About AMBER

AMBER (v.6.2) for Windows is a compartmental modelling package developed by Enviros Consulting and Quintessa. Addition technical and financial assistance has been provided by Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Universidad Politecnica de Madrid (UPM), Empresa Nacional de Residuos Radiactivos SA (ENRESA), JGC Corporation, Japan Nuclear Cycle Development Institute (JNC), UKAEA, SKI and Nirex.

AMBER is a flexible tool that allows users to build their own dynamic compartmental models to represent the migration, degradation and fate of contaminants in an environmental system (Watkins et al., 1999).

Modelling Approaches

The conceptual model developed from the screening of the FEP´s list for selected scenario must be represented in terms of mathematical expressions.

In this case the biosphere is modelled as a series of compartments in which homogeneous conditions are assumed (see Figure 1). The transfer between compartments is described by a “transfer rate”, which represents the fraction of activity in a compartment that is transferred to another per unit of time. Then, the variation of the activity of radionuclide m in the compartment i, $I^m{}_i$, is expressed as:

$$\frac{dI_i^m}{dt} = -\left[\lambda_r^m + \sum_j \lambda_{ij}\right] I_i^m + \lambda_r^{m+1} \cdot I_i^{m+1} + \sum_j \lambda_{ji} \cdot I_j^m$$

where, λ_{ij} is the exchange rate between compartment i and compartment j, $\lambda_r{}^{m+1}$ is the decay rate of the parent radionuclide $m+1$, and λ_r^m is the decay rate of the radionuclide m. This representation results in a set of first order linear differential equations that are solved numerically by means of the software AMBER, [AMBER, 2003].

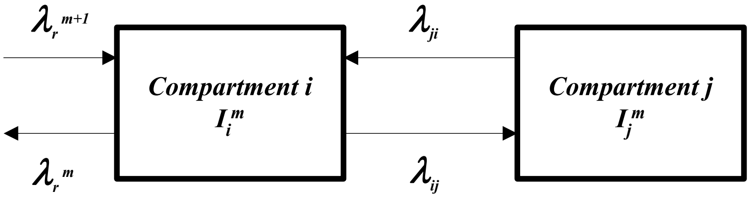

Figure 1. Activity transfer model between compartment.

The intercompartment transfer rate coefficients (λ_{ij}) from donor compartment i to receptor compartment j, are the mathematical representations of the transfer processes identified.

$$\lambda_{ij} = \frac{1}{V_i} \cdot \frac{F_{ij} + K_i M_{ij}}{\theta_i + (1-\varepsilon_{t,i})\rho_{t,i} K_i} = \frac{F_{ij} + K_i M_{ij}}{V_i(\theta_i + \rho_b)K_i}$$

where,

F_{ij}	liquid phase transport ($m^3\ y^{-1}$),
M_{ij}	solid phase transport ($kg\ y^{-1}$)
K_i	solid/liquid distribution coefficient ($m^3\ kg^{-1}$)
θ_i	moisture content (-)
$\varepsilon_{t.i}$	total porosity (-)
$\rho_{t,i}$	grain density ($kg\ m^{-3}$)
ρ_b	bulk density ($kg\ m^{-3}$)
V_i	donor compartment volume (m^3).

Mass balance is represented by matrices for the water and solid material fluxes from compartment i to compartment j (respectively denoted by F_{ij} ($m^3\ y^{-1}$) and M_{ij} ($kg\ y^{-1}$). Radionuclides in any compartment are represented as in solution in the water or sorbed onto the solid material in the compartment. The partitioning is modelled by use of the solid-liquid distribution coefficient K_i (Bq kg^{-1} per Bq m^{-3}). In this form, to identify the inter-compartment transfers it is necessary to identify the mass balance scheme for solute and solids.

The mathematical representation of the inter-compartmental transfer processes takes the form of a matrix of transfer coefficients that allows the compartment inventories to be calculated using a set of first-order linear differential equations.

Applies to the resolution of linear donor controlled compartment models (ex. applied to advective- and diffusive processes, typical of surface and groundwater bodies). Time varying source terms and transfer processes can be represented. In any specified time period, parameter values may be specified as fixed numeric values or algebraic expressions. Cyclic time-dependency can be introduced to represent dependence on day/night or on season, for example.

AMBER incorporates a sampling facility to specify a probabilistic case. A definite probability density function can be assigned to each parameter and multiple calculations are run in order to perform uncertainty and sensitivity analysis.

Conceptual Model

Mathematical model representation and data selection

The transport processes identified in the conceptual model are expressed as differential equations, in which radioactive decay and transfers among components are represented as linear processes. Homogeneous and instantaneous mixing of radioactivity is assumed in each compartment of the system. For the estimation of radionuclide concentrations in vegetation and animal products, equilibrium is assumed relative to the local mixing component. The estimation is then performed by means of concentration factors. Radiation dose is the most relevant indicator for the Safety Assessment because integrates all forms of exposure and it is used to assess the direct impact to man. Here, illustrative results are provided in terms of annual effective doses.

A compilation of mathematical models and parameters describing the transfer among compartments due to the different processes that take place in the environment has been published elsewhere (Agüero et al., 2005).

Source term

$$ALF = \frac{Inf}{Hd \cdot \left(w + \rho \cdot K_d\right)}$$

Inf	Annual infiltration ($m.y^{-1}$)
Hd	Depth of of waste material
W	Porosity
P	Density (Kg m^{-3})
K_d	Partition coefficient ($m^3\ kg^{-1}$)

Concerning dilution in the aquifer, the estimated transit time in geosphere models shows uncertainties, which in some cases can be of significance or at least need to be known for justification of hypotheses adopted in the mathematical model. The information about the transit through the major water-conducting zone (a fault of 20 m width) is given as ranges.

Concentration in sediments and river water

The activity concentration in the river water is assumed to be in equilibrium with the concentration in suspended sediments (IAEA, 2001). The partition coefficient Kd_w (m^3 kg^{-1}) expresses the exchange of radionuclides between the dissolved and sediment-sorbed phases. The dissolved radionuclide concentration in surface water (C_{wr_l}) is given by:

$$C_{wr\_l} = \frac{C_{wr}}{1 + Kd_{sed\_wr} \cdot m_{wr}}$$

where C_{wr} is the radionuclide concentration in river water (Bq m^{-3}), Kd_{sed_wr} is the partition coefficient between water and sediment in river and m_{wr} the mass load in river water (kg m^{-3}).

The radionuclide concentration adsorbed by suspended sediments (C_{sed_wr}) (Bq kg^{-1}) is:

$$C_{sed\_wr} = \frac{Kd_{sed\_wr} \cdot C_{wr}}{1 + Kd_{sed\_wr} \cdot m_{wr}}$$

The concentration of radionuclides in the riverbed sediment is assumed to be in equilibrium with the river water. Thus, the concentration (C_{sed}) of each radionuclide in bed sediments can be calculated using the above equation with values of *Kd* and *m* characteristic of the riverbed.

Taking into account the groundwater flow through the sediments underneath, the concentration of activity in the river sediments (C_{sed} in Bq m^{-3}) is:

$$C_{sed} = \frac{I_{in\_a}\left(\frac{I_{ou\_w}}{V_{wr}} + v_{sed\_wr}\right)}{\frac{I_{ou\_w}}{V_{wr}}\left(\frac{I_{in\_sed}}{V_{sed}\theta_{sed}R_{sed}} + v_{res\_sed}\right)V_{sed}}$$

where, I_{in_sed} means annual groundwater volume inflow (m^3 y^{-1}), I_{ou_w} river water volume outflow (m^3 y^{-1}), I_{in_a} radionuclide inflow rate to the river (Bq y^{-1}), v_{sed_wr} sedimentation rate in river water (y^{-1}), v_{res_sed} resuspension rate of river sediments (y^{-1}), V_{wr} volume of river water (m^3), V_{sed} the volume of sediments (m^3), θ_{sed} sediment porosity (-), R_{sed} retardation coefficient in sediments (-), ρ_{sed} sediment density (kg m^{-3}, dry). The retardation coefficient is given by:

$$R_{sed} = 1 + \rho_{sed}\frac{Kd_{sed}}{\theta_{sed}}$$

Concentration in soil

Dynamic components of the model correspond only to the soil layers, i.e. vegetation is considered through equilibrium concentration ratios. The soil is subdivided for modelling purposes into two layers: surface and deep. The temporal variation for the activity of each radionuclide in each layer can be expressed as:

$$\frac{dA_{s1}}{dt} = k_{irr} \cdot A_{ww} - \lambda_{\inf} A_{s1} - \lambda_r \cdot A_{s1}$$

$$\frac{dA_{s2}}{dt} = \lambda_{\inf} \cdot A_{s1} - \lambda_{per} \cdot A_{s2} - \lambda_r \cdot A_{s2}$$

where, A_{s1} and A_{s2} are the radionuclide activities in the top and deep soil layers, respectively (Bq), A_{ww} the radionuclide activity in the river water (Bq), λ_r the radioactivity decay constant (y^{-1}), k_{irr} the activity transfer coefficient from the river water to the surface soil due to the irrigation process (y^{-1}) defined by:

$$k_{irr} = \frac{I_{irr} \cdot S_s}{V_{ww}}$$

where, I_{irr} is the annual irrigation to the surface soil (m y^{-1}), S_s the agricultural land surface (m^2), V_{ww} the effective volume of irrigation water from the river compartment (m^3), λ_{inf} the activity transport coefficient from the surface soil to the deep soil due to the infiltrating water (y^{-1}):

$$\lambda_{inf} = \frac{I_{pr} + I_{irr} - I_{eva}}{d_{s1} \cdot R_{s1} \cdot \theta_{s1} \cdot \varepsilon_{s1}}$$

where, I_{pr} is the mean annual precipitation (m y^{-1}), I_{eva} the mean annual evaporation (m y^{-1}), d_{s1} the thickness of the top soil layer (m), θ_{s1} the porosity of the soil (-) and ε_{s1} the fraction of that porosity that is water filled (-). The retardation factor in the top soil layer is given by:

$$R_{s1} = 1 + \frac{(1-\theta_{s1}) \cdot \rho_{s1}}{\theta_{s1}} \cdot Kd_{s1}$$

where, Kd_{s1} is the partition coefficient (m^3 kg^{-1}). A similar expression can be written for $\lambda_{per,}$ the percolation water flow into deeper layers from the second one, but the parameter values of the second soil layer (d_{s2}, R_{s2} etc.) are used.

The radionuclide concentration in soil (C_s, Bq kg^{-1}) is estimated as:

$$C_s = \frac{A_s}{V_s \ \rho_s}$$

where, A_s is the radionuclide activity in the surface soil (Bq), ρ_s the dry bulk density of the cultivated soil compartment, (kg m^{-3}) and V_s is the volume of the soil compartment (m^3).

Concentration in vegetable products

The concentration in vegetable products (C_v in Bq kg^{-1}) takes into account the interception of the irrigation water as well as root uptake and rainsplash. The generic expression for the calculation is:

$$C_v = C_{v\_irr} + C_{v\_upt} = \cdot C_w \cdot If_v \cdot I_{irr} / Y_v / L_v + C_{s1} \cdot (m_{s\_v} + B_v)$$

where, C_{v_irr} is the concentration due to irrigation, C_{v_upt} due to root uptake from soil, C_w the concentration in water for irrigation, If_v the interception factor (dimensionless), Y_v the yield capacity (kg f.w. m^{-2}), L_v the weathering and harvesting loss coefficient (y^{-1}), m_{s_v} the soil mass adhered onto the crop surface due to splash, except for root vegetables (kg soil per kg plant edible part) and B_v the soil to plant transfer factor for each crop type (Bq kg^{-1} f. w.) per (Bq kg^{-1} d.w.).

Concentration in animal products

The concentration in terrestrial animal products (Bq kg^{-1} or Bq L^{-1}), due to ingestion of water and contaminated food is given by:

$$C_{anim\_prod} = C_w \,.\, (If_v \,.\, I_{ir\_sa} \,.\, U_{anim\_vg} \,.\, Z/(Y_{vg}.L) + U_{anim\_wd}) * F_{anim\_prod} +$$
$$_{s1} \,.\, ((m_{sv} + B_{vg}) \,.\, Z \,.\, U_{anim\_vg} + U_{anim\_s}) * F_{anim\_prod}$$

where, If_v is the pasture interception factor (-), U_{anim_vg} is the pasture ingestion rate by the animal (kg d.w. d^{-1}), Z is the fresh to dry conversion factor (kg f.w.) per (kg d.w), Y_{vg} is the grass yield (kg f.w. m^{-2}), U_{anim_wd} is the animal water intake rate (m^3 d^{-1}), F_{anim_prod} is the distribution factor for the animal product (d kg^{-1} or d L^{-1}), m_{sv} is the soil mass adhered onto pasture surface (kg soil per kg crop edible part), B_{vg} is the soil to plant transfer factor for pasture (Bq kg^{-1} f.w.) per (Bq kg^{-1} d.w), U_{anim_s} is the soil ingestion intake rate for animals (kg d^{-1}).

The estimation of activity concentration in fish is represented by:

$$C_f = C_{wr} . F_f$$

Where, C_f is the radionuclide concentration (Bq kg^{-1}) in the edible parts of the fish, Cw_r is the radionuclide concentration in river water (Bq m^{-3}), F_f, is the concentration factor for freshwater fish (m^{-3} kg).

Doses to humans

The effective dose due to contaminated water intake is given by:

$$E_{ing}(water) = C_{wd} . Q_{\_win} \ \kappa_{wd} DC_{ing}$$

where, E_{ing}(water) is the annual committed effective dose due to water intake (Sv), $Q_{\_win}$ is the water intake rate for humans (L y^{-1}), κ_{wd} is the activity fraction in the filtered water (-) (where a value of 1.0 can be taken if the water is assumed to be unfiltered), DC_{ing} is the dose conversion factor for ingestion (Sv Bq^{-1}).

The effective dose due to ingestion of vegetables is given by:

$$E_{ing}(veg) = C_v . Q_{\_v} . \kappa_v . DC_{ing}$$

where: E_{ing}(veg) is the annual committed effective dose due to vegetable ingestion (Sv), $Q_{\_v}$ is the intake rate of vegetables (kg y^{-1}), κ_v is the activity retention factor in vegetables after food processing (-) (κ_v is cautiously taken as 1).

The effective dose due to animal products consumption is:

$$E_{anim\_prod} = C_{anim\_prod} \cdot Q_{anim\_prod} \cdot DC_{ing}$$

where, E_{anim_prod} is the annual committed effective dose due to ingestion of an animal product (Sv), Q_{anim_prod} is the annual intake rate of that animal product (kg y^{-1}).

The effective dose due to external irradiation is:

$$E_{ext} = Oc \ DC_{ext} \ 24 \ 365 \ C_{s1}$$

where, E_{ext} is the annual effective dose due to external irradiation (Sv), C_s radionuclide concentration in soil (Bq m^{-3}), Oc occupation fraction on the contaminated land (agricultural activity) (-), DC_{ext} dose conversion factor for external irradiation, assuming soil contaminated to 15 cm depth (Sv h^{-1}) per (Bq m^{-3}).

The committed effective dose due to inhalation is:

$$E_{inh} = m_{sa} \cdot DC_{inh} \cdot Q_{inh} \cdot Oc \cdot C_s$$

where, m_{sa} dust concentration in air (kg m^{-3}), $Q_{\_inh}$ breathing rate (m^3 y^{-1}), Oc occupation fraction on the contaminated land (agricultural activity) (-), DC_{inh} dose conversion factor for inhalation (Sv Bq^{-1}).

Data selection

The parameters needed for the mathematical models had to be quantified for the exposure and radionuclide. Some essential aspects to note are: the relations among parameters; the relevance or influence of the value on the result; and the causes of uncertainties. The use of a computerized tool that contains a parameter database and bibliographic references helps in the process of identifying appropriate values for use in a specific context. The user can search for the information linked to a specific radionuclide, particularizing the reference if known. The rest of the parameters were treated as fixed using best estimate values.

Solution of the model is performed with AMBER tool (Enviros and Quintessa, 2003). This software allows representation of transfers in the environment with compartmental models.

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