Geant4 simulation of the attenuation properties of plastic shield for β^- radionuclides employed in internal radiotherapy

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The need to store, transport and handle β^-–radioactive isotopes poses a safety problem arising from the potential exposure of workers and public to the directly ionising radiation emitted.

This problem can be solved with low-Z material shields, which are able to absorb the high-energy electrons, maximising their energy loss by inelastic collisions and thus minimising the energy losses by radiative (bremsstrahlung) x-ray emission

When it is necessary to handle sources for purpose of, i.e., radiochemical or radiopharmaceutical preparations, special requirements can be posed on the thickness or shape of the shields, as well as on the physical properties of the materials such as :

Trasparency

Thermal conductivity

Electrical conductivity

Elasticity

Range of operating temperatures

To study the attenuation properties of different plastic materials which can be employed to build effective shields in the various applicative contexts

Geant 4

We developed a Monte Carlo simulation in Geant4 environment, in order to compare the attenuation properties as well as the relative bremsstrahlung X-ray production yield in the various plastic materials considered.

β^- radionuclides

Our simulated set-up consisted of a collimated radioactive source of ^{90}**Sr** or ^{90}**Y** in contact with a thick slab of plastic absorber.
The radioactive sources were chosen as representative of low- and high-energy β^- emitters:

Sources	<E>	E_{max}	Half-life
^{90}Y	0.93 MeV	2.27 MeV	64.1 days
^{90}Sr	196 keV	546 keV	28.74 years

Plastic Material

We chose eight different types of plastic material characterized by densities ranging from 0.91 g/cm^3 to 2.16 g/cm^3, by different atomic composition and a variety of thermal, electrical, optical and mechanical properties:

Table 2. Physical properties of the plastic materials studied (Indat 2009, Diadi 2009).

Material	Formula	Density (g cm^{-3})	T_{max} (°C)	Thermal cond. (W mK^{-1})	Electrical resistivity (Ω cm)	Modulus of elasticity (N mm^{-2})	Optical transparency
PP	C_3H_6	0.91	100	0.22	10^{15}	1400	No
PS	C_2H_3	1.05	65	0.16	10^{15}	3400	Yes
PA	$C_6H_{11}ON$	1.14	100	0.23	10^{15}	1500–3000	No
PMMA	$C_5H_8O_2$	1.19	70	0.19	10^{15}	3200	Yes
PC	$C_{16}H_6O_3$	1.2	115	0.12	10^{15}	3200	Yes
PET	$C_{10}H_8O_4$	1.4	120	0.28	10^{16}	3000	Yes
PVC	C_2H_3Cl	1.42	60	0.16	10^{15}	3000	Yes
PTFE	C_2F_4	2.16	260	0.25	10^{18}	3500–6300	No

Geant4 simulation

The simulation was carried out using Geant4 version 9.1 on a Linux Ubuntu 8.04 workstation equipped with Intel Core 2 Duo processors at 1.8 GHz and 2 Gbytes of RAM.

The statistical uncertainties (2σ) associated with the presented results of the Monte Carlo calculations are below 1%, less than the uncertainties on the relative experimental data taken as comparison.

We briefly discuss the validation of the Geant4 processes relevant for our work and we present the results of our code in comparison with different reference data-sets for energy deposition, range and radiative losses for low-energy electrons.

Validation of Geant4 code

By choosing the default values (cut = 1 mm and F_R = 0.02), we found no statistically significant difference between the energy deposition calculated adopting the three physics packages (Standard, Livermore, Penelope).
Adopting the standard physics and the default values for cut and F_R, we compared our results with the SANDIA reference data for different electron energies and beam incidence angles, evaluated with respect to the normal to the target's surface. In table below we present some of our validation results.

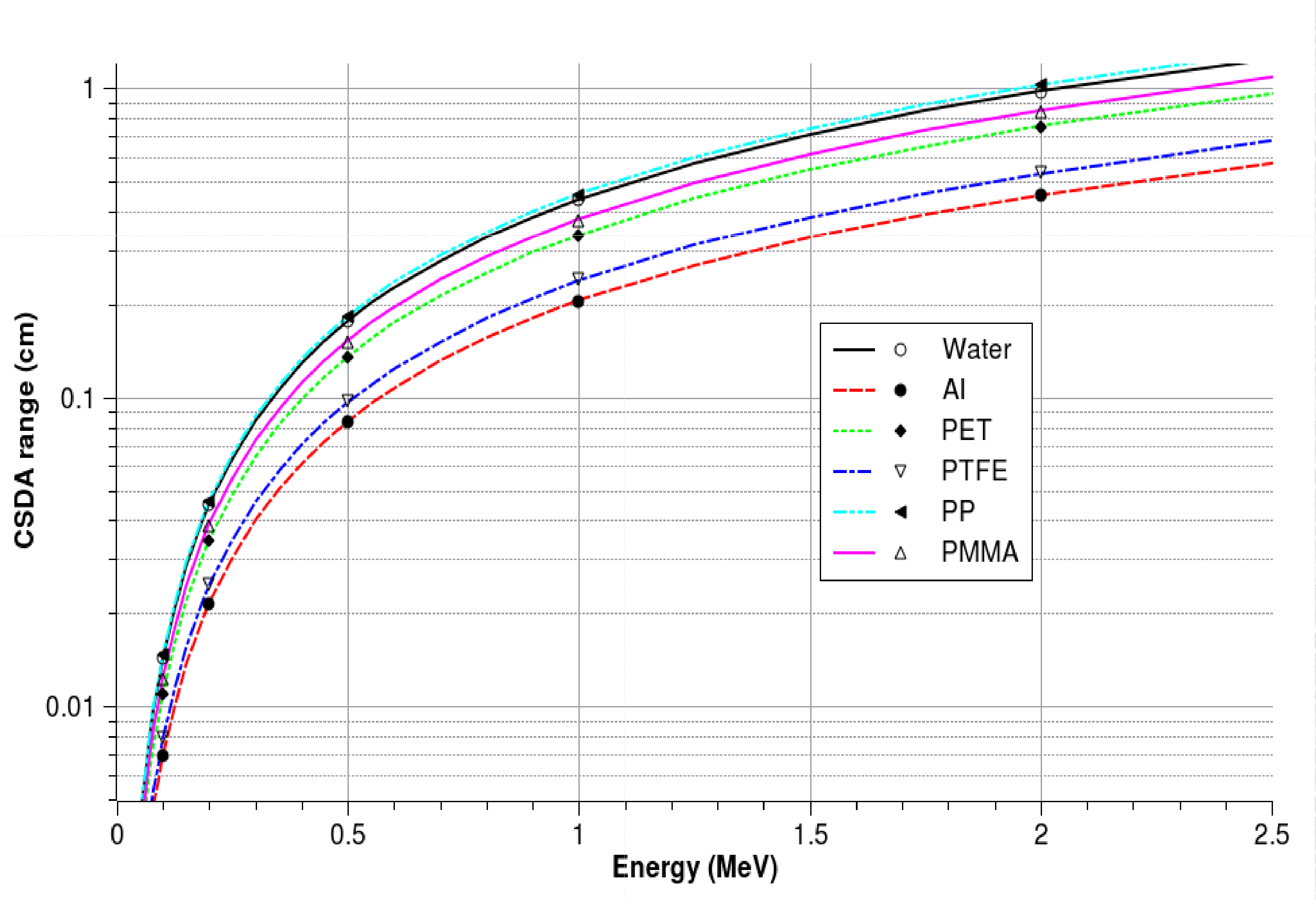
Table 1. Energy deposition: comparison with SANDIA reference data.

Target	E_e (keV)	Angle (deg)	Energy deposited (our simulation) (keV)	Energy deposited (SANDIA) (keV)	ΔE (%)
Al	314	0	293	285	2.8
Al	314	60	236	230	2.6
Al	521	60	398	391	1.8
Al	1033	0	983	970	1.3

Validation of Geant4 code

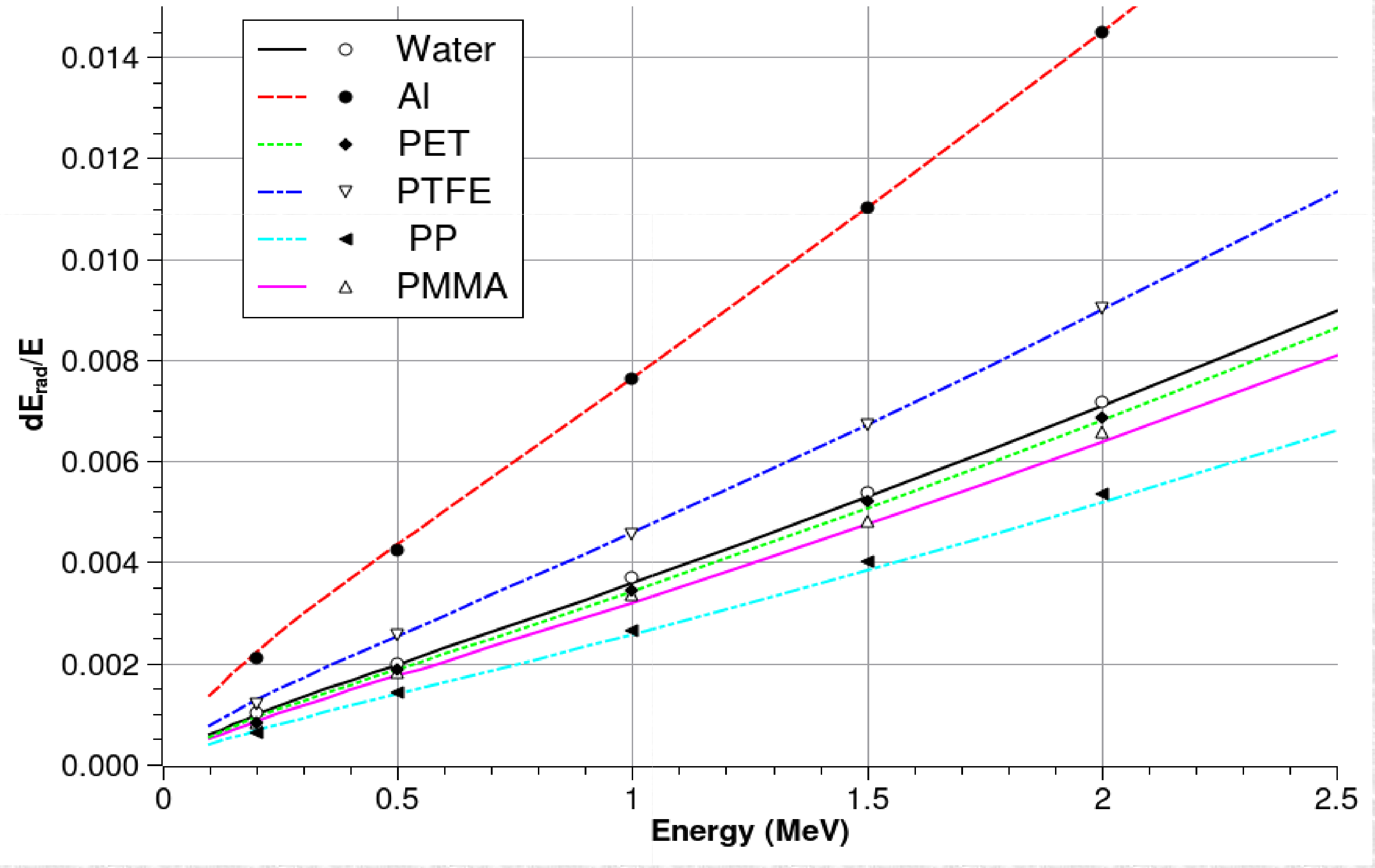
With the same values for range cut and F_R, we compared the CSDA range calculated in our simulation with the data from NIST for aluminium, water and all the plastic materials considered in our study.

In figure below the comparison is shown for some relevant materials, revealing a full match.

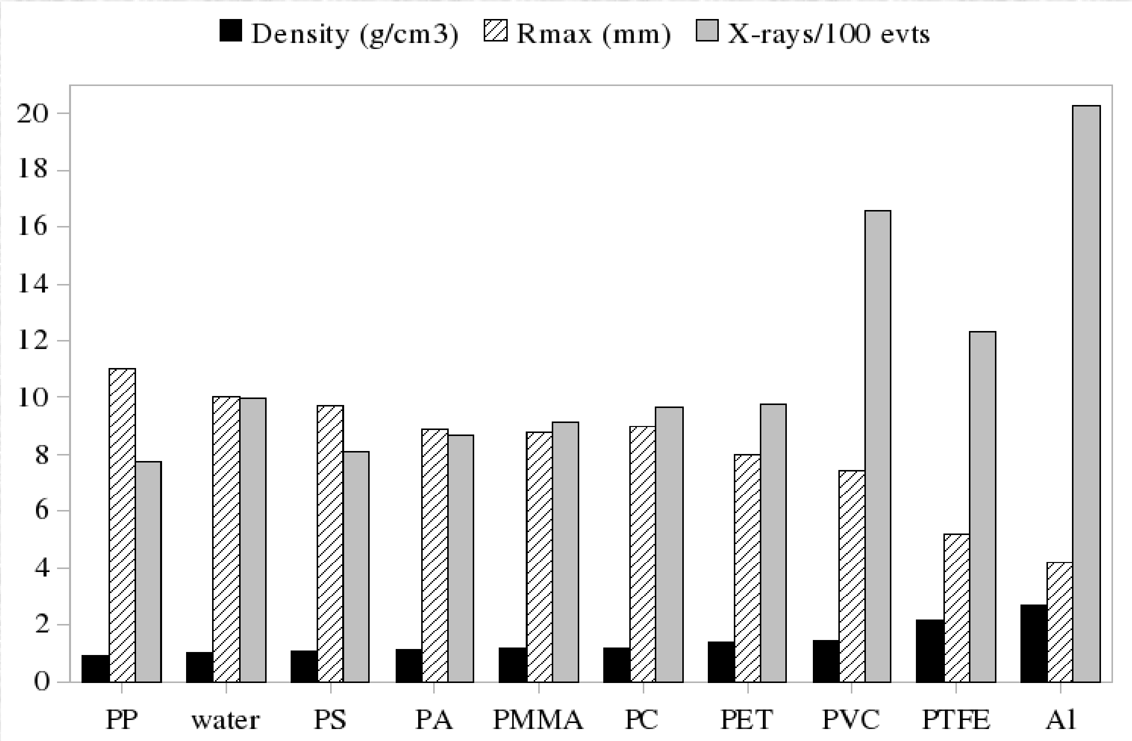


Validation of Geant4 code

We compared the fraction of electron energy lost by radiative emission from our simulation with the NIST reference data for a collimated beam of monoenergetic electrons on the same targets. The uncertainties in NIST data are reported to be within 5% below 2 MeV.

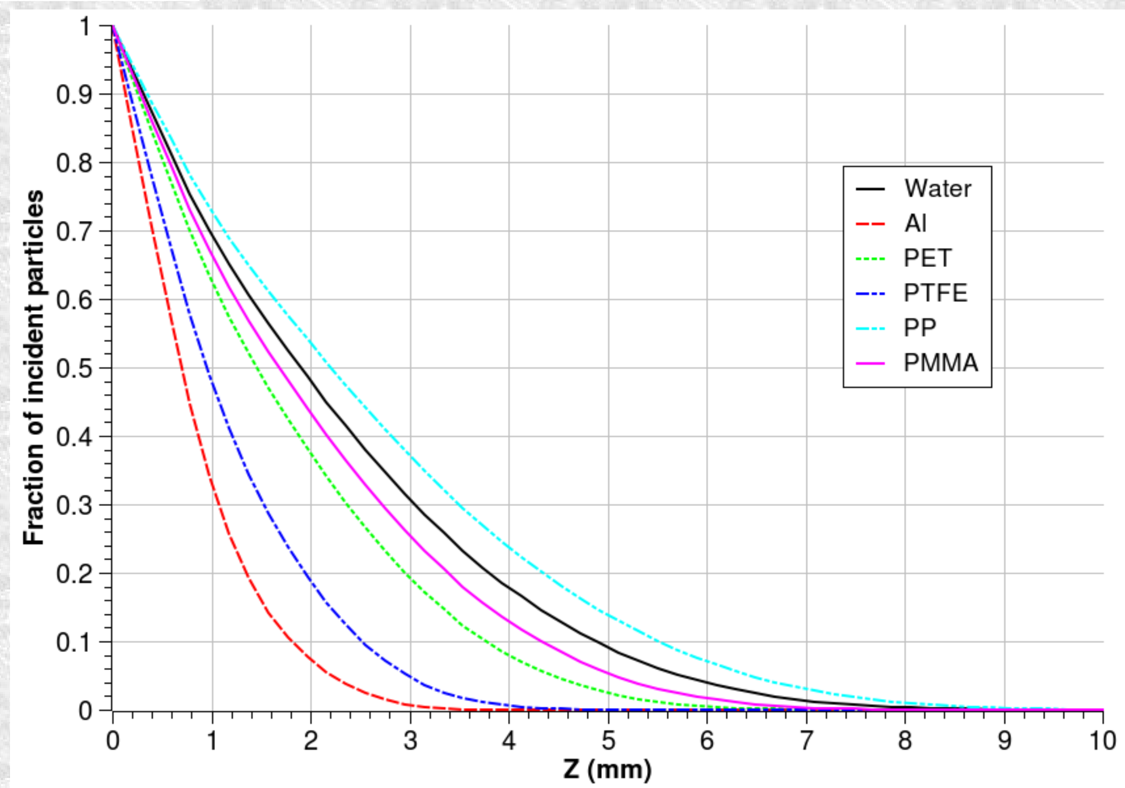


Results for ^{90}Y



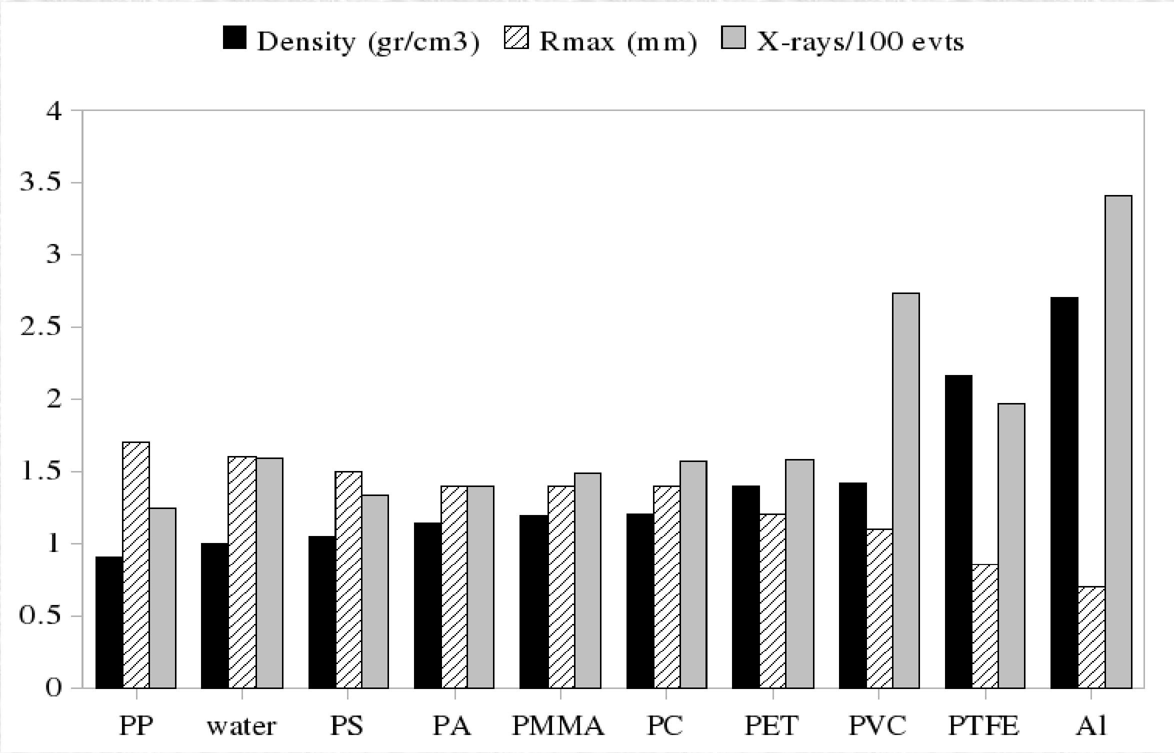
Comparison of maximum ranges and number of X-rays emitted per 100 events

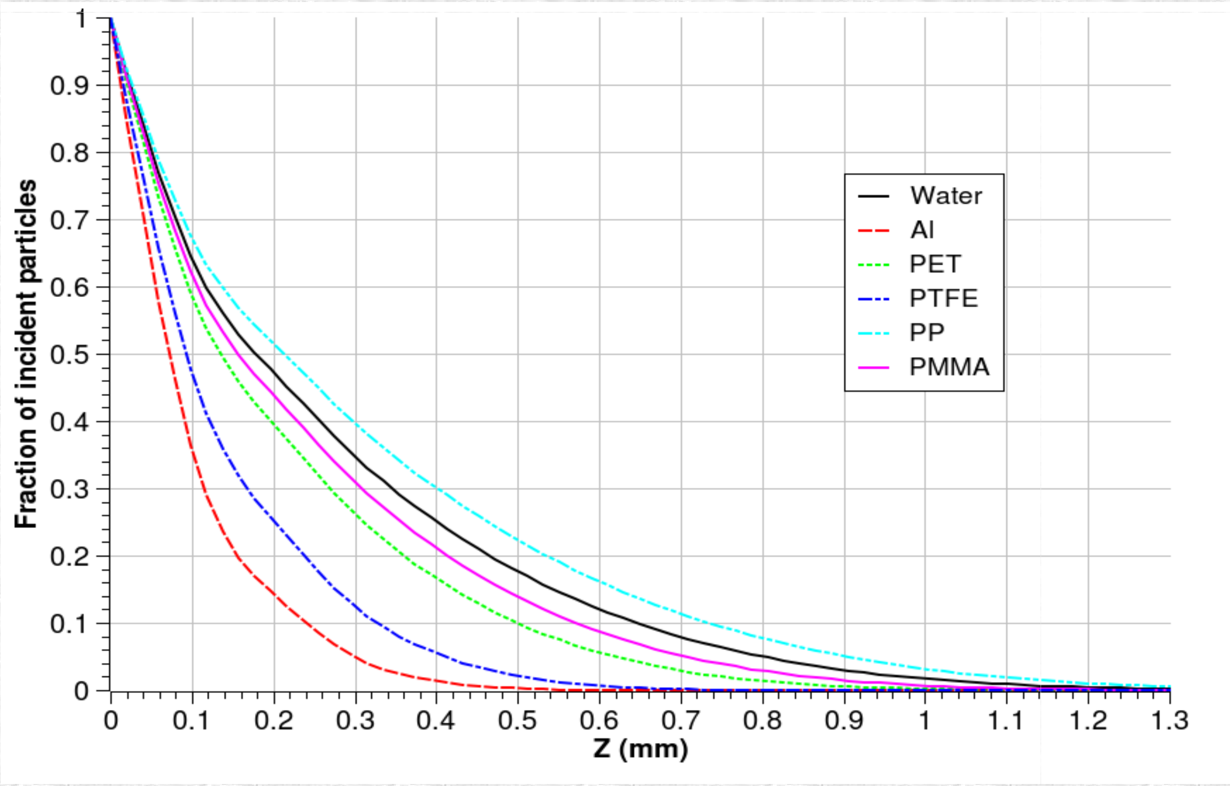
Absorption curves for some relevant materials



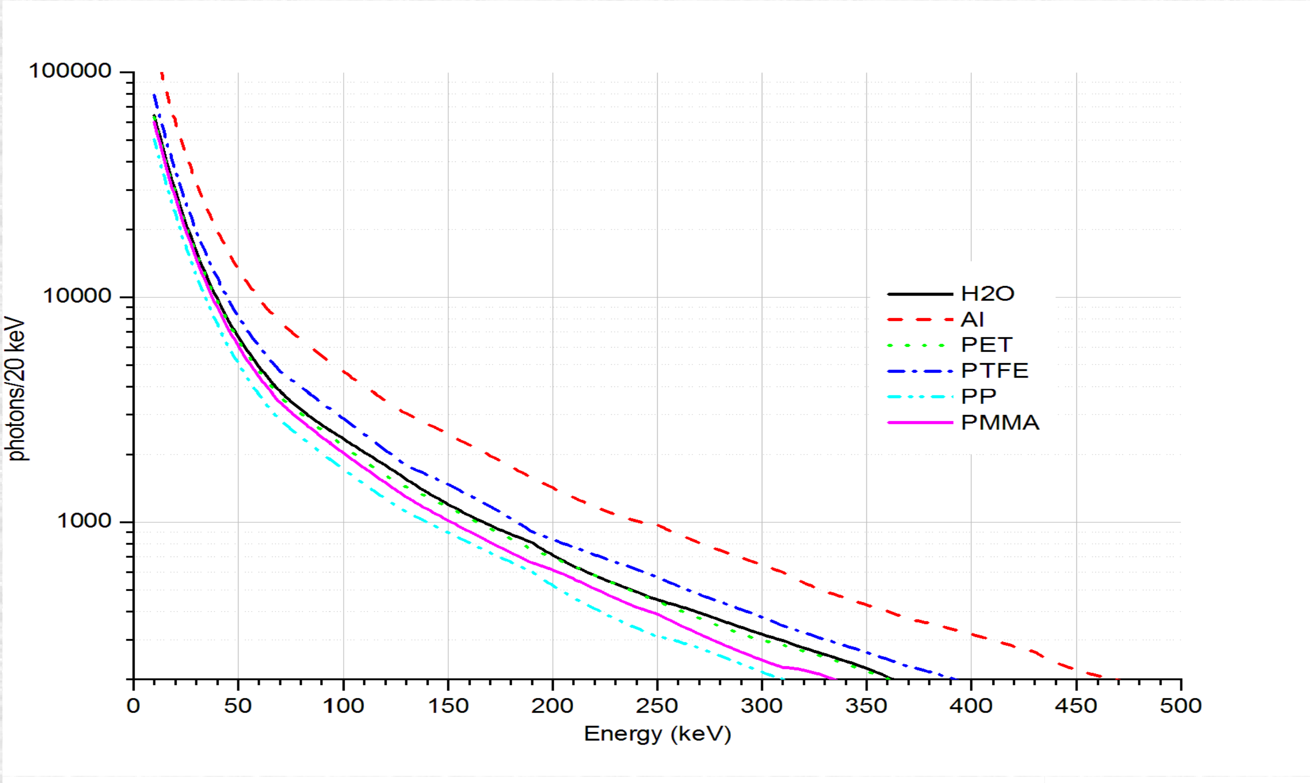
Results for ^{90}Sr

Comparison of maximum ranges and number of X-rays emitted per 100 events



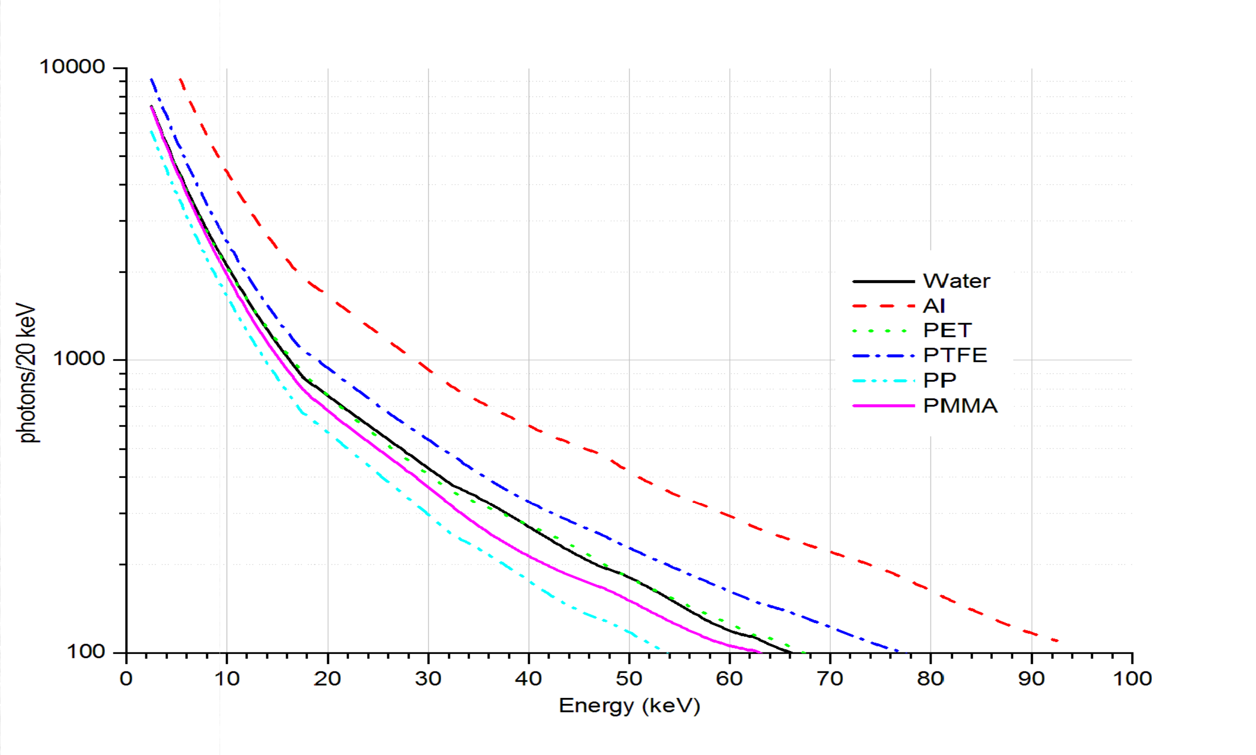


Absorption curves for some relevant materials



Bremsstrahlung emission spectra for ^{90}Y source

Bremsstrahlung emission spectra for ^{90}Sr radioisotope



Summary of ^{90}Y results

The results indicate that ^{90}Y electrons are stopped in 5.2 – 11 mm of material, respectively PTFE and PP.

<E$_X$> ranges between 39.3 keV for PVC and 42.6 KeV for PET.

Values for <dE$_{rad}$/E> are between 0.33% for PP and 0.7% for PVC.

$N_X/10^2$event between 7.72 for PP and 16.55 of the PVC.

Table 4. Average results for a ^{90}Y source.

Material	Formula	Z_{eff}	R_{50} (mm)	R_{max} (mm)	$\langle l \rangle$ (mm)	$\langle \theta \rangle$	$\langle E_X \rangle$ (keV)	$N_X/10^2$ ev.	$\langle dE_{rad}/E \rangle$ (%)
PP	C_3H_6	5.44	2.11	11.0	4.04	1.74	39.8	7.72	0.33
Water	H_2O	7.42	1.83	10.0	3.88	1.95	42.6	9.97	0.45
PS	C_2H_3	5.56	1.85	9.7	3.64	1.77	40.0	8.11	0.35
PA	$C_6H_{11}ON$	6.12	1.70	8.9	3.42	1.83	42.5	8.69	0.40
PMMA	$C_5H_8O_2$	6.47	1.62	8.8	3.34	1.87	40.0	9.14	0.39
PC	$C_{16}H_6O_3$	6.39	1.68	9.0	3.53	1.92	39.7	9.64	0.41
PET	$C_{10}H_8O_4$	6.64	1.42	8.0	2.98	1.92	42.6	9.75	0.44
PVC	C_2H_3Cl	13.86	1.19	7.4	3.07	2.41	39.3	16.55	0.70
PTFE	C_2F_4	8.43	0.97	5.2	2.14	2.15	42.5	12.29	0.56
Al	Al	13	0.74	4.1	1.80	2.60	42.7	20.28	0.93

Summary of ^{90}Sr results

The results indicate that ^{90}Sr electrons are stopped in 0.85 – 1.7 mm of material, respectively PTFE and PP.

$\langle E_X \rangle$ ranges between 14 keV for PP and 16.4 KeV of PTFE.

Values for $\langle dE_{rad}/E \rangle$ are between 0.09% for PP and 0.2% for PVC.

$N_X/10^2$event are between 1.24 for PP and 2.73 for PVC.

Table 3. Average results for a ^{90}Sr source.

Material	Formula	Z_{eff}	R_{50} (mm)	R_{max} (mm)	$\langle l \rangle$ (mm)	$\langle \theta \rangle$	$\langle E_X \rangle$ (keV)	$N_X/10^2$ ev.	$\langle dE_{rad}/E \rangle$ (%)
PP	C_3H_6	5.44	0.22	1.7	0.49	1.81	14.0	1.24	0.09
Water	H_2O	7.42	0.18	1.6	0.47	2.05	15.7	1.59	0.13
PS	C_2H_3	5.56	0.19	1.5	0.44	1.85	14.4	1.34	0.10
PA	$C_6H_{11}ON$	6.12	0.17	1.4	0.41	1.91	15.7	1.40	0.11
PMMA	$C_5H_8O_2$	6.47	0.17	1.4	0.40	1.96	13.8	1.48	0.10
PC	$C_{16}H_6O_3$	6.39	0.17	1.4	0.43	2.01	14.1	1.57	0.11
PET	$C_{10}H_8O_4$	6.64	0.15	1.2	0.36	2.02	16.0	1.58	0.13
PVC	C_2H_3Cl	13.86	0.12	1.1	0.37	2.53	14.1	2.73	0.20
PTFE	C_2F_4	8.43	0.10	0.85	0.26	2.27	16.4	1.97	0.16
Al	Al	13	0.07	0.7	0.22	2.76	17.0	3.41	0.30

Conclusions

PA and **PC**, with similar range and X-ray yield, are valid alternatives to PMMA in realizing low-Z transparent barriers for low- and high-energy β^- emitters.

PP can be privileged when X-rays must be kept at a minimum (15% less than PMMA) even if with a 25% of increase in the maximum range.

PTFE can be a good choice for compact and high-temperature resistant shields, since it provides a 41% shorter maximum range with respect to PMMA, with a 34% of increase of X-ray production yield.
PTFE should be definitively preferred to PVC, apart from its physical properties, because with larger density (2.16 versus 1.42 g/cm^3) achieves 30% reduction in R_{max} together with 26% less X-ray photons. This effect is due to the presence of chlorine in the PVC formula.

Reference

E. Amato and D. Lizio
"Plastic materials as a radiation shield for β^- sources: a comparative study through Monte Carlo calculation"
J. Radiol. Prot. **29** *239-50* (2009)

Thank You!!