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# CARBOWASTE

***Treatment and Disposal of Irradiated Graphite and Other Carbonaceous Waste***

**Grant Agreement Number: FP7-211333**

# Technical Report T-6.4.5

## Report on Performance Assessment for $^{14}C$ (gas and liquid phase) and $^{36}Cl$ (liquid phase) for the disposal of i-graphite from MTR

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**Performance Assessment for $^{14}C$ (gas and liquid phase) and $^{36}Cl$ (liquid phase) for the disposal of i-graphite from MTR**

**Executive summary**

Tasks assumed by INR in the framework of the CARBOWASTE project, in WP6, include experimental studies on migration of $^{14}C$ via gas pathway from carbonaceous waste, model of $^{14}C$ release, performance assessment for $^{14}C$ and $^{36}Cl$ based on the existing concept of the future LIL waste repository from the Saligny site.
This report presents the performance assessment for $^{14}C$ and $^{36}Cl$ based on the existing concept of the future LIL waste repository from the Saligny site.

**Revisions**

| Rev. | Date | Short description | Authors | Internal Review | Task Leader | WP Leader |
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# 1 Generals

In the Romanian scenario, the most likely option for irradiated graphite is a *near surface disposal*. The factors that converge to this solution are (1) the low amount and low activity of i-graphite existing on the territory of the country (the expected amount is maximum 10 t with a total activity not exceeding $2 \cdot 10^{10}$ Bq), (2) the immediate need for a disposal facility to accomodate the i-graphite coming from the decomissioning of the VVSR research reactor in Bucharest and (3) a LLW repository is foreseen in the near future (year 2017), whereas a deep geological disposal facility is expected to be built only after 2050.

Moreover, the radionuclide inventory for the LLW repository estimated for 4 CANDU Units contains already large quantities of C-14, Cs-137 and Co-60 which will be only slowly increased by the irradiated graphite disposal. Having this perspective, one of the INR goals in the CARBOWASTE project was to complete the **performance assessment** for $^{14}C$ with data accounting for irradiated graphite. $^{14}C$ could be transported to the biosphere either as a gas (carbon dioxide or methane) or by groundwater (aqueous carbonate and bicarbonate, dissolved amorphous $^{14}C$).

During transport and in the operational phase, gas production is likely to be of greatest radiological significance for those wastes having a high concentration of $^{14}C$ and that have the potential to degrade rapidly via oxidation or microbiological activity. An important but not fully elucidated consideration concerning this issue is whether this radionuclide, in certain conditions, will be produced and transported mainly as carbon dioxide or methane, as the radiotoxicological properties and environmental behaviour of these two species are completly distinct [1].

Under 'safe storage' conditions in a near surface disposal facility, negligible $^{14}C$ release through gas-phase mechanism is expected from i-graphite, as a temperature of more than 400°C is needed to produce a significant oxidation rate in air for graphite [2]. Neither bacteriological study has indicated a potential significant leaching of $^{14}C$ activity in these conditions [2].

Up to now, the experiments and modeling at INR related to performance assessment of i-graphite focused on a theoretical release of $^{14}C$ as carbon dioxide, through diffusion in media pores.

Samples used in flow tests were collected from the materials – clay and loess – making the cover system of the future Saligny repository. Data gained from the experimental work (e.g.

flow rates throgh media and gas permeability of the media) consist a more realistic input for the mathematical model of $^{14}C$ transport included in the final performance assessment.
Migration of the gas species through environment was accounted to take place through advection and diffusion.

# 2 Romanian disposal concept

The nuclear irradiated graphite in Romania is available in amounts not exceeding 10 tones, coming partly from the thermal column of TRIGA reactor at INR site, partly from decommissioning of the VVRS reactor in Bucharest. The most important radioisotopes for long term activity of disposed irradiated graphite are $^{14}C$ and $^{36}Cl$.

The $^{14}C$ inventory estimated from combined graphite measurements and ORIGEN simulations in irradiated graphite from TRIGA reactor is $2.10^{10}$ Bq. For $^{36}Cl$ inventory only ORIGEN simulations are available amounting it at $8.5.10^{9}$ Bq [3].

An optimal solution for the final disposal of irradiated graphite is sought and the most favoured option currently converges to the disposal in a near surface repository, considering the plan of building a low and intermediate level waste repository at Saligny site, near the Cernavoda NPP.

Performance assessment was accomplished with GoldSim software for irradiated graphite from TRIGA reactor. The dose contribution was computed only for $^{14}C$ (gas and water pathway) and $^{36}Cl$ (water pathway). Two cases were considered: no engineered barriers - in order to obtain the most conservative dose value; and concrete as graphite encapsulation and disposal matrix.

This multi-barrier disposal facility illustrated in **Figure 2.1.1** and **Figure 2.1.2** ensures the safe isolation of the waste through the combination of the natural barrier (Saligny geology) with the following engineered barriers [4, 5]:

- the waste form (mainly cemented waste);
- disposal module (container) – durable element, prefabricated from reinforced concrete in order to ensure the long term radionuclides retention
- the disposal cell, together with the separated drain water systems for the cell infiltrated water and of the meteoric waters;

- the improved foundation ground;
- the multi layered closing system (isolating and draining layers) of the cells acting as a long-term protection barrier against rainwater infiltration inside the disposal unit;
- the geological environment consisting in loess and clay layers laying on a limestone platform.

The Saligny repository is intended to host operational LIL-SL waste but also some limited amounts of LL radionuclides [4] such as C-14, I-129, Cl-36.

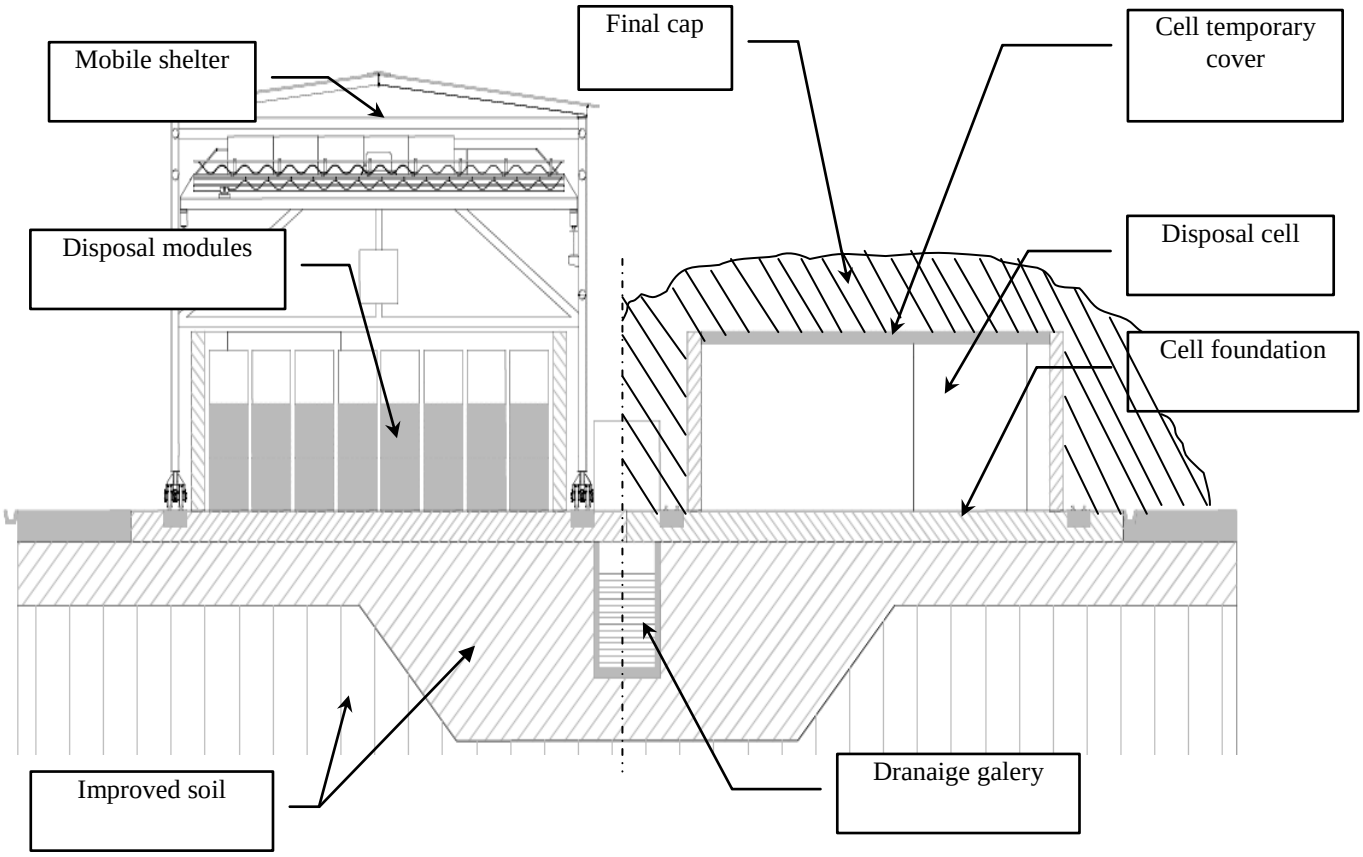


***Figure 2.1.1*** *The cross section of the repository*

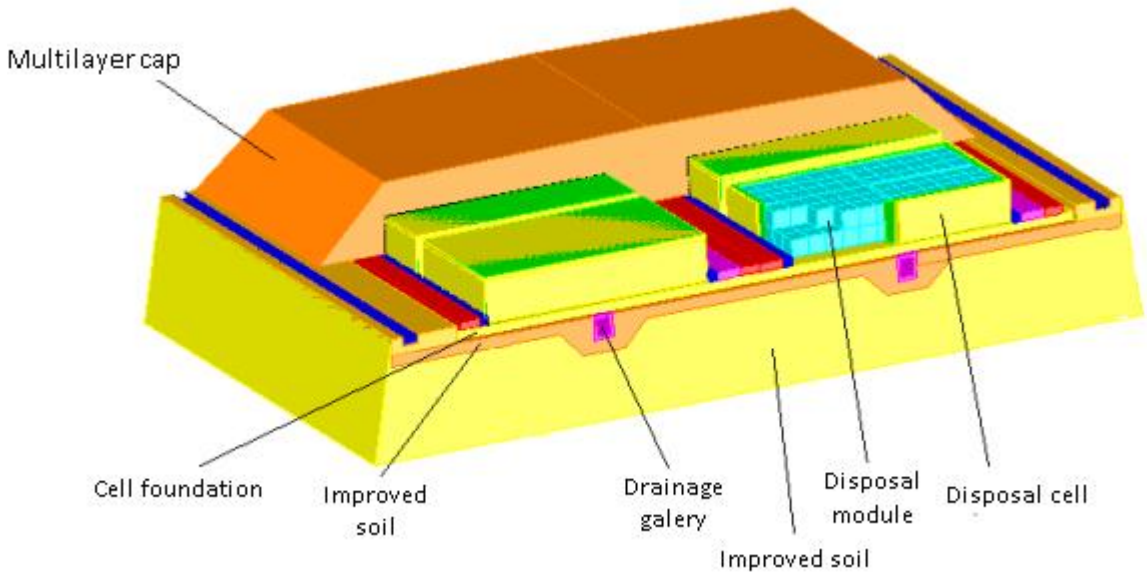


***Figure 2.1.2*** *General view of the disposal system*

The disposal cells are placed in an unsaturated zone at 50 m above the water table in order to provide protection from groundwater infiltration. The cell foundation is an impermeable concrete pad with an integrated drain to allow any infiltrated water to run off by gravity to the water collection system where the presence and activity of water can by monitored.

The disposal cells are also designed to withstand earthquakes.

The repository is designed to accommodate maximum 64 disposal cells (rectangular array of 8x8), each of them containing 384 disposal modules (rectangular array of 8x16 on three levels) with the treated and conditioned wastes. A single type of disposal module will be used: a cubical fibre-reinforced concrete container with 3 $m^3$ loading volume.

The treated radioactive waste will be conditioned by cementation in a disposal module.

# 3 Assessment of radiological impact of $^{14}C$ and $^{36}Cl$ from irradiated graphite surface disposal

The dose assessment model proposed by INR is rather conceptual than realistic, aiming to serve as a template on which adjustments are still to be made as soon as new data become available. The study assumes the independent disposal of 2.5 tones of irradiated graphite accounting for the TRIGA graphite inventory in a near surface facility having Saligny site characteristics. Only dose produced by $^{14}C$ and $^{36}Cl$ potential releases are assessed.

$^{14}C$ has an extremely complex behavior in geological environment and may be partitioned between liquid, gaseous and solid phases, its distribution being controlled by the carbonate chemistry, microbial and gas generating processes. The current performance assessment of the near surface disposal does not take all these into account.

$^{36}Cl$ behaves much simpler, being potentially released only in liquid phase and with no significant interaction with materials expected in a geological disposal facility.

## *3.1 Source term*

The inventory of $^{14}C$ was considered $2 \cdot 10^{10}$ Bq based on radionuclide measurement of samples from TRIGA reactor and complies the Waste Acceptance Criteria (WAC) established for Saligny repository (MAAL=$1.10^{5}$ Bq/g).

The inventory of $^{36}Cl$ amounting $8.5 \cdot 10^{9}$ Bq was inferred from computation using the ORIGEN code, in the absence of experimental data. This amount exceeds with two orders of magnitude the WAC (MAAL=10 Bq/g). Future experimental measurements on irradiated samples must confirm the simulated amount.

The C-14 release is not well understood yet and data from literature show that different graphite samples behave differently and different testing laboratories have not obtained the same values of leaching rates on equivalent samples when comparison have been made [6]. In the absence of dedicated studies to determine the leaching rate of $^{14}C$ and respectively $^{36}C$ from irradiated graphite of the TRIGA thermal column, the model uses the fractional release rates from [7], namely $1.7 \cdot 10^{-2}$ 1/yr for C-14 and $3.7 \cdot 10^{-1}$ 1/yr for $^{36}Cl$.

Two distinct cases were analyzed:

- *Case 1* assumes that both $^{14}C$ and $^{36}Cl$ are available for transport neglecting the concrete surrounding the irradiated graphite, and
- *Case 2* considers 300 years of concrete barrier embedding irradiated graphite dispersed inside a disposal cell, 1m high concrete liner as cell foundation and 0.60m concrete walls around. To conform the WAC for $^{36}Cl$, irradiated graphite disposal in a separate disposal cell is assumed. Sorption on concrete of $K_d$=5 $cm^3/g$ for $^{36}Cl$, and $K_d$=2.10$^3$ $cm^3/g$ for $^{14}C$ is used for assessing the effect of retardation.

## 3.2 Assumptions for $^{14}C$ and $^{36}Cl$ transport

Gaseous $^{14}C$ is supposed to migrate in the cover system of the repository through advection and diffusion. The advective characteristics were determined in laboratory on compacted loess and clay samples with porosities and saturation specific for the cover layers as part of WP 6.4. It is considered that $^{14}C$ is released initially in aqueous phase and it is further partitioned between gaseous and aqueous phase according to Henry law. $^{36}Cl$ will not be transported through the cover material.

In order to assess the impact on the annual individual dose, the model takes into account all contamination pathways: ingestion, inhalation and external exposure using the reference scenario corresponding to a residence farm built on the site after 300 years when the institutional surveillance ends.

## 3.3 Dose assessment for $^{14}C$ and $^{36}Cl$ released from irradiated graphite

The entire computation was performed using GoldSim software based on submodels for transport and dose conversion developed as part of the INR work in WP6.4 and depicted in **Figure 3.3.1** and **Figure 3.3.2.** Concentration of $^{14}C$ in the atmosphere and concentration of $^{14}C$ and $^{36}Cl$ in a fountain located at 100 m far away from the disposal area were converted to dose inside the **Biosphere Submodel.** The **Bisophere Submodel** contains several expresions and parameters taken from the conceptual model ERMYN (*Environmental Radiation Model for Yucca Mountain, Nevada*) [8,9,10] and from the User Manual of the RESRAD code [11].

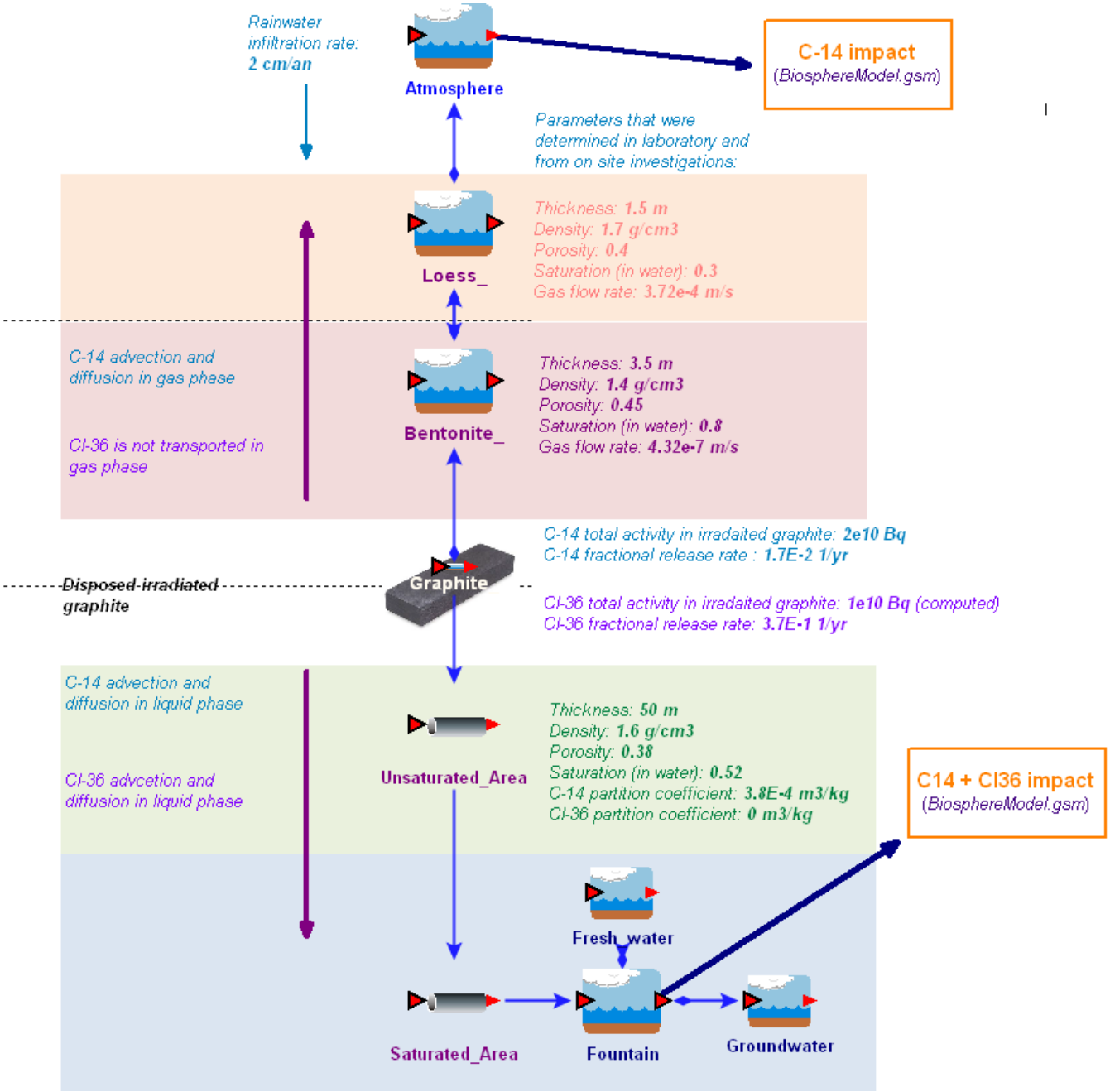


***Figure 3.3.1*** *GoldSim Transport Submodel for C-14 and Cl-36 released from irradiated graphite*

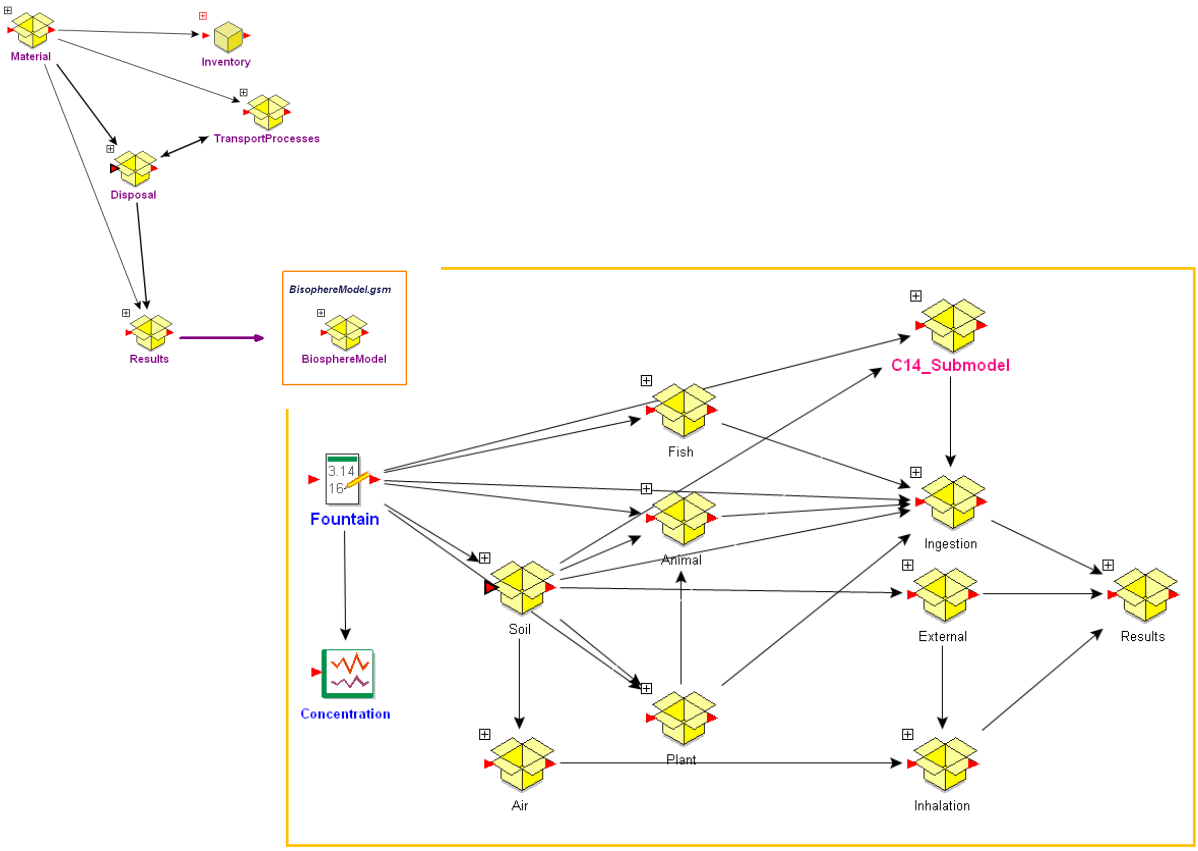


***Figure 3.3.2*** *Diagram of model for assessing the dose from $^{14}C$ and $^{36}Cl$ release*

## 3.4 Description of the Biosphere Submodel

The main pathway for $^{14}C$ intake by humans from a contaminated site is usually through food ingestion.

$^{14}C$ soil-to-plant transfer factors are often used to estimate the radiological dose to humans from soil contaminated with $^{14}C$.

Usually, dose assessment models take into account two separate pathways: (1) direct root uptake and (2) uptake by foliage of gases volatilized from the soil and absorbed from the atmosphere.

In general, the direct root uptake pathway should depend on the magnitude of the soil source; the atmospheric pathway should depend on the volatilization rate from the soil, the uptake rate of foliage, and the meteorological dispersion conditions [11].

For each pathway, the transport of $^{14}C$ is assumed to follow that of stable carbon.

The $^{14}C$ concentrations in meat and milk are assumed to be derived totally from the livestock diets. The transfer of $^{14}C$ from the livestock diets to meat and milk is assumed to follow the same route as that of stable carbon. The $^{14}C$ contents in meat and milk are related to the intake rates of stable carbon and $^{14}C$ by livestock [11].

In order to take into account these considerations, a special submodel for $^{14}C$ was created.

$^{36}Cl$ is not considered for air transport.

### 3.4.1 Soil component

**Table 3.4.1.1** contains the description of the input and computed data for the Soil component.

***Table 3.4.1.1*** *Description of the Soil component*

| Input Data | Value |
|---|---|
| Annual average irrigation rate on land (annual irrigation rate) (m/yr), IR<br>(typical range of irrigation rates is from 0.5 to 1.0 m/yr) | 1.0 m/yr |
| Crop overwatering rate (m/yr), OW | 1.0 m/yr |
| Annual average erosion rate for the surface soil kg/($m^2$·yr)<br>(range: 0.19 to 1.1 kg/($m^2$·yr)) | 1.0 kg/$m^2$/yr |
| Surface soil depth (m) | 1.0 m |
| Radioactive decay constant for the radionuclide ($yr^{-1}$), lambda_d<br>(input as half-life in Radionuclides properties) | For $^{14}C$: 2.302E-06 $yr^{-1}$<br>For $^{36}Cl$: 1.212E-04 $yr^{-1}$ |
| Volumetric water content of soil (dimensionless)<br>(input in Surface Soil properties as porosity) | 0.3 |
| Density of surface soil (kg/$m^3$):<br>(input in Surface Soil properties as bulk density) | 2000 kg/$m^3$ |
| Saturation ratio of contaminated zone, (dimensionless), CZRs | 0.5 |
| **Computed Data** | **Expression** |
| Equilibrium activity concentration of the radionuclide in surface soil per unit area (Bq/$m^2$), Cs | Cw*IR/(lambda_d+ lambda_l)+Cw*IR/lambda_e |
| Volumetric water content, (dimensionless), CZteta | SurfaceSoil:Porosity*CZRs |
| Activity concentration of the radionuclide in the groundwater (Bq/$m^3$), Cw (computed from groundwater pathway) | Concentration of radionuclide in the Fountain object from the Transport Pathway |
| Average annual leaching removal constant for the radionuclide ($yr^{-1}$), lambda_l | OW/(SurfaceSoilDepth*CZteta * (1+SurfaceSoilDensity/CZteta* SurfaceSoil:Partition_Coefficients[RN])), where RN= $^{14}C$, $^{36}Cl$ |
| Average annual surface soil erosion removal constant ($yr^{-1}$), lambda_e | ErosionRate/(SurfaceSoilDensity*SurfaceSoilDepth) |
| Concentration of C-14 in soil, Bq/kg, SC14 | Cs[C14]/(SurfaceSoilDensity*SurfaceSoilDepth) |

### 3.4.2 Radionuclide Transport to Crops

Environmental transport pathways considered in the biosphere model for the groundwater exposure scenario that result in radionuclide transport to crops are:

- **Deposition of contaminated water on crop surfaces**
- **Root uptakes of radionuclides present in surface soil**

Crop types considered are leafy vegetables, other vegetables, fruits, grains and forage. Data needed for radionuclide transport to crops are presented in **Table 3.4.2.1, Table 3.4.2.2, Table 3.4.2.3** and **Table 3.4.2.4.**

***Table 3.4.2.1*** *Data needed for radionuclide transport to crops*

| **Crop Data** | **Value** |
|---|---|
| Daily average irrigation rate for crop type *j* during the growing season (m/d), *IRDj* [8] | For leafy veg: 5.41 mm/d<br>For Other veg: 7.71 mm/d<br>For Fruits: 7.41 mm/d<br>For Grains: 4.64 mm/d<br>For Forage: 6.55 mm/d |
| Fraction of irrigation applied using overhead methods for plant type *j* (dimensionless), *fo,j* [8] | For leafy veg: 0.75<br>For Other veg: 0.75<br>For Fruits: 0.5<br>For Grains: 0.9<br>For Forage: 0.9 |
| Interception fraction of irrigation water for crop type *j* (dimensionless), *Rwj* [8] | For leafy veg: 0.216<br>For Other veg: 0.301<br>For Fruits: 0.360<br>For Grains: 0.470<br>For Forage: 0.258 |
| Translocation factor for crop type *j* (dimensionless), *Tj* [8] | For leafy veg: 1.0<br>For Other veg: 0.1<br>For Fruits: 0.1<br>For Grains: 0.1<br>For Forage: 1.0 |
| Weathering half-life (d), Tw [8] | 14 d |
| Crop growing time for crop type *j* (d), *tg, j* [8] | For leafy veg: 75 d<br>For Other veg: 80 d<br>For Fruits: 160 d<br>For Grains: 200 d<br>For Forage: 75 d |
| Crop yield or wet biomass for crop type *j* (kg wet weight/m$^2$), *Yj* [8] | For leafy veg: 3.30 kg/m^2<br>For Other veg: 4.13 kg/m^2<br>For Fruits: 2.75 kg/m^2<br>For Grains: 0.59 kg/m^2<br>For Forage: 2.14 kg/m^2 |
| Soil-to-plant transfer factor for the radionuclide and crop type *j* (Bq/kg dry plant per Bq/kg dry soil) *Fs→p,j* [8] | For leafy veg: 6.4E-01<br>For Other veg: 6.4E-01<br>For Fruits: 6.4E-01<br>For Grains: 2.4E-01<br>For Forage: 7.5E-01 |
| Dry-to-wet weight ratio for edible part of plant (kg dry-plant /kg wet-plant), *DWj*<br>[8] | For leafy veg: 0.07<br>For Other veg: 0.103<br>For Fruits: 0.120<br>For Grains: 0.903<br>For Forage: 0.220 |
| **Computed Data** | **Value** |
| Weathering constant (per d), which can be calculated from weathering half-life (*Tw* in units of day) by $\lambda w = \ln(2) / Tw$ | 0.0495 d$^{-1}$ |

**Deposition on crop surface:** Radionuclide concentrations in crops due to leaf uptake from contaminated irrigation water sprayed on plants

**Table 3.4.2.2** *Computed data for deposition on crop surface*

| Computed Data | Value/ Expression |
|---|---|
| Deposition rate of a radionuclide due to application of irrigation water on crop type *j* (Bq/(m$^2$ d)), *Dwj* | IRD[Crop]*Cw[RN], where RN= $^{36}$Cl and Crop= leafy vegetables, other vegetables, fruits, grains, forage |
| Radionuclide concentration in crop type *j* due to application of irrigation water (Bq/kgwet weight), *Cpwater,j* | Dw[RN,Crop]*fo[Crop]*Rw[Crop]*T[Crop]*(1-exp(-lambda_w*Tg[Crop]))/(lambda_w*Y[Crop]), where RN= $^{36}$Cl and Crop = leafy vegetables, other vegetables, fruits, grains, forage |

**Root uptake:** Root uptake is the second most important environmental transport pathway that gives rise to radionuclide concentration in crops.

***Table 3.4.2.3*** *Computed data for root uptake*

| Computed Data | Value/ Expression |
|---|---|
| The activity concentration of radionuclides in crops from root uptake, Cp root,j (Bq/kg wet weight) | Cs[RN]/(SurfaceSoilDensity* SurfaceSoilDepth)* SoilToPlantTransferFactor[RN, Crop]*Dry_to_Wet_WeightRatio[Crop], where RN= $^{36}$Cl and Crop= leafy vegetables, other vegetables, fruits, grains, forage |

***Table 3.4.2.4*** *Data needed for $^{14}$C transport*

| Data | Value/ Expression |
|---|---|
| Fraction of stable carbon in plants (dimensionless), Ccv [11] | For leafy veg: 0.09<br>For Other veg: 0.4<br>For Fruits: 0.09<br>For Grains: 0.09<br>For Forage: 0.09 |
| Fraction of carbon in plants derived from carbon in air, (dimensionless), Fa [11] | 0.98 |
| Fraction of carbon in plants derived from carbon in soil, (dimensionless), Fs [11] | 0.02 |
| **Computed data** | **Value** |
| Soil-to-lant transfer factor, including all sources, (Bq/kg | If (SC14=0 Bq/kg, 0, |

| | |
|---|---|
| plant)/(Bq/kg soil), Bc14v | Ccv[Crop]*(Fa*CC14a[C14]/(Cc aeqm*SC14)+Fs/Sc)), where Crop = leafy vegetables, other vegetables, fruits, grains, forage |
| Concentration of C-14 in plants, Bq/kg, CC14v | Bc14v[Crop]*SC14, where Crop = leafy vegetables, other vegetables, fruits, grains, forage |

### 3.4.3 Radionuclide Transport to Animals

Environmental transport pathways considered in the biosphere model that result in radionuclide transport to animal products are (1) animal consumption of feed, water and soil; and, indirectly, (2) environmental transport pathways leading to radionuclide accumulation in forage plants and in the surface soil [11].
For $^{14}C$, 97-98% of this radionuclide in animal products is from ingestion of feed, and 2-3% from ingestion of water and less than 0.02% from soil [11].
Ingestion of soil is a negligible source of $^{14}C$ in animal products.
Animal products considered in the computation are beef, milk, poultry, eggs. Data needed for radionuclide transport to animals are presented in **Table 3.4.3.1.**

***Table 3.4.3.1*** *Data needed for radionuclide transport to animals*

| **Animal Product Data** | **Value** |
|---|---|
| Animal product transfer coefficient for meat, Fm1, d/kg [8] | For $^{14}C$: 0 d/kg<br>For $^{36}Cl$: 4.6E-02 d/kg |
| Animal product transfer coefficient for milk, Fm2, d/L [8] | For $^{14}C$: 0 d/L<br>For $^{36}Cl$: 1.8E-02 d/L |
| Animal product transfer coefficient for poultry, Fm3, d/kg [8] | For $^{14}C$: 0 d/kg<br>For $^{36}Cl$: 3.0E-02 d/kg |
| Animal product transfer coefficient for eggs, Fm4, d/kg [8] | For $^{14}C$: 0 d/kg<br>For $^{36}Cl$: 4.4E-02 d/kg |
| **Animal consumption rate of feed** | **Value** |
| Beef cattle, Qf1 [8] | 29 kg/d |
| Dairy cow, Qf2 [8] | 50 kg/d |
| Poultry, Qf3 [8] | 0.12 kg/d |
| Laying hen, Qf4 [8] | 0.12 kg/d |
| **Animal Consumption rate of water** | **Value** |
| Beef cattle, Qw1 [8] | 60 L/d |
| Dairy cow, Qw2 [8] | 60 L/d |
| Poultry, Qw3 [8] | 0.5 L/d |
| Laying hen, Qw4 [8] | 0.5 L/d |
| **Animal consumption rate of soil** | **Value** |
| Beef cattle, Qs1 [8] | 0.4 kg/d |
| Dairy cow, Qs2 [8] | 0.8 kg/d |
| Poultry, Qs3 [8] | 0.01 kg/d |
| Laying hen, Qs4 [8] | 0.01 kg/d |
| Fraction of stable carbon in meat (dimensionless), | 0.24 |

| | |
|---|---|
| CCmeat [11] | |
| Concentration of stable carbon in livestock water, (kg/L), Wc [11] | 2e-5 kg/L |
| Daily intake rate of water by livestock, (L/d), FImeat5 [11] | 50 L/d |
| Concentration of stable carbon in livestock fodder (kg/kg), FDRCmeat [11] | 0.24 |
| Livestock soil intake rate, (kg/d), FImeat6 [11] | 0.5 kg/d |
| Pasture intake by beef cattle (kg/d), PastureIntakeBC [11] | 14 kg/d |
| Grain intake by beef cattle (kg/d), GrainIntakeBC [11] | 54 kg/d |
| Fraction of stable carbon in milk (dimensionless), CCmilk [11] | 0.07 |
| Daily intake rate of water by livestock, (L/d), FImilk5 [11] | 160 L/d |
| Concentration of stable carbon in livestock fodder (kg/kg), FDRCmilk [11] | 0.07 |
| Livestock soil intake rate, (kg/d), FImilk6 [11] | 0.5 kg/d |
| Pasture intake by milk cow (kg/d), PastureIntakeMC [11] | 44 kg/d |
| Grain intake by milk cow (kg/d), GrainIntakeMC [11] | 11 kg/d |
| **Computed** | **Value** |
| Activity concentration of a radionuclide in beef, Bq/kg fresh weight, Cd1 | Fm1[RN]*(Cpwater[RN,Forage]*Qf1+Fountain[RN]*Qw1+ Cs[RN]*Qs1/(SurfaceSoilDensity*SurfaceSoilDepth)), where RN= Cl36 |
| Activity concentration of a radionuclide in milk, Bq/L , Cd2 | Fm2[RN]*(Cpwater[RN,Forage]*Qf2+Fountain[RN]*Qw2+ Cs[RN]*Qs2/(SurfaceSoilDensity*SurfaceSoilDepth)), where RN= Cl36 |
| Activity concentration of a radionuclide in poultry, Bq/kg fresh weight, Cd3 | Fm3[RN]*(Cpwater[RN,Grains]*Qf3+Cw[RN]*Qw3+ Cs[RN]*Qs3/(SurfaceSoilDensity*SurfaceSoilDepth)), where RN= Cl36 |
| Activity concentration of a radionuclide in eggs, Bq/kg fresh weight, Cd4 | Fm4[RN]*(Cpwater[RN,Grains]*Qf4+Cw[RN]*Qw4+ Cs[RN]*Qs4/(SurfaceSoilDensity*SurfaceSoilDepth)), where RN= Cl36 |
| Livestock fodder intake rate, (kg/d), FImeatq [11] | GrainIntakeBC+PastureIntakeBC |
| Intake rate of stable carbon in the diet of beef cattle, (kg/d), FICmeat [11] | Wc*FImeat5+FDRCmeat*FImeatq+Sc*FImeat6 |
| Transfer factor for meat, (d/kg), FQRC14meat [11] | CCmeat/FICmeat |
| Intake rate of C-14 in the diet of beef cattle, (Bq/d), FIC14meat [11] | Fountain[C14]*FImeat5+CC14v[Forage]*FImeatq+ |

| | |
|---|---|
| | Cs[C14]/(SurfaceSoilDensity*SurfaceSoilDepth)*FImeat6 |
| Intake rate of C-14 in the diet of beef cattle, (Bq/d), FIC14meat [11] | FQRC14meat*FIC14meat |
| Livestock fodder intake rate, (kg/d), FImilkq [11] | GrainIntakeMC+PastureIntakeMC |
| Intake rate of stable carbon in the diet of milk cow, (kg/d), FICmilk [11] | Wc*FImilk5+FDRCmilk*FImilkq+Sc*FImilk6 |
| Transfer factor for milk, (d/kg), FQRC14milk [11] | CCmilk/FICmilk |
| Intake rate of C-14 in the diet of milk cow, (Bq/d), FIC14milk [11] | Fountain[C14]*FImilk5+CC14v[Forage]*FImilkq+ Cs[C14]/(SurfaceSoilDensity*SurfaceSoilDepth)*FImilk6 |
| Concentration of C-14 in milk, (Bq/kg), CC14milk [11] | FQRC14milk*FIC14milk |

### 3.4.4 Radionuclide Transport to Aquatic Fish

Data needed for radionuclide transport to aquatic fish is presented in **Table 3.4.4.1**

***Table 3.4.4.1*** *Data needed for radionuclide transport to aquatic fish*

| **Aquatic food data** | **Value** |
|---|---|
| Bioaccumulation factor for the radionuclide in freshwater fish (L/kg), BF [8] | For $^{14}$C: 4.6E+3 L/kg<br>For $^{36}$Cl: 2.2E+02 L/kg |
| Water concentration modifying factor for the radionuclide (dimensionless) , MF [8]<br>The water concentration modifying factor accounts for water evaporation from fish ponds and is developed using site-specific conditions.<br>The bioaccumulation of radionuclides in fish is element specific and the fish consumption pathway is important for only a few radionuclides that have high values of bioaccumulation factor (carbon, cesium, and lead). | For $^{14}$C:1<br>For $^{36}$C:1 |
| **Computed data** | **Expression** |
| Activity concentration of a radionuclide in fish, Bq/kg wet, Cf | BF[RN]*MF[RN]*Fountain[RN], where RN= $^{14}$C, $^{36}$Cl |

### 3.4.5 Radionuclide Transport to Air

$^{36}$Cl is not considered for air transport.

Inorganic and organic reactions convert most forms of soil carbon to carbon dioxide ($CO_2$). Because of the volatile nature of $CO_2$, soil carbon is usually lost to the air, where it becomes absorbed in plants through photosynthesis. The concentration of $^{14}$C in air above a contaminated zone depends on the volatilization (evasion) rate of carbon from the soil, the size and location of the source area, and meteorological dispersion conditions.

Data needed for radionuclide transport to air are presented in **Table 3.4.5.1.**

***Table 3.4.5.1*** *Data needed for radionuclide transport to air*

| **Data** | **Value** |
|---|---|
| Evasion loss rate constant, (1/yr) EC14 [11] | 22 1/yr |
| Reference soil depth, (m) dref [11] | 0.3 m |
| Height into which the CO2 is uniformly mixed (2 m for the human inhalation pathway; 1.0 m for the plant, meat, and milk ingestion pathways), (m), Hmix [11] | 2 m |
| Equilibrium concentration of stable carbon in air, ($g/m^3$), Ccaeqm [11] | 0.18 $g/m^3$ |
| Average evasion rate of stable carbon from soil, (1/yr), EC12 [11] | 0.0032 1/yr |
| Fraction of soil that is stable carbon (0.03, dimensionless), Sc This parameter varies with soil type and would be considerably higher for soils rich in organic content [11] | 0.03 |
| **Computed** | **Expression** |
| $^{14}C$ flux at soil surface from $^{14}CO_2$ release from i-graphite (gas is obtained by equilibrium with liquid phase according to Henry law), C14gas | result from the Transport submodule |
| $^{14}C$ flux (evasion rate) from the contaminated area, EVSN [11] | 1e6*Cs[C14]/(SurfaceSoilDepth* SurfaceSoilDensity)* EC14*CZDensity*dref+C14gas |
| Average concentration of $^{14}C$ in air over a contaminated area of finite size ($Bq/m^3$), CC14a [11] | (3.17e-8*0.5*EVSN[C14]*sqrt(A))/(Hmix*U) |
| Equilibrium concentration of $^{14}C$ in air, ($Bq/m^3$), CC14aeqm [11] | Ccaeqm*EC14*Cs[C14]/ (SurfaceSoilDensity*SurfaceSoil Depth)/(EC12*Sc) |

# 4 Results

The maximum total annual dose due to the $^{14}C$ summing all contamination pathways is estimated to an order of $10^{-2}$ mSv/year (**Figure 4.1**) if no engineered barriers are considered and decreases to $10^{-6}$ mSv/yr when cementitous barriers and sorption on cement are considered (**Figure 4.2**).The most important contribution to the dose is given by $^{14}C$ inhalation as $^{14}CO_2$, in both cases while external exposure contribution to the dose is neglijable.

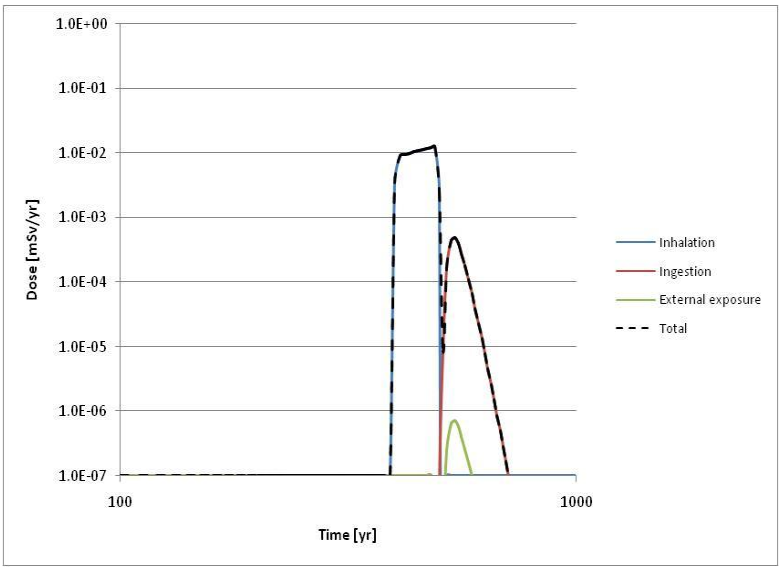


***Figure 4.1*** *Annual individual dose due to $^{14}C$ release from irradiated graphite if no engineered barriers are considered (Case 1)*

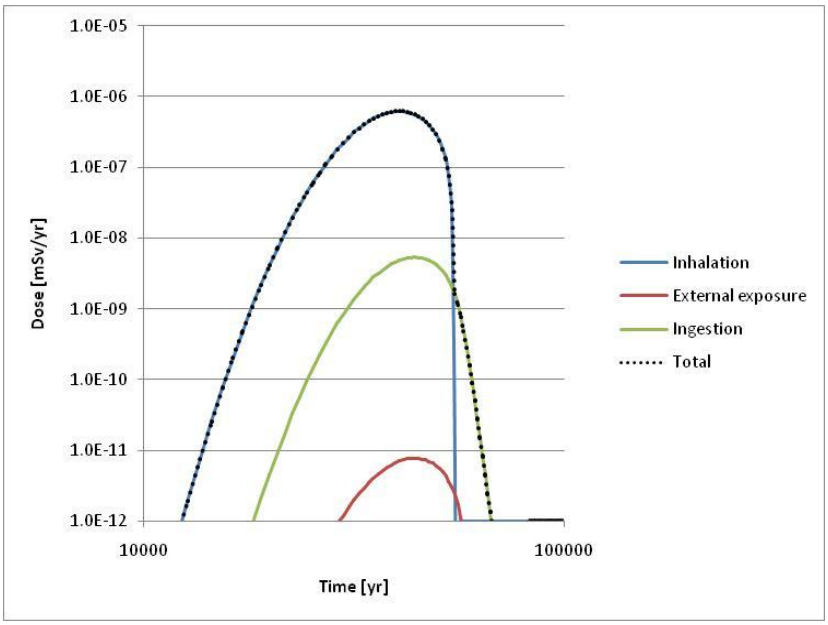


***Figure 4.2*** *Annual individual dose due to $^{14}C$ release from irradiated graphite if cementitous barriers are considered (Case 2)*

If no engineered barriers are considered (*case 1*), the value for $^{36}Cl$ dose largely exceeds the accepted dose limit (1 mSv/year) (**Figure 4.3**).

If the graphite is dispersed in a cementitous matrix inside a disposal cell, the dose value becomes acceptable, the maximum having the order of $10^{-2}$ mSv/yr (**Figure 4.4**). However, due to its higher radiotoxicity, the value is much higher than the one estimated for $^{14}C$ in the same conditions ($10^{-6}$ mSv/yr). For $^{36}Cl$ the most significant contribution to the dose is given by ingestion, in both cases.

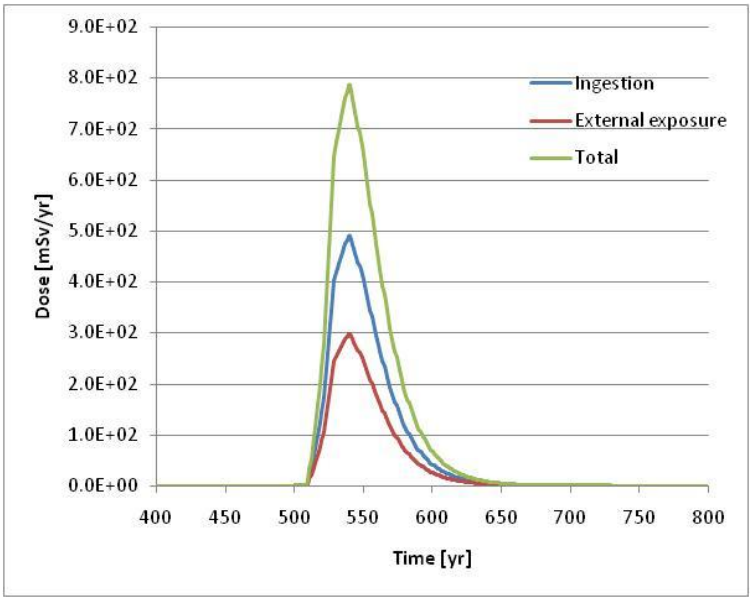


***Figure 4.3*** *Individual annual dose due to $^{36}Cl$ release if no engineering barriers are considered (Case 1)*

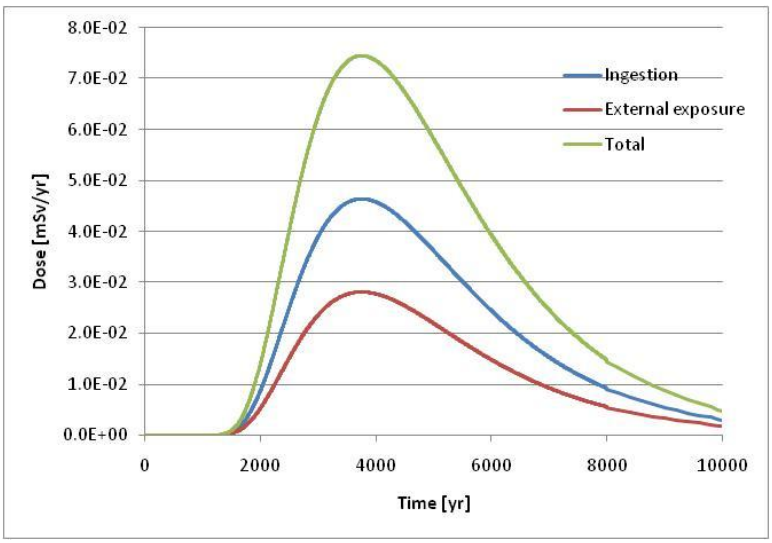


***Figure 4.4*** *Individual annual dose considering cementitous barriers (Case2)*

# 5 Conclusions

1. $^{14}C$ does not represent a concern for surface disposal of irradiated graphite from TRIGA reactor, neither as gas nor as solute.
2. $^{36}Cl$ could be accommodated in a surface repository if appropriate disposal concept minimizing the specific activity under the WAC limit is considered. In these conditions, dose constrain is fulfilled.

# 6 References

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[11] User Manual for RESRAD Version 6

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