EMRAS: Theme 2 - Remediation of sites with radioactive residues

W.G. 1 Hypothetical area source scenario (v. 1.11)

Applied Models: DOSDIM & HYDRUS

DOSDIM is a compartmental type of model of the biosphere, partly dynamic, depending on the time frame and on the exposure pathways considered. It has been expanded with a module, calculating radon concentrations in the air from large area sources. For the modelling of the transport of the radionuclides in the variably saturated medium under the dumping grounds, the HYDRUS 1D programme has been used.

The DOSDIM model has been used several times in international biosphere model verification studies, such as:

- BIOMOVS: Scenario A4 – Multiple Model Testing using Chernobyl Fallout Data (BIOMOVS Technical Report 13, 1991)
- VAMP, Multiple Pathways Assessment Working Group:

  Validation of models using Chernobyl fallout data, from the Central Bohemia region (IAEA-TECDOC-795, 1995)

  Validation of models using Chernobyl fallout data, from southern Finland (IAEA-TECDOC-904, 1996)
- BIOMASS, Remediation Assessment Working Group (Theme 2):
  Testing of environmental transfer models using data from the remediation of a radium extraction site (IAEA - BIOMASS - 7, 2003)

The HYDRUS computer code numerically solves the Richards equation for variably-saturated water flow and convection-dispersion type equations for heat and solute transport. The program may be used to model water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The governing flow and transport equations are solved numerically using Galerkin-type linear finite element schemes.

Here, the one-dimensional version HYDRUS 1D is used for the modelling of the transport of the radionuclides through the VADOSE zone under the waste dump, into the aquifer. The concentrations of the radionuclides in the aquifer at the location of the exposure point (a well at the house), are calculated with the analytical solution of the first order differential equation, describing the advection-dispersion transport movement (e.g. Ogata and Banks, 1961).

Exposure pathways to be considered

Inhalation of radon exhaled from the waste dump

The individual dose to the exposure group due to inhalation of radon, has been assessed outdoors (on the field) and indoors (in the houses). Distinction has further been made between the exposure on the dumping grounds (see figure 1: zone 1) and outside those grounds (zone 2 and 3), and between covered and uncovered dumps. For long time ranges (> 100a) the thickness of the uncontaminated cover layer is considered to diminish exponentially with time due to erosion and downward migration of the contamination.

External irradiation from the waste dump

This exposure pathway is only important on the fields and in the house on the dumping grounds. Covered as well as uncovered dumps are considered.

Inhalation of resuspended dust

This pathway is only relevant for uncovered dumping grounds. In DOSDIM the radionuclide concentrations in the resuspended dust is derived from the concentrations in the top soil, with which they are assumed to be in equilibrium, apart from an enhancemant factor due to the relatively small size of the resuspended particles.

Inhalation of resuspended daughter radionuclides of ^{222}Rn, exhaled from the dump, could also be taken into consideration; however its radiological consequence is estimated to be unimportant.

Ingestion of water from a contaminated well

The migration of the radionuclides transported with the groundwater through the bottom cover into the aquifer is modelled with HYDRUS 1D and the concentrations of the radionuclides in a well near to the houses are calculated by the analytical solution of a classical advection-dispersion equation. During the entire transport, the decay and ingrowth of the short-lived daughter radionuclides have been taken into account.

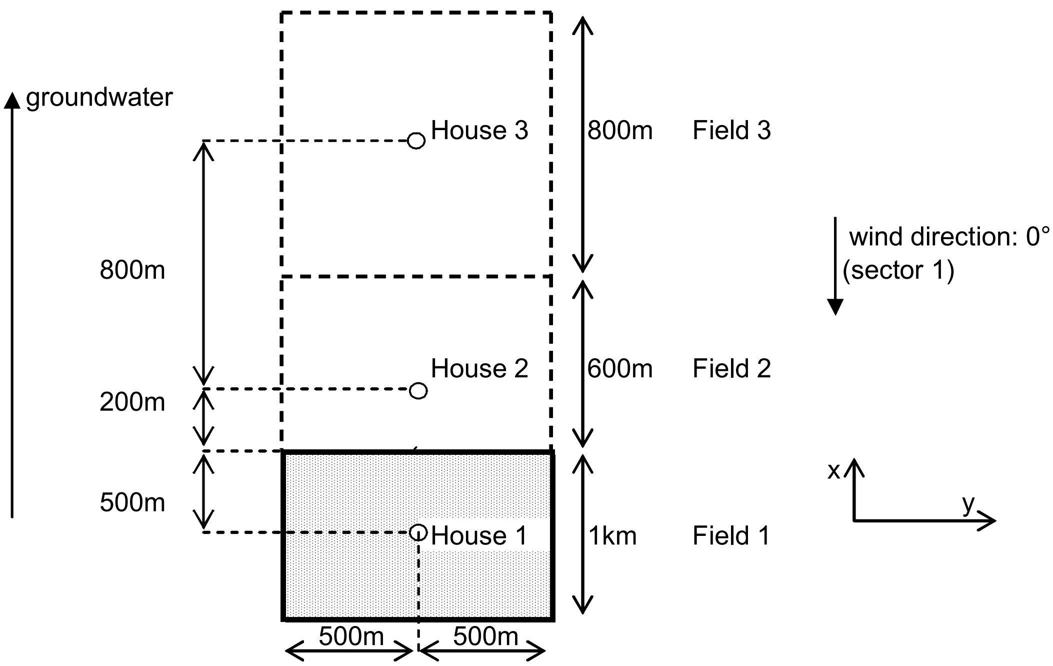


Fig. 1 Configuration of area source and exposure points

Shaded part = area source

Exposure points: houses 1 and 2 (3: not considered) and fields 1 and 2 (representative points in the centre)

Specification of applied models

Modelling of the ^{222}Rn concentrations in the air due to exhalation from the dump

This is performed with the extra module of the DOSDIM model. The extended area source, formed by the dump, is herein divided into elementary square sources of 100m x 100m (x 10m deep). The total impact from the dump is then calculated as the sum of impacts from all these elementary sources, which are considered to be located at their centres. The distances and directions to the exposure points are easily calculated, locating the latter at the centre of the houses and fields in the zones 1 (at the dumping grounds), 2 and 3 (outside the dumping grounds).

For the modelling of the atmospheric dispersion of exhaling radon and its daughter radio-nuclides, we apply a 2-dimensional Gaussian model. The well-known Pasquill-Gifford dispersion parameters (i.e. the standard deviations of the cross-wind and vertical wind distributions) are expressed as a function of the Pasquill weather type and of the distance from the elementary source (centre) to the exposure point.

For each elementary source – exposure point configuration, the frequency of occurrence of the wind blowing in the sector, encompassing the exposure point considered, and of the wind blowing in the adjacent sectors, is calculated from a table of meteorological observations. Then, for the same configurations, and for each stability class, the time-averaged dilution factor is calculated, taking into account the distribution of the wind direction.

The contributions for the wind blowing in the sector comprising the receptor, and the "fringes" for the wind blowing in the adjacent sectors, are summed up, yielding the average dilution factor for the exposure point considered (for each elementary source and each stability class). Multiplying those dilution factors with the frequency of occurrence of each stability class and of the wind direction considered and summing up those weighted dilution factors results in the total average dilution factor for the exposure point, from the whole dump (= all the elementary sources).

Multiplication with the exhalation flux of radon yields the average radon concentration in the air at the exposure point, from which the individual dose due to inhalation of exhaled radon may be assessed. The radon exhalation rate from the covered dump is lower than that of the uncovered dump and consequently also the individual dose from such a dump is lower. Due to the erosion, the thickness of the cover in the fromer case will diminish with time down to approximately 1m at 10 000 years.

External irradiation from the waste dump and Inhalation of resuspended dust

These two exposure pathways are easily modelled with DOSDIM, as described in the VAMP and BIOMASS reports mentioned above.

But only for the labourers working and living on the dumping grounds, the doses are relevant. A higher individual dose rate will be received on the uncovered waste than on the covered one. The inhalation dose will be zero, and the external dose rate lower than the one for the uncovered waste, as long as the thickness of the covering layer has not been reduced to 0.

In the DOSDIM model the radionuclide concentrations in the resuspended dust are considered to be in equilibrium with the concentrations in the top soil, apart from an enhancement factor (5; Müller and Proehl, 1993) because of the finer (more inhalable fraction) size of the particles in the air with respect to those in the top soil.

With respect to the location of the labourers on the field, working on the edge of the dumping grounds, would result in an external dose rate equal to half the value at the centre of the dumping grounds, and in an inhalation dose rate from resuspension, varying between 0 and a certain maximum value (depending on the prevalent wind directions). Therefore the central point of the fields have been considered as the representative points, where the dose rates will be assessed.

Ingestion of water from a contaminated well (p.m.)

As mentioned before, the transport of the radionuclides of the ^{238}U decay chain through the unsaturated bottom cover under the waste dump have been modelled with the HYDRUS 1D software programme and the concentrations of the radionuclides at the well sunk into the aquifer at the location of the houses calculated, applying the analytical solution of a 1-dimensional differential equation, according to the method of Ogdell and Banks (1961):

$$C(x,t)=0.5C_0\cdot\{\exp(\frac{\bar{v}_x\cdot x}{D_L})\cdot erfc(\frac{x+\bar{v}_x\cdot t)}{2\cdot\sqrt{D_L\cdot t}})+erfc(\frac{x-\bar{v}_x\cdot t)}{2\cdot\sqrt{D_L\cdot t}})\}$$

RESULTS – CONCENTRATIONS

For the calculation of the radionuclide concentrations in the exposing media, next to the radioactive decay and ingrowth of the relatively "short"-lived daughter radionuclides, also the processes of erosion and of downward migration of the radionuclides are taken into account. The process of erosion reduces the thickness of the covering layer and through this, increases the exhaled ^{222}Rn concentration in the air and the external dose rate from the covered waste. However both effects are counter acted by the downward migration of the radionuclides. The resultant effect on the long term is an enhancement of the ^{222}Rn concentration in the air and of the external dose rate from the covered waste, with time.

Concentrations of the critical radionuclides on the dumping grounds

^{222}Rn concentrations in the air due to exhalation from the dump *(Bq/m³)*				
Time	***Uncovered waste***		***Covered waste***	
	House 1	*Field 1*	*House 1*	*Field 1*
1a, 10a, 100a	354	11.8	7.08	0.236
1 000a	354	11.8	7.57	0.253
10 000a	354	11.8	13.6	0.453
^{226}Ra concentrations in the dump *(Bq/kg)* for external irradiation				
Time	***Uncovered waste***		***Covered waste***	
	House 1	*Field 1*	*House 1*	*Field 1*
all	1000	1000	1000	1000
For covered waste: external dose rates increasing with time due to decrease of cover thickness				
^{230}Th concentrations in the resuspended dust *(Bq/kg)* for inhalation				
Time	***Uncovered waste***		***Covered waste***	
	House 1	*Field 1*	*House 1*	*Field 1*
all	5000	5000	0	0
All concentrations in the well *(Bq/m³)*				
Time	***Uncovered waste***		***Covered waste***	
	House 1	*Field 1*	*House 1*	*Field 1*
1a, 10a, 100a	0	0	0	0
1 000a	^{238}U, ^{234}U: 2.94 10^{-5}	^{230}Th: 3.84 10^{-8}	Idem as uncovered waste	
	^{226}Ra: 2.16 10^{-9}	^{210}Pb: 1.11 10^{-9}		
10 000a	^{238}U, ^{234}U: 71.7 *	^{230}Th: 2.31	* maximum at 61 000a: 119 Bq/m³	
	^{226}Ra: 1.40	^{210}Pb: 1.01		

Concentrations of the critical radionuclides outside the dumping grounds

^{222}Rn concentrations in the air due to exhalation from the dump *(Bq/m³)*				
Time	***Uncovered waste***		***Covered waste***	
	House 2	*Field 2*	*House 2*	*Field 2*
1a, 10a, 100a	3.07	2.26	0.0613	0.0452
1 000a	3.07	2.26	0.0656	0.0484
10 000a	3.07	2.26	0.118	0.0868
^{226}Ra concentrations in the dump *(Bq/kg)* for external irradiation: irrelevant				
^{230}Th concentrations in the resuspended dust *(Bq/kg)* for inhalation				
Time	***Uncovered waste***		***Covered waste***	
	House 2	*Field 2*	*House 2*	*Field 2*
all	1300	950	0	0
All concentrations in the well *(Bq/m³)*for ingestion: irrelevant				

RESULTS – ANNUAL DOSES (Sv/a)

Individual doses on the dumping grounds

^{222}Rn inhalation due to exhalation from the dump *(Sv/a)*				
Time	***Uncovered waste***		***Covered waste***	
	House 1	*Field 1*	*House 1*	*Field 1*
1a, 10a, 100a	$6.4\ 10^{-3}$	$1.1\ 10^{-4}$	$1.3\ 10^{-4}$	$2.1\ 10^{-6}$
1 000a	$6.4\ 10^{-3}$	$1.1\ 10^{-4}$	$1.4\ 10^{-4}$	$2.3\ 10^{-6}$
10 000a	$6.4\ 10^{-3}$	$1.1\ 10^{-4}$	$2.5\ 10^{-4}$	$4.1\ 10^{-6}$
External irradiation through the radionuclides (^{226}Ra + daughters) in the dump *(Sv/a)*				
Time	***Uncovered waste***		***Covered waste***	
	House 1	*Field 1*	*House 1*	*Field 1*
all	$1.0\ 10^{-3}$	$1.2\ 10^{-3}$	$< 10^{-12}$	$< 10^{-12}$
Inhalation of resuspended dust (^{230}Th + daughters) from the dump *(Sv/a)*				
Time	***Uncovered waste***		***Covered waste***	
	House 1	*Field 1*	*House 1*	*Field 1*
all	$1.4\ 10^{-4}$	$4.5\ 10^{-4}$	0	0
Ingestion of water from the well ($^{238}U^{+}$ + ^{234}U + $^{230}Th^{+}$ + $^{226}Ra^{+}$ + $^{210}Pb^{+}$) *(Sv/a)*				
Time	***Uncovered waste***		***Covered waste***	
	House 1	*Field 1*	*House 1*	*Field 1*
1a - 1000a	< approximat 10^{-6}	-	< approximat 10^{-6}	-
6,100a for U (max	$2.3\ 10^{-6}$		$2.3\ 10^{-6}$	

Total Doses on the dumping grounds (Sv/a)

Time	***Uncovered waste***		***Covered waste***	
	House 1	*Field 1*	*House 1*	*Field 1*
1a, 10a, 100a	**$7.5\ 10^{-3}$**	**$1.8\ 10^{-3}$**	**$1.3\ 10^{-4}$**	**$2.1\ 10^{-6}$**
1 000a	**$7.5\ 10^{-3}$**	**$1.8\ 10^{-3}$**	**$1.4\ 10^{-4}$**	**$2.3\ 10^{-6}$**
10 000a	**$7.5\ 10^{-3}$**	**$1.8\ 10^{-3}$**	**$2.5\ 10^{-4}$**	**$4.1\ 10^{-6}$**

For the impact on the dumping grounds, the inhalation of radon exhaled from the dump is the critical pathway, in both cases: for the covered and uncovered waste.

As mentioned before we have also taken into account the effect of the processes of erosion and of downward migration of the radionuclides, on the doses from the covered waste.
We can also observe that the residents in the houses on the dumping grounds, which would spend most of their time inside their house, are receiving a higher dose than the "associated workers".

Individual doses outside the dumping grounds

^{222}Rn inhalation due to exhalation from the dump *(Sv/a)*				
Time	***Uncovered waste***		***Covered waste***	
	House 2	*Field 2*	*House 2*	*Field 2*
1a, 10a, 100a	5.6 10^{-5}	2.0 10^{-5}	1.1 10^{-6}	4.1 10^{-7}
1 000a	5.6 10^{-5}	2.0 10^{-5}	1.2 10^{-6}	4.4 10^{-7}
10 000a	5.6 10^{-5}	2.0 10^{-5}	2.1 10^{-6}	7.9 10^{-7}
External irradiation through the radionuclides (^{226}Ra + daughters) in the dump *(Sv/a): irrelevant*				
Inhalation of resuspended dust (^{230}Th + daughters) from the dump *(Sv/a)*				
Time	***Uncovered waste***		***Covered waste***	
	House 2	*Field 2*	*House 2*	*Field 2*
all	3.6 10^{-5}	8.6 10^{-5}	0	0
Ingestion of water from the well (^{230}Th^{+} + ^{226}Ra^{+} + ^{210}Pb^{+}) *(Sv/a): irrelevant*				

Total Doses outside the dumping grounds (Sv/a)

Time	***Uncovered waste***		***Covered waste***	
	House 2	*Field 2*	*House 2*	*Field 2*
1a, 10a, 100a	**9.2 10^{-5}**	**1.06 10^{-4}**	**1.1 10^{-6}**	**4.1 10^{-7}**
1 000a	**9.2 10^{-5}**	**1.06 10^{-4}**	**1.2 10^{-6}**	**4.4 10^{-7}**
10 000a	**9.2 10^{-5}**	**1.06 10^{-4}**	**2.1 10^{-6}**	**7.9 10^{-7}**

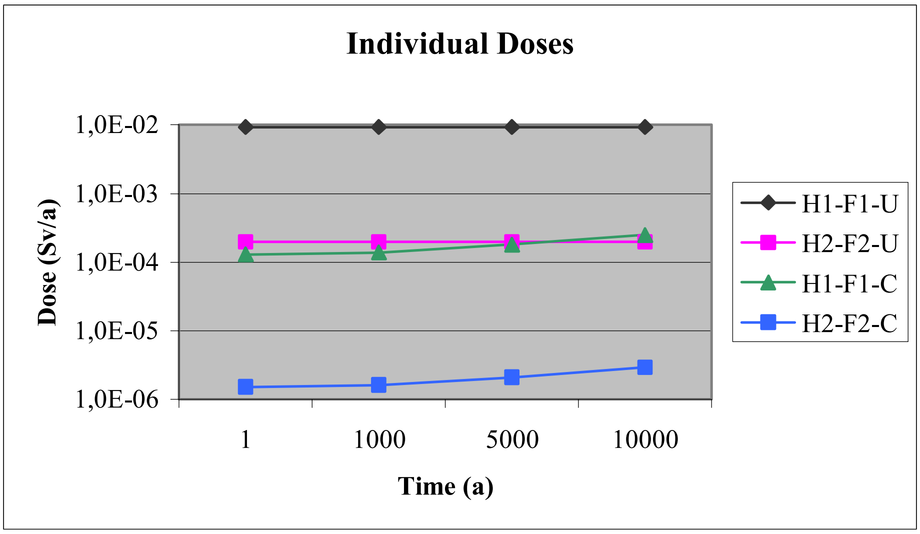
For the impact from the uncovered waste, outside the dumping grounds, the inhalation of resuspended dust is now the critical pathway for the "associated workers" (because of their occupation times on the fields outside and the high concentrations in the dust on the fields).

The "associated workers" are now also receiving a higher dose than the residents, spending most of their time inside their house.

CONCLUDING TABLE / GRAPH

Time evolution of total doses (Sv/a)

TIME	Uncovered waste		Covered waste	
	H1 + F1	H2 + F2	H1 + F1	H2 + F2
1; 10; 100 a	9,3E-03	2,0E-04	1,3E-04	1,5E-06
1 000 a	9,3E-03	2,0E-04	1,4E-04	1,6E-06
5 000a	9,3E-03	2,0E-04	1,8E-04	2,1E-06
10 000 a	9,3E-03	2,0E-04	2,5E-04	2,9E-06



References

Simunek, J., van Genuchten, M., Th. and Sejna, M., 2005. The HYDRUS-1D Software Package for simulating the one-dimensional movement of water, heat and multiple solutes in variably-saturated media, Version 3.0, HYDRUS Software Series 1, Department of Evironmental Sciences, University of California Riverside, Riverside, California, USA.

Ogata, A. and Banks, R., B., 1961. A Solution of the Differential Equation of Longitudinal Dispersion in Porous Media. (U.S. Geol. Survey Professional Paper 411-A.) 7 pp.
In: Wang, H., F., and Anderson, M., P., 1982. Introduction to Groundwater Modelling. Finite Difference and Finite Element Methods. Academic Press, Inc.

Müller, H. and Pröhl, G.,1993. Ecosys-87: a dynamic model for assessing radiological consequences of nuclear accidents. Health Phys. 64(3):232-252; 1993