Models for safety assessment of disposal options for VLLW

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Contents

Problem context

Large amounts of **very low-level waste (VLLW)** will be generated from the decommissioning of Swedish nuclear power reactors.

Most of this waste can be:

- deposited in near surface repositories**,** **MLAs** (*markdeponi lågaktivt avfall*), at the plant sites,
- deposited in conventional **municipal landfills**, or
- **cleared** for re-use or recycling.

Finding properly justifiable solutions like these is a cost-effective alternative to sending the VLLW to the SKB Final Repository (SFR).

Scope of the project

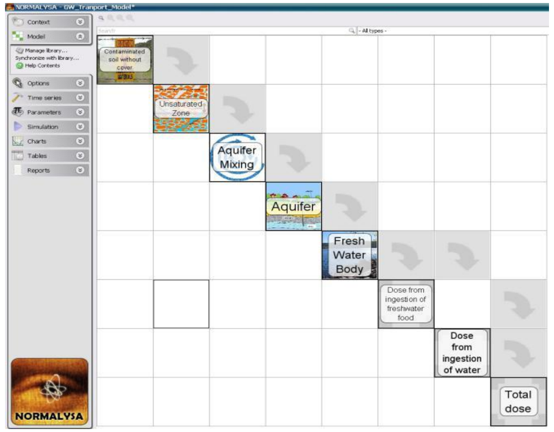
Modeling capabilities and calculation results are compared between three software tools for conducting safety assessment and dose calculations for various VLLW management options.

The software tools that are compared are:

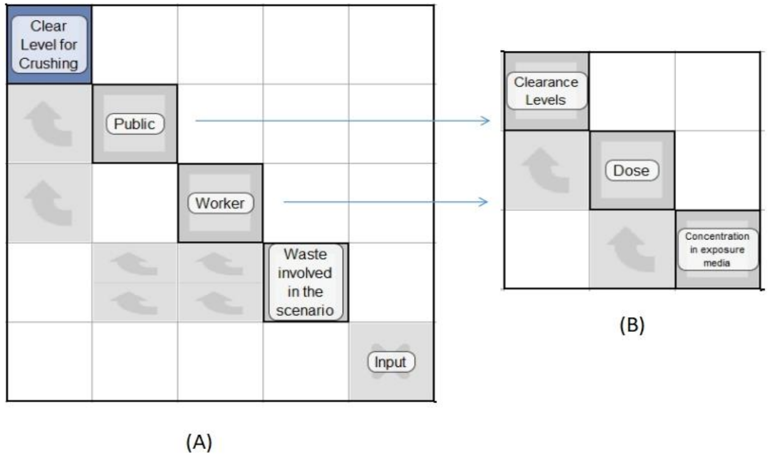
- RESRAD-OFFSITE (Yu et al., 2007),
- NORMALYSA (Avila et al., 2018), and
- IAEA clearance tool (IAEA, 2018).

The last two tools belong to the family of Ecolego-based tools.

NORMALYSA



IAEA Clearance Tool



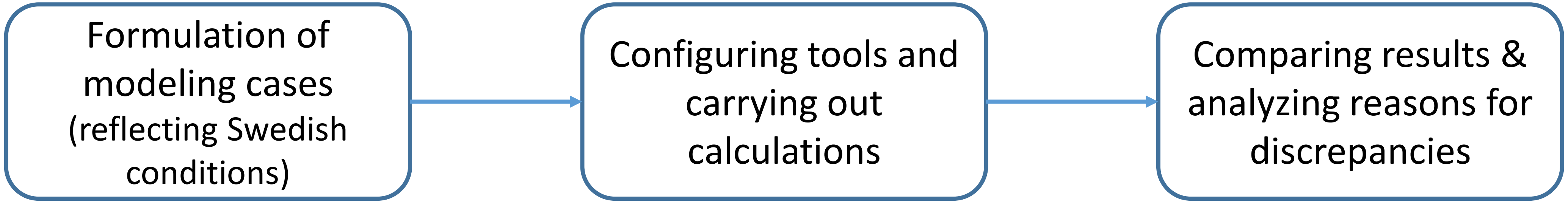
RESRAD-OFFSITE

Objectives

To provide **quantitative comparisons between the software tools** (RESRAD-OFFSITE, NORMALYSA, IAEA Clearance Tool) for a set of VLLW disposal and re-use scenarios, under Swedish conditions, in order to:

- Provide demonstration of relevant modeling methodologies,
- Better understand functionality and limitations of compared software tools,
- Check robustness of assessment results by these tools.

The end-users of this study are both the applicants (license holders) and the reviewer (SSM).



Considered VLLW management options and waste characteristics

The following VLLW **management options** were considered:

- Disposal of VLLW in a “generic” MLA facility;
- Disposal of VLLW in Hazardous Solid Waste Landfill (site-specific data for Fortum Waste Solutions in Kumla HSW landfill were used);
- Specific Clearance of VLLW material.

Assumptions on **waste characteristics**:

- Waste source term is composed **of non-organic materials** such as, concrete rubble and/or contaminated soils.
- The following **radionuclides** are considered : Co-60, Cs-137, Pu-238, Pu-239, Am-241, Cm-244, Sr-90 and Ni-63.
- The **specific activi**ty of VLLW used in disposal scenarios is based on radioactivity inventory data for Ringhals MLA on 2017-12-31 (SSM, 2019).

  (The VLLW **clearance scenarios** are carried out assuming a factor of 5 lower specific activity).

Assessment time frame and institutional control period

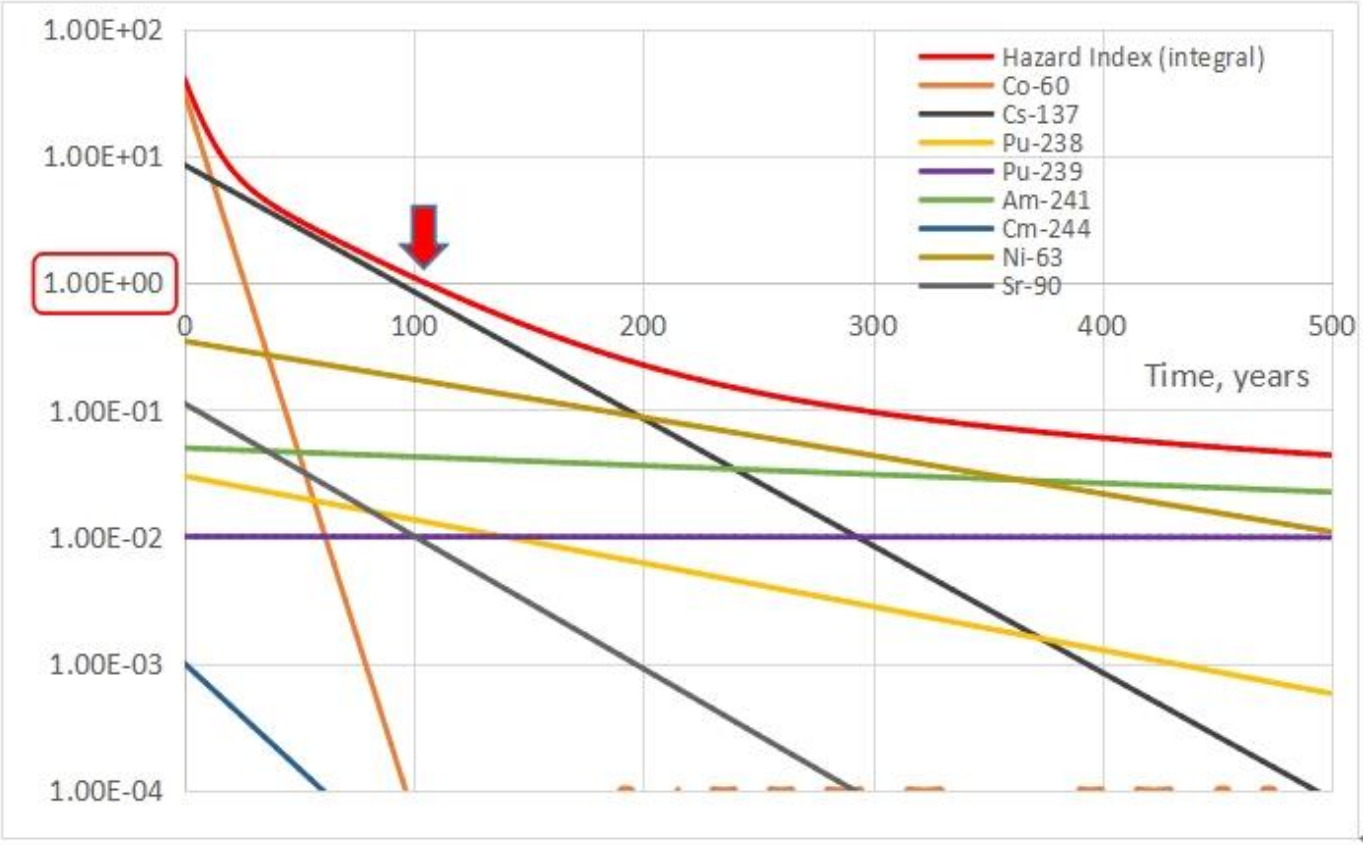
- A **200-year assessment time frame** is used. This encompasses the period when the waste potentially poses an unacceptable radiological hazard to humans (based on calculated "Hazard Index" > 1):

$$HI(t) = \sum_i \frac{C_i(t)}{CL_i}$$

Here CL_i is clearance level of radionuclide '*i*'

- For **groundwater transport** analyses, a 1000-year assessment time frame is used.
- An **institutional control period** of 30 years is assumed for the MLA facility and HSW landfill.

Time dynamics of "Hazard Index" calculated for the "reference activity" inventory



Radiological protection criteria

- The yearly effective dose to a representative person of the public:
  - for all **likely exposure situations** shall not be higher than **10 µSv/a**, and
  - for **unlikely exposure situations** shall not exceed **1 mSv/a**.

The above criteria are considered sufficiently low as not to warrant regulatory control (IAEA, 2018) in line with the EU Directive 2013/59/Euratom.

- The endpoint for the safety assessment is the **yearly effective dose to an adult** of the public ("representative person") through all relevant pathways.

Environmental characteristics, radioecological parameters and human habit data

Model parameter values were selected that reflect specific Swedish assessment context and environmental conditions : meteorology, physical soil properties – based on (Bergström et al., 1999; Broed et al., 2015); radioecological parameters – SR PSU study (Tröjbom et al., 2013); habits of reference persons - Vattenfall study on assessment of doses from operational releases near the Barsebäck NPP (Broed et al., 2015).

Modelling cases considered

- **Disposal in a MLA**

  SC1 Radionuclide release to adjacent coastal water system by discharge of leachate water from the drainage system of facility (A - normal leaching; B - fast leaching)

  SC2 Radionuclide release to adjacent coastal water system because of erosion of the soil cover and transport by surface runoff

- **Disposal the HSWL Fortum's Waste Solution in Kumla**

  SC3 Radionuclide leaching to groundwater and transport to well

  SC4 Intrusion scenario: small excavation to the HSW landfill

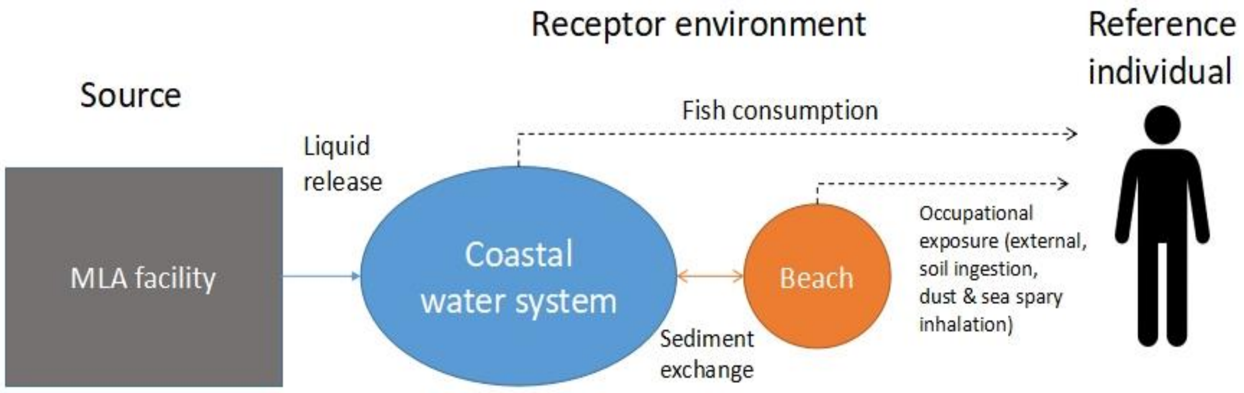
- **Re-use**

  SC5 Use of concrete for construction of public place

  SC6 Agricultural use of soils

Assessments of VLLW disposal in a generic MLA facility

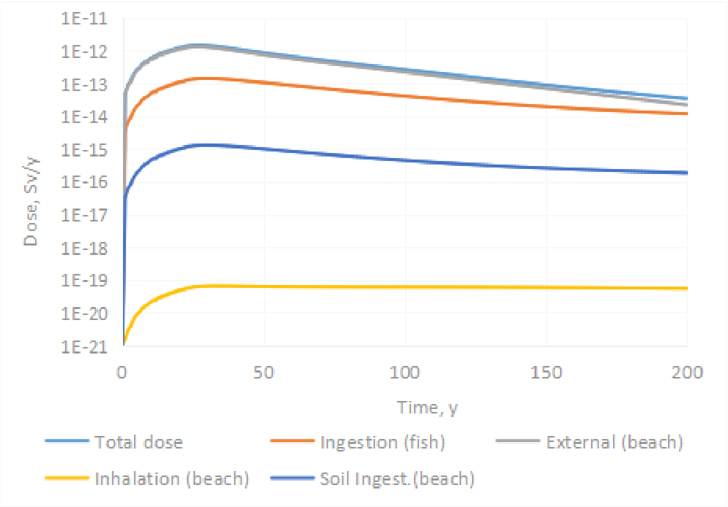
Block-scheme
for scenario SC1-A/B



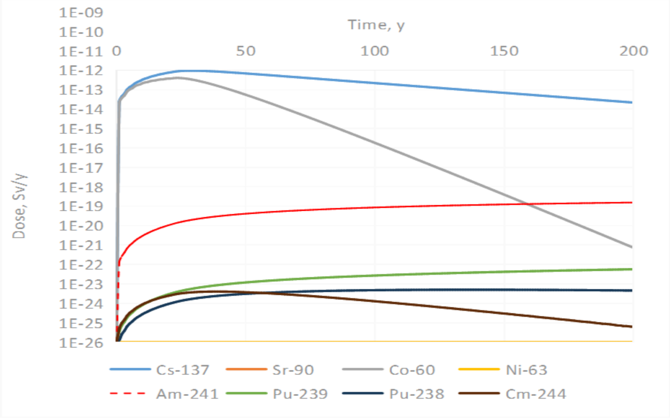
Scenario ID	Disposal / Re-use scenario	Description	Release mechanism	Receptor environment	Reference persons	Exposure pathways
SC1	Disposal in the MLA facility (OKG)	Radionuclide release from the MLA facility to adjacent coastal water system by discharge of leachate water from the facility´s drainage system <u>Modeling cases: </u>A: 'normal' leaching (intact cover); B: 'fast leaching' (degradation of cover)	Infiltration leaching through waste	Coastal water system	Coastal system island residents	External exposure, ingestion of soil, inhalation of dust and sea spray (beach occupancy); Internal exposure from consumption of fish
SC2	Disposal in the MLA facility (OKG)	Radionuclide release from the MLA facility to adjacent coastal water system caused by erosion of the soil cover and transport by surface run-off.	Transport in surface run-off from eroded soil cover	Same as SC1	Same as SC1	Same as SC1

Example simulation results: Dose consequences of activity release to coastal water system due to leaching (SC1) and erosion by run-off (SC2)

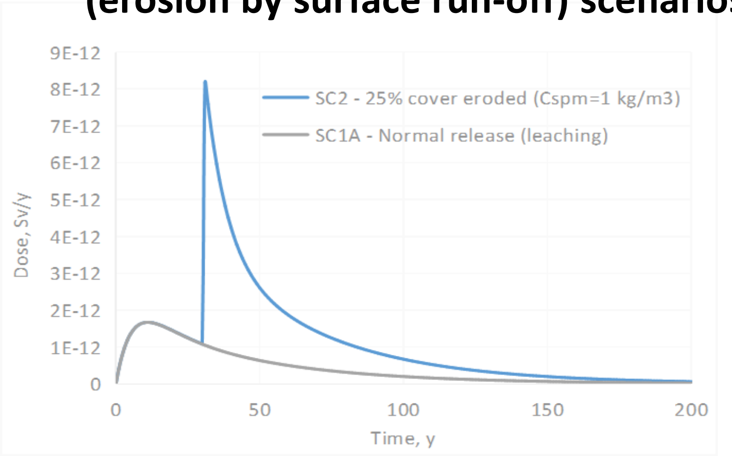
Contributions of pathways to the total dose (SC1A)



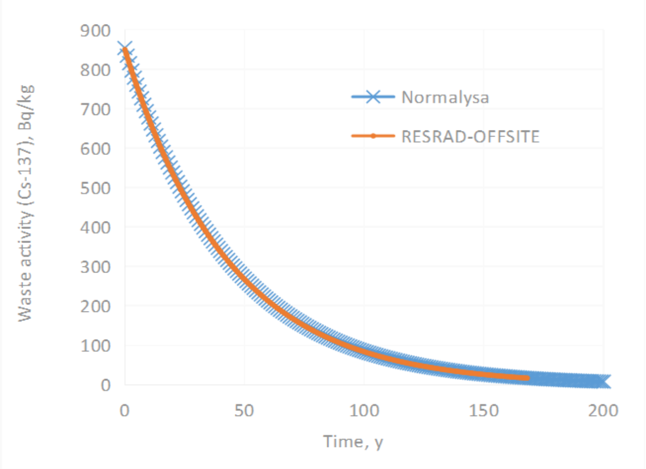
Contributions of different radionuclides to dose from external irradiation at the beach (SC1A)



Comparison of total dose for SC1A (leaching) and SC2 (erosion by surface run-off) scenarios

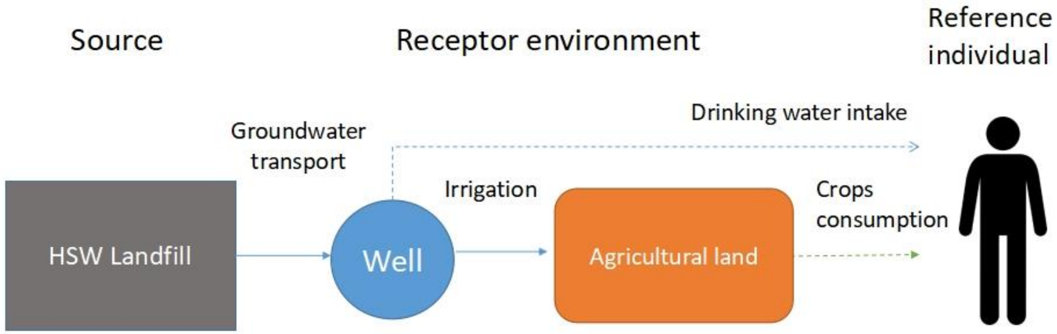


Comparison of source term leaching models for RESRAD and NORMALYSA (SC1A)

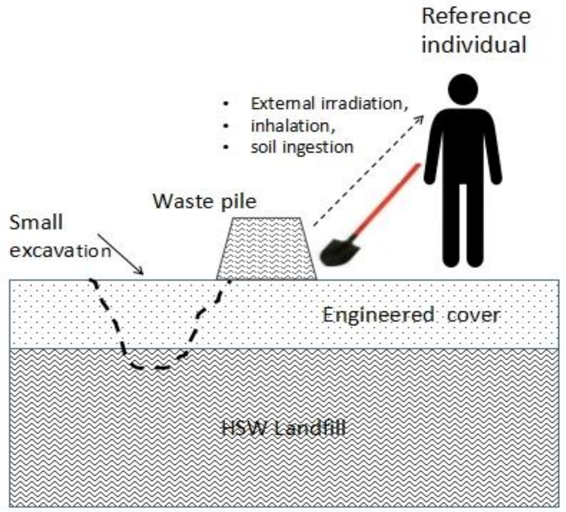


Assessments of VLLW disposal in the hazardous solid waste landfill (HSWL) Kumla

Block-scheme for scenario SC3 (groundwater transport to well)



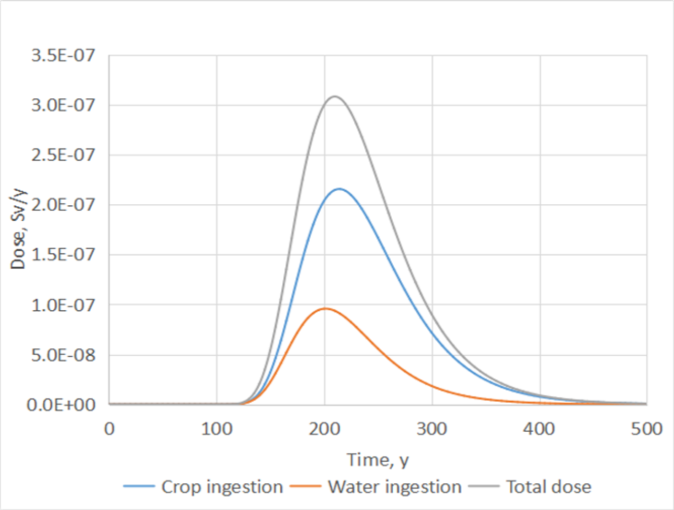
Block-scheme for scenario SC4 (intrusion)



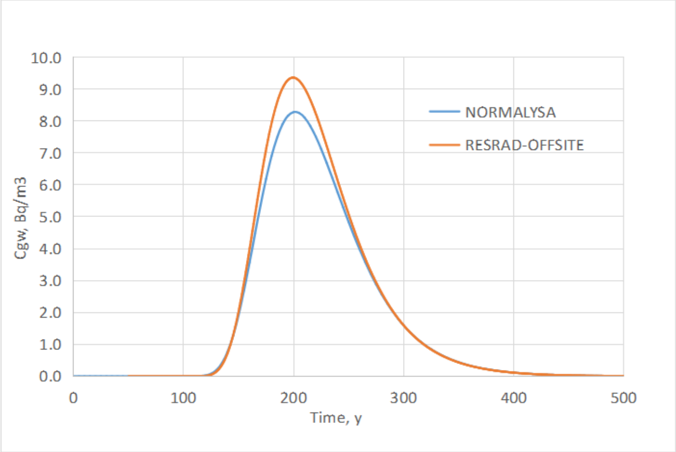
Scenario ID	Disposal / Re-use scenario	Description	Release mechanism	Receptor environment	Reference persons	Exposure pathways
SC3	Disposal in HSW landfill (Kumla)	Radionuclide leaching from HSW to the groundwater and transport to a water abstraction well. Input dataset is based on the site-specific dataset for HSW landfill Kumla.	Leaching by infiltration from waste and groundwater transport to well	Irrigated cropland	Site resident consuming water and crops	Internal exposure due to consumption of contaminated water, and ingestion of crops irrigated with contam. groundwater
SC4	Disposal in HSW landfill (Kumla)	Intrusion by an excavation into the HSW landfill Kumla ('small excavation' for construction works)	Excavation of waste /dust transport	Excavated cover of landfill	Intruder (worker)	External exposure and internal exposure related to inhalation and inadvertent ingestion of soil during excavation works

Example calculation results for scenarios of groundwater transport (SC3) and intrusion (SC4 – small excavation) for HSWL Kumla

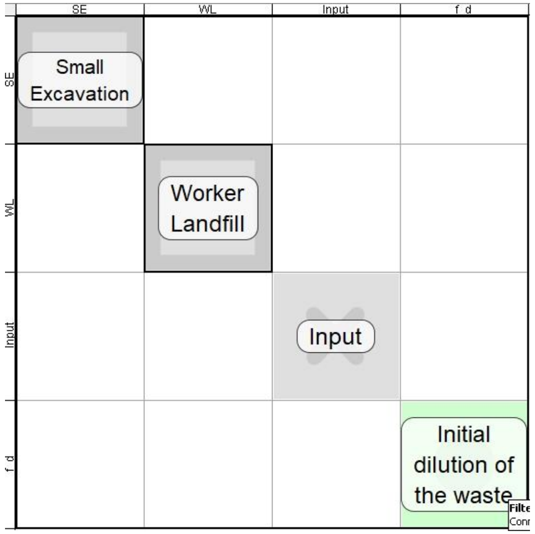
Contribution of different pathways to the total dose for SC3



Comparison of Sr-90 concentrations in the well for RESRAD-OFFSITE and NORMALYSA (SC3)



Modules of Clearance Tool which are used for calculations for SC4

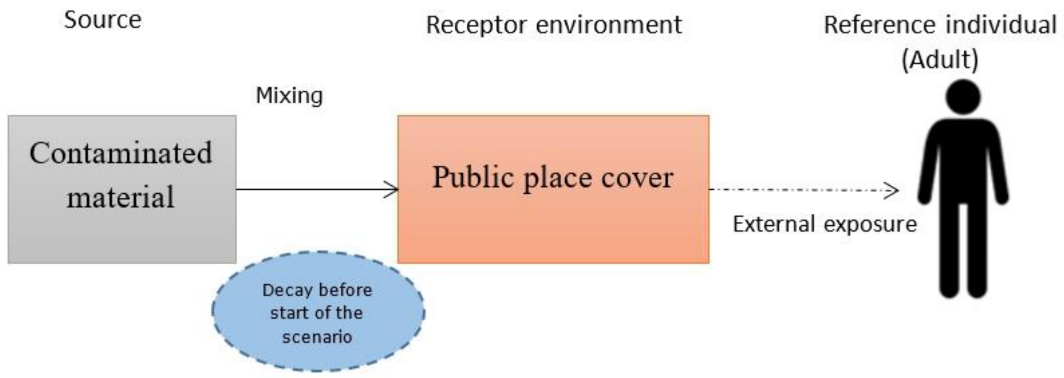


Comparison of results for SC4 by RESRAD-OFFSITE and the IAEA Clearance Tool

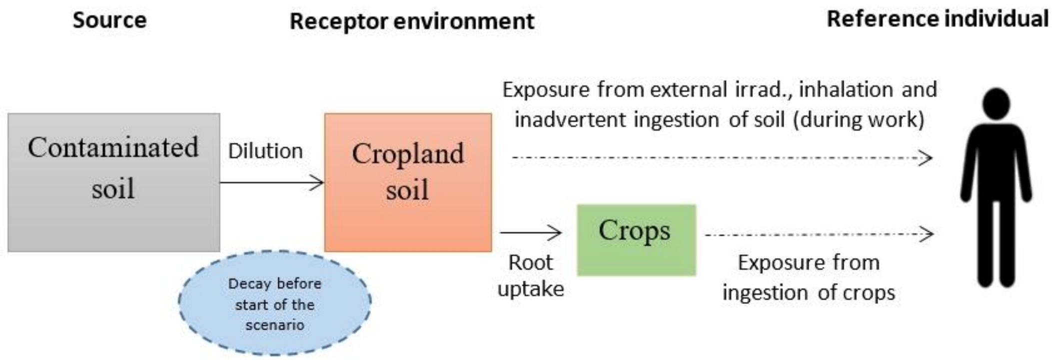
	RESRAD-OFFSITE			Clearance Tool
Primary contamination size ->	5 x 5 x 0.4 m	10x10x0.1 m	100x100x0.1 m	heap 5 x 2 x 1 m
Total dose, µSv/y	6.10E-03	1.03E-02	3.44E-02	1.48E-02
External, µSv/y	5.60E-03	9.80E-03	3.33E-02	1.04E-02
Inhalation, µSv/y	4.50E-04	5.20E-04	8.20E-04	3.90E-03
Soil Ingestion, µSv/y	6.90E-06	2.80E-05	2.80E-04	5.40E-04

Assessments for the clearance of VLLW

Block-scheme for scenario SC5: Using contaminated material to construct a pavement for public area



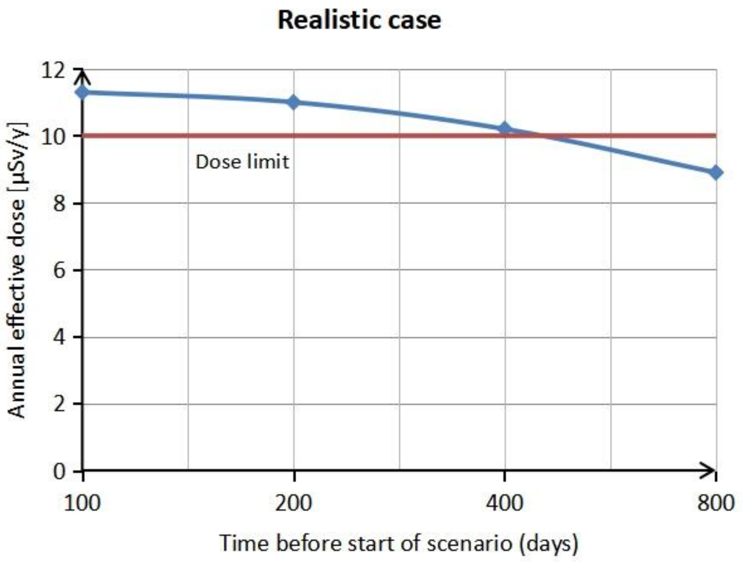
Block-scheme for scenario SC6: Agricultural use of contaminated soil



Scenario ID	Disposal / Re-use scenario	Description	Release mechanism	Receptor environment	Reference persons	Exposure pathways
SC5	Re-use (construction)	Reuse of concrete in construction of public place Modeling cases: 'Realistic' and 'Low-probability' - following assumptions of IAEA, 2005a (duration of exposure; waste mixing coefficient; time before scenario, etc.)	Use of contaminated concrete (mixed with uncontam. material)	Public place (parking lot, walkway)	Member of public	External exposure
SC6	Re-use (agriculture)	Reuse of contaminated soils in agricultural activities. Modeling cases: 'Realistic' and 'Low-probability' - following assumptions of IAEA, 2005a (see above)	Use of contaminated soil in agriculture (mixed with uncontam. material)	Agricultural land	Farmer	Internal exposure due to consumption of agricultural products; External exposure, inhalation and ingestion of soils (occupancy in the agricultural area)

Example calculation results for scenarios of re-use of concrete (SC5 - construction) and soil (SC6 – agricultural use)

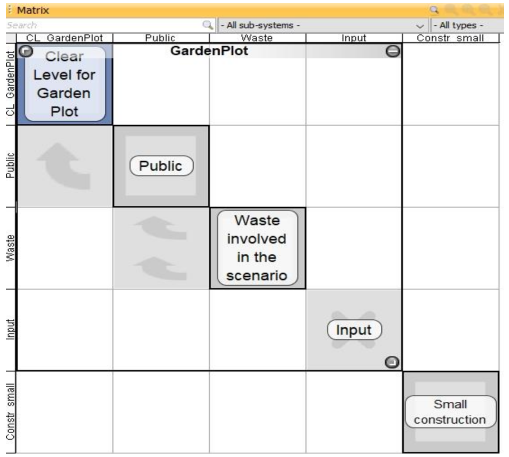
Sensitivity analyses for SC5: Total dose for different values of 'time before the start' parameter



Comparison of results for SC5 by RESRAD-OFFSITE and the IAEA Clearance Tool

Total dose by tool	Realistic case	Low-probability case
RESRAD-OFFSITE, μSv/year	10.3	127
Clearance Tool, μSv/year	11.3	142

Model for scenario SC6 using the IAEA Clearance Tool



Comparison of results for SC6 by RESRAD-OFFSITE and the IAEA Clearance Tool

Pathway	RESRAD-OFFSITE, μSv/year	Clearance Tool, μSv/year
External exposure	4.14E+00	4.40E+00
Ingestion of crops	9.06E-01	9.14E-01
Ingestion of soil	2.12E-03	4.24E-03
Inhalation	6.78E-04	2.34E-03
Total	5.06E+00	5.32E+00

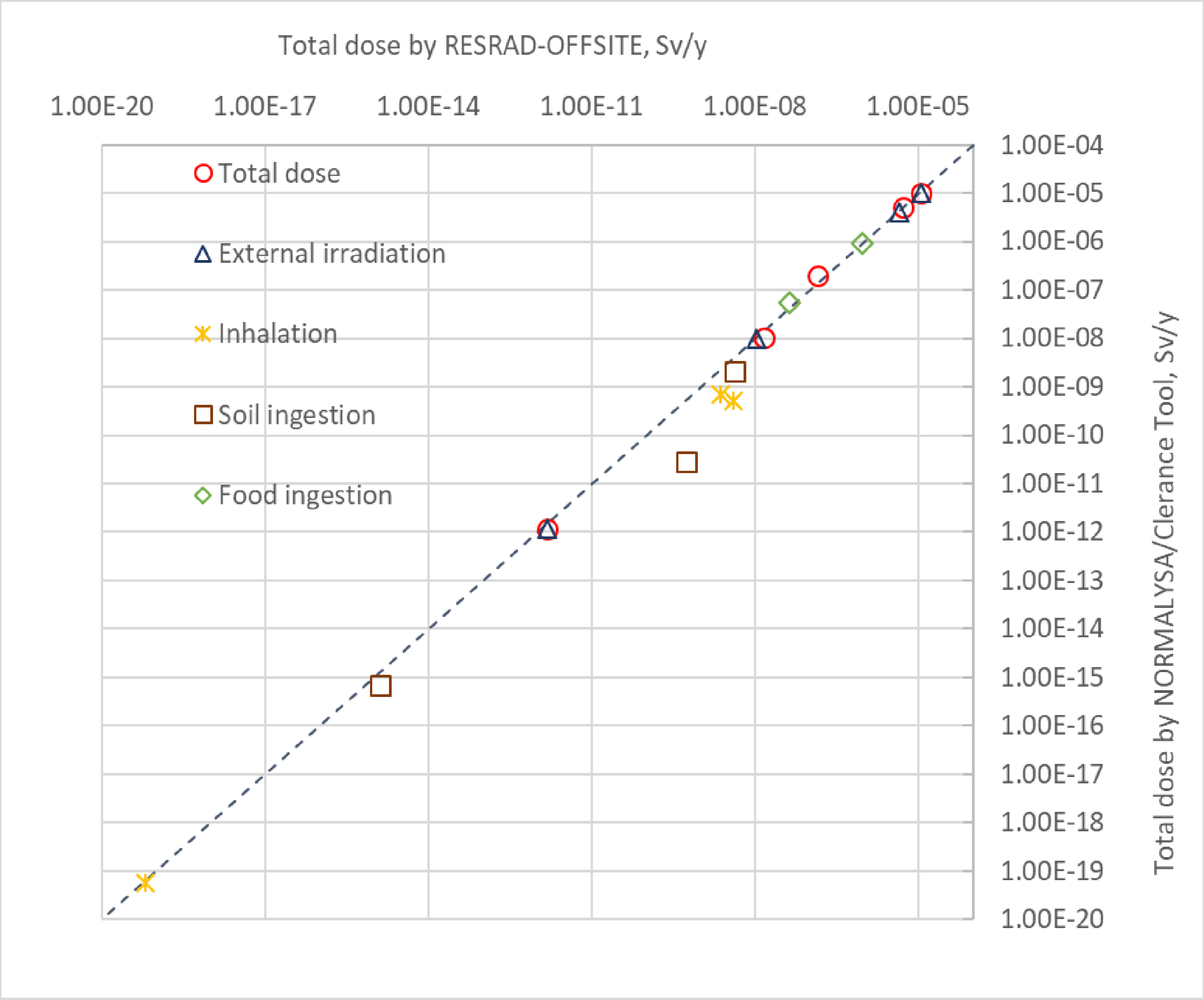
Important exposure pathways, main dose-contributing radionuclides and sensitive parameters

Scenario	Important pathways	Important radionuclides	Time of max dose (T_{max}), y	Sensitive parameters
SC1: Release from the MLA to coastal system (leaching)	External irradiation (beach), ingestion of fish	Cs-137, Co-60	30	Waste backfill Kd, infiltration rate
SC2: Release from the MLA to coastal system (run-off)	External exposure (beach), ingestion of fish	Cs-137, Co-60	30	Eroded area of the MLA; concentration of suspended particles in run-off
SC3: Release from HSWL to groundwater	Groundwater intake and irrigated crop ingestion	Sr-90	200 - 700	Kd of geological layers; infiltration rate
SC4: Intrusion to HSWL (small excavation)	External irradiation, inhalation	Cs-137, Am-241	30 - 100	Time of intrusion; waste dilution coefficient
SC5: Re-use – construction of public place	External irradiation	Co-60, Cs-137	0.3	Time before scenario; waste dilution coefficient
SC6: Re-use – agricultural land	External irradiation, crop ingestion	Co-60, Cs-137	5 - 10	Waste dilution coefficient; CR crops

Conclusions on inter-comparison of results

- In most cases, total doses calculated by the compared software tools are in good agreement.
- External irradiation doses calculated by RESRAD-OFFSITE usually are somewhat lower than by Ecolego-based tools (up to 10-20%) due to more sophisticated external exposure model used in RESRAD-OFFSITE.
- There is noticeable difference in models/results for the inhalation and soil ingestion pathways between software tools: the RESRAD-OFFSITE (contrary to NORMALYSA and the Clearance Tool) does not account for concentration of activity in the fine fraction of soil for inhalation (factor of 4 and soil ingestion (factor of 2) - these factors are based on recent recommendations from the IAEA.
- Due to described above differences overall, dose estimates by NORMALYSA and the Clearance tool tend to be more conservative than by RESRAD-OFFSITE.

Comparison graph of dose assessment results with different tools



Conclusions on functionality: RESRAD-OFFSITE

Advantages

- Capabilities for probabilistic analysis and uncertainty analysis.
- Large radionuclide database (> 1200 radionuclides) and well documented parameter database
- Long application history. Many supporting documents (manuals) and publications
- Approved by many US federal agencies. Has been used in many IAEA model validation exercises

Limitations

- "Closed software architecture" (user cannot modify/ add a new mathematical sub-model
- The tool is tailored first of all for the US regulatory framework
- Some modeling capabilities (e.g., marine system modeling) are missing
- Model parameters are constants (not variable in time). Dose models do not consider activity concentration factors in the fine fraction for inhalation and soil ingestion
- Dose assessment models do not allow to consider the parameter 'time before the start of scenario' (e.g., for temporary storage, processing etc.)

Conclusions on functionality: NORMALYSA

Advantages

- Modern software architecture and powerful computation capabilities. It allows time-dependent parameters
- It has an open software architecture (modules can be modified or added).
- It implements several IAEA-recommended models as well as those, developed by SKB for safety assessment of nuclear repositories
- Capabilities for probabilistic analysis and uncertainty analysis.
- It has been used in IAEA model validation exercises; the user manual is being prepared for publication by IAEA

Limitations

- Relatively small application history, relatively few supporting documents. Small default radionuclide database
- Uses relatively simple models for assessing doses from external irradiation
- Requires better-trained software users, familiar with the underlying mathematical models

Conclusions on functionality: IAEA Clearance Tool

Advantages

- It implements IAEA recommended methodology for calculation of clearance levels
- It has the capability to assess both VLLW disposal options for all main types of landfills (inert, municipal, hazardous) and main re-use/recycling options
- It incorporates the full set of relevant exposure scenarios both for operational and post-closure phases
- Software interface is well-structured and easy to use: to run the tool the user just needs to input (adapt) a set of site-specific parameters

Limitations

- For some scenarios, it implements simplified and conservative models, which may lead to higher clearance levels.
- It implements a ‘fixed’ schematization of the radionuclide transport problem and dose assessment procedures.
- It lacks some country-specific models that are needed for Swedish cases (e.g., a coastal marine model)

Recommendations on selection software tools

- The IAEA Clearance Tool can be recommended as a basic tool for calculation of country-specific clearance levels
  (as it has fullest set of program modules, allowing assessments for a systematic list of scenarios, based on IAEA recommendations. It is well-structured and easy to use)
- In the case that a country/site-specific scenario or adequate model is lacking in the Clearance Tool, the missing model can be complemented by NORMALYSA
  (e.g., coastal marine system model, detailed groundwater transport model, etc.)
- RESRAD-OFFSITE can be used for checks and verifications of results from the Clearance Tool and NORMALYSA (where it is applicable).
  (It lacks, however, some important functionality for a standalone tool for assessment of VLLW management options).
- All three tools have limited models/capabilities for external dose calculations.
  (Therefore, for specific source-geometries some additional tool can be potentially used, e.g., MicroShield)