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Drainage of runoff water from 157_2 into157_1 via a stream – Biosphere complementary information for SR-PSU

1.1 Introduction

Uncertainties with respect to the size, configuration and development of areas affected by radionuclides in the far future will inevitably be large. In SR-PSU a limited set of biosphere objects were used to evaluate consequences of a radionuclide release to aquatic and terrestrial ecosystems, considering a broad repertoire of human land use variants.

The spatial distribution of discharge points (from hydrogeological calculations) and the reference evolution of the biosphere (from landscape modelling) were the starting points for defining the main biosphere calculation case in SR-PSU (BCC1) (**Biosphere synthesis report**, Section 7.4). In this calculation case the landscape is represented by a chain of three biosphere objects once the area has emerged from the sea, and direct discharge of radionuclides from the repository is restricted to the first object in the chain (157_2). From this mire area radionuclides are exported to a small down-stream lake mire complex (157_1), through runoff via a diffuse overland water flow, and radionuclides finally reach a large lake (116) with stream water.

The effects of uncertainties with respect to the location of the release in the landscape and the properties of the discharge area were examined in separate calculation cases. In BCC6, SKB examined the effects of spatial dispersion of the release over the landscape, and the calculation case included direct discharge of radionuclides to several lake objects in the landscape (**Biosphere synthesis report**, Sections 7.4 and 10.4). In BCC7, effects of uncertainties associated with the size and delineation of the primary discharge area (157_2) were examined, and the calculations included joint spatial variation with respect to regolith depth/stratigraphy and groundwater flow rates (**Biosphere synthesis report**, Sections 7.4 and 10.8).

The reference evolution of the landscape has been constructed to give as a reasonable representation of the future landscape above the repository and reflects the present site description and SKB's understanding of landscape developing processes. Given the present topography, it was deemed unlikely that a lake would form and persist for an extended period of time in the primary discharge area, i.e. object 157_2 (Brydsten and Strömgren 2013, Section 2.5). Thus in BCC1, potential human dose consequences of radionuclides reaching lake ecosystems were instead evaluated in the down-stream objects 157_1 and 116. Landscape analysis of the topography also suggested the mean runoff of from the wetland in 157_2 would be insufficient to support a stream (Brydsten and Strömgren 2013, Section 2.7.4). The flow of shallow groundwater water from the wetland in 157_2 to the down-stream lake-mire complex in 157_1 was conceptualized as a diffuse outflow of overland-water (Werner et al. 2013, Section 6.2.3). Consequently no stream was implemented in the biosphere model (Saetre et al. 2013, Section 4.3.2). Nevertheless wetland runoff-water from object 157_2 was cautiously utilized as drinking water for humans and livestock in exposure calculations (Saetre et al. 2013, Sections 9.3 and 9.4).

To examine the sensitivity of the modelled ground water hydrology of object 157_2 to the chosen representation of the transport of runoff water, a stream was added to a separate MIKE SHE model setup (Werner et al. 2013, Section 7.5.2). The sensitivity calculations demonstrated that the added stream pathway had a limited effect on the water balance components of object 157_2. However as a stream inlet by-passes the wetland area surrounding a down-stream lake in SKB's conceptual and numerical biosphere model (e.g. Saetre et al. 2013, Figure 4.1), the dose effects of connecting the two objects 157_2 and 157_1 with a stream were examined in this study.
The reference evolution does not include large scale human modifications of the landscape which could affect the hyrological regime. Thus a direct release of deep groundwater to a stream has not been considered as a plausible event in SKB's FEP-analysis. However, a large scale draining enterprise (e.g. for forestry purposes) can be postulated as a potential future human action. SKB has no estimates how large proportion of the discharge that could reasonably be discharged into stream of a deep man-made ditch, and SKB's biosphere model has not been parametrized to explicitly describe transport in stream ecosystem (which tend to be hot-spots of degassing). Nevertheless, an upper boundary for consequences under such conditions can be calculated by assuming that all radionuclides are discharged to the stream connecting 157_2 1nd 157_1, and by cautiously representing degassing of C-14 from stream water by conditions of non-running water (used in the regular biosphere model).

1.2 Methods

To study the potential effects of the presence of a stream between object 157_2 and 157_1, the biosphere model was updated so that runoff water from object 157_2 was directly discharged into the lake/stream water of object 157_1 (without passing any of the mire areas bordering the open lake). Apart from this modification, the model was structurally identical to that used in BCC1.
Hydrological parameters for object 157_2 were updated to reflect the presence of the stream (Figure 1). As the modified MIKE SHE / MIKE 11 simulation was only run for one time slice (5000 AD), the same water flux parameters were used to represent surface hydrology in object 157_2 at all times after lake isolation in the present calculations. The length of the added stream was taken to be 180 m (Werner et al. 2013, Figure 7-18), and the stream width was estimated to be 0.5 m, (based on an empirical relationship between stream width and watershed area of small streams). As the other small streams in the area, the stream in 157_2 was assumed to be shallow (<1 m), and consequently could not support any sustainable production of edible fish and cray-fish.

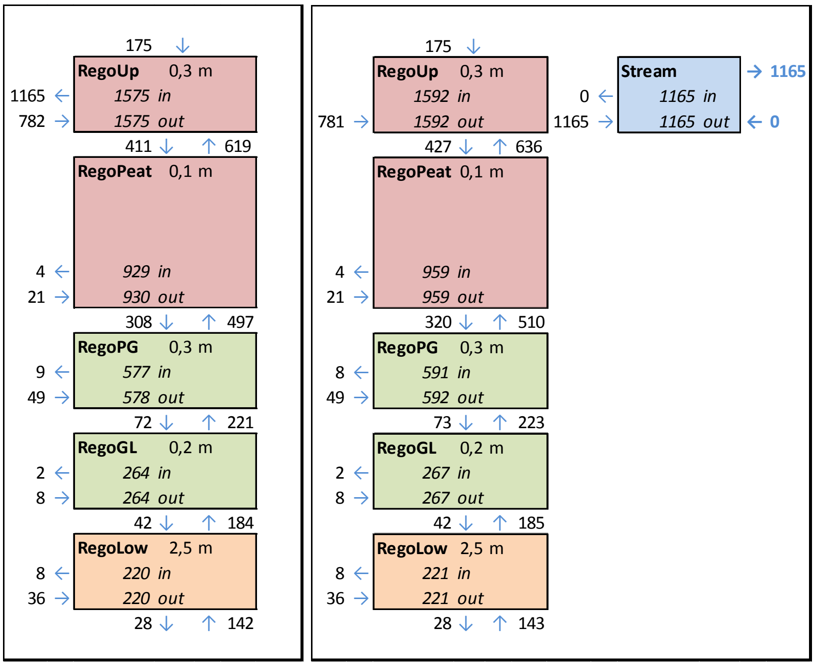


Figure 1. *Water-flux components for five regolith compartments of object 157_2 used to parameterise the radionuclide model. Left) Area specific groundwater flux used in the original model (base) at point of isolation. Corresponding parameter values are listed in Table D-1 in Grolander 2013. Right) Area specific groundwater flux for the stream model (derived from Werner et al. 2013, Figure A1-56). Flux rates are given in units of mm year^{-1}.*

Transport and accumulation of radionuclides were simulated for the temperate climate conditions and the landscape development assumed under the global warming climate case (i.e. the conditions used in BCC1). Two release scenarios were evaluated. A) a unit release of each of 55 radionuclides to object 157_2 between 2000 and 20,000 resulting in *LDF-values*[1], and B) a time varying deterministic release to object 157_2 between 2000 and 102,000 (radionuclide release from the geosphere from the deterministic simulation of the *global warming calculation case* (CCM_GW) reported in Section 8.3.1 of the **Main report**, also described in more details in Section 4.1.1 of the **Radionuclide transport report**) resulting in a total dose. For the second release scenario a variant where all radionuclides were released directly to the stream-water was also considered. This variant is considered to set the upper boundary for consequences from radio-carbon given a deep man-made ditch draining biosphere object 157_2.

1.3 Results and discussion

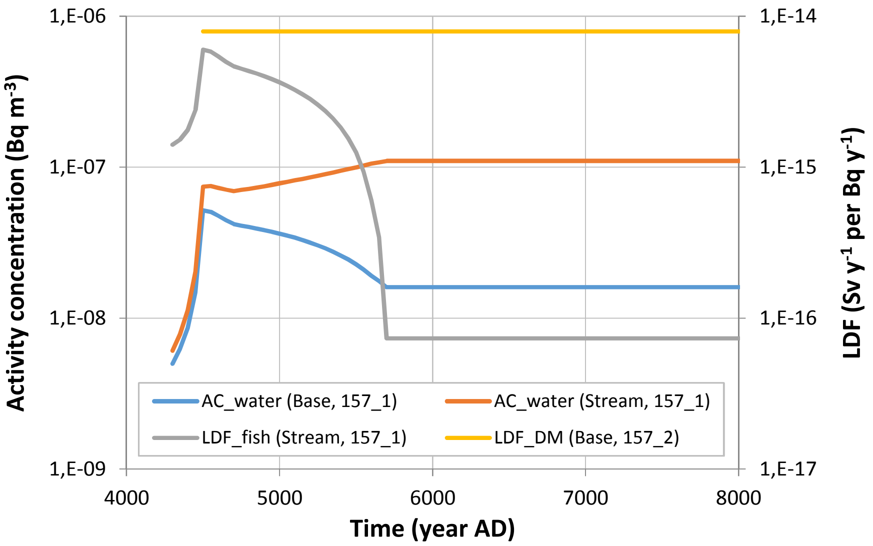
The added stream had limited effect on groundwater flux in the up-stream mire (157_2) at the examined time slice, and individual parameters describing the vertical flux rates (mm year^{-1}) in the mire of 157_2 deviated less than 4% between the case with and without a stream (left and right panel in Figure 1). Thus the two first calculations primarily illustrates how the type of surface water connection between the two objects affects activity concentrations and calculated dose in the down-stream object (157_1). In the last variant radionuclides enters surface water without passage through wetland areas, where degassing of CO_2 is effective.

[1] The analysed radionuclides were the ones for which LDF-values had been calculated in BCC1 as reported in **Biosphere synthesis report**, Table 10-1. To make LDF-values comparable to those previously reported in SR-PSU, ingrowth of radioactive daughters was not accounted for in the unit release calculations.

This calculation sets an upper bound on C-14 concentration in surface water and the dose from radiocarbon in aquatic food.

1.3.1 LDF-values

As expected from the small effect on water-balance components, the values and time point for the maximum LDF-value of most radionuclides were marginally affected by adding a stream (Appendix 1), and the land-use resulting in the highest LDF-value was unaffected. The maximum LDF-value resulted from draining and cultivating the mire, and values were always highest in object 157_2. LDF-values were typically within 5% of the values from the original calculations[2]. For a few radionuclides the LDF-value increased (maximum values were 17% and 14% for C-14 and Cl-36) and for some the LDF-value decreased (at most 20% for Ag-108m, external exposure). The deviations between the stream and the original calculations were primarily driven by a short-coming of the data used to parametrize the stream model. That is, in the stream calculations one set of groundwater parameters were used throughout the terrestrial simulations (representing stable groundwater conditions). In the original calculations two sets of groundwater parameters were estimated for the land period, one for the time of isolation and one for the time of mire completion (Grolander 2013, Appendix D-1). When the base model was parametrised with stable groundwater fluxes throughout the terrestrial period, the difference in maximum LDF-values between the base and stream model was within a few percent for all radionuclides (data not shown).
With a stream added, discharge water from object 157_2 reached the open water in 157_1 without having to pass the mire component of the down-stream object. This resulted in a reduced accumulation of all radionuclides in peat in the down-stream object (data not shown). Moreover, degassing of C-14 from surface and groundwater was also reduced. Thus adding a stream resulted in an increased activity concentration of C-14 in lake water (Figure 2). In the early lake stage C-14 concentration in water was only marginally higher in the stream calculation than in the original calculations, reflecting that only a limited part of the lake had been covered by ingrowth of mire vegetation. However, the effects of a reduced degassing becomes larger as mire vegetation expands into the lake with time; At 5000 AD the activity concentration of lake water was twice as high in the model with the stream as in the original model, and the relative difference increased to a factor 7 at the time when mire ingrowth was completed.



[2] Typically refers to the range between 25th to 75th percentile of the distribution of deviations in LDF-values from 57 examined radionuclides.

Figure 2. C-14 *activity concentration in surface water and LDF-values in two connected biosphere objects. C-14 concentrations in the surface water (lake or stream) of the down-stream object (157_1) are shown for two calculation cases: the base model used in the SR-PSU assessment (blue line), and the stream model in which all runoff water from the up-stream object (157_2) is discharged to the down-stream object via stream water (red line). The grey line represents LDF-values for a family consuming all fish produced in the recipient lake (157_1) from the stream model, and the LDF-value from the original (base) model, used in the safety assessment, is given as a point of reference (yellow line, Avila et al. 2010, Table 10-1).*

The increased C-14 water concentration could potentially lead to an elevated LDF for C-14, as consumption of fish is an important exposure pathway for radiocarbon. However, the size of the downstream lake did only allow for a limited production of fish, and the potential dose from consuming fish in object 157_1 did not exceed that from draining and cultivating the upstream object (in the original model) at any point in time (Figure 2). That is, even if all fish produced in the lake was consumed by one family (5 adult individuals), fish production could only account for 3% of the dietary carbon at the point of lake isolation (when the LDF-value for this small group peaked)[3]. The fact that fish production decrease as the area of the lake is reduced, explains why the LDF-value from fish consumption decrease with time after isolation, although the activity concentration in the lake water increase (grey and orange lines in Figure 2).

1.3.2 Dose from the deterministic CCM_GW release

Similar to the LDF-results, the effect of adding a stream connecting objects 157_2 and 157_1 had a marginal effect on the total dose in object 157_2 from a deterministic time varying release from SFR1 and SFR3 (red lines in Figure 3). That is, at peak dose levels (~ 5500 - 6500 AD) the total dose were no more than 10% higher in the stream model as compared to the original (base) model (Fig 3), and this difference was reduced to less than 1% when stable groundwater parameters were used for the terrestrial period in the base calculations (data not shown). Moreover, making the aquatic parts of object 157_1 the primary recipient of radionuclides in the runoff from 157_2 reduced the maximum dose in the down-stream object by more than an order of magnitude (blue line in Figure 3). That is, by-passing the wetland in the down-stream object with a stream resulted in significantly reduced accumulation of radionuclides in peat, and reduced the dose to humans from the down-stream object.

[3] A dietary fraction of 3% is comparable to the typical intake of fish and crayfish for a contemporary average diet in Sweden. Saetre P, Valentin J, Lagerås P, Avila R, Kautsky U, 2013. Land use and food intake of future inhabitants: outlining a representative individual of the most exposed group for dose assessment. Ambio 42, 488–496.

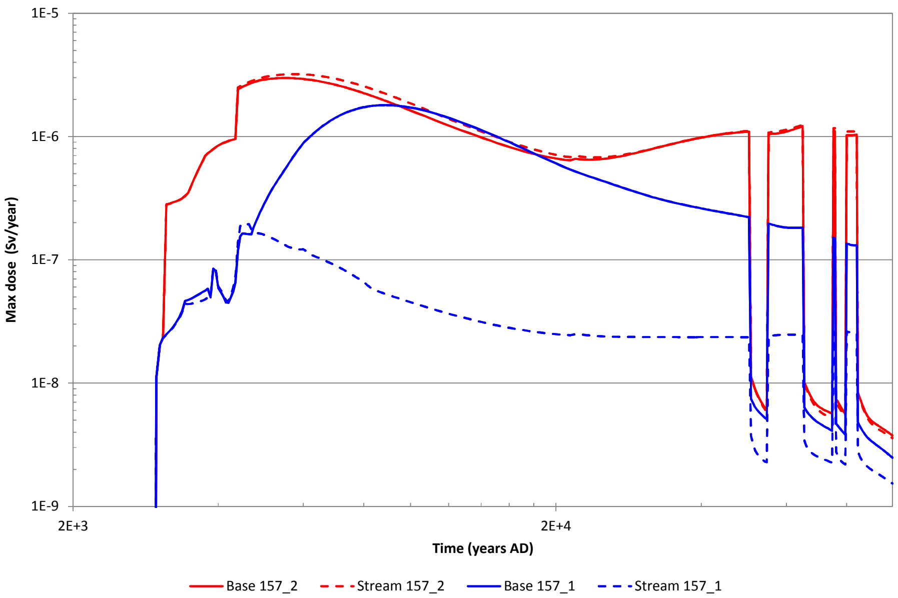


Figure 3. *Total dose from a time varying release from SFR1 and SFR3 as a function of time. The curves represents the maximum dose at any time across four different exposed groups, living in and utilising natural resources in the object 157_1 (blue) or object 157_2 (red). Solid lines represents results from the biosphere model used in the safety assessment (base), whereas dashed lines represents results from a model in which all runoff water from the up-stream object (157_2) is discharged to the down-stream object via stream water.*

Only in a narrow time window at lake isolation (when ingestion of C-14 from fish was the primary exposure pathway for hunter and gatherers) did the total dose from object 157_1 in the stream calculations exceed that from the same object in the original calculations (Figure 3). However, the total dose levels from object 157_1 at this point in time was much lower than the total dose from the upstream mire object (157_2), which corresponds to the dose calculations used in the safety assessment.

1.3.3 Direct release to the stream (bounding calculations)

Redirecting the geosphere release from the deepest regolith layer (till) to stream water clearly influenced the dose curves for both biosphere objects (dashed vs solid lines in Figure 4). This was not surprising as accumulation of radionuclides in regolith layers almost eliminated in the variant calculations, and surface water dominated human exposure. The peak dose occurred briefly after lake isolation, and was similar to the maximum dose from draining and cultivating the mire in the base calculation (used in the assessment). Thus uncertainties with respect to the groundwater pathways through the regolith layers are unlikely to have a significant effect on the assessed maximum dose.

As retention in regolith layers was highly reduced, exposure from C-14 dominated the dose through consumption of aquatic food and surface water. The most exposed group was a band of hunter and gatherers, which harvested all fish produced in the lake of object 157_1, and camped in either object 157_2 or in object 157_1. As groundwater did not pass any wetland in this calculation variant, degassing of C-14 prior to reaching lake 157_1 was greatly reduced. That is, at the time for the maximum dose, the C-14 concentration of discharging surface water from object 157_2 water was approximately 20 times higher in this variant than in the base case calculations, and the difference in the activity concentration of water in lake 157_1 was even greater. The dominance of C-14 in the calculated total dose can be seen in the shape of the dose-curve, which combines the shark fin shaped LDF-curve from fish consumption (Figure 2) with a slowly declining release from the geosphere.

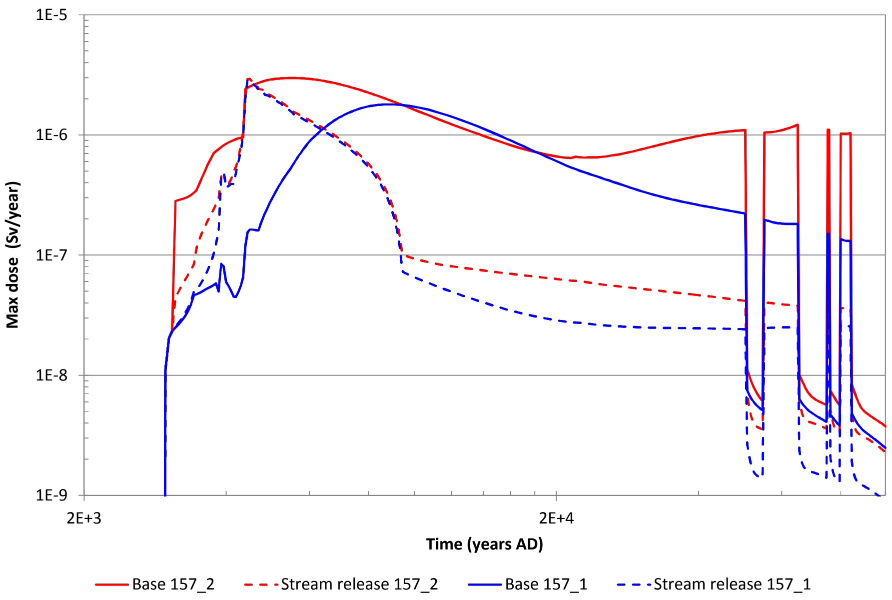


Figure 4. *Total dose from a time varying release from SFR1 and SFR3 as a function of time. The curves represents the maximum dose at any time across four different exposed groups, living in and utilising natural resources in the object 157_1 (blue) or object 157_2 (red). Solid lines represents results from the biosphere model used in the safety assessment (base), whereas dashed lines represents results from a model in which radionuclides are released directly to a stream which discharges into the down-stream lake without passing any wetland areas (stream release).*

1.4 Conclusions

In this study we have examined to what extent the assumptions made on the surface water outlet from the main discharge area affects the calculated dose. As expected from the existing analysis of water-balance components, the effects of adding a stream to the hydrological description of object 157_2 has a marginal effect on groundwater fluxes, on the accumulation of radionuclides and on the calculated dose, in the primary discharge area. A redirection of the inlet water to the down-stream object (157_1), from the wetland areas to the open water component of the recipient, will however affect both the accumulation of radionuclides and degassing of C-14 in the down-stream object. However, as the long-term accumulation of radionuclides in peat decrease with the presence of a stream-inlet, and as the productivity of fish is limited in a small lake, doses from the down-stream object never exceed those resulting from the up-stream object. By allowing the geosphere release to reach a stream directly, an upper boundary for the concentration of radio carbon in stream and lake water was calculated. The reduction in wetland degassing increased stream and lake water C-14 activity concentration by more than an order of magnitude, but the total maximum dose was similar to that of the original assessment. Thus it is concluded that uncertainties with respect to the presence of a stream in object 157_2, do not have a significant effect on the overall assessment result in SR-PSU.

1.5 References

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Appendix A. Maximum LDF-values calculated with the biosphere model for a landscape variant where object 157_2 and 157_1 are connected via a stream. The maximum is taken over four exposed groups (H&G = hunter and gatherers, IO = inland outfield farmers, DM = drained mire farmers, GP = garden plot household) and the two biosphere objects

Radionucl.	Exp. pop.	Biosph. object	Time	Max LDF	LDF vs Base	Exposure route (%)			
			(year AD)	*(Sv/y per Bq/y)*	*(%)*	Ing. food	Ing. wat.	Inhal.	Ext.
Ac-227	GP	157_2	4 350	1.0E-11	0%	1.0%	99.0%	0.0%	0.0%
Ag-108m	H&G	157_2	15 750	4.3E-14	-19%	1.3%	0.1%	0.0%	98.6%
Am-241	GP	157_2	15 700	1.7E-12	0%	1.0%	99.0%	0.0%	0.0%
Am-242m	GP	157_2	15 700	1.6E-12	0%	1.0%	99.0%	0.0%	0.0%
Am-243	DM	157_2	20 000	2.0E-12	-2%	13.2%	86.6%	0.0%	0.1%
Ba-133	GP	157_2	4 350	1.3E-14	0%	1.9%	97.5%	0.0%	0.6%
C-14	DM	157_2	5 100	9.3E-15	17%	90.2%	9.8%	0.0%	0.0%
Ca-41	DM	157_2	20 000	6.7E-14	7%	92.6%	7.4%	0.0%	0.0%
Cd-113m	GP	157_2	4 300	2.2E-13	0%	9.0%	91.0%	0.0%	0.0%
Cl-36	DM	157_2	15 450	8.6E-13	14%	96.7%	3.3%	0.0%	0.0%
Cm-242	GP	157_2	3 300	1.0E-13	0%	1.0%	99.0%	0.0%	0.0%
Cm-243	GP	157_2	4 450	1.3E-12	0%	1.0%	99.0%	0.0%	0.0%
Cm-244	GP	157_2	4 350	1.0E-12	0%	1.0%	99.0%	0.0%	0.0%
Cm-245	DM	157_2	20 000	2.1E-12	-2%	14.5%	85.4%	0.1%	0.0%
Cm-246	DM	157_2	20 000	2.0E-12	-1%	8.4%	91.6%	0.0%	0.0%
Co-60	GP	157_2	4 300	3.0E-14	0%	1.3%	97.2%	0.0%	1.5%
Cs-135	DM	157_2	20 000	1.7E-13	-14%	89.8%	10.2%	0.0%	0.0%
Cs-137	DM	157_2	15 450	1.3E-13	0%	13.0%	87.0%	0.0%	0.0%
Eu-152	GP	157_2	4 350	1.2E-14	0%	0.9%	96.1%	0.0%	2.9%
H-3	GP	157_2	3 200	1.2E-15	0%	1.0%	99.0%	0.0%	0.0%
Ho-166m	DM	157_2	20 000	2.0E-14	-3%	1.1%	85.7%	0.0%	13.3%
I-129	IO	157_2	3 400	8.0E-12	0%	11.9%	88.1%	0.0%	0.0%
Mo-93	DM	157_2	5 400	5.2E-12	-7%	98.2%	1.8%	0.0%	0.0%
Nb-93m	GP	157_2	4 350	1.0E-15	0%	1.0%	99.0%	0.0%	0.0%
Nb-94	DM	157_2	20 000	3.4E-14	-10%	9.3%	42.4%	0.0%	48.3%
Ni-59	DM	157_2	20 000	2.8E-14	-5%	96.7%	3.3%	0.0%	0.0%
Ni-63	DM	157_2	15 450	1.7E-15	0%	26.3%	73.7%	0.0%	0.0%
Np-237	DM	157_2	20 000	1.2E-12	-4%	21.6%	78.1%	0.1%	0.3%
Pa-231	DM	157_2	20 000	8.1E-12	-4%	24.9%	75.1%	0.0%	0.0%
Pb-210	GP	157_2	4 400	6.0E-12	0%	1.3%	98.7%	0.0%	0.0%
Pd-107	DM	157_2	20 000	1.8E-14	-5%	96.7%	3.3%	0.0%	0.0%
Po-210	GP	157_2	3 200	1.0E-11	0%	1.0%	99.0%	0.0%	0.0%
Pu-238	GP	157_2	15 700	2.0E-12	0%	1.0%	99.0%	0.0%	0.0%
Pu-239	DM	157_2	20 000	2.6E-12	-3%	18.0%	81.9%	0.1%	0.0%
Pu-240	DM	157_2	20 000	2.4E-12	-2%	8.9%	91.0%	0.0%	0.0%
Pu-241	GP	157_2	4 350	4.2E-14	0%	1.0%	99.0%	0.0%	0.0%
Pu-242	DM	157_2	20 000	2.7E-12	-4%	23.0%	76.9%	0.1%	0.0%
Ra-226	DM	157_2	20 000	4.0E-12	-5%	40.1%	59.5%	0.0%	0.4%
Ra-228	DM	157_2	15 450	6.0E-12	0%	1.2%	98.8%	0.0%	0.0%
Se-79	DM	157_2	20 000	3.5E-13	14%	74.0%	26.0%	0.0%	0.0%
Sm-151	GP	157_2	18 300	8.5E-16	0%	1.0%	99.0%	0.0%	0.0%
Sn-126	DM	157_2	20 000	1.8E-13	-9%	46.2%	23.6%	0.0%	30.2%
Sr-90	GP	157_2	4 400	2.8E-13	0%	5.0%	95.0%	0.0%	0.0%
Tc-99	DM	157_2	20 000	1.5E-13	-12%	96.3%	3.7%	0.0%	0.0%

Th-228	GP	157_2	3 250	1.2E-12	0%	1.0%	99.0%	0.0%	0.0%
Th-229	DM	157_2	20 000	5.8E-12	-2%	9.4%	90.5%	0.0%	0.0%
Th-230	DM	157_2	20 000	2.3E-12	-4%	20.6%	79.3%	0.0%	0.0%
Th-232	DM	157_2	20 000	2.5E-12	-4%	22.5%	77.5%	0.1%	0.0%
U-232	DM	157_2	15 450	3.0E-12	0%	5.6%	94.4%	0.0%	0.0%
U-233	GP	157_2	18 300	6.8E-12	15%	36.8%	24.3%	38.9%	0.0%
U-234	GP	157_2	18 300	6.6E-12	15%	36.6%	24.1%	39.3%	0.0%
U-235	GP	157_2	18 300	6.5E-12	15%	36.1%	23.6%	36.3%	3.9%
U-236	GP	157_2	18 300	6.3E-12	15%	37.2%	24.3%	38.5%	0.0%
U-238	GP	157_2	18 300	6.3E-12	15%	38.4%	25.1%	35.6%	0.9%
Zr-93	DM	157_2	20 000	1.6E-13	-12%	93.9%	6.1%	0.0%	0.0%