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CERN n_TOF Facility:

Waste calculations and dose rate simulations of the n_TOF spallation target

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Abstract

The n_TOF facility, a spallation neutron source, uses a pure lead target for production of neutrons with a proton beam extracted from the Proton Synchrotron (PS) of CERN with an energy of 20 GeV. During operation, since 2001, a steady transfer of radioactive spallation products into the cooling water has been observed. From August 2004 on, this transfer has been accelerated. After more than two years of cooling, the present spallation target is considered as damaged and will be moved to its provisional storage place available in the n_TOF service gallery. A new spallation target shall be constructed and will replace the old one. For the removal and the storage of the lead target, isotope production and dose rate calculations were performed. This report presents in a first part the considered technical layout, pictures of the lead target assembly and the actual implementation in the FLUKA simulation. The second part gives detailed results about the activation of n_TOF target and the surrounding installation. The last part refers to the residual dose rates around the target. All results are given for a representative cooling time referring to September 2007 as well as numerous other decay times ranging from one to 100 years.

CERN, 1211 Geneva 23, Switzerland
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1. Introduction

In 1998, plans were made for a spallation neutron source at the CERN Proton Synchrotron (PS). A proton beam with a momentum of 20 GeV/c hits a production target made from lead and generates neutrons by spallation. The nominal proton intensity is 7×10^{12} in one pulse, and 4 pulses per supercycle of 16.8 s duration i.e. 1.6×10^{12} s^{-1} [1]. In 2004, CERN's Research Board authorized a total of 1.6×10^{19} protons/year for n_TOF. The spallation neutrons emerging from the lead target are moderated by cooling water in contact with the target and then enter the evacuated time-of-flight tube (~ 200 m long) at an angle of 10° to the proton beam direction.

The present spallation target is considered as damaged and has to be removed in order to install a new one. To limit risks of contamination during the removal of the target and also for its storage at PSI, isotope production and residual dose rate simulations were performed by using the Monte Carlo code FLUKA [2] [3].

Several technical designs and pictures taken from the TT2A tunnel were used to verify and update the geometrical existing implementation [4]. For this purpose, existing geometries were combined to obtain a complete geometry of the TT2a tunnel, updating latest details of the target area and the used n_TOF target, as well as the entire layout up to the experimental region 200m downstream.

For the present study however, to characterize the existing target, only the target assembly and a surrounding layer of shielding are taken into account. In order to obtain the characteristic nuclide vector needed for the radioactive waste characterization, all chemical compositions were accounted for in detail, in particular the lead. To obtain a better statistical accuracy, trace elements within the lead were temporarily boosted with a later renormalization of the respective related specific activities. This allowed obtaining a complete inventory of radioactive isotopes produced within lead, in particular good statistics for all alpha emitters.

In this report, the implementation of the target assembly is briefly reviewed in the first part. The second part shows the specific activity of the target and the total activity of each material. Additional results about specific isotopes production are then presented in the third part. In a last part, for a possible intervention scenario, as well as the transport of the target, residual dose rates at the surface and all around the target were simulated.

For all calculations, beam parameters and irradiation history were set to the actual irradiation history of the target, accounting for proper build-up and decay. In the first parts, all results refer to a cooling time of three years after the last radiation, corresponding to September 2007. All results for different cooling times are further collected in the Appendix.

2. The lead target assembly

The spallation target of n_TOF is made of high purity (99.998%) lead shaped as a block of 80 × 80 × 60 cm^3 with a volume of 30 × 55 × 20 cm^3 removed to allow the entry of the proton line (see Figure 1). The target is surrounded by a stainless steel support and immersed in water contained in an aluminum tank. A thin single metallic window made out of aluminum alloy of 1.6 mm thickness represents the interface between the water moderator (thickness 6 cm) and the vacuum tube (see

Figure 2). In the simulation, the z-axis coincides with the beam axis, the y-axis with the vertical axis and the origin set at the center of the lead target.

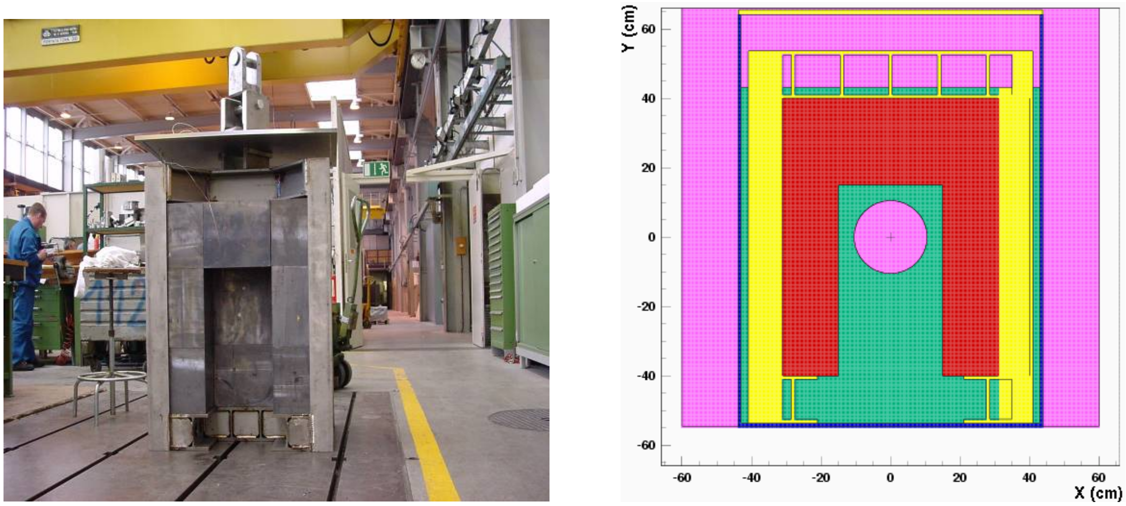

Figure 1: Picture of the n_TOF target assembly [1] (left) and simulation design with FLUKA (right) showing the beam impact in the entrance cavity and the aluminum container with water inside.

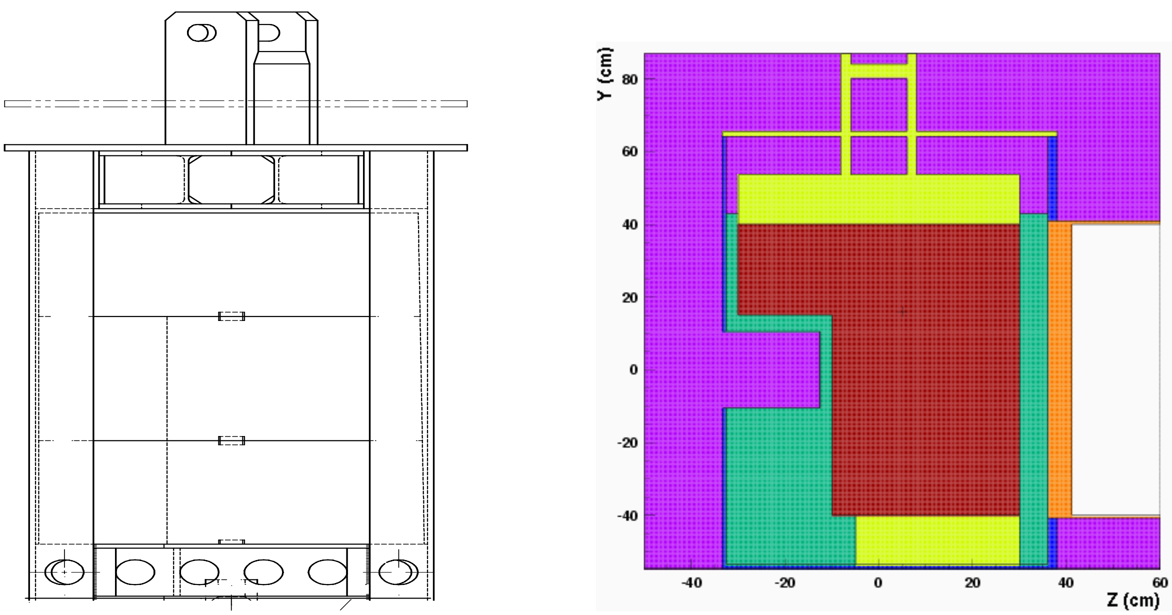

Figure 2: Lead target with its stainless steel support; Side view, proton beam going from left to right. Technical design TOFLTT0012 (left) and simulation design with FLUKA (right) showing also the aluminum container filled with water and the n_TOF tube at right (in white) after the aluminum window (in orange) and the water moderator (in green).

Figure 3: Stainless steel assembly all around the lead target. Front view. Technical design TOFLTT0012 (left), picture and simulation design with FLUKA (right) showing also the aluminum container filled with water.

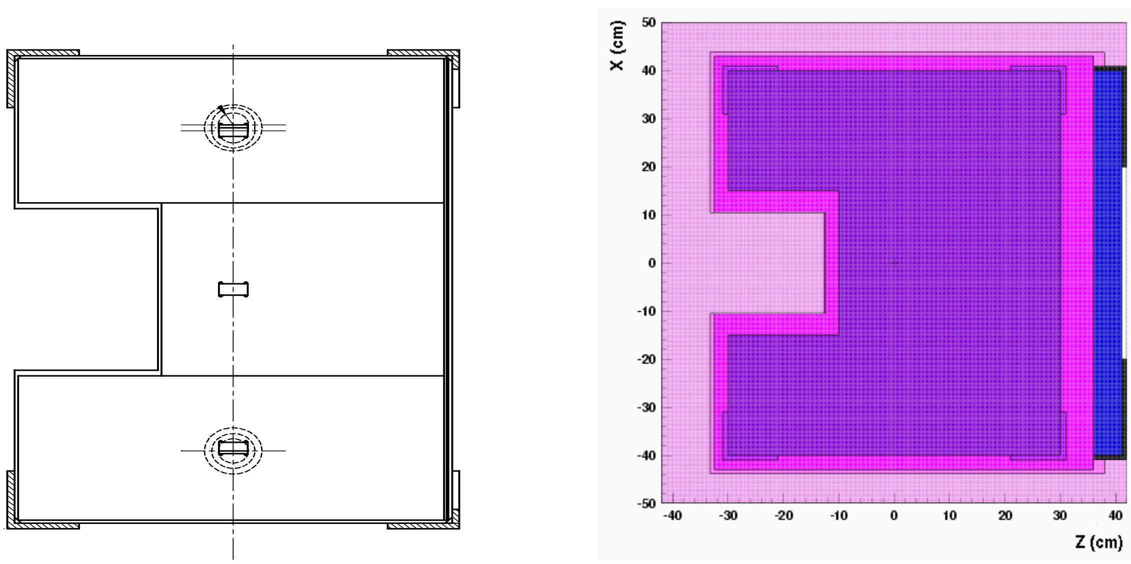

Figure 4: Lead target top view, proton beam going from left to right. Technical design TOFLTT0012 (left) and simulation design with FLUKA (right).

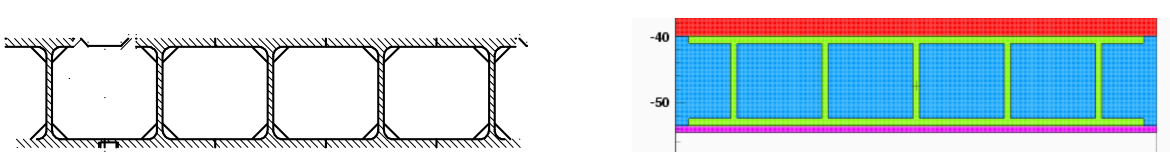

Figure 5: Support in stainless steel. Technical design TOFLTT0010 (left) and simulation design with FLUKA (right).

3. Activation of the target

The proton beam was first extracted from the Proton Synchrotron (PS) in 2000. The main commissioning phase extended throughout 2001. The first nominal operation started in April 2001. All calculated results refer to the same irradiation profile, *i.e.*, 6 months of irradiation from April 2001 until October 2001 followed by 6 months of cooling, continued the same way until October 2004, considering an average beam intensity of 8.4×10^{11} pr/s.

For all calculations of resulting specific activities, the real water quantity and lead volume were considered: *i.e.*, 800 kg of water and 4 000 kg of lead and 400kg for the stainless steel part. For the latter it shall be noted that the technical layouts indicate 400 kg of stainless steel, as compared to the geometry included in FLUKA referring to approximately 330 kg of stainless steel.

For the performed simulation and the respective chemical composition of lead the following cases were considered:

- lead composition with elements described in table 1 [1] and taking into account all impurities;
- a modified lead composition to compare the results with those done by NAGRA, i.e., by including thorium and uranium;
- for both cases, boosting the impurities by three orders of magnitudes, i.e., enhancing the statistical significance without significantly influencing the particle fluence spectra, however properly renormalizing the respective production of single important isotopes.

Element	**Concentration** (ppmw)	**Error Spread** (ppmw)	**Systematic Error** (ppmw)	**Total Error** (ppmw)
Na	0.006	0.007	0.0001	0.0075
Mg	0.003	0.005	0.0006	0.005
Al	0.02	0.01	0.004	0.01
Cu	0.09	0.2	0.01	0.2
Ag	3.78	0.6	0.07	0.6
Cd	0.09	0.04	0.006	0.045
Te	0.215	0.09	0.025	0.09
Sb	0.14	0.14	0.006	0.14
Tl	4.6	1.3	0.3	1.4
Bi	19.0	2.8	0.3	2.8
Au	0.0009	0.0002	0.00035	0.0004

Table 1: Summary of measured impurity concentrations for manufactured lead blocks. The systematic error is the error quoted by the laboratory, which performed the measurement; the third column shows the spread between all measurements of a given sample. The total error is the quadratic sum of the two contributions [1].

In a first step, the concentration of bismuth is increased by a factor 1000 as compared to the original lead being only 19 ppmw. In a second step, in order to be able to compare the nuclide vector with calculation performed by NAGRA, in particular alpha emitting radionuclides, thorium and uranium of 1 ppm each were added in lead chemical composition and then boosted like for bismuth by a factor 1000. The aim of this method is to get a complete list of the heavy nuclides specific activities within lead with good statistics even for those radio-isotopes being produced from trace elements. In the following, all results are properly renormalized, compensating the original boost factor.

The support around the target is made out of stainless steel as well as the shielding structure around being essentially made up of marble and concrete. Tables 2, 3 and 4 show the chemical composition as used in the FLUKA simulation. Without detailed specifications, we assume a concentration of 0.01 % of cobalt within stainless steel. This value is motivated by similar stainless steel being used at CERN, as well as confirmed by a dedicated simulation and measurement of residual dose rates performed close to the stainless steel cover. Assuming 0.01% of cobalt resulted in a good agreement between the radioprotection measurements performed in June 2006 and the respective FLUKA simulations [5].

Element	**Concentration (%)**
Ca	20
C	20
O	60

Table 2: Marble composition in mass fraction.

Element	**Concentration (%)**
H	1
C	0.1
O	52.9
Na	1.6
Mg	0.2
Al	3.4
Si	33.7
K	1.3
Ca	4.4
Fe	1.4

Table 3: Concrete composition in mass fraction.

Element	**Concentration (%)**
Fe	64.385
Cr	20
Ni	12.5
C	0.03
Si	1

Mn	2
P	0.045
S	0.03
Co	0.01

Table 4: Stainless steel composition in mass fraction.

A representation of the geometry with the different used materials is given in figure 6.

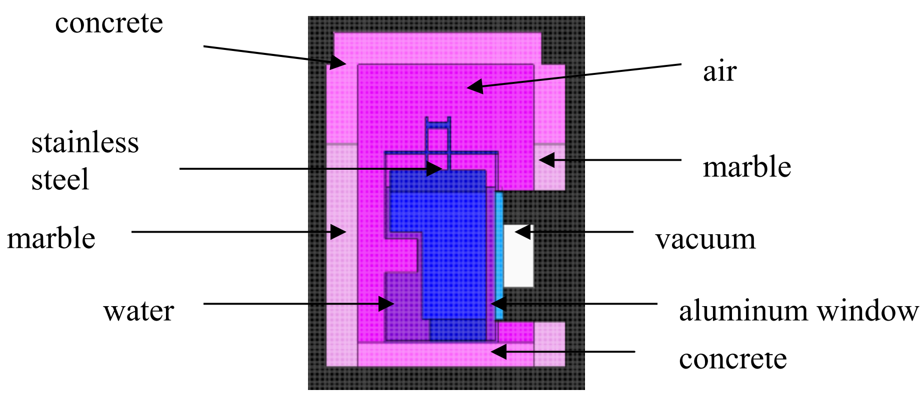

Figure 6: Description of the different materials around the lead target. Side view.

For the nuclide vector simulations only the target zone with a thin thickness of shielding around (~20 cm) was considered, stopping the particle cascade further out (see Figure 7). This allows getting better statistics in those components one is interested in, without loosing calculation time following the cascade in parts of the geometry not leading to a significant contribution or change of the nuclide vector of the target assembly.

To study the evolution of the nuclide vector in terms of time after the last irradiation, several cooling times were chosen:

- 1 year 8 month (May 2006),
- 3 years (September 2007),
- 3 years 8 months (May 2008),
- 10 years (September 2014),
- and 100 years (September 2104).

All results presented in the following refer to the cooling time of three years (*i.e.*, September 2007), whereas all additional results are collected in the Appendix of this report.

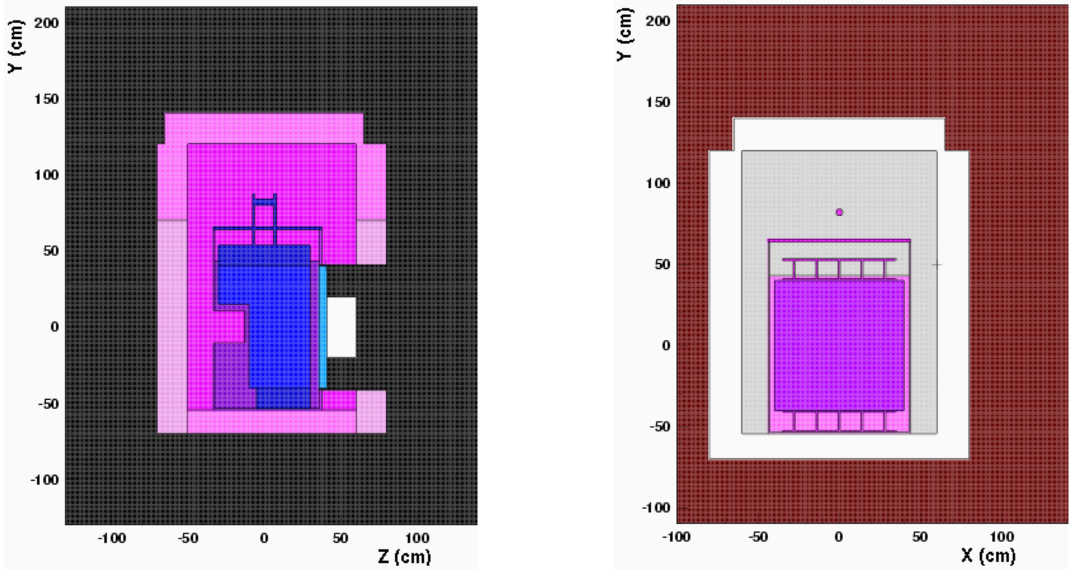

Figure 7: Simulation with FLUKA of the target zone with black hole around. Side view (left) proton beam going from left to right, and front view (right).

To visualize the distribution of the isotope production inside the lead target, Figure 8 shows the average specific activity (Bq/g), after 3 years of cooling, averaged over 10 cm thickness. The respective regions refer to the central target lead, the water container and stainless steel hook in contact with air, both at two different projections: projection on x-axis for the side view and projection on z-axis for the front view.

Furthermore, the average specific activity of the marble shielding (20 cm thickness) in front and behind the target and concrete all around is also visible for the first 20 cm lateral thickness.

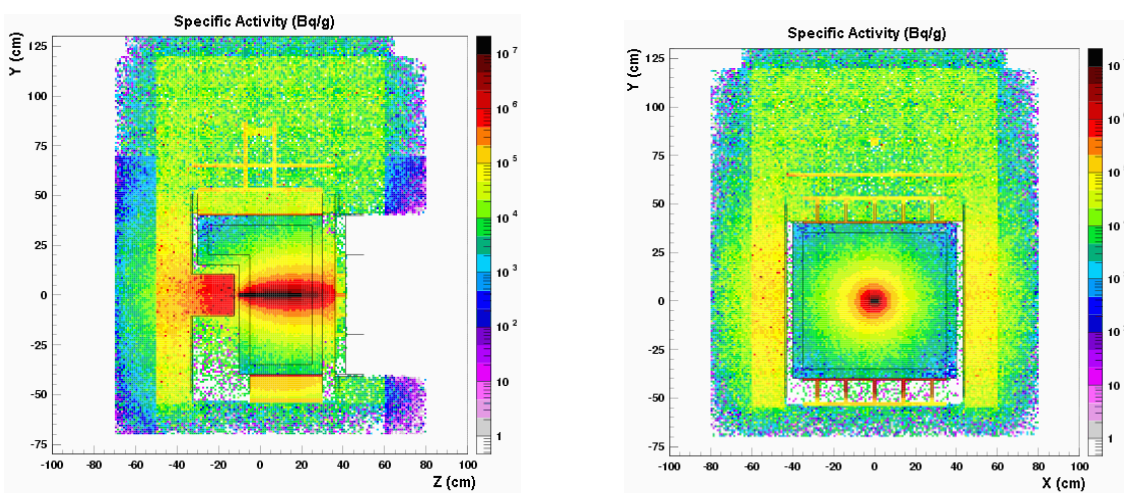

Figure 8: Specific Activity in Bq/g after a cooling time of ***3 years*** *(**September 2007**). Side view (left) and front view (right).*

The following graph shows the total activity (Bq) evolution in time for the lead, stainless steel, cooling water, concrete and marble. It can be noticed that from 3 to 10 years of cooling the lead total activity is reduced by a factor of two, as well as for the stainless steel part by a factor of four.

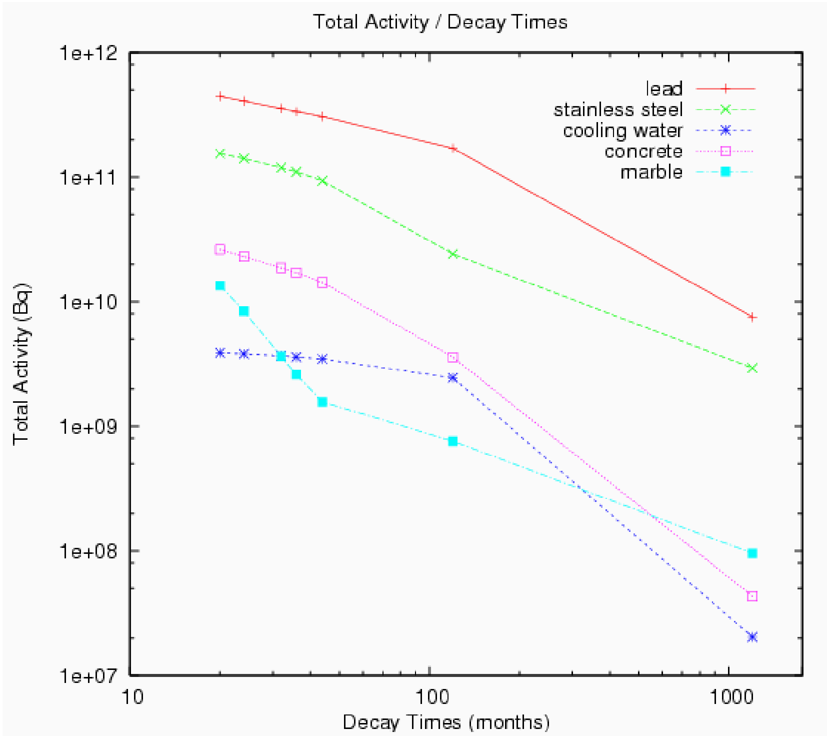

Figure 9: Graph showing the total activity (Bq) in lead, stainless steel, water, concrete and marble as a function of cooling time.

In Figure 8 it can be furthermore noticed that the specific activity in the air and water around the target remains constant after a long cooling time, and seems to remain higher in the marble shielding in front of the target as compared to the adjacent concrete parts. This is due to the fact of specific isotopes produced in the respective materials and is explained in more details at the end of the following section.

4. Isotopes production

This section lists the nuclide vector for the different components, i.e., the specific activities of the isotopes being produced in lead, stainless steel, water, marble and concrete. In addition, the results are also given in terms of the respective exemption limit (L_E) according to Swiss legislation [6, 7]. In this terms, components are considered wastes if the activity concentration (specific activity) *a* of an isotope exceeds the exemption limit L_E and the total activity *A* of that isotope exceeds 100 L_E.

The values of L_E are defined isotope-specifically [6, 7]. In case of components containing a multitude of isotopes, they must furthermore fulfill the following conditions:

(1) $\sum_i \frac{\text{ai}}{\text{LEi}} > 1$ *$a_{i:}$ specific activities of nuclides i: 1, 2,..., n in Bq/g*

$LE_{i:}$ exemption limits of nuclides i: 1, 2,..., n in Bq/g [6, 7]

(2) $\sum_i \frac{\text{Ai}}{\text{LEi}} > 100$ *$A_{i:}$ total activities of nuclides i: 1, 2,..., n in Bq/g*

Table 5 compares the activity concentration *a* and total activity *A* of (non-alpha emitting) isotopes within the **lead** of the n_TOF target assembly, **3 years** after the last radiation corresponding to **September 2007**. Because of the important number of produced isotopes, the table only lists isotopes with a specific activity being superior to 5 L_E equivalents.

For the same cooling time, thanks to this method, Table 6 in turn lists all alpha emitting radionuclides within lead classified by multiple of L_E. Results for all other cooling times are listed in the Appendix.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{204}Tl	1.19E+08	2.27E+04	0.14	8.00	**2841.17**	9.05E+10	1.13E+08
^{194}Hg	1.40E+10	3.02E+02	0.10	0.20	**1509.07**	1.20E+09	6.01E+07
^{60}Co	1.66E+08	3.21E+02	0.54	1.00	**320.53**	1.28E+09	1.28E+07
^{3}H	3.89E+08	5.48E+04	0.06	200.00	**274.25**	2.18E+11	1.09E+07
^{207}Bi	1.04E+09	1.82E+03	0.14	8.00	**227.32**	7.24E+09	9.05E+06
^{172}Lu	5.79E+05	1.29E+03	0.44	8.00	**160.86**	5.12E+09	6.40E+06
^{172}Hf	5.90E+07	1.27E+03	0.44	10.00	**127.42**	5.07E+09	5.07E+06
^{90}Sr	9.12E+08	1.91E+01	1.72	0.40	**47.66**	7.59E+07	1.90E+06
^{195}Au	1.61E+07	1.56E+03	0.12	40.00	**39.07**	6.22E+09	1.56E+06
^{109}Cd	3.99E+07	1.54E+02	0.65	5.00	**30.79**	6.13E+08	1.23E+06
^{173}Lu	4.32E+07	1.01E+03	0.27	40.00	**25.22**	4.02E+09	1.00E+06
^{65}Zn	2.11E+07	6.28E+01	0.76	3.00	**20.93**	2.50E+08	8.33E+05
^{202}Pb	1.66E+12	1.58E+01	0.06	1.00	**15.84**	6.31E+07	6.31E+05
^{194}Au	1.37E+05	3.02E+02	0.10	20.00	**15.09**	1.20E+09	6.01E+05
^{101}Rh	1.04E+08	2.72E+02	0.81	20.00	**13.60**	1.08E+09	5.42E+05
^{54}Mn	2.70E+07	1.27E+02	0.57	10.00	**12.75**	5.08E+08	5.08E+05
^{193}Pt	1.58E+09	3.48E+03	0.07	300.00	**11.60**	1.39E+10	4.62E+05
^{179}Ta	5.74E+07	2.02E+03	0.29	200.00	**10.08**	8.03E+09	4.01E+05
^{5}5Fe	8.64E+07	2.76E+02	0.91	30.00	**9.20**	1.10E+09	3.66E+05
^{106}Ru	3.23E+07	9.19E+00	2.98	1.00	**9.19**	3.66E+07	3.66E+05
^{106}Rh	2.98E+01	9.19E+00	2.98	1.00	**9.19**	3.66E+07	3.66E+05
^{133}Ba	3.32E+08	6.11E+01	1.14	10.00	**6.11**	2.43E+08	2.43E+05
^{134}Cs	6.52E+07	2.97E+00	6.62	0.50	**5.94**	1.18E+07	2.37E+05
TOTAL		**9.19E+04**				**3.70E+11**	

*Table 5: List of (non-alpha emitting) radioactive isotopes within **lead**, **3 years** (**September 2007**) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	2.95E+01	1.06	0.20	**147.42**	1.17E+08	5.87E+06
^{208}Po	9.15E+07	6.97E-02	1.31	0.01	**6.97**	2.77E+05	2.77E+05
^{210}Po	1.20E+07	8.10E-02	0.07	0.04	**2.02**	3.22E+05	8.06E+04
^{145}Pm	5.59E+08	7.32E+01	0.82	90.00	**0.81**	2.92E+08	3.24E+04
^{209}Po	3.22E+09	1.04E-03	2.95	0.01	**0.10**	4.16E+03	4.16E+03
^{151}Gd	1.07E+07	3.13E+00	0.41	50.00	**0.06**	1.25E+07	2.49E+03
^{146}Sm	3.25E+15	1.99E-05	0.83	0.20	**0.00**	7.92E+01	3.96E+00
^{148}Eu	4.71E+06	2.97E-05	6.04	8.00	**0.00**	1.18E+02	1.48E-01
^{190}Pt	2.05E+19	1.35E-07	0.09	1.00	**0.00**	5.36E-01	5.36E-03
^{147}Sm	3.35E+18	1.75E-08	0.80	0.20	**0.00**	6.98E-02	3.49E-03
^{152}Gd	3.41E+21	1.87E-11	0.76	0.20	**0.00**	7.46E-05	3.73E-06
^{147}Eu	2.08E+06	1.54E-11	0.68	20.00	**0.00**	6.15E-05	3.07E-08
^{188}Pt	8.81E+05	5.57E-29	0.17	10.00	**0.00**	2.22E-22	2.22E-25
^{149}Gd	8.02E+05	2.56E-33	0.83	20.00	**0.00**	1.02E-26	5.11E-30
^{206}Po	7.60E+05	4.86E-39	1.57	0.08	**0.00**	1.94E-32	2.42E-33
^{154}Dy	9.47E+13	8.92E-04	0.49	0.00	**0.00**	3.55E+03	0.00E+00
^{150}Gd	5.65E+13	1.04E-03	0.86	0.00	**0.00**	4.15E+03	0.00E+00
TOTAL		**1.06E+02**				**4.22E+08**	

Table 6: List of all alpha-emitting radionuclides within ***lead*****,** ***3 years (September 2007)*** *after the last radiation.*

In Switzerland, typical standard lead contains a certain fraction of uranium and thorium, not being detected in the uncertainties of the chemical analysis of the n_TOF lead target. However, since previous preliminary NAGRA studies [8] for conservative purposes used such a chemical composition for lead, in a second step Uranium and Thorium were added to the chemical composition of lead and results are compared in the following.

Including the contributions coming from Uranium and Thorium, Table 7 shows the complete list of the alpha emitting radionuclides produced within **lead, 3 years** after the last radiation corresponding to **September 2007**. Please note that the Appendix contains all complete lists of alpha emitting radionuclides produced within lead for all considered cooling times. It can be seen that this leads to an increase of about a factor of four in the total specific activity of alpha emitters.

In Switzerland all is defined as "Low and Intermediate radioactive waste" what is not spent fuel and alphatoxic waste (ATA). In this context, waste is considered as ATA when the alpha inventory exceeds 20.000 Bq/g [9]. As can be seen in Tables 6 and 7, both considered cases show clearly lower activation levels, thus confirming the fact that the n_ToF target doesn't fall into the ATA category.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	8.33E+01	0.44	0.20	**416.30**	3.32E+08	1.66E+07
^{202}Pb	1.66E+12	1.63E+01	0.12	1.00	**16.30**	6.49E+07	6.49E+05
^{208}Po	9.15E+07	7.20E-02	1.77	0.01	**7.20**	2.87E+05	2.87E+05
^{145}Pm	5.59E+08	3.05E+02	0.62	90.00	**3.39**	1.22E+09	1.35E+05
^{210}Po	1.20E+07	9.23E-02	0.32	0.04	**2.31**	3.68E+05	9.19E+04
^{210}Pb	7.01E+08	1.31E-02	1.94	0.01	**1.31**	5.23E+04	5.23E+04
^{239}Pu	7.61E+11	4.08E-02	0.10	0.04	**1.02**	1.63E+05	4.06E+04
^{228}Th	6.03E+07	9.15E-02	1.29	0.10	**0.91**	3.64E+05	3.64E+04
^{227}Ac	6.87E+08	7.45E-03	4.90	0.01	**0.83**	2.97E+04	3.30E+04
^{224}Ra	3.14E+05	9.20E-02	1.29	0.20	**0.46**	3.66E+05	1.83E+04
^{151}Gd	1.07E+07	8.69E+00	0.35	50.00	**0.17**	3.46E+07	6.92E+03
^{209}Po	3.22E+09	1.55E-03	3.05	0.01	**0.16**	6.18E+03	6.18E+03
^{223}Ra	9.88E+05	7.48E-03	4.90	0.10	**0.07**	2.98E+04	2.98E+03
^{232}U	2.17E+09	1.41E-03	4.49	0.03	**0.05**	5.61E+03	1.87E+03
^{233}U	5.02E+12	4.39E-03	0.13	0.20	**0.02**	1.75E+04	8.74E+02
^{231}Pa	1.03E+12	1.45E-04	0.62	0.01	**0.01**	5.79E+02	5.79E+02
^{229}Th	2.32E+11	1.72E-04	1.35	0.02	**0.01**	6.87E+02	3.43E+02
^{227}Th	1.61E+06	7.36E-03	4.90	1.00	**0.01**	2.93E+04	2.93E+02
^{236}Pu	9.02E+07	2.75E-04	12.06	0.10	**0.00**	1.10E+03	1.10E+02
^{212}Bi	3.63E+03	9.20E-02	1.29	40.00	**0.00**	3.66E+05	9.16E+01
^{210}Bi	4.33E+05	1.32E-02	1.94	8.00	**0.00**	5.24E+04	6.55E+01
^{212}Po	4.51E+01	5.89E-02	1.29	40.00	**0.00**	2.35E+05	5.87E+01
^{238}Pu	2.77E+09	3.95E-05	25.00	0.04	**0.00**	1.57E+02	3.93E+01
^{226}Ra	5.05E+10	2.90E-05	5.08	0.04	**0.00**	1.15E+02	2.89E+01
^{230}Th	2.38E+12	3.11E-05	0.43	0.05	**0.00**	1.24E+02	2.48E+01
^{225}Ac	8.64E+05	1.72E-04	1.35	0.40	**0.00**	6.86E+02	1.72E+01
^{211}Bi	1.28E+02	7.48E-03	4.90	60.00	**0.00**	2.98E+04	4.96E+00
^{223}Fr	1.32E+03	1.03E-04	4.90	4.00	**0.00**	4.09E+02	1.02E+00
^{237}Np	6.77E+13	1.74E-06	0.51	0.09	**0.00**	6.93E+00	7.70E-01
^{234}U	7.75E+12	1.93E-06	2.62	0.20	**0.00**	7.67E+00	3.83E-01
^{213}Bi	2.74E+03	1.72E-04	1.35	50.00	**0.00**	6.86E+02	1.37E-01
TOTAL		**4.14E+02**				**1.65E+09**	

Table 7: List of all the alpha emitting radionuclides within ***lead*****, 3 years (September 2007)** *after the last radiation.*

Considering the remaining target components, Table 8 compare the activity concentration *a* and total activity *A* of isotopes within **stainless steel** with these limits, **3 years** after the last radiation corresponding to **September 2007**. Additional cooling times are listed in the Appendix.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 330 kg	Multiple of 100 L_E
^{60}Co	1.66E+08	1.31E+04	1.49	1	**13149.27**	4.31E+09	4.31E+07
^{55}Fe	8.64E+07	3.00E+05	0.18	30	**9996.44**	9.82E+10	3.27E+07
^{54}Mn	2.70E+07	2.99E+03	0.63	10	**298.72**	9.79E+08	9.79E+05
^{63}Ni	3.16E+09	1.73E+04	0.15	70	**247.27**	5.67E+09	8.10E+05
^{57}Co	2.35E+07	7.65E+02	0.58	50	**15.29**	2.51E+08	5.01E+04
^{22}Na	8.21E+07	1.95E+01	12.34	3	**6.49**	6.37E+06	2.12E+04
^{3}H	3.89E+08	6.30E+02	2.04	200	**3.15**	2.06E+08	1.03E+04
^{44}Ti	1.89E+09	5.29E+00	9.89	2	**2.65**	1.73E+06	8.67E+03
^{49}V	2.84E+07	1.11E+03	0.66	600	**1.85**	3.63E+08	6.04E+03
^{59}Ni	2.40E+12	1.46E+02	0.08	200	**0.73**	4.78E+07	2.39E+03
^{45}Ca	1.41E+07	1.95E+00	7.84	10	**0.19**	6.37E+05	6.37E+02
^{44}Sc	1.43E+04	5.29E+00	9.89	30	**0.18**	1.73E+06	5.78E+02
^{58}Co	6.12E+06	7.23E-01	0.37	10	**0.07**	2.37E+05	2.37E+02
^{56}Co	6.67E+06	2.17E-01	2.49	4	**0.05**	7.10E+04	1.78E+02
^{42}K	4.44E+04	5.86E-01	50.92	20	**0.03**	1.92E+05	9.61E+01
^{32}P	1.23E+06	1.01E-01	33.33	4	**0.03**	3.32E+04	8.31E+01
^{46}Sc	7.24E+06	1.64E-01	2.96	7	**0.02**	5.39E+04	7.70E+01
^{32}Si	4.83E+09	1.01E-01	33.33	20	**0.01**	3.32E+04	1.66E+01
^{35}S	7.56E+06	1.97E-02	6.10	10	**0.00**	6.46E+03	6.46E+00
^{14}C	1.80E+11	1.49E-02	23.41	20	**0.00**	4.88E+03	2.44E+00
^{59}Fe	3.84E+06	1.54E-03	0.71	6	**0.00**	5.04E+02	8.39E-01
^{41}Ca	3.22E+12	5.28E-03	7.03	30	**0.00**	1.73E+03	5.77E-01
^{26}Al	2.26E+13	4.59E-04	5.38	3	**0.00**	1.50E+02	5.01E-01
^{60}Fe	4.73E+13	9.48E-06	40.82	0	**0.00**	3.11E+00	3.45E-01
^{36}Cl	9.50E+12	8.86E-04	11.97	10	**0.00**	2.90E+02	2.90E-01
^{53}Mn	1.18E+14	1.65E-02	0.61	300	**0.00**	5.41E+03	1.80E-01
^{10}Be	4.77E+13	4.95E-05	19.38	9	**0.00**	1.62E+01	1.80E-02
^{40}K	3.94E+16	5.43E-07	9.12	2	**0.00**	1.78E-01	8.90E-04
^{7}Be	4.60E+06	4.66E-05	8.33	400	**0.00**	1.53E+01	3.82E-04
^{51}Cr	2.39E+06	2.33E-06	0.15	300	**0.00**	7.65E-01	2.55E-05
^{33}P	2.19E+06	2.78E-12	16.10	40	**0.00**	9.09E-07	2.27E-10
^{48}V	1.38E+06	5.84E-18	1.70	5	**0.00**	1.91E-12	3.82E-15
TOTAL		**3.36E+05**				**1.10E+11**	

Table 8: List of radioactive isotopes within ***stainless steel*, *3 years (September 2007)*** *after the last radiation.*

Table 9 compare the activity concentration *a* and total activity *A* of isotopes within **cooling water** with these limits, **3 years** after the last radiation corresponding to **September 2007**. Additional cooling times are listed in the Appendix.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 800 kg	Multiple of 100 L_E
^{3}H	3.89E+08	4.51E+03	0.40	200.00	**22.53**	3.61E+09	1.80E+05
^{14}C	1.80E+11	6.23E+00	0.29	20.00	**0.31**	4.99E+06	2.49E+03
^{10}Be	4.77E+13	7.85E-03	0.66	9.00	**0.00**	6.28E+03	6.98E+00
^{7}Be	4.60E+06	6.26E-03	0.98	400.00	**0.00**	5.01E+03	1.30E-01
TOTAL		**4.51E+03**				**3.61E+09**	

Table 9: List of radioactive isotopes within ***cooling water*****,** ***3 years*** ***(September 2007)*** *after the last radiation.*

For a better visualization of the isotope distribution in terms of the exemption limit, Figure 10 shows the average specific activity in multiple of L_E allocated in 10 cm thickness (average) of lead, water container and stainless steel in contact with air. One can also see the average specific activity in multiple of L_E of marble shielding in front and behind the target and the concrete all around being visible for the first 20 cm thickness. The results refer to a cooling time of **3 years** after the last radiation corresponding to **September 2007**. For all others cooling times, please refer to the Appendix of this document.

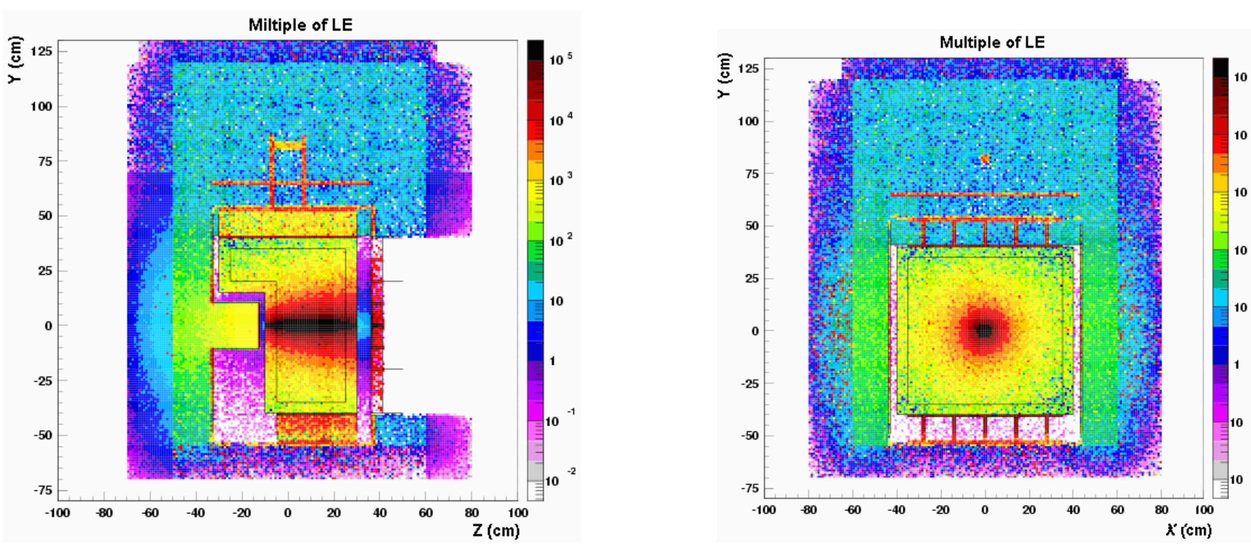

Figure 10: Specific Activity in Multiple of LE after a cooling time of ***3 years (September 2007)****. Side view (left) and front view (right).*

As already observed before, the specific activity of the air is high due to the presence of the isotope ^{14}C which has a long half life time equal to 1.8×10^{11} s. This is due to the fact that for the simulation no exchange of air or water is assumed. For a more complete understanding the list of isotopes produced within air volume are presented in the Appendix for several cooling times.

Furthermore, to study the slightly higher remaining specific activity in marble as compared to the adjacent concrete, Tables 10 and 11 show the radioactive isotopes being produced within **marble 1 year 8 months** and **3 years** after the last radiation. Isotopes are again classified by multiple of L_E and limited to those with a multiple of L_E being superior to 0.01. For completeness, all other cooling times are listed in the Appendix.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 1842 kg	Multiple of 100 L_E
^{45}Ca	1.41E+07	6.69E+03	0.11	10.00	**668.59**	1.23E+10	1.23E+07
^{22}Na	8.21E+07	1.04E+01	5.07	3.00	**3.46**	1.91E+07	6.36E+04
^{3}H	3.89E+08	5.72E+02	0.25	200.00	**2.86**	1.05E+09	5.26E+04
^{41}Ca	3.22E+12	3.90E+01	0.13	30.00	**1.30**	7.18E+07	2.39E+04
^{35}S	7.56E+06	2.05E+00	1.46	10.00	**0.21**	3.78E+06	3.78E+03
^{14}C	1.80E+11	5.96E-01	0.49	20.00	**0.03**	1.10E+06	5.49E+02
^{42}K	4.44E+04	3.68E-01	8.16	20.00	**0.02**	6.77E+05	3.38E+02
^{32}P	1.23E+06	3.91E-02	14.60	4.00	**0.01**	7.20E+04	1.80E+02
TOTAL		**7.32E+03**				**1.35E+10**	

Table 10: List of radioactive isotopes within ***marble*****,** ***1 year 8 months*** *(**May 2006**) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 1842 kg	Multiple of 100 L_E
^{45}Ca	1.41E+07	8.20E+02	0.11	10.00	**81.96**	1.51E+09	1.51E+06
^{3}H	3.89E+08	5.30E+02	0.25	200.00	**2.65**	9.75E+08	4.88E+04
^{22}Na	8.21E+07	7.22E+00	5.07	3.00	**2.41**	1.33E+07	4.43E+04
^{41}Ca	3.22E+12	3.90E+01	0.13	30.00	**1.30**	7.18E+07	2.39E+04
^{14}C	1.80E+11	5.96E-01	0.49	20.00	**0.03**	1.10E+06	5.49E+02
^{42}K	4.44E+04	3.57E-01	8.16	20.00	**0.02**	6.58E+05	3.29E+02
^{32}P	1.23E+06	3.89E-02	14.60	4.00	**0.01**	7.16E+04	1.79E+02
TOTAL		**1.41E+03**				**2.60E+09**	

Table 11: List of radioactive isotopes within ***marble*****,** ***3 years*** *(**September 2007**) after the last radiation.*

It can be noticed that presence of isotope ^{45}Ca is dominant 1 year 8 months and 3 years after the last radiation and significantly higher as in the adjacent concrete (see also *e.g.*, Table 12). The lateral distribution in the marble layer is further visualized in Figure 11 showing the ^{45}Ca distribution in terms of multiple of L_E within the marble block in front of the target, averaging over 20 cm thickness, in this case for a cooling time of 1 year and 8 months after the last radiation.

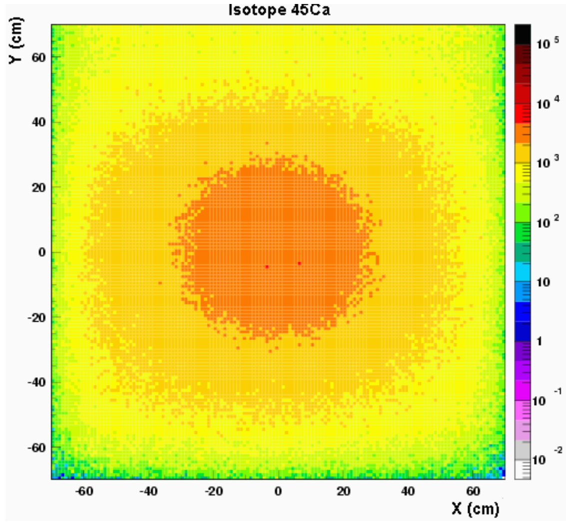

*Figure 11: Specific Activity in Multiple of LE for the isotope ^{45}C within **marble** after a cooling time of **1 year 8 months** (**May 2006**). Front view.*

For even longer cooling times the same behavior can be observed due to the presence of the ^{41}Ca having a long half life time equal to 3.22×10^{12} s. To better visualize the difference of ^{41}Ca being produced within the two blocks of marble in front and behind the target, as well as the adjacent concrete shielding, Figure 12 shows the distribution of the respective specific activity, in this case for a cooling time of **100 years** after the last radiation.

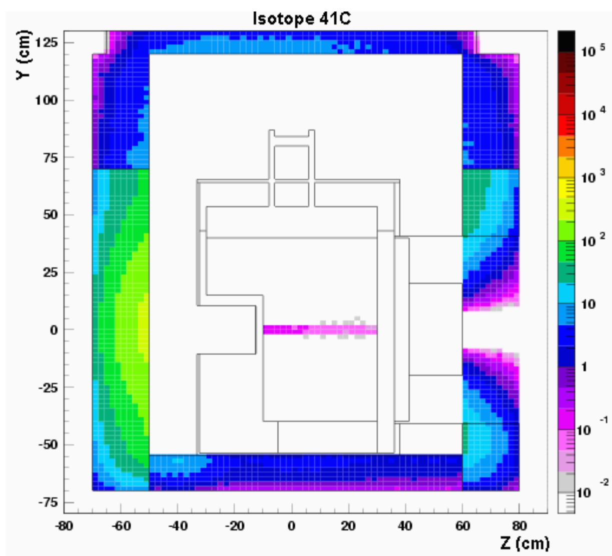

*Figure 12: Specific Activity in Multiple of LE for the isotope ^{41}C within **marble** after a cooling time of **100 years** (**September 2104**). Side view.*

In terms of cooling times, Figure 13 shows the evolution in time of the most abundant isotopes and their specific activity and multiple of L_E in the marble shielding.

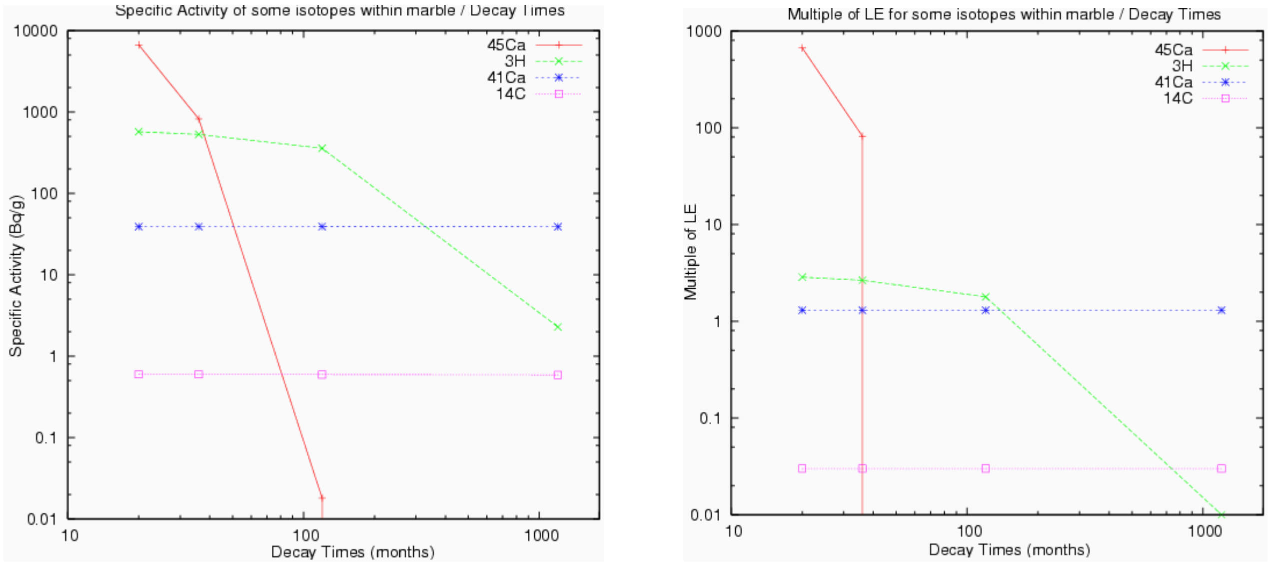

Figure 13: Graphs showing evolution in time of some principal isotopes within ***marble****. Specific activity (left) and multiple of LE (right).*

The following graphs show the evolution in time of the most abundant isotopes and their specific activity and multiple of L_E within concrete.

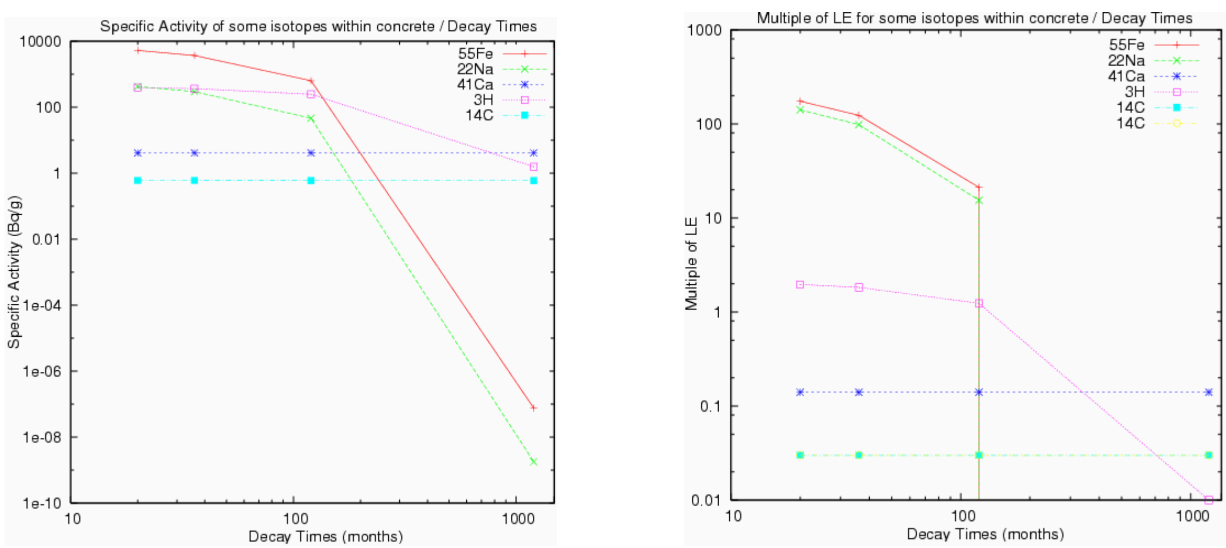

Figure 14: Graphs showing evolution in time of some principal isotopes within ***concrete****. Specific activity (left) and multiple of LE (right).*

Finally, for comparison, Table 12 lists the radioactive isotopes being produced in **concrete** for a cooling time of **3 years** after the last radiation. Isotopes are classified by multiple of L_E and results are listed in the Appendix for all others cooling times.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 3820 kg	Multiple of 100 L_E
^{55}Fe	8.64E+07	3.70E+03	0.16	30.00	**123.44**	1.41E+10	4.71E+06
^{22}Na	8.21E+07	2.95E+02	0.41	3.00	**98.24**	1.13E+09	3.75E+06
^{45}Ca	1.41E+07	8.67E+01	0.15	10.00	**8.67**	3.31E+08	3.31E+05
^{3}H	3.89E+08	3.65E+02	0.26	200.00	**1.83**	1.40E+09	6.98E+04
^{54}Mn	2.70E+07	1.33E+01	1.22	10.00	**1.33**	5.07E+07	5.07E+04
^{41}Ca	3.22E+12	4.11E+00	0.12	30.00	**0.14**	1.57E+07	5.23E+03
^{14}C	1.80E+11	6.01E-01	0.38	20.00	**0.03**	2.29E+06	1.15E+03
^{44}Ti	1.89E+09	1.16E-02	23.08	2.00	**0.01**	4.44E+04	2.22E+02
^{49}V	2.84E+07	2.39E+00	2.38	600.00	**0.00**	9.13E+06	1.52E+02
^{32}P	1.23E+06	8.84E-03	21.21	4.00	**0.00**	3.37E+04	8.44E+01
^{42}K	4.44E+04	3.87E-02	24.34	20.00	**0.00**	1.48E+05	7.39E+01
^{26}Al	2.26E+13	4.87E-03	0.25	3.00	**0.00**	1.86E+04	6.20E+01
^{26}Al	2.26E+13	4.87E-03	0.25	3.00	**0.00**	1.86E+04	6.20E+01
^{36}Cl	9.50E+12	9.26E-03	0.35	10.00	**0.00**	3.54E+04	3.54E+01
^{36}Cl	9.50E+12	9.26E-03	0.35	10.00	**0.00**	3.54E+04	3.54E+01
^{35}S	7.56E+06	6.64E-03	3.67	10.00	**0.00**	2.54E+04	2.54E+01
^{32}Si	4.83E+09	8.84E-03	21.21	20.00	**0.00**	3.37E+04	1.69E+01
^{44}Sc	1.43E+04	1.16E-02	23.08	30.00	**0.00**	4.44E+04	1.48E+01
^{44}Sc	1.43E+04	1.16E-02	23.08	30.00	**0.00**	4.44E+04	1.48E+01
^{44}Sc	1.43E+04	1.16E-02	23.08	30.00	**0.00**	4.44E+04	1.48E+01
^{40}K	3.94E+16	5.26E-04	0.12	2.00	**0.00**	2.01E+03	1.00E+01
^{40}K	3.94E+16	5.26E-04	0.12	2.00	**0.00**	2.01E+03	1.00E+01
^{10}Be	4.77E+13	6.86E-04	0.56	9.00	**0.00**	2.62E+03	2.91E+00
^{46}Sc	7.24E+06	3.75E-04	3.71	7.00	**0.00**	1.43E+03	2.04E+00
^{46}Sc	7.24E+06	3.75E-04	3.71	7.00	**0.00**	1.43E+03	2.04E+00
^{57}Co	2.35E+07	1.18E-03	99.00	50.00	**0.00**	4.50E+03	9.00E-01
^{56}Co	6.67E+06	8.02E-05	12.53	4.00	**0.00**	3.06E+02	7.65E-01
^{59}Fe	3.84E+06	1.87E-05	0.63	6.00	**0.00**	7.16E+01	1.19E-01
^{7}Be	4.60E+06	4.68E-04	0.66	400.00	**0.00**	1.79E+03	4.46E-02
^{53}Mn	1.18E+14	8.33E-05	0.94	300.00	**0.00**	3.18E+02	1.06E-02
^{51}Cr	2.39E+06	7.19E-11	2.28	300.00	**0.00**	2.74E-04	9.15E-09
^{33}P	2.19E+06	1.76E-12	4.53	40.00	**0.00**	6.73E-06	1.68E-09
^{48}V	1.38E+06	1.52E-20	5.69	5.00	**0.00**	5.80E-14	1.16E-16
TOTAL		**4.49E+03**				**1.71E+10**	

Table 12: List of radioactive isotopes within ***concrete*****,** ***3 years*** *(****September 2007****) after the last radiation.*

5. Residual Dose Rate

In order to account for the target handling and transport, using fluence-to-dose conversion factors [9], ambient residual dose rates were calculated around the lead target in its present location, i.e., installed in the pit. Figure 15 gives for a vertical and longitudinal cut the average dose rate (μSv/h) in a thickness of 80 cm corresponding to the dimension of the target, in this case for a cooling time of **3 years** after the last radiation (**September 2007**). Others cooling times chosen to evaluate ambient dose rate are presented in the Appendix.

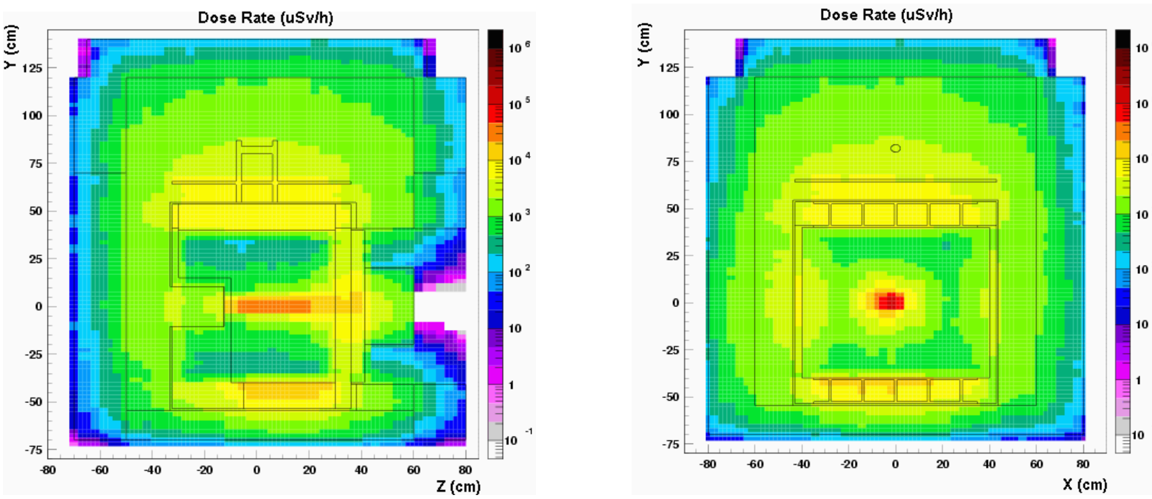

Figure 15: Dose Rate in µSv/h after a cooling time of ***3 years*** *(**September 2007**). Side view (left) and front view (right).*

For a better representation of the residual dose rate peak values, Figure 16 shows residual dose rate distributions (µSv/h) averaged over only a thickness of 10 cm along the centre of the target and again for **3 years** after the last radiation (**September 2007**).

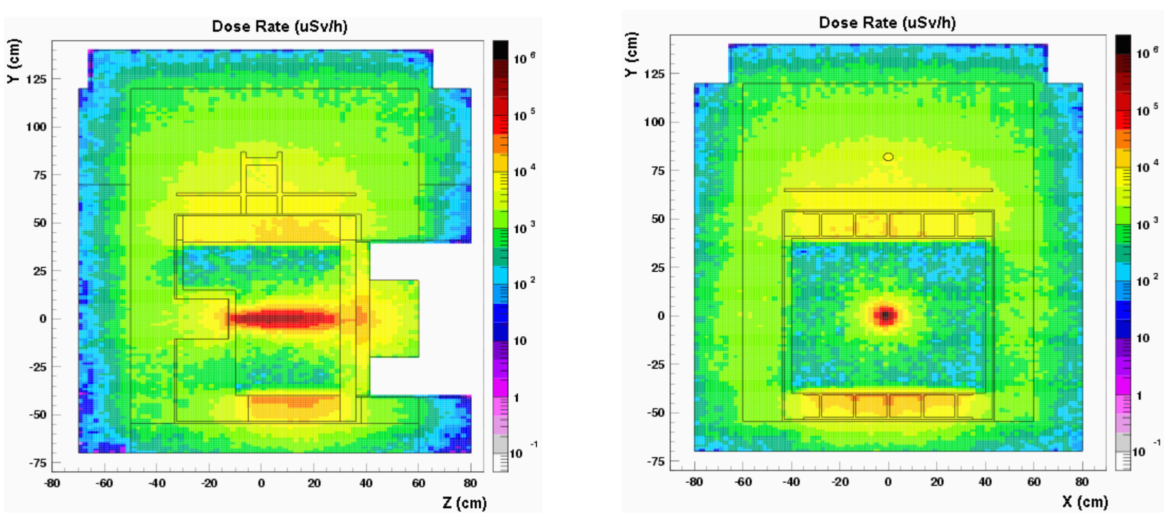

Figure 16: Dose Rate in µSv/h after a cooling time of ***3 years*** *(**September 2007**). Side view (left) and front view (right).*

Residual dose rates obtained at different locations around the target and for different cooling periods are summarized in Table 13.

$I=8.4\times10^{11}$pr/s	Cooling Time = 1 year 8 months	Cooling Time = 3 years	Cooling Time = 10 years
At the beam entrance	3.6	2.6	4.2
At the beam exit	29.6	19.2	4.3
At the top of the target	2.3	1.7	0.6

Table 13: Dose equivalent rates expressed in ***mSv/h*** *around the lead target for different cooling times.*

It can be noted, that from one year and eight months to three years after the last radiation, residual dose rates were reduced by a factor of 1.5. An equivalent factor of four would be obtained between three and ten years of cooling. The following graph shows evolution in time of the dose rate measured at three different locations around the target.

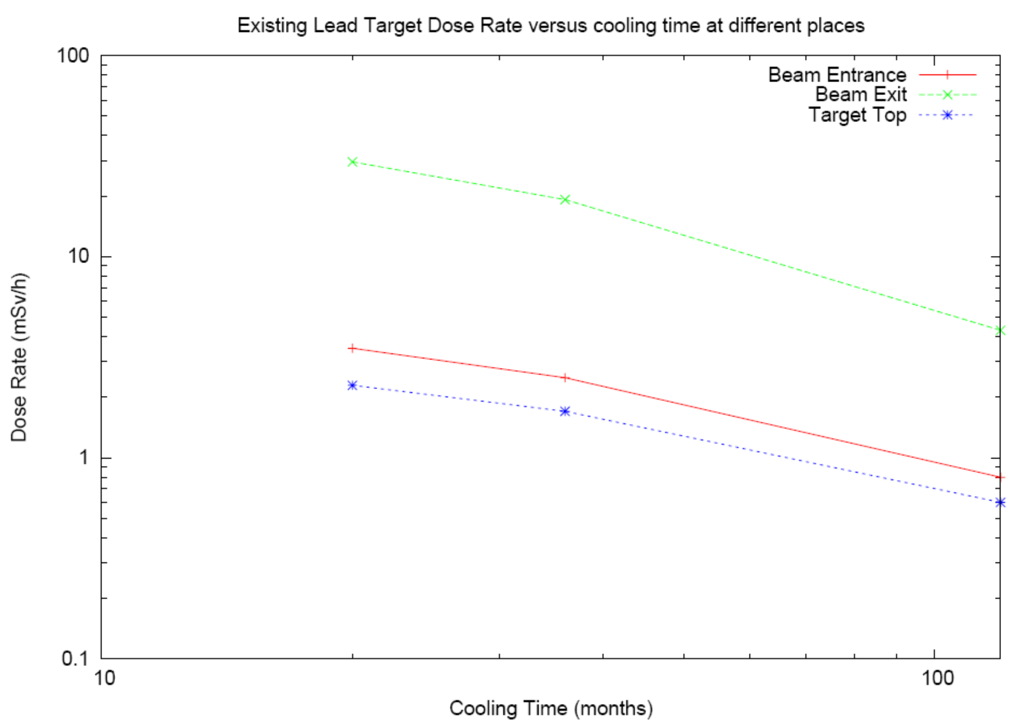

Figure 17: Graph showing dose rate in ***mSv/h*** *versus cooling time at different places around the lead target.*

6. Conclusion

This report presents simulation results needed for the waste characterization of the n_TOF target. It includes calculations of specific and total activity, as well as residual dose rate simulations for the n_TOF lead target. In a first part the considered technical layout, pictures of the lead target assembly and the actual implementation in the FLUKA simulation were presented. The second part included detailed results for the activation of the n_TOF target and the surrounding installation. The last part referred to the residual dose rates around the target. All results are given for a representative cooling time referring to September 2007 as well as numerous other decay times ranging from one to 100 years collected in the Appendix of this document.

After four years of operations and three years of cooling, in September 2007, the average specific activity of the lead is equal to 9.3×10^4 Bq/g with 1.0×10^2 Bq/g for alpha-emitters. Even if Uranium and Thorium of 1 ppm each are added in lead composition, this value increases by a factor four and remains below the ATA reference value which is fixed at 20.000 Bq/g, confirming thereby the fact that the n_ToF target does not fall into the ATA category. Moreover, the total activity of the lead target is equal to 3.7×10^{11} Bq and decreases only by a factor 2 after ten years of cooling. Finally, dose rate around the target ranges from 2 mSv/h at the entrance beam to a peak of 20 mSv/h at the exit beam, showing that hot spots of the target can be shielded locally during transport.

All these results confirm a classification of Type A for the transport of the target [10] and define all input required for a possible waste disposal through NAGRA and PSI in Switzerland [11].

7. References

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[10] Y. Donjoux, private communication, *n_TOF Target - expédition PSI/NAGRA - Aspect radiologique du transport*, Radioactive Shipping Service, 07/13/2007.

[11] Meeting with PSI representatives, *n_TOF Target - expédition PSI/NAGRA*, CERN, 07/11/2007.

APPENDIX

Target area activation – Isotopes distribution

Figures 18 to 22 show the average specific activity (Bq/g), for different cooling times (averaged over 10 cm thickness) of the lead, water container and stainless steel hook in contact with air, at different projections: projection along the x-axis for the side view and projection on z-axis for the front view.

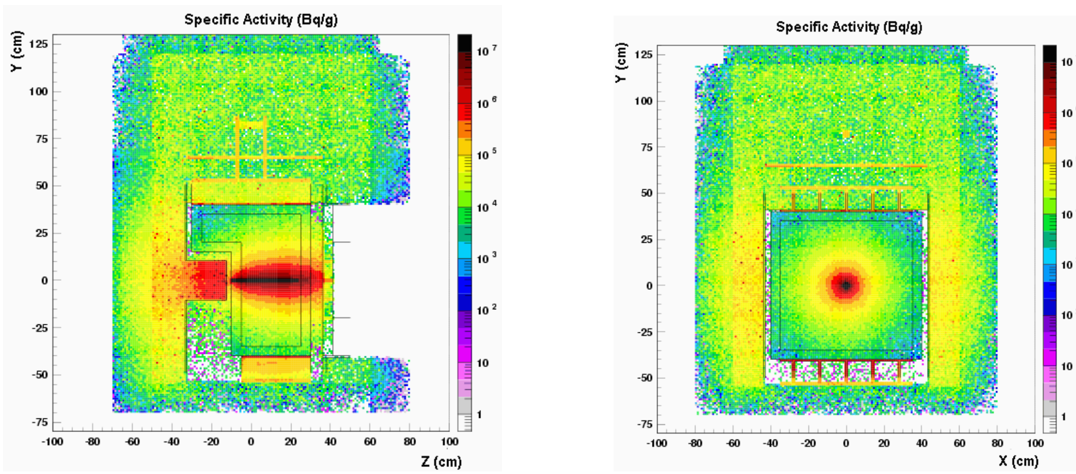


Figure 18: Specific Activity in Bq/g after a cooling time of ***1 year 8 months (May 2006)****. Side view (left) and front view (right).*

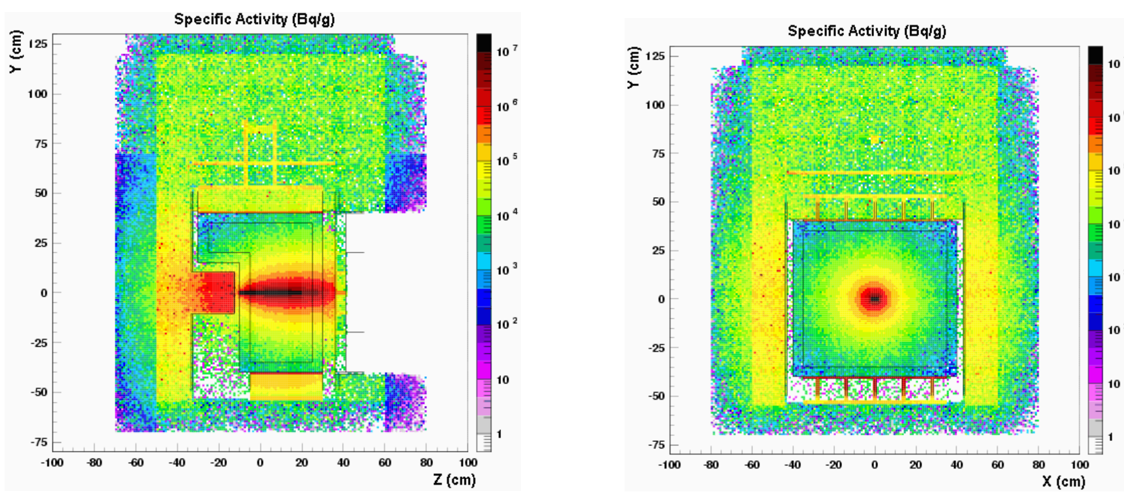


Figure 19: Specific Activity in Bq/g after a cooling time of ***3 years (September 2007)****. Side view (left) and front view (right).*

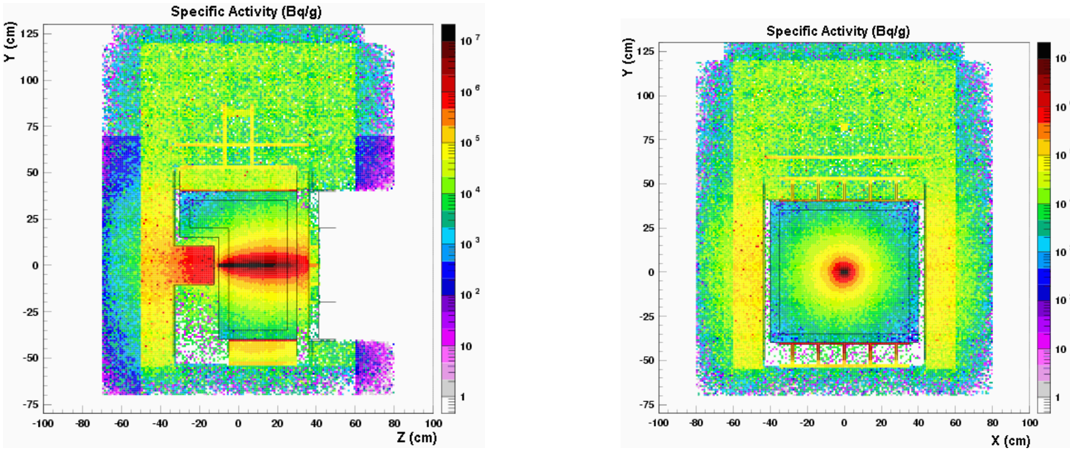


Figure 20: Specific Activity in Bq/g after a cooling time of ***3 years 8 months** (**May 2008**)*. *Side view (left) and front view (right).*

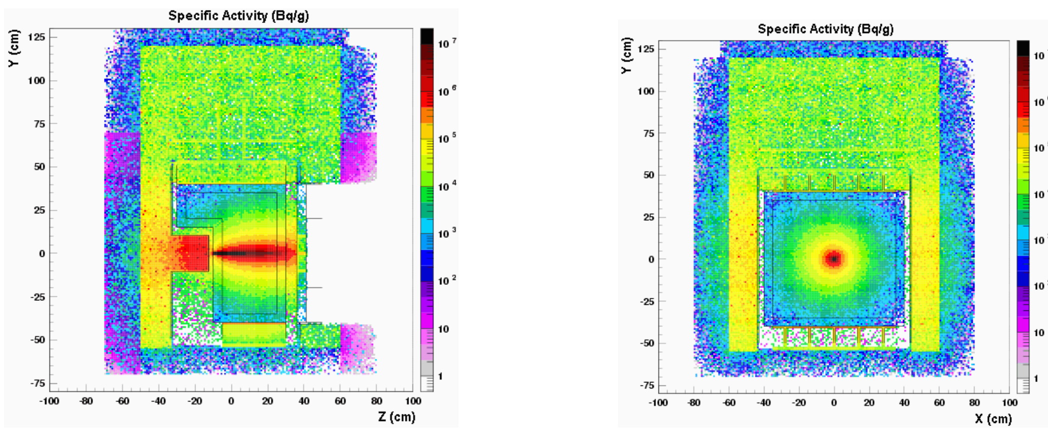


Figure 21: Specific Activity in Bq/g after a cooling time of ***10 years** (**September 2014**)*. *Side view (left) and front view (right).*

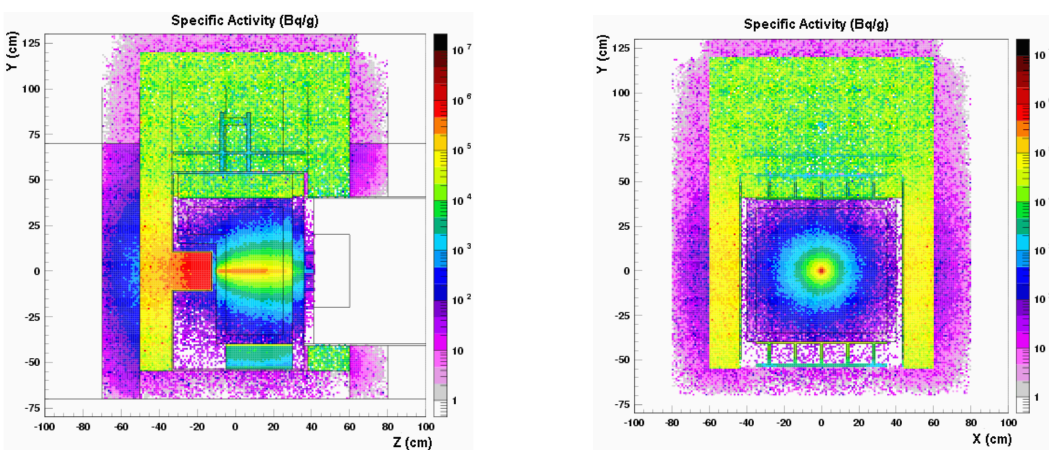


Figure 22: Specific Activity in Bq/g after a cooling time of ***100 years** (**September 2104**)*. *Side view (left) and front view (right).*

Isotopes production

Tables 14, 16, 18 and 20 compare the activity concentration *a* and total activity *A* of isotopes within **lead** of n_TOF, only beta and gamma emitters, for several cooling times. Because of an important number of produced isotopes, we limited those lists to all isotopes with a multiple of L_E superior to 5 only. For each cooling time, the calculations also separately predicted all alpha emitting radionuclides within lead classified by multiple of L_E (see Tables 15, 17, 19 and 21).

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{204}Tl	1.19E+08	2.92E+04	0.14	8.00	**3645.21**	1.16E+11	1.45E+08
^{194}Hg	1.40E+10	3.02E+02	0.10	0.20	**1511.71**	1.20E+09	6.02E+07
^{60}Co	1.66E+08	3.83E+02	0.54	1.00	**383.24**	1.53E+09	1.53E+07
^{3}H	3.89E+08	5.92E+04	0.06	200.00	**296.02**	2.36E+11	1.18E+07
^{172}Lu	5.79E+05	2.13E+03	0.44	8.00	**266.19**	8.48E+09	1.06E+07
^{195}Au	1.61E+07	9.92E+03	0.12	40.00	**247.88**	3.95E+10	9.87E+06
^{207}Bi	1.04E+09	1.87E+03	0.14	8.00	**234.21**	7.46E+09	9.33E+06
^{172}Hf	5.90E+07	2.11E+03	0.44	10.00	**210.86**	8.40E+09	8.40E+06
^{65}Zn	2.11E+07	2.57E+02	0.76	3.00	**85.51**	1.02E+09	3.40E+06
^{109}Cd	3.99E+07	3.24E+02	0.65	5.00	**64.74**	1.29E+09	2.58E+06
^{173}Lu	4.32E+07	2.01E+03	0.27	40.00	**50.16**	7.99E+09	2.00E+06
^{90}Sr	9.12E+08	1.97E+01	1.72	0.40	**49.25**	7.84E+07	1.96E+06
^{54}Mn	2.70E+07	3.84E+02	0.57	10.00	**38.36**	1.53E+09	1.53E+06
^{106}Ru	3.23E+07	2.31E+01	2.98	1.00	**23.06**	9.18E+07	9.18E+05
^{106}Rh	2.98E+01	2.31E+01	2.98	1.00	**23.06**	9.18E+07	9.18E+05
^{88}Y	9.21E+06	1.61E+02	0.72	8.00	**20.18**	6.43E+08	8.04E+05
^{75}Se	1.04E+07	7.52E+01	0.66	4.00	**18.80**	2.99E+08	7.49E+05
^{101}Rh	1.04E+08	3.62E+02	0.81	20.00	**18.10**	1.44E+09	7.21E+05
^{179}Ta	5.74E+07	3.41E+03	0.29	200.00	**17.06**	1.36E+10	6.79E+05
^{68}Ge	2.34E+07	1.32E+02	1.05	8.00	**16.47**	5.25E+08	6.56E+05
^{202}Pb	1.66E+12	1.58E+01	0.06	1.00	**15.84**	6.31E+07	6.31E+05
^{194}Au	1.37E+05	3.02E+02	0.10	20.00	**15.12**	1.20E+09	6.02E+05
^{102}Rh	1.79E+07	5.52E+01	0.82	4.00	**13.80**	2.20E+08	5.49E+05
^{55}Fe	8.64E+07	3.90E+02	0.91	30.00	**12.99**	1.55E+09	5.17E+05
^{193}Pt	1.58E+09	3.55E+03	0.07	300.00	**11.83**	1.41E+10	4.71E+05
^{185}Os	8.09E+06	2.31E+02	0.21	20.00	**11.57**	9.22E+08	4.61E+05
^{134}Cs	6.52E+07	4.69E+00	6.62	0.50	**9.39**	1.87E+07	3.74E+05
^{45}Ca	1.41E+07	8.09E+01	0.56	10.00	**8.09**	3.22E+08	3.22E+05
^{133}Ba	3.32E+08	6.68E+01	1.14	10.00	**6.68**	2.66E+08	2.66E+05
^{22}Na	8.21E+07	1.89E+01	4.24	3.00	**6.31**	7.54E+07	2.51E+05
^{83}Rb	7.45E+06	3.10E+01	0.32	5.00	**6.20**	1.23E+08	2.47E+05
TOTAL		**1.17E+05**				**4.66E+11**	

*Table 14: List of radioactive isotopes within **lead**, **1 year 8 months** (**May 2006**) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	2.99E+01	1.06	0.20	**149.29**	1.19E+08	5.94E+06
^{210}Po	1.20E+07	9.71E-01	0.07	0.04	**24.28**	3.87E+06	9.67E+05
^{208}Po	9.15E+07	9.64E-02	1.31	0.01	**9.64**	3.84E+05	3.84E+05
^{145}Pm	5.59E+08	7.14E+01	0.84	90.00	**0.79**	2.84E+08	3.16E+04
^{209}Po	3.22E+09	1.05E-03	2.95	0.01	**0.11**	4.19E+03	4.19E+03
^{148}Eu	4.71E+06	1.63E-02	6.04	8.00	**0.00**	6.48E+04	8.11E+01
^{146}Sm	3.25E+15	1.99E-05	0.83	0.20	**0.00**	7.91E+01	3.96E+00
^{147}Eu	2.08E+06	2.42E-05	0.68	20.00	**0.00**	9.65E+01	4.82E-02
^{190}Pt	2.05E+19	1.35E-07	0.09	1.00	**0.00**	5.36E-01	5.36E-03
^{147}Sm	3.35E+18	1.75E-08	0.79	0.20	**0.00**	6.95E-02	3.48E-03
^{152}Gd	3.41E+21	1.87E-11	0.76	0.20	**0.00**	7.46E-05	3.73E-06
^{188}Pt	8.81E+05	2.42E-14	0.17	10.00	**0.00**	9.65E-08	9.65E-11
^{206}Po	7.60E+05	4.51E-22	1.57	0.08	**0.00**	1.79E-15	2.24E-16
^{149}Gd	8.02E+05	1.96E-17	0.83	20.00	**0.00**	7.82E-11	3.91E-14
^{210}Bi	4.33E+05	1.72E-33	0.07	8.00	**0.00**	6.85E-27	8.56E-30
^{154}Dy	9.47E+13	8.92E-04	0.49	0.00	**0.00**	3.55E+03	0.00E+00
^{150}Gd	5.65E+13	1.04E-03	0.86	0.00	**0.00**	4.15E+03	0.00E+00
TOTAL		**1.18E+02**				**4.71E+08**	

Table 15: List of all the alpha emitting radionuclides within ***lead*****,** ***1 year 8 months*** *(****May 2006****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{204}Tl	1.19E+08	2.27E+04	0.14	8.00	**2841.17**	9.05E+10	1.13E+08
^{194}Hg	1.40E+10	3.02E+02	0.10	0.20	**1509.07**	1.20E+09	6.01E+07
^{60}Co	1.66E+08	3.21E+02	0.54	1.00	**320.53**	1.28E+09	1.28E+07
^{3}H	3.89E+08	5.48E+04	0.06	200.00	**274.25**	2.18E+11	1.09E+07
^{207}Bi	1.04E+09	1.82E+03	0.14	8.00	**227.32**	7.24E+09	9.05E+06
^{172}Lu	5.79E+05	1.29E+03	0.44	8.00	**160.86**	5.12E+09	6.40E+06
^{172}Hf	5.90E+07	1.27E+03	0.44	10.00	**127.42**	5.07E+09	5.07E+06
^{90}Sr	9.12E+08	1.91E+01	1.72	0.40	**47.66**	7.59E+07	1.90E+06
^{195}Au	1.61E+07	1.56E+03	0.12	40.00	**39.07**	6.22E+09	1.56E+06
^{109}Cd	3.99E+07	1.54E+02	0.65	5.00	**30.79**	6.13E+08	1.23E+06
^{173}Lu	4.32E+07	1.01E+03	0.27	40.00	**25.22**	4.02E+09	1.00E+06
^{65}Zn	2.11E+07	6.28E+01	0.76	3.00	**20.93**	2.50E+08	8.33E+05
^{202}Pb	1.66E+12	1.58E+01	0.06	1.00	**15.84**	6.31E+07	6.31E+05
^{194}Au	1.37E+05	3.02E+02	0.10	20.00	**15.09**	1.20E+09	6.01E+05
^{101}Rh	1.04E+08	2.72E+02	0.81	20.00	**13.60**	1.08E+09	5.42E+05
^{54}Mn	2.70E+07	1.27E+02	0.57	10.00	**12.75**	5.08E+08	5.08E+05
^{193}Pt	1.58E+09	3.48E+03	0.07	300.00	**11.60**	1.39E+10	4.62E+05
^{179}Ta	5.74E+07	2.02E+03	0.29	200.00	**10.08**	8.03E+09	4.01E+05
^{5}5Fe	8.64E+07	2.76E+02	0.91	30.00	**9.20**	1.10E+09	3.66E+05
^{106}Ru	3.23E+07	9.19E+00	2.98	1.00	**9.19**	3.66E+07	3.66E+05
^{106}Rh	2.98E+01	9.19E+00	2.98	1.00	**9.19**	3.66E+07	3.66E+05
^{133}Ba	3.32E+08	6.11E+01	1.14	10.00	**6.11**	2.43E+08	2.43E+05
^{134}Cs	6.52E+07	2.97E+00	6.62	0.50	**5.94**	1.18E+07	2.37E+05
TOTAL		**9.19E+04**				**3.70E+11**	

Table 16: List of radioactive isotopes within ***lead****,* ***3 years*** *(****September 2007****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	2.95E+01	1.06	0.20	**147.42**	1.17E+08	5.87E+06
^{208}Po	9.15E+07	6.97E-02	1.31	0.01	**6.97**	2.77E+05	2.77E+05
^{210}Po	1.20E+07	8.10E-02	0.07	0.04	**2.02**	3.22E+05	8.06E+04
^{145}Pm	5.59E+08	7.32E+01	0.82	90.00	**0.81**	2.92E+08	3.24E+04
^{209}Po	3.22E+09	1.04E-03	2.95	0.01	**0.10**	4.16E+03	4.16E+03
^{151}Gd	1.07E+07	3.13E+00	0.41	50.00	**0.06**	1.25E+07	2.49E+03
^{146}Sm	3.25E+15	1.99E-05	0.83	0.20	**0.00**	7.92E+01	3.96E+00
^{148}Eu	4.71E+06	2.97E-05	6.04	8.00	**0.00**	1.18E+02	1.48E-01
^{190}Pt	2.05E+19	1.35E-07	0.09	1.00	**0.00**	5.36E-01	5.36E-03
^{147}Sm	3.35E+18	1.75E-08	0.80	0.20	**0.00**	6.98E-02	3.49E-03
^{152}Gd	3.41E+21	1.87E-11	0.76	0.20	**0.00**	7.46E-05	3.73E-06
^{147}Eu	2.08E+06	1.54E-11	0.68	20.00	**0.00**	6.15E-05	3.07E-08
^{188}Pt	8.81E+05	5.57E-29	0.17	10.00	**0.00**	2.22E-22	2.22E-25
^{149}Gd	8.02E+05	2.56E-33	0.83	20.00	**0.00**	1.02E-26	5.11E-30
^{206}Po	7.60E+05	4.86E-39	1.57	0.08	**0.00**	1.94E-32	2.42E-33
^{154}Dy	9.47E+13	8.92E-04	0.49	0.00	**0.00**	3.55E+03	0.00E+00
^{150}Gd	5.65E+13	1.04E-03	0.86	0.00	**0.00**	4.15E+03	0.00E+00
TOTAL		**1.06E+02**				**4.22E+08**	

Table 17: List of all the alpha emitting radionuclides within ***lead***, ***3 years (September 2007)*** *after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{194}Hg	1.40E+10	2.99E+02	0.10	0.20	**1495.13**	1.19E+09	5.95E+07
^{204}Tl	1.19E+08	6.36E+03	0.14	8.00	**795.44**	2.53E+10	3.17E+07
^{207}Bi	1.04E+09	1.56E+03	0.14	8.00	**195.16**	6.22E+09	7.77E+06
^{3}H	3.89E+08	3.71E+04	0.06	200.00	**185.63**	1.48E+11	7.39E+06
^{60}Co	1.66E+08	1.29E+02	0.54	1.00	**128.65**	5.12E+08	5.12E+06
^{90}Sr	9.12E+08	1.61E+01	1.72	0.40	**40.32**	6.42E+07	1.61E+06
^{202}Pb	1.66E+12	1.58E+01	0.06	1.00	**15.84**	6.31E+07	6.31E+05
^{194}Au	1.37E+05	2.99E+02	0.10	20.00	**14.95**	1.19E+09	5.95E+05
^{172}Lu	5.79E+05	9.82E+01	0.44	8.00	**12.27**	3.91E+08	4.89E+05
^{193}Pt	1.58E+09	3.16E+03	0.07	300.00	**10.54**	1.26E+10	4.20E+05
^{172}Hf	5.90E+07	9.72E+01	0.44	10.00	**9.72**	3.87E+08	3.87E+05
TOTAL		**4.99E+04**				**1.99E+11**	

Table 18: List of radioactive isotopes within ***lead***, ***10 years (September 2014)*** *after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	2.76E+01	1.06	0.20	**138.21**	1.10E+08	5.50E+06
^{208}Po	9.15E+07	1.32E-02	1.31	0.01	**1.32**	5.27E+04	5.27E+04
^{145}Pm	5.59E+08	5.84E+01	0.81	90.00	**0.65**	2.33E+08	2.58E+04
^{209}Po	3.22E+09	9.96E-04	2.95	0.01	**0.10**	3.96E+03	3.96E+03
^{210}Po	1.20E+07	2.49E-07	0.07	0.04	**0.00**	9.90E-01	2.48E-01
^{146}Sm	3.25E+15	1.99E-05	0.84	0.20	**0.00**	7.94E+01	3.97E+00
^{190}Pt	2.05E+19	1.35E-07	0.09	1.00	**0.00**	5.36E-01	5.36E-03
^{147}Sm	3.35E+18	1.77E-08	0.82	0.20	**0.00**	7.04E-02	3.52E-03
^{151}Gd	1.07E+07	2.21E-06	0.41	50.00	**0.00**	8.78E+00	1.76E-03
^{152}Gd	3.41E+21	1.87E-11	0.76	0.20	**0.00**	7.46E-05	3.73E-06
^{148}Eu	4.71E+06	2.99E-19	6.04	8.00	**0.00**	1.19E-12	1.49E-15
^{147}Eu	2.08E+06	3.44E-43	0.68	20.00	**0.00**	1.37E-36	6.85E-40
^{154}Dy	9.47E+13	8.92E-04	0.49	0.00	**0.00**	3.55E+03	0.00E+00
^{150}Gd	5.65E+13	1.04E-03	0.86	0.00	**0.00**	4.15E+03	0.00E+00
TOTAL		**8.61E+01**				**3.43E+08**	

Table 19: List of all the alpha emitting radionuclides within ***lead*****,** ***10 years*** *(****September 2014****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{194}Hg	1.40E+10	2.65E+02	0.10	0.20	**1326.10**	1.06E+09	5.28E+07
^{207}Bi	1.04E+09	2.16E+02	0.14	8.00	**27.02**	8.61E+08	1.08E+06
^{202}Pb	1.66E+12	1.58E+01	0.06	1.00	**15.82**	6.30E+07	6.30E+05
^{194}Au	1.37E+05	2.65E+02	0.10	20.00	**13.26**	1.06E+09	5.28E+05
TOTAL		**2.01E+03**				**7.99E+09**	

Table 20: List of radioactive isotopes within ***lead*****,** ***100 years*** *(****September 2014****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	1.20E+01	1.06	0.20	**59.89**	4.77E+07	2.38E+06
^{209}Po	3.22E+09	5.40E-04	2.95	0.01	**0.05**	2.15E+03	2.15E+03
^{145}Pm	5.59E+08	1.72E+00	0.81	90.00	**0.02**	6.86E+06	7.62E+02
^{146}Sm	3.25E+15	2.00E-05	0.84	0.20	**0.00**	7.96E+01	3.98E+00
^{208}Po	9.15E+07	5.93E-12	1.31	0.01	**0.00**	2.36E-05	2.36E-05
^{190}Pt	2.05E+19	1.35E-07	0.09	1.00	**0.00**	5.36E-01	5.36E-03
^{147}Sm	3.35E+18	1.77E-08	0.82	0.20	**0.00**	7.05E-02	3.52E-03
^{152}Gd	3.41E+21	1.88E-11	0.76	0.20	**0.00**	7.47E-05	3.74E-06
^{154}Dy	9.47E+13	8.92E-04	0.49	0.00	**0.00**	3.55E+03	0.00E+00
^{150}Gd	5.65E+13	1.04E-03	0.86	0.00	**0.00**	4.15E+03	0.00E+00
TOTAL		**1.37E+01**				**5.46E+07**	

Table 21: List of all the alpha emitting radionuclides within ***lead*, *100 years* (*September 2014*)** *after the last radiation.*

In Switzerland, the considered standard lead also contains uranium and thorium; however the given chemical composition of the n_TOF lead target doesn't contain it. Therefore, since preliminary NAGRA studies using such a composition of lead were performed, for comparison reason a similar composition was taken into account and results are given in the following Tables 22 to 25.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	8.43E+01	0.44	0.20	**421.59**	3.36E+08	1.68E+07
^{210}Po	1.20E+07	9.61E-01	0.14	0.04	**24.02**	3.83E+06	9.56E+05
^{202}Pb	1.66E+12	1.63E+01	0.12	1.00	**16.30**	6.49E+07	6.49E+05
^{208}Po	9.15E+07	9.97E-02	1.77	0.01	**9.97**	3.97E+05	3.97E+05
^{145}Pm	5.59E+08	2.97E+02	0.62	90.00	**3.30**	1.18E+09	1.31E+05
^{151}Gd	1.07E+07	1.39E+02	0.35	50.00	**2.78**	5.54E+08	1.11E+05
^{228}Th	6.03E+07	1.48E-01	1.32	0.10	**1.48**	5.89E+05	5.89E+04
^{210}Pb	7.01E+08	1.37E-02	1.94	0.01	**1.37**	5.46E+04	5.46E+04
^{239}Pu	7.61E+11	4.08E-02	0.10	0.04	**1.02**	1.63E+05	4.06E+04
^{227}Ac	6.87E+08	7.77E-03	4.90	0.01	**0.86**	3.10E+04	3.44E+04
^{224}Ra	3.14E+05	1.49E-01	1.32	0.20	**0.74**	5.92E+05	2.96E+04
^{209}Po	3.22E+09	1.57E-03	3.05	0.01	**0.16**	6.24E+03	6.24E+03
^{223}Ra	9.88E+05	7.80E-03	4.90	0.10	**0.08**	3.11E+04	3.11E+03
^{232}U	2.17E+09	1.42E-03	4.53	0.03	**0.05**	5.67E+03	1.89E+03
^{233}U	5.02E+12	4.39E-03	0.13	0.20	**0.02**	1.75E+04	8.74E+02
^{148}Eu	4.71E+06	9.94E-02	2.14	8.00	**0.01**	3.96E+05	4.95E+02
^{231}Pa	1.03E+12	1.45E-04	0.62	0.01	**0.01**	5.79E+02	5.79E+02
^{229}Th	2.32E+11	1.72E-04	1.36	0.02	**0.01**	6.84E+02	3.42E+02
^{236}Pu	9.02E+07	3.83E-04	12.06	0.10	**0.00**	1.52E+03	1.52E+02
^{212}Bi	3.63E+03	1.49E-01	1.32	40.00	**0.00**	5.93E+05	1.48E+02
^{212}Po	4.51E+01	9.54E-02	1.32	40.00	**0.00**	3.80E+05	9.49E+01
^{210}Bi	4.33E+05	1.37E-02	1.94	8.00	**0.00**	5.46E+04	6.83E+01
^{238}Pu	2.77E+09	4.00E-05	25.00	0.04	**0.00**	1.59E+02	3.98E+01
^{226}Ra	5.05E+10	2.90E-05	5.09	0.04	**0.00**	1.15E+02	2.89E+01
^{230}Th	2.38E+12	3.11E-05	0.43	0.05	**0.00**	1.24E+02	2.48E+01
^{225}Ac	8.64E+05	1.72E-04	1.36	0.40	**0.00**	6.84E+02	1.71E+01
^{211}Bi	1.28E+02	7.80E-03	4.90	60.00	**0.00**	3.11E+04	5.18E+00
^{223}Fr	1.32E+03	1.07E-04	4.90	4.00	**0.00**	4.27E+02	1.07E+00
^{237}Np	6.77E+13	1.74E-06	0.51	0.09	**0.00**	6.93E+00	7.70E-01
^{234}U	7.75E+12	1.93E-06	2.62	0.20	**0.00**	7.67E+00	3.83E-01
^{213}Bi	2.74E+03	1.72E-04	1.36	50.00	**0.00**	6.83E+02	1.37E-01
TOTAL		**5.38E+02**				**2.14E+09**	

Table 22: List of all the alpha emitting radionuclides within ***lead*****,** ***1 year 8 months*** *(****May 2006****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	8.33E+01	0.44	0.20	**416.30**	3.32E+08	1.66E+07
^{202}Pb	1.66E+12	1.63E+01	0.12	1.00	**16.30**	6.49E+07	6.49E+05
^{208}Po	9.15E+07	7.20E-02	1.77	0.01	**7.20**	2.87E+05	2.87E+05
^{145}Pm	5.59E+08	3.05E+02	0.62	90.00	**3.39**	1.22E+09	1.35E+05
^{210}Po	1.20E+07	9.23E-02	0.32	0.04	**2.31**	3.68E+05	9.19E+04
^{210}Pb	7.01E+08	1.31E-02	1.94	0.01	**1.31**	5.23E+04	5.23E+04
^{239}Pu	7.61E+11	4.08E-02	0.10	0.04	**1.02**	1.63E+05	4.06E+04
^{228}Th	6.03E+07	9.15E-02	1.29	0.10	**0.91**	3.64E+05	3.64E+04
^{227}Ac	6.87E+08	7.45E-03	4.90	0.01	**0.83**	2.97E+04	3.30E+04
^{224}Ra	3.14E+05	9.20E-02	1.29	0.20	**0.46**	3.66E+05	1.83E+04
^{151}Gd	1.07E+07	8.69E+00	0.35	50.00	**0.17**	3.46E+07	6.92E+03
^{209}Po	3.22E+09	1.55E-03	3.05	0.01	**0.16**	6.18E+03	6.18E+03
^{223}Ra	9.88E+05	7.48E-03	4.90	0.10	**0.07**	2.98E+04	2.98E+03
^{232}U	2.17E+09	1.41E-03	4.49	0.03	**0.05**	5.61E+03	1.87E+03
^{233}U	5.02E+12	4.39E-03	0.13	0.20	**0.02**	1.75E+04	8.74E+02
^{231}Pa	1.03E+12	1.45E-04	0.62	0.01	**0.01**	5.79E+02	5.79E+02
^{229}Th	2.32E+11	1.72E-04	1.35	0.02	**0.01**	6.87E+02	3.43E+02
^{227}Th	1.61E+06	7.36E-03	4.90	1.00	**0.01**	2.93E+04	2.93E+02
^{236}Pu	9.02E+07	2.75E-04	12.06	0.10	**0.00**	1.10E+03	1.10E+02
^{212}Bi	3.63E+03	9.20E-02	1.29	40.00	**0.00**	3.66E+05	9.16E+01
^{210}Bi	4.33E+05	1.32E-02	1.94	8.00	**0.00**	5.24E+04	6.55E+01
^{212}Po	4.51E+01	5.89E-02	1.29	40.00	**0.00**	2.35E+05	5.87E+01
^{238}Pu	2.77E+09	3.95E-05	25.00	0.04	**0.00**	1.57E+02	3.93E+01
^{226}Ra	5.05E+10	2.90E-05	5.08	0.04	**0.00**	1.15E+02	2.89E+01
^{230}Th	2.38E+12	3.11E-05	0.43	0.05	**0.00**	1.24E+02	2.48E+01
^{225}Ac	8.64E+05	1.72E-04	1.35	0.40	**0.00**	6.86E+02	1.72E+01
^{211}Bi	1.28E+02	7.48E-03	4.90	60.00	**0.00**	2.98E+04	4.96E+00
^{223}Fr	1.32E+03	1.03E-04	4.90	4.00	**0.00**	4.09E+02	1.02E+00
^{237}Np	6.77E+13	1.74E-06	0.51	0.09	**0.00**	6.93E+00	7.70E-01
^{234}U	7.75E+12	1.93E-06	2.62	0.20	**0.00**	7.67E+00	3.83E-01
^{213}Bi	2.74E+03	1.72E-04	1.35	50.00	**0.00**	6.86E+02	1.37E-01
TOTAL		**4.14E+02**				**1.65E+09**	

Table 23: List of all the alpha emitting radionuclides within ***lead*****,** ***3 years (September 2007)*** *after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	7.81E+01	0.44	0.20	**390.30**	3.11E+08	1.55E+07
^{202}Pb	1.66E+12	1.63E+01	0.12	1.00	**16.29**	6.49E+07	6.49E+05
^{145}Pm	5.59E+08	2.44E+02	0.62	90.00	**2.71**	9.70E+08	1.08E+05
^{208}Po	9.15E+07	1.37E-02	1.77	0.01	**1.37**	5.45E+04	5.45E+04
^{210}Pb	7.01E+08	1.06E-02	1.94	0.01	**1.06**	4.22E+04	4.22E+04
^{239}Pu	7.61E+11	4.08E-02	0.10	0.04	**1.02**	1.63E+05	4.06E+04
^{227}Ac	6.87E+08	6.00E-03	4.88	0.01	**0.67**	2.39E+04	2.66E+04
^{210}Po	1.20E+07	1.08E-02	1.94	0.04	**0.27**	4.29E+04	1.07E+04
^{209}Po	3.22E+09	1.48E-03	3.05	0.01	**0.15**	5.90E+03	5.90E+03
^{228}Th	6.03E+07	9.23E-03	1.55	0.10	**0.09**	3.68E+04	3.68E+03
^{223}Ra	9.88E+05	6.02E-03	4.88	0.10	**0.06**	2.40E+04	2.40E+03
^{224}Ra	3.14E+05	9.27E-03	1.54	0.20	**0.05**	3.69E+04	1.85E+03
^{232}U	2.17E+09	1.32E-03	4.41	0.03	**0.04**	5.27E+03	1.76E+03
^{233}U	5.02E+12	4.39E-03	0.13	0.20	**0.02**	1.75E+04	8.74E+02
^{231}Pa	1.03E+12	1.45E-04	0.62	0.01	**0.01**	5.79E+02	5.79E+02
^{229}Th	2.32E+11	1.75E-04	1.33	0.02	**0.01**	6.98E+02	3.49E+02
^{210}Bi	4.33E+05	1.06E-02	1.94	8.00	**0.00**	4.22E+04	5.28E+01
^{238}Pu	2.77E+09	3.74E-05	25.00	0.04	**0.00**	1.49E+02	3.72E+01
^{226}Ra	5.05E+10	2.90E-05	5.07	0.04	**0.00**	1.15E+02	2.89E+01
^{230}Th	2.38E+12	3.11E-05	0.43	0.05	**0.00**	1.24E+02	2.48E+01
^{236}Pu	9.02E+07	5.11E-05	12.06	0.10	**0.00**	2.04E+02	2.04E+01
^{225}Ac	8.64E+05	1.75E-04	1.33	0.40	**0.00**	6.97E+02	1.74E+01
^{212}Bi	3.63E+03	9.28E-03	1.54	40.00	**0.00**	3.69E+04	9.23E+00
^{212}Po	4.51E+01	5.94E-03	1.54	40.00	**0.00**	2.37E+04	5.91E+00
^{211}Bi	1.28E+02	6.02E-03	4.88	60.00	**0.00**	2.40E+04	4.00E+00
^{223}Fr	1.32E+03	8.28E-05	4.88	4.00	**0.00**	3.30E+02	8.24E-01
^{237}Np	6.77E+13	1.74E-06	0.51	0.09	**0.00**	6.93E+00	7.70E-01
^{234}U	7.75E+12	1.93E-06	2.62	0.20	**0.00**	7.67E+00	3.84E-01
^{213}Bi	2.74E+03	1.75E-04	1.33	50.00	**0.00**	6.97E+02	1.39E-01
TOTAL		**3.38E+02**				**1.35E+09**	

Table 24: List of all the alpha emitting radionuclides within ***lead*****,** ***10 years*** *(****September 2014****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 4000 kg	Multiple of 100 L_E
^{148}Gd	2.24E+09	3.38E+01	0.44	0.20	**169.13**	1.35E+08	6.73E+06
^{202}Pb	1.66E+12	1.63E+01	0.12	1.00	**16.28**	6.48E+07	6.48E+05
^{239}Pu	7.61E+11	4.07E-02	0.10	0.04	**1.02**	1.62E+05	4.05E+04
^{145}Pm	5.59E+08	7.18E+00	0.62	90.00	**0.08**	2.86E+07	3.18E+03
^{209}Po	3.22E+09	8.03E-04	3.05	0.01	**0.08**	3.20E+03	3.20E+03
^{210}Pb	7.01E+08	6.73E-04	1.98	0.01	**0.07**	2.68E+03	2.68E+03
^{227}Ac	6.87E+08	4.75E-04	3.54	0.01	**0.05**	1.89E+03	2.10E+03
^{233}U	5.02E+12	4.39E-03	0.13	0.20	**0.02**	1.75E+04	8.74E+02
^{232}U	2.17E+09	5.36E-04	4.39	0.03	**0.02**	2.13E+03	7.11E+02
^{210}Po	1.20E+07	6.85E-04	1.98	0.04	**0.02**	2.73E+03	6.82E+02
^{231}Pa	1.03E+12	1.45E-04	0.62	0.01	**0.01**	5.78E+02	5.78E+02
^{229}Th	2.32E+11	2.11E-04	1.10	0.02	**0.01**	8.40E+02	4.20E+02
^{228}Th	6.03E+07	5.51E-04	4.39	0.10	**0.01**	2.19E+03	2.19E+02
^{223}Ra	9.88E+05	4.76E-04	3.55	0.10	**0.00**	1.90E+03	1.90E+02
^{224}Ra	3.14E+05	5.51E-04	4.39	0.20	**0.00**	2.19E+03	1.10E+02
^{226}Ra	5.05E+10	2.91E-05	4.87	0.04	**0.00**	1.16E+02	2.89E+01
^{230}Th	2.38E+12	3.11E-05	0.43	0.05	**0.00**	1.24E+02	2.47E+01
^{225}Ac	8.64E+05	2.11E-04	1.10	0.40	**0.00**	8.39E+02	2.10E+01
^{227}Th	1.61E+06	4.69E-04	3.55	1.00	**0.00**	1.87E+03	1.87E+01
^{238}Pu	2.77E+09	1.84E-05	25.00	0.04	**0.00**	7.32E+01	1.83E+01
^{210}Bi	4.33E+05	6.74E-04	1.98	8.00	**0.00**	2.68E+03	3.35E+00
^{237}Np	6.77E+13	1.74E-06	0.51	0.09	**0.00**	6.93E+00	7.70E-01
^{212}Bi	3.63E+03	5.51E-04	4.39	40.00	**0.00**	2.19E+03	5.49E-01
^{234}U	7.75E+12	1.93E-06	2.61	0.20	**0.00**	7.70E+00	3.85E-01
^{212}Po	4.51E+01	3.53E-04	4.39	40.00	**0.00**	1.41E+03	3.51E-01
^{211}Bi	1.28E+02	4.76E-04	3.55	60.00	**0.00**	1.90E+03	3.16E-01
^{213}Bi	2.74E+03	2.11E-04	1.10	50.00	**0.00**	8.38E+02	1.68E-01
TOTAL		**5.73E+01**				**2.28E+08**	

Table 25: List of all the alpha emitting radionuclides within ***lead*****,** ***100 years (September 2014****) after the last radiation.*

Tables 26 to 29 compare the activity concentration *a* and total activity *A* of isotopes in the **stainless steel** for several cooling times. Tables 26 and 27 are limited to isotopes having with a multiple of L_E superior to 0.1, as well as superior to 0.01 for Tables 28 and 29.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 330 kg	Multiple of 100 L_E
^{60}Co	1.66E+08	1.57E+04	1.49	1	**15721.62**	5.15E+09	5.15E+07
^{55}Fe	8.64E+07	4.23E+05	0.18	30	**14114.78**	1.39E+11	4.62E+07
^{54}Mn	2.70E+07	8.99E+03	0.63	10	**898.78**	2.94E+09	2.94E+06
^{63}Ni	3.16E+09	1.75E+04	0.15	70	**249.62**	5.72E+09	8.18E+05
^{57}Co	2.35E+07	2.71E+03	0.58	50	**54.18**	8.88E+08	1.78E+05
^{22}Na	8.21E+07	2.79E+01	12.34	3	**9.31**	9.15E+06	3.05E+04
^{58}Co	6.12E+06	9.28E+01	0.37	10	**9.28**	3.04E+07	3.04E+04
^{49}V	2.84E+07	3.06E+03	0.66	600	**5.10**	1.00E+09	1.67E+04
^{56}Co	6.67E+06	1.86E+01	2.49	4	**4.64**	6.08E+06	1.52E+04
^{3}H	3.89E+08	6.80E+02	2.04	200	**3.40**	2.23E+08	1.11E+04
^{44}Ti	1.89E+09	5.39E+00	9.89	2	**2.70**	1.77E+06	8.83E+03
^{45}Ca	1.41E+07	1.59E+01	7.84	10	**1.59**	5.20E+06	5.20E+03
^{46}Sc	7.24E+06	9.95E+00	2.96	7	**1.42**	3.26E+06	4.66E+03
^{59}Ni	2.40E+12	1.46E+02	0.08	200	**0.73**	4.78E+07	2.39E+03
^{59}Fe	3.84E+06	3.48E+00	0.71	6	**0.58**	1.14E+06	1.90E+03
^{44}Sc	1.43E+04	5.39E+00	9.89	30	**0.18**	1.77E+06	5.89E+02
^{35}S	7.56E+06	1.00E+00	6.10	10	**0.10**	3.28E+05	3.28E+02
TOTAL		**4.72E+05**				**1.55E+11**	

Table 26: List of radioactive isotopes within ***stainless steel****,* ***1 year 8 months*** *(****May 2006****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 330 kg	Multiple of 100 L_E
^{60}Co	1.66E+08	1.31E+04	1.49	1	**13149.27**	4.31E+09	4.31E+07
^{55}Fe	8.64E+07	3.00E+05	0.18	30	**9996.44**	9.82E+10	3.27E+07
^{54}Mn	2.70E+07	2.99E+03	0.63	10	**298.72**	9.79E+08	9.79E+05
^{63}Ni	3.16E+09	1.73E+04	0.15	70	**247.27**	5.67E+09	8.10E+05
^{57}Co	2.35E+07	7.65E+02	0.58	50	**15.29**	2.51E+08	5.01E+04
^{22}Na	8.21E+07	1.95E+01	12.34	3	**6.49**	6.37E+06	2.12E+04
^{3}H	3.89E+08	6.30E+02	2.04	200	**3.15**	2.06E+08	1.03E+04
^{44}Ti	1.89E+09	5.29E+00	9.89	2	**2.65**	1.73E+06	8.67E+03
^{49}V	2.84E+07	1.11E+03	0.66	600	**1.85**	3.63E+08	6.04E+03
^{59}Ni	2.40E+12	1.46E+02	0.08	200	**0.73**	4.78E+07	2.39E+03
^{45}Ca	1.41E+07	1.95E+00	7.84	10	**0.19**	6.37E+05	6.37E+02
^{44}Sc	1.43E+04	5.29E+00	9.89	30	**0.18**	1.73E+06	5.78E+02
TOTAL		**3.36E+05**				**1.10E+11**	

Table 27: List of radioactive isotopes within ***stainless steel****,* ***3 years*** *(****September 2007****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 330 kg	Multiple of 100 L_E
^{60}Co	1.66E+08	5.28E+03	1.49	1	**5277.78**	1.73E+09	1.73E+07
^{55}Fe	8.64E+07	5.15E+04	0.18	30	**1715.20**	1.69E+10	5.62E+06
^{63}Ni	3.16E+09	1.65E+04	0.15	70	**235.67**	5.40E+09	7.72E+05
^{44}Ti	1.89E+09	4.80E+00	9.89	2	**2.40**	1.57E+06	7.86E+03
^{3}H	3.89E+08	4.27E+02	2.04	200	**2.13**	1.40E+08	6.99E+03
^{54}Mn	2.70E+07	1.07E+01	0.63	10	**1.07**	3.52E+06	3.52E+03
^{22}Na	8.21E+07	3.06E+00	12.34	3	**1.02**	1.00E+06	3.34E+03
^{59}Ni	2.40E+12	1.46E+02	0.08	200	**0.73**	4.78E+07	2.39E+03
^{44}Sc	1.43E+04	4.80E+00	9.89	30	**0.16**	1.57E+06	5.24E+02
^{42}K	4.44E+04	5.07E-01	50.92	20	**0.03**	1.66E+05	8.30E+01
^{32}P	1.23E+06	9.86E-02	33.33	4	**0.02**	3.23E+04	8.08E+01
^{57}Co	2.35E+07	1.19E+00	0.58	50	**0.02**	3.91E+05	7.82E+01
^{49}V	2.84E+07	6.13E+00	0.66	600	**0.01**	2.01E+06	3.35E+01
TOTAL		**7.38E+04**				**2.42E+10**	

Table 28: List of radioactive isotopes within ***stainless steel*****,** ***10 years*** *(****September 2014****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 330 kg	Multiple of 100 L_E
^{63}Ni	3.16E+09	8.85E+03	0.15	70	**126.37**	2.90E+09	4.14E+05
^{59}Ni	2.40E+12	1.46E+02	0.08	200	**0.73**	4.78E+07	2.39E+03
^{44}Ti	1.89E+09	1.34E+00	9.89	2	**0.67**	4.40E+05	2.20E+03
^{44}Sc	1.43E+04	1.34E+00	9.89	30	**0.04**	4.40E+05	1.47E+02
^{60}Co	1.66E+08	3.83E-02	1.49	1	**0.04**	1.25E+04	1.25E+02
^{32}P	1.23E+06	6.86E-02	33.33	4	**0.02**	2.25E+04	5.62E+01
^{3}H	3.89E+08	2.71E+00	2.04	200	**0.01**	8.87E+05	4.44E+01
TOTAL		**9.00E+03**				**2.95E+09**	

Table 29: List of radioactive isotopes within ***stainless steel*****,** ***100 years*** *(****September 2104****) after the last radiation.*

Tables 30 to 33 compare the activity concentration *a* and total activity *A* of isotopes produced in the considered **cooling water**. Results are limited to isotopes with a multiple of L_E superior to 0.01

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 800 kg	Multiple of 100 L_E
^{3}H	3.89E+08	4.86E+03	0.40	200.00	**24.32**	3.89E+09	1.95E+05
^{14}C	1.80E+11	6.23E+00	0.29	20.00	**0.31**	4.99E+06	2.49E+03
^{7}Be	4.60E+06	3.96E+00	0.98	400.00	**0.01**	3.17E+06	7.93E+01
TOTAL		**4.87E+03**				**3.90E+09**	

Table 30: List of radioactive isotopes within ***cooling water****,* ***1 year 8 months*** *(****May 2006****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 800 kg	Multiple of 100 L_E
^{3}H	3.89E+08	4.51E+03	0.40	200.00	**22.53**	3.61E+09	1.80E+05
^{14}C	1.80E+11	6.23E+00	0.29	20.00	**0.31**	4.99E+06	2.49E+03
TOTAL		**4.51E+03**				**3.61E+09**	

Table 31: List of radioactive isotopes within ***cooling water****,* ***3 years*** *(****September 2007****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 800 kg	Multiple of 100 L_E
^{3}H	3.89E+08	3.05E+03	0.40	200.00	**15.25**	2.44E+09	1.22E+05
^{14}C	1.80E+11	6.23E+00	0.29	20.00	**0.31**	4.98E+06	2.49E+03
TOTAL		**3.06E+03**				**2.45E+09**	

Table 32: List of radioactive isotopes within ***cooling water****,* ***10 years*** *(****September 2014****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 800 kg	Multiple of 100 L_E
^{14}C	1.80E+11	6.16E+00	0.29	20.00	**0.31**	4.93E+06	2.46E+03
^{3}H	3.89E+08	1.94E+01	0.40	200.00	**0.10**	1.55E+07	7.75E+02
TOTAL		**2.55E+01**				**2.04E+07**	

Table 33: List of radioactive isotopes within ***cooling water****,* ***100 years*** *(****September 2104****) after the last radiation.*

Figures 23 to 27 show the average specific activity in multiple of L_E averaged over a thickness of 10 cm. Furthermore, the average specific activity is also expressed in multiple of L_E for the surrounding marble shielding (20 cm thickness) in front and behind the target and concrete all around (20 cm thickness), as well as for several cooling times.

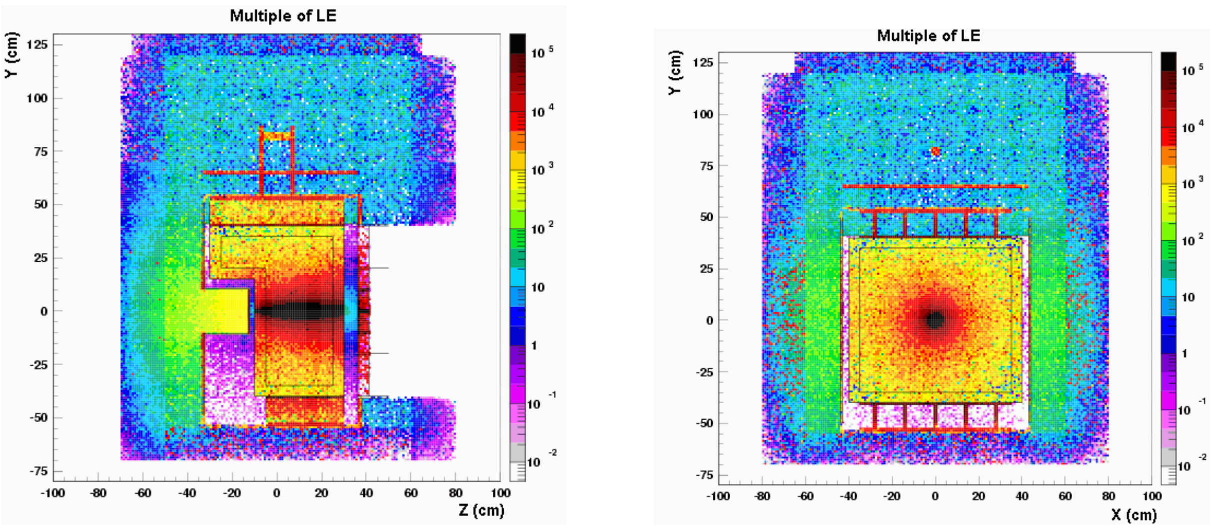


Figure 23: Specific Activity in Multiple of LE after a cooling time of ***1 year 8 months (May 2006)****. Side view (left) and front view (right).*

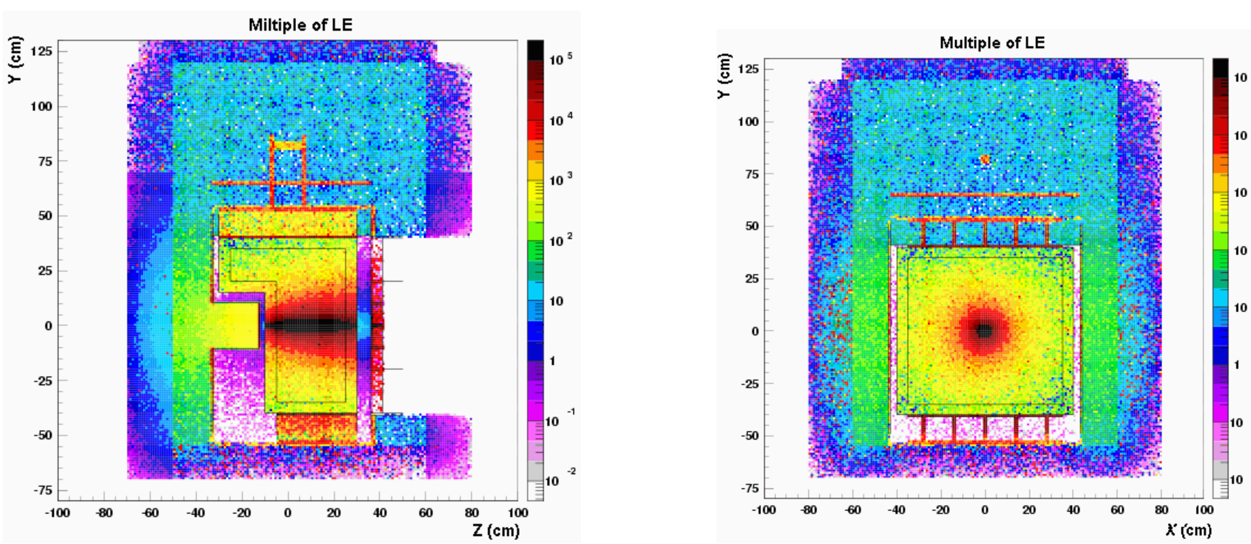


Figure 24: Specific Activity in Multiple of LE after a cooling time of ***3 years (September 2007)****. Side view (left) and front view (right).*

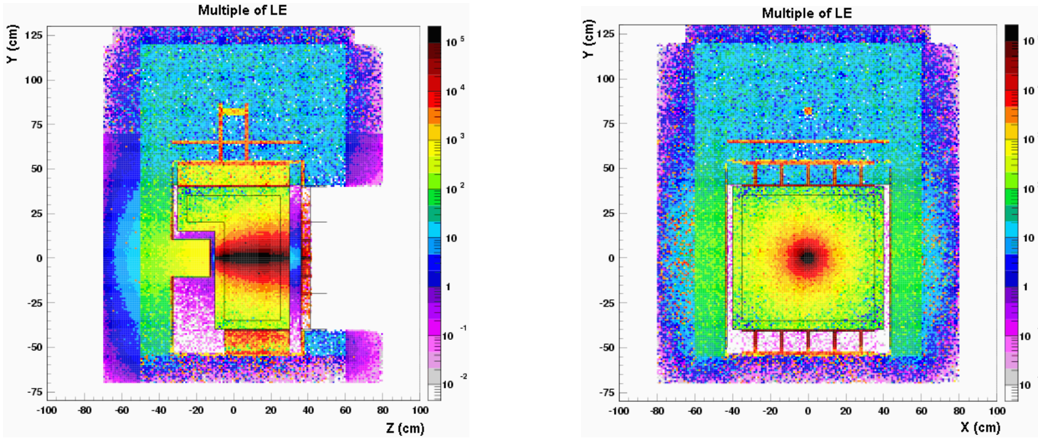


Figure 25: Specific Activity in Multiple of LE after a cooling time of ***3 years 8 months*** *(****May 2008****). Side view (left) and front view (right).*

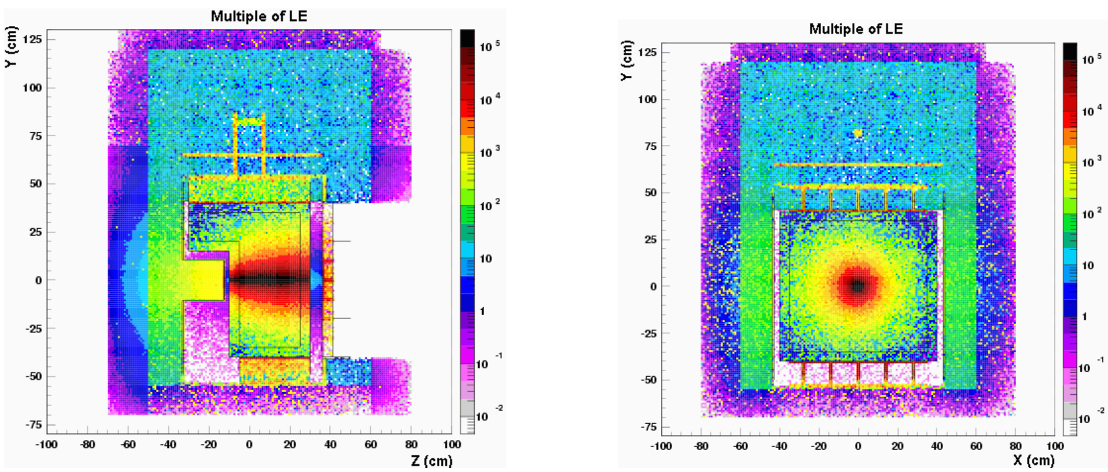


Figure 26: Specific Activity in Multiple of LE after a cooling time of ***10 years*** *(****September 2014****). Side view (left) and front view (right).*

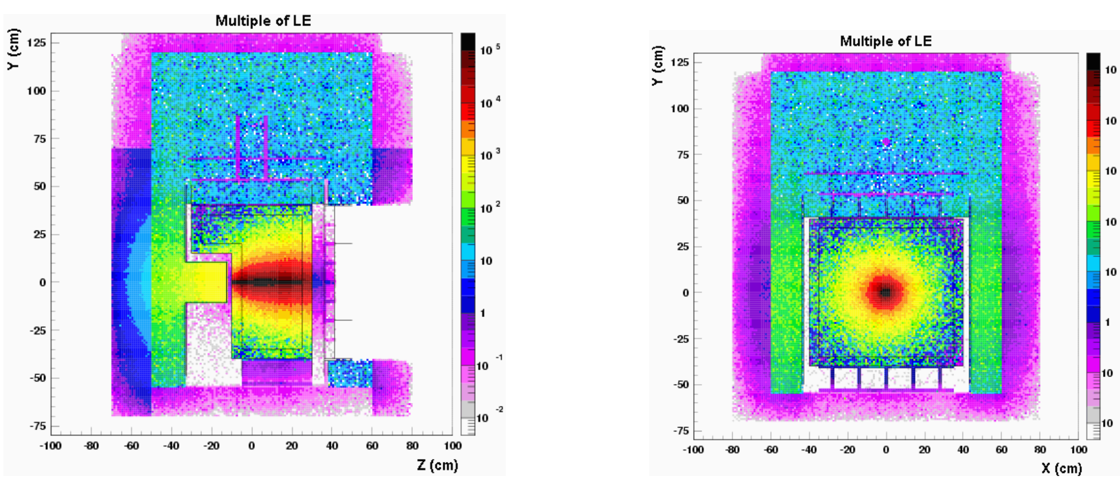


Figure 27: Specific Activity in Multiple of LE after a cooling time of ***100 years*** *(****September 2104****). Side view (left) and front view (right).*

In order to better understand previous results for the specific activity in certain components (Figures 18 to 21) and multiple of L_E (Figures 23 to 27) in the surrounding air, the following tables list the isotopes produced in **air** (see Tables 34 to 37) for several cooling times. Isotopes are classified by multiple of L_E and results are limited to those isotopes with a multiple of L_E superior to 0.01.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 1.75 kg	Multiple of 100 L_E
^{14}C	1.80E+11	3.82E+04	0.11	20.00	**1910.35**	6.70E+07	3.35E+04
^{3}H	3.89E+08	3.94E+03	2.78	200.00	**19.69**	6.91E+06	3.46E+02
^{35}S	7.56E+06	1.76E+00	40.82	10.00	**0.18**	3.08E+03	3.08E+00
TOTAL		**4.22E+04**				**7.40E+07**	

Table 34: List of radioactive isotopes within ***air****,* ***1 year 8 months*** *(****May 2006****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 1.75 kg	Multiple of 100 L_E
^{14}C	1.80E+11	3.82E+04	0.11	20.00	**1910.03**	6.70E+07	3.35E+04
^{3}H	3.89E+08	3.65E+03	2.78	200.00	**18.24**	6.40E+06	3.20E+02
TOTAL		**4.19E+04**				**7.34E+07**	

Table 35: List of radioactive isotopes within ***air****,* ***3 years*** *(****September 2007****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 1.75 kg	Multiple of 100 L_E
^{14}C	1.80E+11	3.82E+04	0.11	20.00	**1908.44**	6.70E+07	3.35E+04
^{3}H	3.89E+08	2.47E+03	2.78	200.00	**12.35**	4.33E+06	2.17E+02
TOTAL		**4.06E+04**				**7.13E+07**	

Table 36: List of radioactive isotopes within ***air****,* ***10 years*** *(****September 2014****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 1.75 kg	Multiple of 100 L_E
^{14}C	1.80E+11	3.78E+04	0.11	20.00	**1887.78**	6.62E+07	3.31E+04
^{3}H	3.89E+08	1.57E+01	2.78	200.00	**0.08**	2.75E+04	1.38E+00
TOTAL		**3.78E+04**				**6.63E+07**	

Table 37: List of radioactive isotopes within ***air****,* ***100 years*** *(****September 2104****) after the last radiation.*

It can be noticed that after a long cooling time, isotope ^{14}C remains present in air with a high specific activity, thus explaining the important specific activity in the air region as seen in Figures 18 to 27. Figures 28 to 30 show the isotope concentration of ^{14}C in multiple of L_E within the air around the target 3 years, 10 years and 100 years after the last radiation. Evidently such a concentration is purely virtual as the air volume is not tight, thus mixes with the surrounding structure. The presented results serve for a better understanding of previous results only.

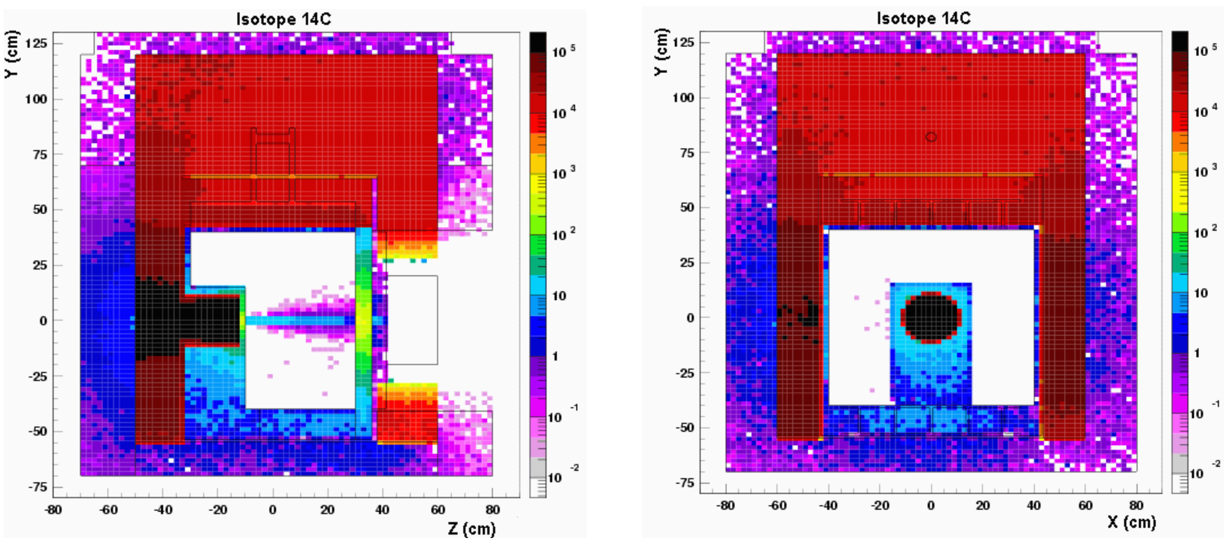


*Figure 28: Specific Activity in Multiple of LE for the isotope ^{14}C after a cooling time of **3 years** (**September 2007**). Side view (left) and front view (right).*

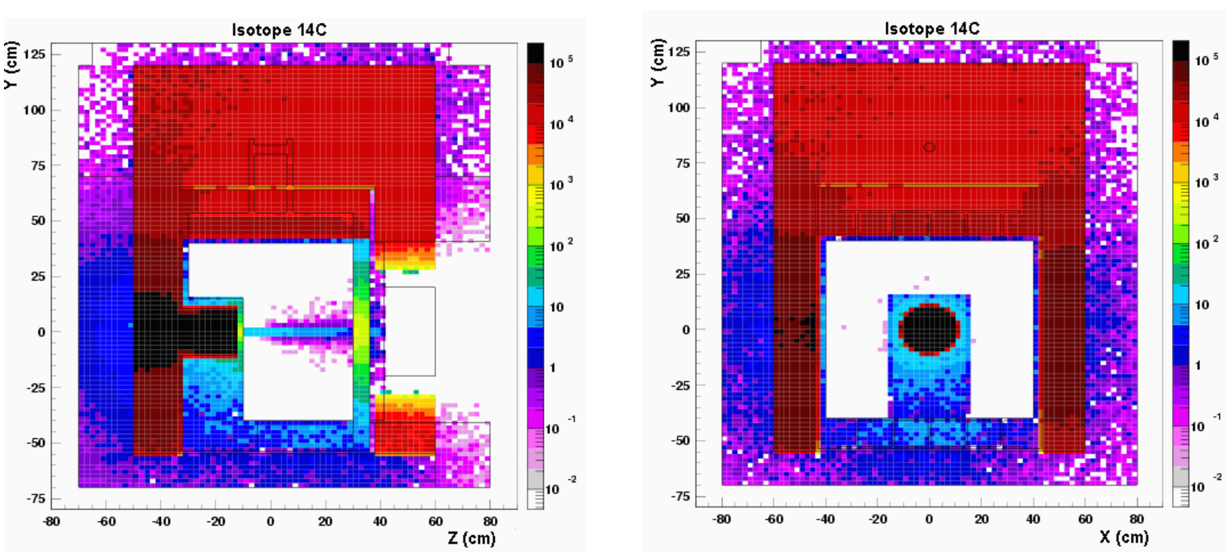


*Figure 29: Specific Activity in Multiple of LE for the isotope ^{14}C after a cooling time of **10 years** (**September 2014**). Side view (left) and front view (right).*

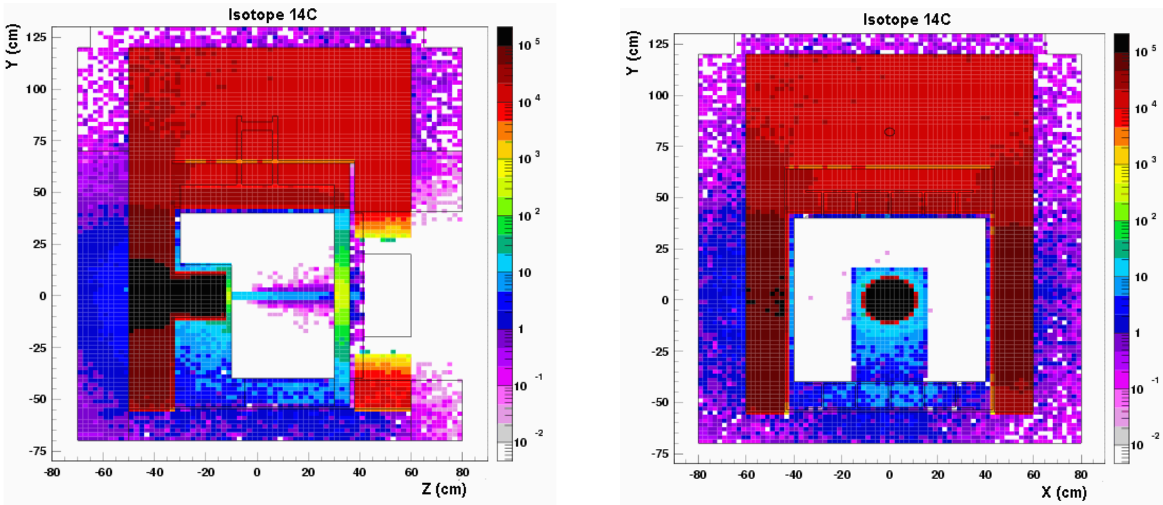


Figure 30: Specific Activity in Multiple of LE for the isotope ^{14}C after a cooling time of ***100 years (September 2104****). Side view (left) and front view (right).*

It can be seen that even after a long cooling time of 100 years ^{14}C remains an important contributor to the activity in air (see also Tables 34 to 37). For comparison, Figure 31 shows the time evolution of ^{14}C and ^{3}H in terms of their specific activity and multiple of L_E in air.

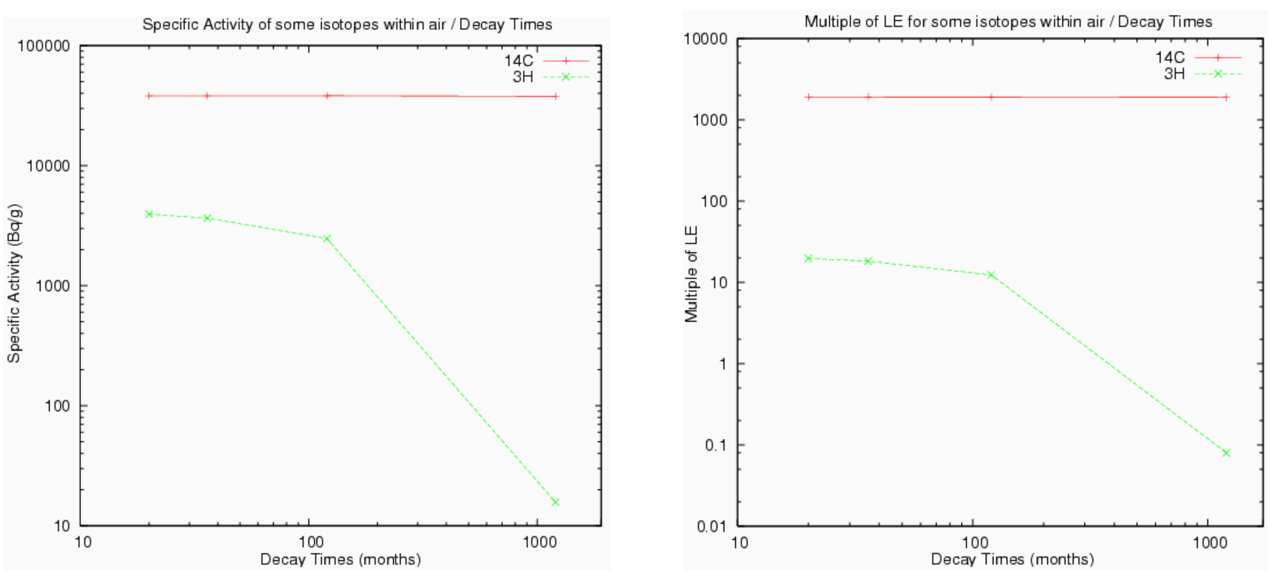


Figure 31: Graphs showing evolution in time of isotopes 14C and 3H within air. Specific activity (left) and multiple of LE (right).

Tables 38 to 41 show radioactive isotopes produced in **marble** for several cooling times. Isotopes are classified by multiple of L_E. Results are limited to isotopes with a multiple of L_E superior to 0.01.

Isotope	**T 1/2 (s)**	**Specific activity a (Bq/g)**	**Error statistic (%)**	**Exemption Limit L_E (Bq/g)**	**Multiple of L_E**	**Total activity *A* (Bq) in 1842 kg**	**Multiple of 100 L_E**
^{45}Ca	1.41E+07	6.69E+03	0.11	10.00	**668.59**	1.23E+10	1.23E+07
^{22}Na	8.21E+07	1.04E+01	5.07	3.00	**3.46**	1.91E+07	6.36E+04
^{3}H	3.89E+08	5.72E+02	0.25	200.00	**2.86**	1.05E+09	5.26E+04
^{41}Ca	3.22E+12	3.90E+01	0.13	30.00	**1.30**	7.18E+07	2.39E+04
^{35}S	7.56E+06	2.05E+00	1.46	10.00	**0.21**	3.78E+06	3.78E+03
^{14}C	1.80E+11	5.96E-01	0.49	20.00	**0.03**	1.10E+06	5.49E+02
^{42}K	4.44E+04	3.68E-01	8.16	20.00	**0.02**	6.77E+05	3.38E+02
^{32}P	1.23E+06	3.91E-02	14.60	4.00	**0.01**	7.20E+04	1.80E+02
TOTAL		**7.32E+03**				**1.35E+10**	

*Table 38: List of radioactive isotopes within **marble**, **1 year 8 months** (**May 2006**) after the last radiation.*

Isotope	**T 1/2 (s)**	**Specific activity a (Bq/g)**	**Error statistic (%)**	**Exemption Limit L_E (Bq/g)**	**Multiple of L_E**	**Total activity *A* (Bq) in 1842 kg**	**Multiple of 100 L_E**
^{45}Ca	1.41E+07	8.20E+02	0.11	10.00	**81.96**	1.51E+09	1.51E+06
^{3}H	3.89E+08	5.30E+02	0.25	200.00	**2.65**	9.75E+08	4.88E+04
^{22}Na	8.21E+07	7.22E+00	5.07	3.00	**2.41**	1.33E+07	4.43E+04
^{41}Ca	3.22E+12	3.90E+01	0.13	30.00	**1.30**	7.18E+07	2.39E+04
^{14}C	1.80E+11	5.96E-01	0.49	20.00	**0.03**	1.10E+06	5.49E+02
^{42}K	4.44E+04	3.57E-01	8.16	20.00	**0.02**	6.58E+05	3.29E+02
^{32}P	1.23E+06	3.89E-02	14.60	4.00	**0.01**	7.16E+04	1.79E+02
TOTAL		**1.41E+03**				**2.60E+09**	

*Table 39: List of radioactive isotopes within **marble**, **3 years** (**September 2007**) after the last radiation.*

Isotope	**T 1/2 (s)**	**Specific activity a (Bq/g)**	**Error statistic (%)**	**Exemption Limit L_E (Bq/g)**	**Multiple of L_E**	**Total activity *A* (Bq) in 1842 kg**	**Multiple of 100 L_E**
^{3}H	3.89E+08	3.58E+02	0.25	200.00	**1.79**	6.60E+08	3.30E+04
^{41}Ca	3.22E+12	3.90E+01	0.13	30.00	**1.30**	7.18E+07	2.39E+04
^{22}Na	8.21E+07	1.14E+00	5.07	3.00	**0.38**	2.09E+06	6.97E+03
^{14}C	1.80E+11	5.95E-01	0.49	20.00	**0.03**	1.10E+06	5.48E+02
^{42}K	4.44E+04	3.09E-01	8.16	20.00	**0.02**	5.68E+05	2.84E+02
^{32}P	1.23E+06	3.78E-02	14.60	4.00	**0.01**	6.96E+04	1.74E+02
TOTAL		**4.13E+02**				**7.60E+08**	

*Table 40: List of radioactive isotopes within **marble**, **10 years** (**September 2014**) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 1842 kg	Multiple of 100 L_E
^{41}Ca	3.22E+12	3.89E+01	0.13	30.00	**1.30**	7.17E+07	2.39E+04
^{14}C	1.80E+11	5.89E-01	0.49	20.00	**0.03**	1.08E+06	5.42E+02
^{3}H	3.89E+08	2.28E+00	0.25	200.00	**0.01**	4.19E+06	2.10E+02
^{32}P	1.23E+06	2.63E-02	14.60	4.00	**0.01**	4.84E+04	1.21E+02
TOTAL		**5.20E+01**				**9.57E+07**	

Table 41: List of radioactive isotopes within ***marble****,* ***100 years*** *(****September 2104****) after the last radiation.*

Finally, Tables 42 to 45 summarize the radioactive isotopes produced within the surrounding **concrete** structure (only the first 20cm of depths) for several cooling times. Isotopes are classified by multiple of L_E and limited to those with a multiple of L_E superior to 0.01.

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 3820 kg	Multiple of 100 L_E
^{55}Fe	8.64E+07	5.23E+03	0.16	30.00	**174.29**	2.00E+10	6.65E+06
^{22}Na	8.21E+07	4.23E+02	0.41	3.00	**141.10**	1.62E+09	5.39E+06
^{45}Ca	1.41E+07	7.07E+02	0.15	10.00	**70.74**	2.70E+09	2.70E+06
^{54}Mn	2.70E+07	4.00E+01	1.22	10.00	**4.00**	1.53E+08	1.53E+05
^{3}H	3.89E+08	3.94E+02	0.26	200.00	**1.97**	1.51E+09	7.53E+04
^{41}Ca	3.22E+12	4.11E+00	0.12	30.00	**0.14**	1.57E+07	5.23E+03
^{35}S	7.56E+06	3.38E-01	3.67	10.00	**0.03**	1.29E+06	1.29E+03
^{14}C	1.80E+11	6.01E-01	0.38	20.00	**0.03**	2.29E+06	1.15E+03
^{49}V	2.84E+07	6.61E+00	2.38	600.00	**0.01**	2.52E+07	4.21E+02
^{59}Fe	3.84E+06	4.25E-02	0.63	6.00	**0.01**	1.62E+05	2.70E+02
^{44}Ti	1.89E+09	1.19E-02	23.08	2.00	**0.01**	4.53E+04	2.27E+02
TOTAL		**6.85E+03**				**2.62E+10**	

Table 42: List of radioactive isotopes within ***concrete****,* ***1 year 8 months*** *(****May 2006****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 3820 kg	Multiple of 100 L_E
^{55}Fe	8.64E+07	3.70E+03	0.16	30.00	**123.44**	1.41E+10	4.71E+06
^{22}Na	8.21E+07	2.95E+02	0.41	3.00	**98.24**	1.13E+09	3.75E+06
^{45}Ca	1.41E+07	8.67E+01	0.15	10.00	**8.67**	3.31E+08	3.31E+05
^{3}H	3.89E+08	3.65E+02	0.26	200.00	**1.83**	1.40E+09	6.98E+04
^{54}Mn	2.70E+07	1.33E+01	1.22	10.00	**1.33**	5.07E+07	5.07E+04
^{41}Ca	3.22E+12	4.11E+00	0.12	30.00	**0.14**	1.57E+07	5.23E+03
^{14}C	1.80E+11	6.01E-01	0.38	20.00	**0.03**	2.29E+06	1.15E+03
^{44}Ti	1.89E+09	1.16E-02	23.08	2.00	**0.01**	4.44E+04	2.22E+02
TOTAL		**4.49E+03**				**1.71E+10**	

Table 43: List of radioactive isotopes within ***concrete****,* ***3 years*** *(****September 2007****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 3820 kg	Multiple of 100 L_E
^{55}Fe	8.64E+07	6.35E+02	0.16	30.00	**21.18**	2.43E+09	8.09E+05
^{22}Na	8.21E+07	4.64E+01	0.41	3.00	**15.46**	1.77E+08	5.90E+05
^{3}H	3.89E+08	2.47E+02	0.26	200.00	**1.24**	9.44E+08	4.72E+04
^{41}Ca	3.22E+12	4.11E+00	0.12	30.00	**0.14**	1.57E+07	5.23E+03
^{14}C	1.80E+11	6.00E-01	0.38	20.00	**0.03**	2.29E+06	1.15E+03
^{44}Ti	1.89E+09	1.06E-02	23.08	2.00	**0.01**	4.03E+04	2.01E+02
TOTAL		**9.40E+02**				**3.59E+09**	

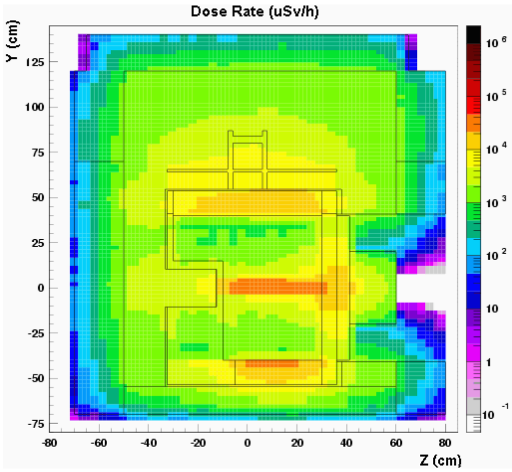
Table 44: List of radioactive isotopes within ***concrete****,* ***10 years*** *(****September 2014****) after the last radiation.*

Isotope	T 1/2 (s)	Specific activity a (Bq/g)	Error statistic (%)	Exemption Limit L_E (Bq/g)	Multiple of L_E	Total activity *A* (Bq) in 3820 kg	Multiple of 100 L_E
^{41}Ca	3.22E+12	4.11E+00	0.12	30.00	**0.14**	1.57E+07	5.23E+03
^{14}C	1.80E+11	5.94E-01	0.38	20.00	**0.03**	2.27E+06	1.13E+03
^{3}H	3.89E+08	1.57E+00	0.26	200.00	**0.01**	6.00E+06	3.00E+02
TOTAL		**1.13E+01**				**4.33E+07**	

Table45: List of radioactive isotopes within ***concrete****,* ***100 years*** *(****September 2104****) after the last radiation.*

Residual Dose Rate

Figures 32 to 36 show average residual dose rate distribution (μSv/h) in a thickness of 80 cm corresponding to the dimension of the target, for several cooling times.



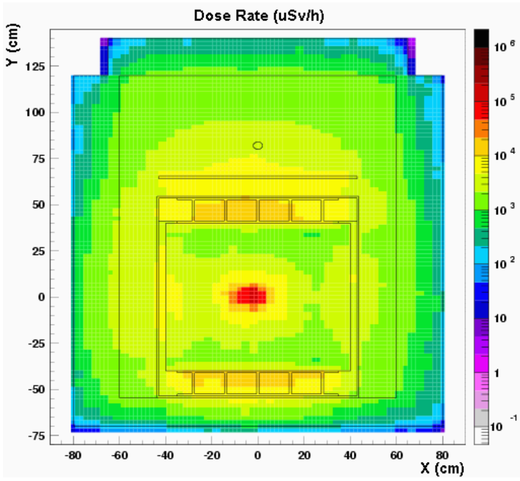
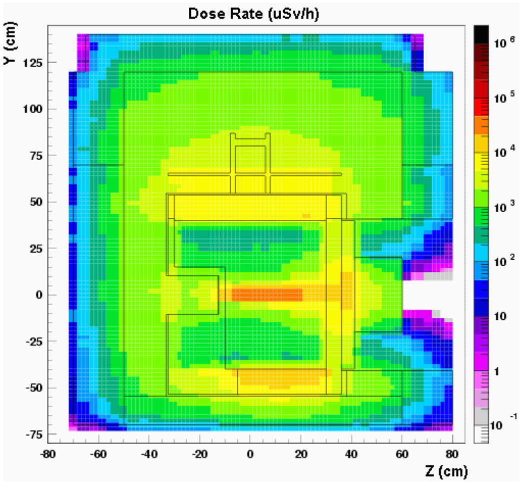


Figure 32: Dose Rate in μSv/h after a cooling time of ***1 year 8 months (May 2006****). Side view (left) and front view (right).*



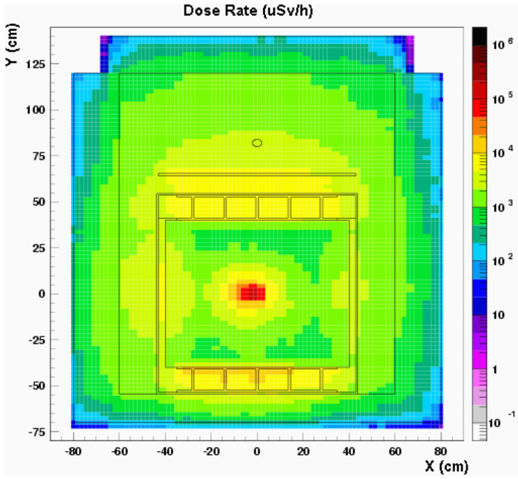


Figure 33: Dose Rate in μSv/h after a cooling time of ***2 years 8 months (May 2007****). Side view (left) and front view (right).*

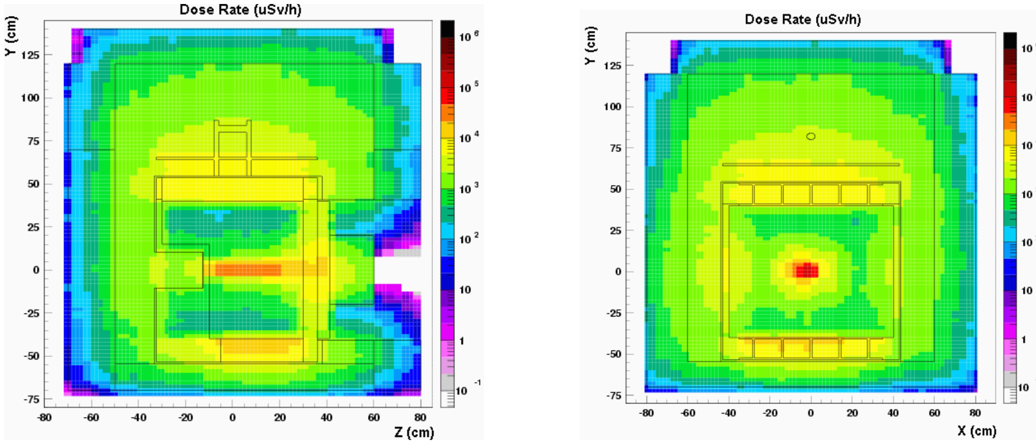


Figure 34: Dose Rate in µSv/h after a cooling time of ***3 years (September 2007)****. Side view (left) and front view (right).*

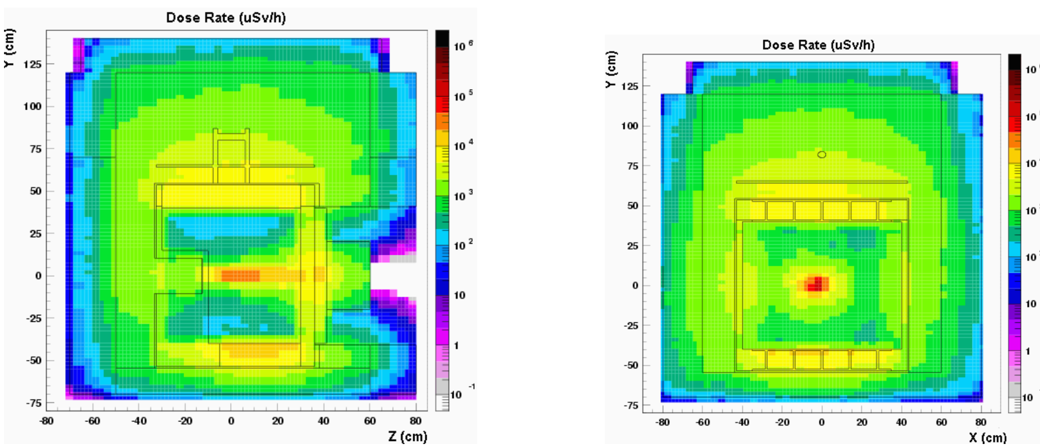


Figure 35: Dose Rate in µSv/h after a cooling time of ***3 years 8 months (May2008)****. Side view (left) and front view (right).*

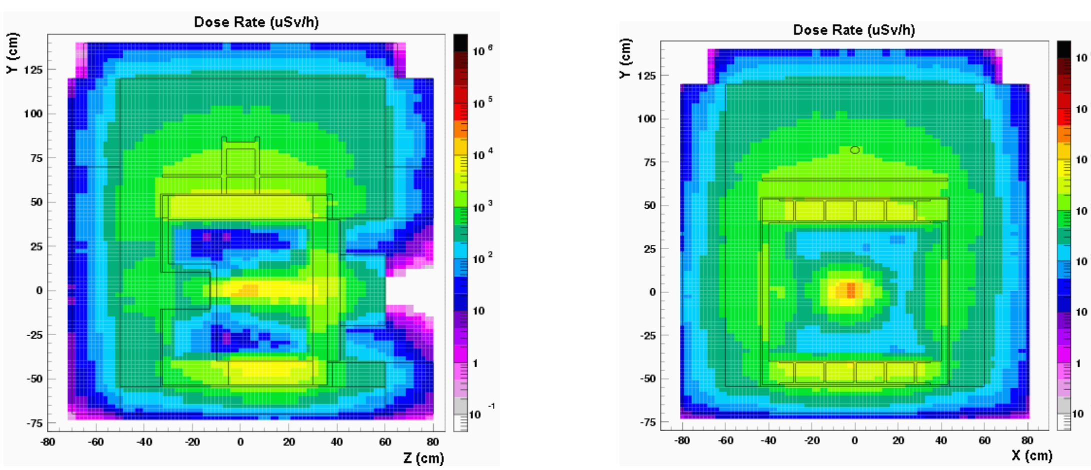


Figure 36: Dose Rate in µSv/h after a cooling time of ***10 years (September 2014)****. Side view (left) and front view (right).*

For a better representation of the residual dose rate peaks Figures 37 to 41 show the residual dose rate distributions (μSv/h) averaged only over a thickness of 10 cm along the centre of the target, again for the same previous cooling times.

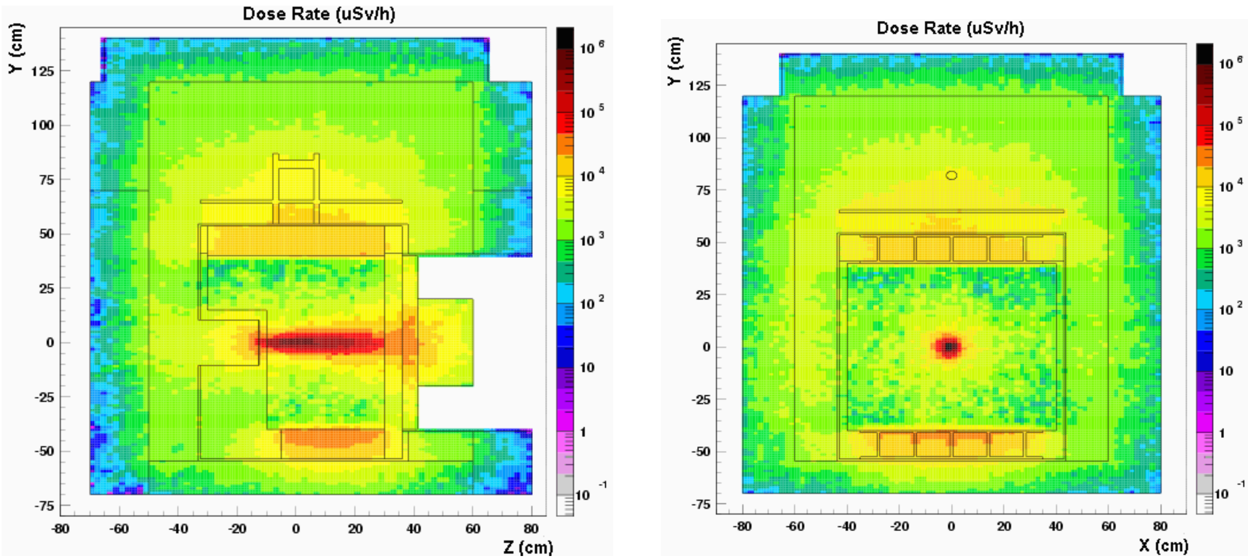


Figure 37: Dose Rate in μSv/h after a cooling time of ***1 year 8 months (May 2006)****. Side view (left) and front view (right).*

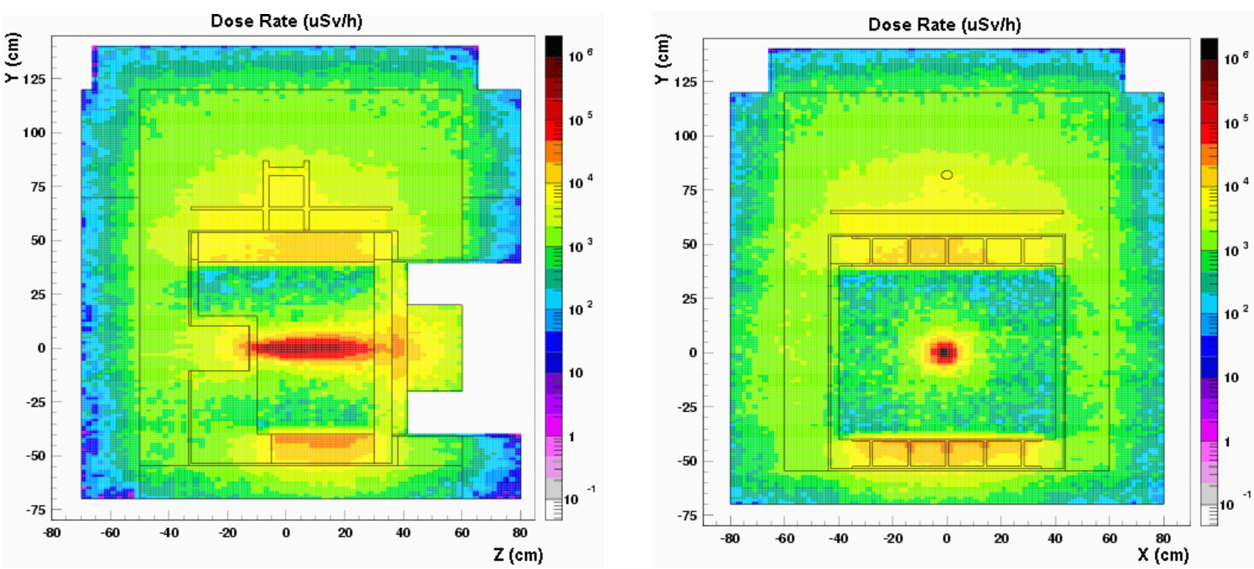


Figure 38: Dose Rate in μSv/h after a cooling time of ***2 years 8 months (May 2007)****. Side view (left) and front view (right).*

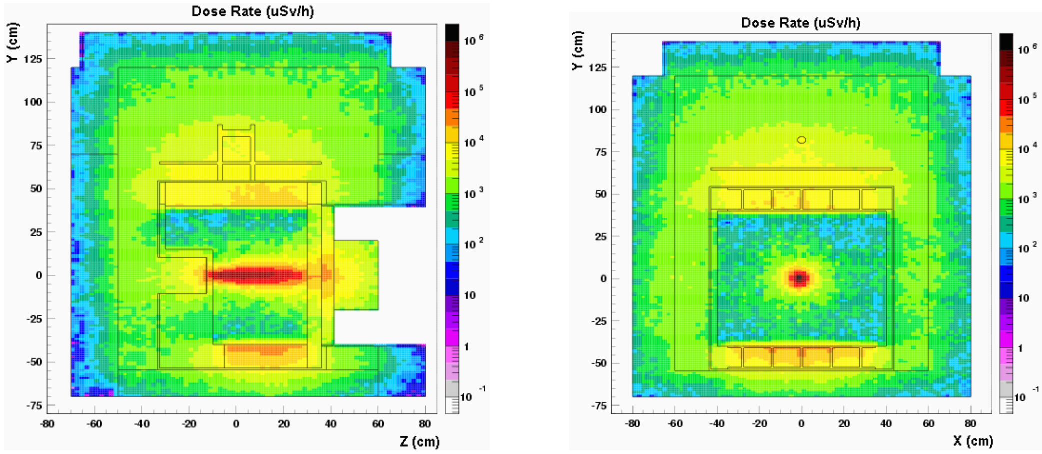


Figure 39: Dose Rate in µSv/h after a cooling time of ***3 years (September 2007)****. Side view (left) and front view (right).*

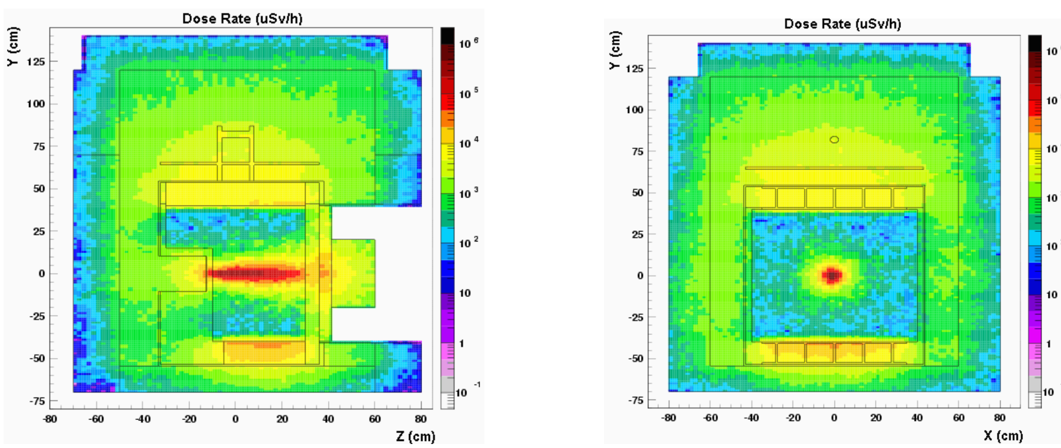


Figure 40: Dose Rate in µSv/h after a cooling time of ***3 years 8 months (May2008)****. Side view (left) and front view (right).*

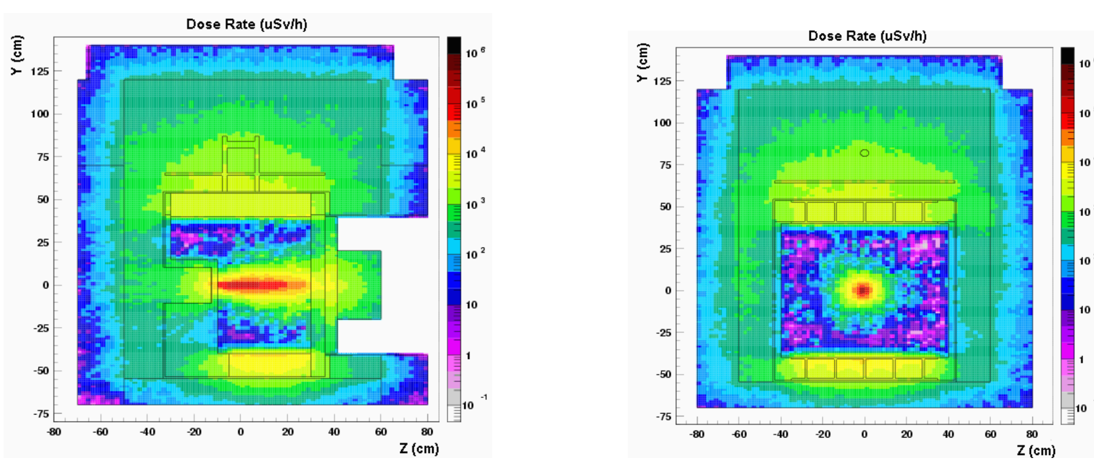


Figure 41: Dose Rate in µSv/h after a cooling time of ***10 years (September 2014)****. Side view (left) and front view (right).*