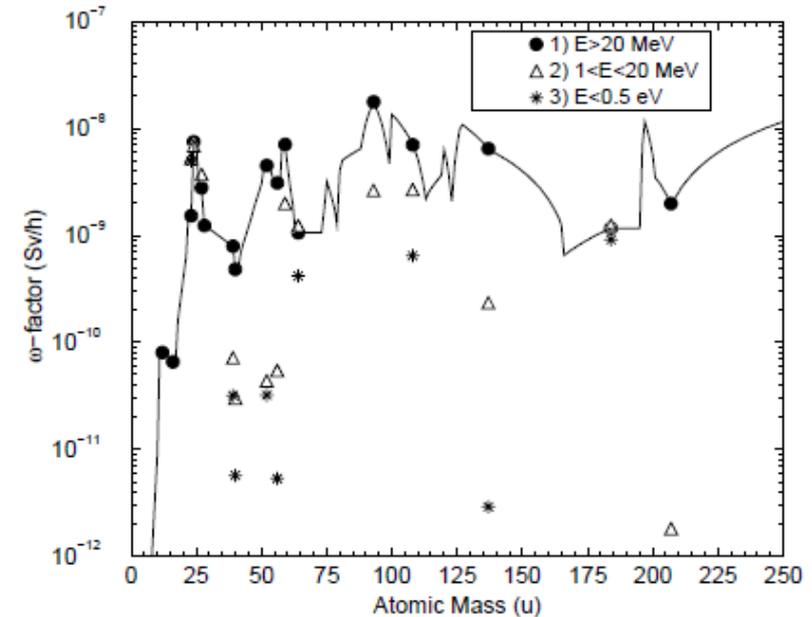
These nuclei represent 70% of activity – correct.

Isotope	Activity, Bq	Γ , mSv/(h-MBq) @ 1m	Dose at 1 meter, mSv	Dose at 1 foot, mSv	Source of the specific gamma-ray constant, Γ
Eu-146	3.47E+10	2.52E-04	8.75E+00	1.03E+02	calculated
Yb-169	3.10E+11	8.84E-05	2.74E+01	2.95E+02	[6]
Lu-171	2.14E+11	8.71E-05	1.86E+01	2.00E+02	calculated
Lu-172	1.24E+11	2.86E-04	3.56E+01	3.83E+02	calculated
Hf-175	4.91E+11	4.52E-05	2.22E+01	2.39E+02	calculated
Hf-178m	1.89E+11	1.46E-04	2.75E+01	2.96E+02	calculated
Ta-178	5.50E+11	8.83E-06	4.86E+00	5.23E+01	calculated
Hf-179m	1.39E+11	3.10E-05	4.31E+00	1.74E-22	calculated
Re-184	1.03E+11	1.57E-04	1.62E+01	1.74E+02	[6]
Os-185	1.10E+12	1.31E-04	1.44E+02	1.55E+03	[6]
Ir-188	8.84E+11	4.66E-04	4.12E+02	4.43E+03	calculated
Pt-188	7.21E+11	2.04E-05	1.47E+01	1.58E+02	calculated
Ir-189	1.36E+12	3.77E-06	5.11E+00	5.50E+01	calculated
Ir-190	2.96E+11	2.68E-04	7.95E+01	8.55E+02	[6]
Pt-191	4.11E+11	6.57E-05	2.70E+01	2.91E+02	ORNL
Ir-192	3.87E+11	1.60E-04	6.19E+01	6.66E+02	[6]
Au-194	6.43E+10	1.78E-04	1.15E+01	1.24E+02	[6]
Au-195	1.61E+12	2.36E-05	3.80E+01	4.09E+02	[6]
Au-196	1.31E+12	9.92E-05	1.30E+02	1.40E+03	[6]
		Sum dose	1.09E+03	1.17E+04	

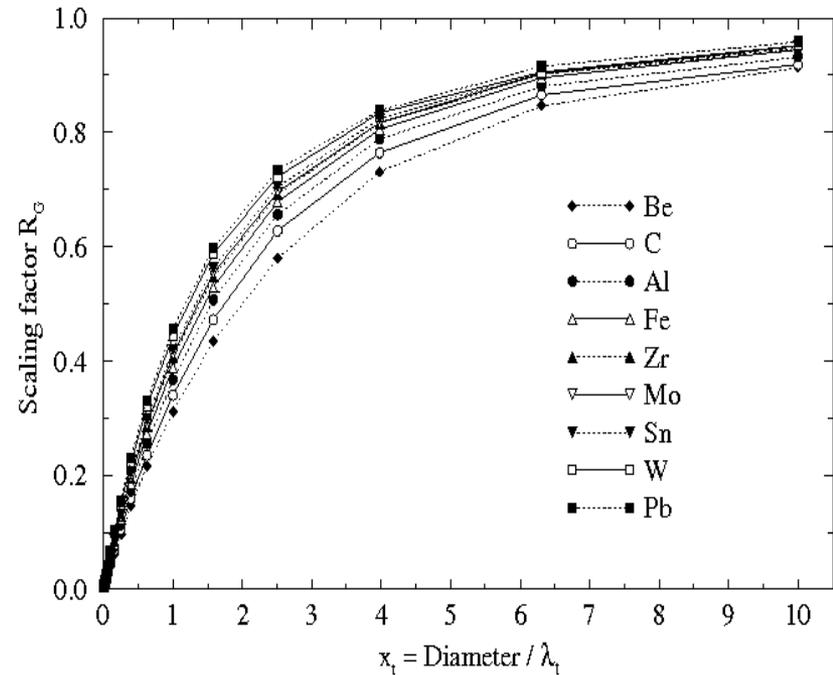
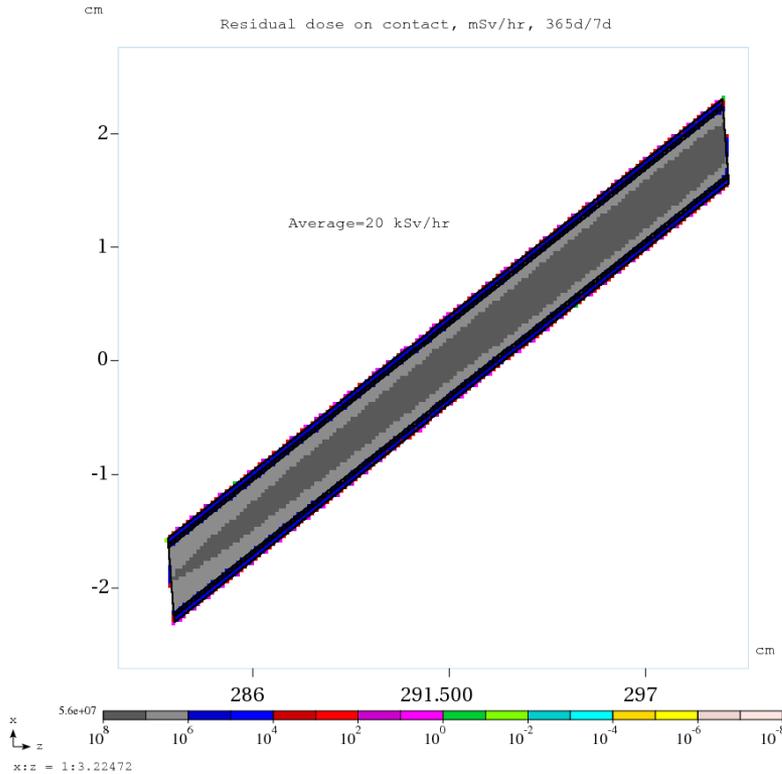
The Health Physics and Radiological Health Handbook, ed. B.Shleien, Scinta, 1992, p. 167.

Contact Dose Model in MARS15

- ω -factor model (star density/flux to dose)
 - Distinguishes 3 energy groups:
($> 20\text{MeV}$, $1\text{ MeV} < E < 20\text{MeV}$, $E < 0.5\text{ eV}$)
(n , xn_p), (n , xn), (n , p), (n , γ)
 - Cascades in 17 elements: C, O, Na, Mg, Al, Si, K, Ca, Cr, Fe, Ni, Cu, Nb, Ag, Ba, W, Pb. Induced by energetic hadrons. Residual nuclei formation was simulated.
 - Decay chains are followed by DeTra to determine the emission rates of the de-excitation photons.
 - $12\text{ hours} < T_{irr} < 20\text{ years}$ and $1\text{ sec} < T_{cool} < 20\text{ years}$
 - Corresponding dose rates on the outer surfaces were calculated from proton fluxes and related to 1) star density ($>20\text{ MeV}$), and neutron fluxes (for $1\text{ MeV} < E < 20\text{ MeV}$, $E < 0.5\text{ eV}$). Sophisticated interpolation algorithm. Calculated on the surface of irradiated samples $> 0.5\lambda$
- See also FERMILAB-Conf-01/304-E.



Correction for a Small Target Size



Fermilab-FN-0788-AD

x_t – ratio of the target diameter to the mean free path of the 1 MeV photons (λ_t (Au) \approx 0.745 cm). $R_G=0.41$ for Mu2e target.

<http://physics.nist.gov/PhysRefData/contents.html>

Dose at a Distance from the Target

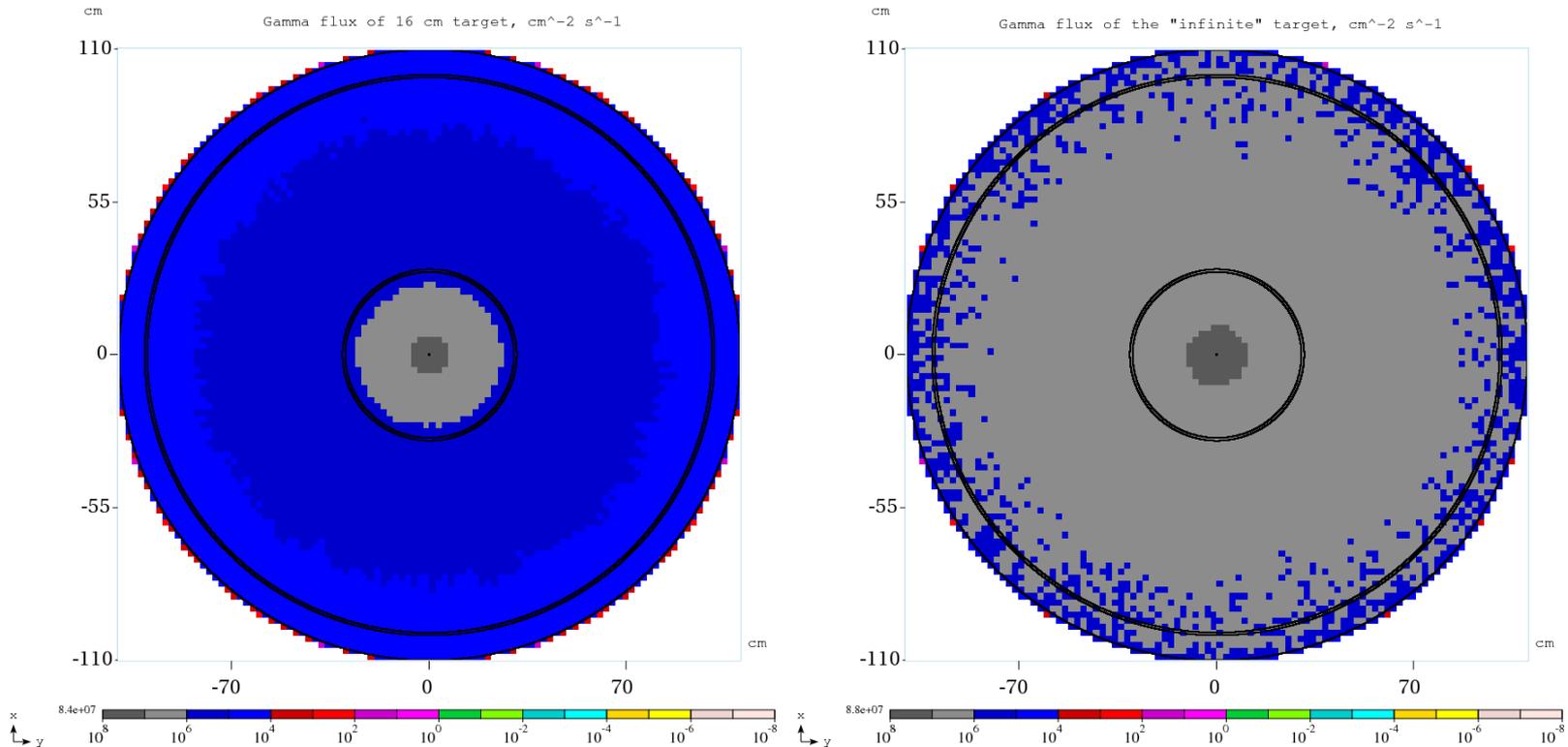
- The residual dose $D(x,y,z)$ in the air due to residual activity of an irradiated object assuming isotropic angular distribution of γ -rays emitted from the surface of the object: $D(x, y, z) = k_d \Phi(x, y, z) = k_d \int dS \frac{A_s}{2\pi\rho^2}$
- $\Phi(x, y, z)$ -- flux of γ -rays, A_s -- surface emission rate of γ -rays per unit area and per 2π solid angle, ρ -- distance between the observation point and the surface element dS , and k_d -- flux-to-dose conversion factor. $E_\gamma=1$ MeV
- Uniformly activated infinite cylindrical object, closed form.
- $D(r) = \frac{D_0}{1+\frac{r}{R}} F(\varphi \setminus \alpha)$, where D_0 – dose on contact with the target,

$r = \sqrt{x^2 + y^2 + z^2}$, R – radius of the cylinder, $F(\varphi \setminus \alpha) = \int_0^\varphi (1 - \sin^2 \alpha \sin^2 \theta)^{-\frac{1}{2}} d\theta$,

incomplete elliptic integral of the first kind, $\varphi = \sin^{-1} \sqrt{\frac{1+R/r}{2}}$, $\alpha = \sin^{-1} \left(\frac{2\sqrt{r/R}}{1+r/R} \right)$.

$f(r - R) \equiv \frac{D(r)}{D_0}$. $f(30) = 0.0078$ and $f(100) = 0.0023$ (for Mu2e target)

Correction for Finite Target Length



Gamma flux is determined at the distance of the expected detector with the actual (16 cm, Mu2e) and quasi-infinite (20 m) targets and the ratio of these fluxes is used

as the correction factor. $f_s = \frac{\phi^{short}}{\phi^{long} * k_{vol}}$, $f_s(30)=0.203$, $f_s(100)=0.0611$

Conclusions

- **Two methods** to calculate the residual dose rates around small targets starting from the contact dose or nuclide production rate generated by **MARS15** are described.
- The **first one uses production rates** for residual isotopes calculated by **MARS15** as an input for **DeTra**, then **activities** are converted to dose at one foot using **specific gamma-ray constants**.
- The **second method** employs **MARS15** for the calculation of the residual dose on contact, and then uses **scaling factors to correct for the target size, incomplete elliptic integral of the first kind** to introduce the **distance correction** and the **Monte-Carlo-based finite size correction**.
- The methods reveal a **good agreement**.

Distance from the target, cm	Dose, Sv/hr (first method)	Dose, Sv/hr (second method)
30	16.7	13.0
100	1.6	1.2