HTO uptake in plants and the OBT formation during the day time

A. Melintescu, D. Galeriu

I. Introduction

Tritium is a radioactive isotope of hydrogen that can be released to the environment in small amounts during routine operation of nuclear facilities, and in higher amounts during some types of accidents.

Tritium emitted into the atmosphere is subjected to environmental conditions, such as:

- diffusion, which implies that the tritium concentration decreases due to local mixing conditions;
- advection, which implies that the bulk material is transported to the downwind.

All forms of tritium, including tritium vapours (*i.e.* HTO and T_2O) and molecular tritium (*i.e.* HT and T_2) species are not different from the other species of radionuclides when they emitted in accidental release conditions. Similar to the transport of the other radioactive species, the atmospheric tritium plumes are depleted via **wet and dry deposition mechanisms**. While the dry deposition behaviour is observed for most of the non-noble gas radioactive species and it results in diminished plume concentrations as a function of downwind transport, **the mechanisms governing the dry deposition of tritium are quite unique**.

The major biophysical processes which characterise the tritium dry deposition are:

- the initial settling to ground and vegetation;
- HT conversion to HTO in soil, due to bacterial action;
- HTO uptake by plants and the partial conversion to OBT;
- HTO re-emission from soil and plant;
- HTO uptake by vegetation root systems;
- HTO transport into the deeper soil regions;

The overall effect of the above processes can be generalized as the quotient of the net tritium flux to the ground and vegetation, and the tritium air concentration at the same location is normally termed as **deposition velocity, V_{dep}, or exchange velocity, V_{ex},** because tritium transfer is reversible process. For HT and T_2, V_{dep} is largely a function of the soil oxidation, ambient wind speed, and stability conditions. For HTO and T_2O, V_{dep} is controlled by the vegetation uptake (thus subject to the diurnal fluctuations), the deposition to soil, and for the case of the molecular tritium, is subjected to the existing meteorological conditions.

II. Dynamics of HTO uptake in leaves

There are three phases in the dynamics of tritium in SVAT (soil-vegetation-atmosphere transport). The first one refers to the period of the active deposition, when the cloud of HTO passes the area of interest and the atmospheric concentration is the driving force for tritium. The last one starts few days after the cloud passage, when the soil water tritium is the driving force. The middle stage refers to the re-emission of the HTO from the vegetation and soil surface into the atmosphere, a fast process, which takes place immediately after the cloud passage and slowed down afterwards. The active and the transition phases are sensitive to the existed meteorological parameters (sunshine, humidity, temperature, and rainfall), as well as on the plant physiological characteristics and the growth stage of the plants. In the later stage, the processes which must be considered are the movement of the HTO in the root soil, the depth distribution of roots, the evapotranspiration and plant photosynthesis. These processes can be modeled with a slow dynamics, using the climatic data and the approximate dynamics of some plant parameters. After an atmospheric dry deposition episode, the HTO concentration in plant decreases fast, while the OBT concentration in the whole plant decreases very slow, but part of the OBT will be translocated to the storage plant parts. For crops harvested one time in the year, most of the tritium found in the harvested plant is in form of OBT, while for the continuously harvested plants, as grass and leafy vegetables, in the first few days after the accident, the concentration of HTO is high. An operational model must include both situations under various agro-meteorological conditions. More details are given elsewhere (Melintescu and Galeriu, 2005).

The driving equation for the transfer of HTO from atmosphere to leave, ignoring the fraction of tritium input from OBT respiration and tritium output for OBT formation, is (Belot et al., 1996):

$$\frac{dC}{dt} = \frac{\gamma V_{exc}}{M_w}\left(C_{air} - \frac{\rho_s C_s}{\beta}\right) + \frac{V_{exc}}{M_w}(\rho_s - \rho)C_s \qquad (1)$$

where: C is the HTO concentration in plant water (mainly leaf water) (Bq kg^{-1}), C_{air} is the HTO concentration in air (Bq m^{-3}), C_s is the HTO concentration in the sap water (transpiration water), resulting from water extraction of roots at different depths (Bq kg^{-1}), ρ_s is the saturated air humidity at the vegetation temperature (kg m^{-3}), ρ is the air humidity at the reference level (kg m^{-3}), M_w is the mobile water mass in the vegetation leaves on a unit soil surface (kg m^{-2}), V_{exc} is the exchange velocity between the atmosphere and plant canopy (m s^{-1}), γ is the ratio between HTO exchange velocity and water exchange velocity (typically 0.95) , β is the isotopic fractionation between tritium and hydrogen (typically 1.1).

The eq. (1) is used for the whole canopy, ignoring the transfer of air HTO to steams, because this exchange velocity is smaller with one order of magnitude. The initial diffusion of leaf water to steams is also ignored, because its slow exchange velocity and the flushing of the steams by a sap flux with a definitely less HTO concentration in the active phase. In the transition period, the steams water and leaves water gradually equilibrates with the root soil water and generally, the details of this period are ignored for steams, because its minor contribution to the plant water concentration. The second term in eq. (1) includes in fact the transpiration flux.

The eq. (1) can be simplified, if it is assumed that the HTO concentration in air, C_{air}, is constant, the exchange velocity between atmosphere and plant canopy, V_{exc}, is constant and ignoring the tritium transfer to soil:

$$C_{TFWT} = C_\infty (1 - e^{-kt}) \qquad (2)$$

where: C_{TFWT} is the HTO concentration in plant at the considered time *t* (Bq L^{-1}), C_∞ is the steady-state tissue free water tritium (TFWT) concentration (Bq L^{-1}), k is the constant rate for the HTO uptake (h^{-1}), t is the time after the beginning of the exposure (h).

In the eq. (2), the steady-state tissue free water tritium (TFWT) concentration, C_∞, and the constant rate for the HTO uptake, k, are given by the following equations:

$$C_\infty = \frac{\rho_a}{\beta\rho_s} C_{ah} \tag{3}$$

where: ρ_s is the water vapour density in leaf stomatal pore (g m^{-3}), ρ_a is the water vapour density in the atmosphere (g m^{-3}), C_{ah} is the air water HTO concentration (Bq L^{-1}).

$$k = \frac{\gamma V_{exc}\rho_s}{\beta M_w} \tag{4}$$

The eqs. (2), (3), and (4) were used in different studies (Ichimasa et al., 2002, 2003, 2005; Atarashi et al., 1997) in order to explain the experimental data for various plants and environmental conditions. In all these studies (Ichimasa et al., 2002, 2003, 2005; Atarashi et al., 1997), it was emphasized that there is a large variability between plants and the environmental conditions which involves the need to consider the variability of the exchange velocity.

III. Exchange velocity approach

It is well known that there is a similitude between the water vapour transport in nature and the electric circuits in electricity, because in both cases the transport of the specific scalars are due to their specific gradients: the specific humidity in case of water transport and the electric potential in case of electricity, respectively. Consequently, all the environmental resistances have analogies with the electric resistances, because in both cases the resistance represents the ratio between a potential difference and a flux o a certain scalar.

It is well established that the HTO transfer from air to leaves depends on leaves resistances (Belot et al., 1996). At the canopy level, the transfer from the reference level to the canopy (atmospheric resistance, R_a (s m^{-1})) must be considered together with the transfer from the canopy air to leaves (boundary layer resistance, R_b (s m^{-1})) and the transfer from leaf surface to leaf interior (canopy resistance, R_c (s m^{-1})) (see the Figure 1) The canopy resistance, R_c, is an integral over the all stomatal resistances of the plant leaves. The exchange velocity, V_{exc} (m s^{-1}) is defined as:

$$V_{exc} = \frac{1}{R_a + R_b + R_c} \tag{5}$$

In eq. (5), the canopy resistance, R_c, is the predominant factor.

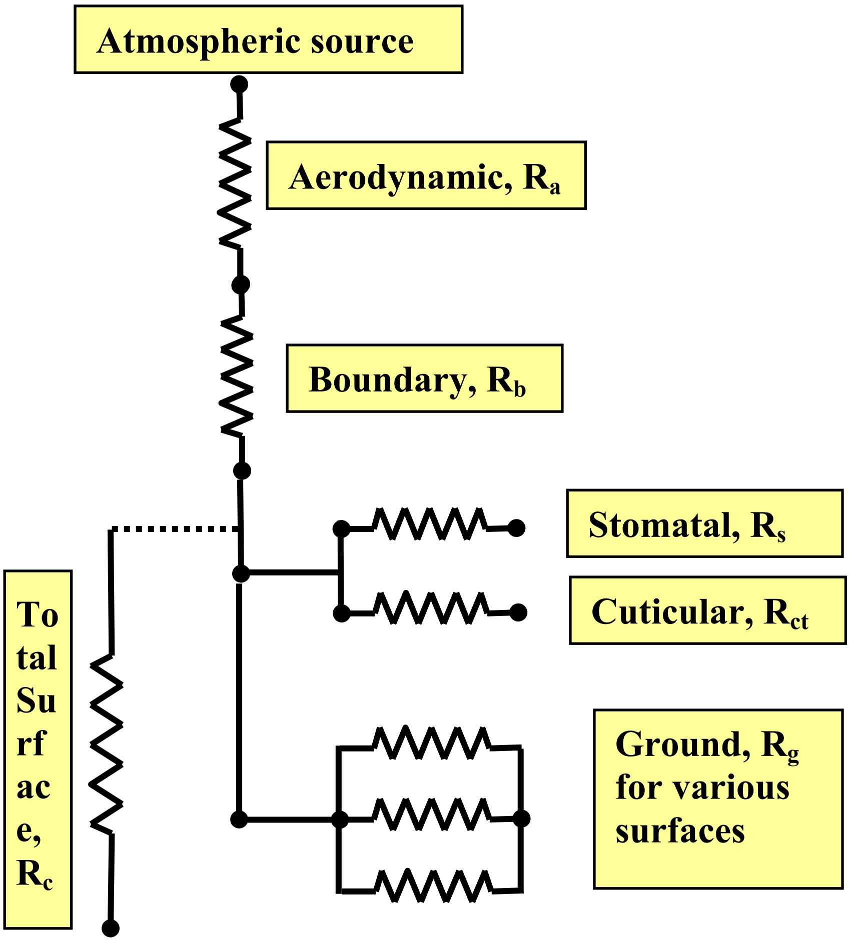

Figure 1. The analogy between environmental resistances and the electric circuits

The layer of air adjacent to leaves or soil surface is called the **leaf boundary layer**. This boundary layer is extremely important for the functioning of life, as it is a critical path for the transfer of trace gases, momentum and energy between the atmosphere and biosphere (Schuepp 1993). Furthermore, it is a path that cannot be circumvented by metabolizing organisms.

Turbulent eddies are responsible for transporting the material, tritium in the present case, through the surface boundary layer. The transport processes associated with the transfer of heat, mass and momentum modify the properties of the atmosphere. The momentum must be transferred downward (see Figure 2). A **force** is needed to change the momentum transfer from one level to another. This **drag force** or shear stress is also equivalent to the **momentum flux density**.

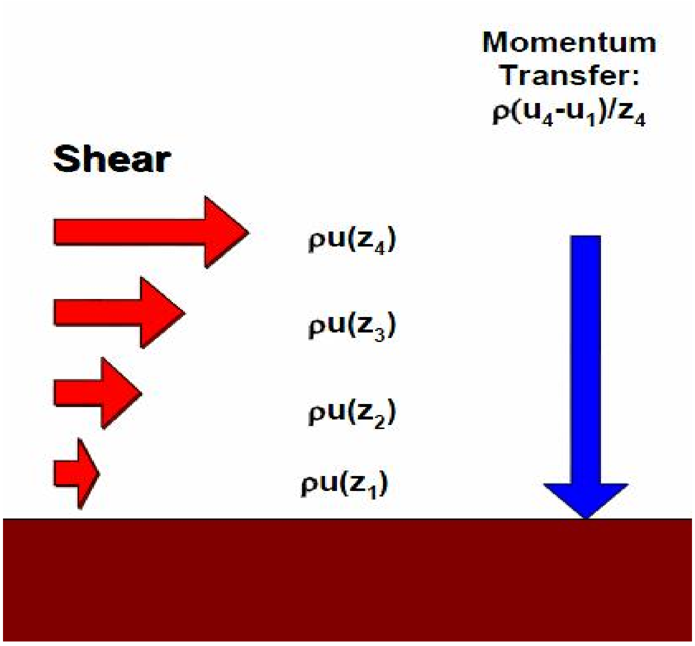

Figure 2. Visualization of the momentum transfer (from Dennis Baldocchi, Lecture 17 - Wind and Turbulence, Surface Boundary Layer: Theory and Principles Part II, http://nature.berkeley.edu/biometlab/espm129/overheads/Lecture%2017%20ESPM%20129%20Wind%20and%20Turbulence,%20Part%20II%20overheads.pdf)

The classic view of evolution of flow over a leaf starts with a uniform and laminar stream of air upwind from a plate or leaf. As the air encounters the leaf there is drag at the surface and shear starts. A wind velocity profile and a boundary layer evolve. Initially the flow remains laminar throughout the boundary layer. But after a distance into the edge, flow becomes tripped and turbulence is generated. A logarithmic wind profile develops in the turbulent zone. But there is always a laminar boundary layer in close contact with the leaf, as the height above the ground goes to zero. In the turbulent zone, there is a turbulent and laminar boundary layer. The logarithmic wind profile is given by:

$$u(z) = \frac{u_*}{k}\ln(\frac{z}{z_0}) \tag{6}$$

where: u* is the friction velocity (m s^{-1}), k is von Karmann's constant (typically 0.40), z is the height above the ground (m), z_0 is the **roughness parameter**. It defines the effectiveness of a canopy to absorb momentum and it is valid only for the very short vegetation and for a neutrally stratified atmosphere.

The aerodynamic resistance determines the rate that momentum, and other scalars, are transported between a given level in the atmosphere and the vegetation's effective surface sink and is given by:

$$R_a = \frac{1}{ku_*}\ln\frac{z-d}{z_0} - \Psi_c \tag{7}$$

where: d is the **Zero-Plane Displacement Height** and it represents the level at which surface drag acts on the roughness elements or level which would be obtained by flattening out all the roughness elements into a smooth surface, Ψ_c is the adiabatic correction function.

In the boundary layer, heat and water vapour are transferred through molecular diffusion (conduction). The long timescale involved can be represented by a large resistance, the *boundary layer resistance*, given by the following relationship:

$$R_b = \frac{1}{ku_*}\ln\frac{z_0}{z_c} = \frac{const}{ku_*}(\frac{Sc}{\mathrm{Pr}})^{\frac{2}{3}} \tag{8}$$

where: z_c is the scalar roughness length (m), Sc is the Schmidt number, Pr is the Prandtl number, const is a constant often assumed to be 2 over the closed canopies, but it can be much larger over the rough incomplete canopies.

The magnitude of the boundary layer resistance, R_b, depends mainly on the depth of the boundary layer and is proportional to the ratio between the leaf size and wind speed.

Both R_a and R_b are affected by the meteorological conditions like wind speed and atmospheric stability, as well as the crop height and the leaf size and both of them decrease with the increasing of the wind speed and crop height. Typically, these resistances are smaller over the tall forests than over the short grass and also, they are smaller under unstable atmospheric thermal stratification than under neutral and stable stratification. Some typical values for boundary layer resistance are given in Table 1 for a wind speed of 4 m s^{-1} (Niyogi et al., 2003).

Table 1. Typical values for boundary layer resistance over different types of vegetation and for a wind speed of 4 m s^{-1} (Niyogi et al., 2003)

Vegetation type	Crop height (m)	R_b (s m^{-1})
Grass	0.1	60
Crop	1	20
Coniferous forest	10	10

A study (Niyogi et al., 2003) indicates a typical value less than 20 m s^{-1} for both atmospheric resistance and boundary layer resistance over a temperate deciduous forest during the daytime, but the same study (Niyogi et al., 2003) gives a value grater than 150 m s^{-1} for atmospheric resistance during the night time, when the turbulent mixing height is reduced. In the most cases, the canopy resistance prevails.

IV. Modelling approaches for canopy conductance

Canopy resistance, R_c, is a function of canopy stomatal resistance, R_{stom} (s m^{-1}), canopy cuticle resistance, $R_{cuticle}$ (s m^{-1}), and soil resistance, R_{soil} (s m^{-1}), all of them acting in parallel, according to the following simple relationship:

$$\frac{1}{R_c} = \frac{1}{R_{stom}} + \frac{1}{R_{cuticle}} + \frac{1}{R_{soil}} \tag{9}$$

All the resistances involved in eq. (9) are affected by leaf area, stomatal physiology, soil pH, and the presence and chemistry of the liquid drops and films.

The simplest approach describing the canopy resistance is the so called 'Big-Leaf' resistance approach which assumes the whole canopy as a single big leaf. This approach is based on an electric analogy, because the current flow (*i.e.* mass or energy flux density) in such a transfer scheme is given by the ratio between a potential and the sum of the resistances to the flow, according to the relationship:

$$F_C = \frac{C_a - C_0}{R_a + R_b + R_c} \tag{10}$$

where: F_C is the flux of a scalar (tritium in the present case) (Bq m^{-2} s^{-1}), C_a is the concentration of a scalar (tritium in the present case) in the atmosphere over the vegetation (Bq m^{-3}), C_0 is the internal concentration of the scalar (tritium in the present case) (Bq m^{-3}).

More elaborate and complex approaches for canopy resistance use multilayer canopy, considering the partial flux for each layer. In both approaches the key point is the scaling from stomatal resistance to canopy resistance using different level of complexity and details. The basic idea of these approaches is that the stomatal cavity represents a common pathway for water and carbon dioxide transport and the leaf is a sum of all the stomata.

The water and carbon dioxide, CO_2, move by diffusion in opposite directions between the leaves stomata and the air. The water evaporates from the cells walls, and moves from the stomata to the air, whereas CO_2 moves from the air, via the stomata into the mesophyll, where it is reduced to sugars by chemical reactions in the Calvin cycle. If the resistance for CO_2 transport from the stomata to the mesophyll is neglected, then the diffusion equations can be written as:

$$E = 1.6 * g * \frac{\rho_a}{M_a} * \frac{e_i - e_a}{p} = 1.6 * g * D \tag{11}$$

$$A_n = A_g - R_d = g_{sc} * (C_s - C_i) \tag{12}$$

where: E is the water evaporation (mol $m^{-2}s^{-1}$), g is the effective aerodynamic and stomatal conductance (m s-^{1}), ρ_a is the specific mass of air (kg m^{-3}), M_a is the molar mass of air (kg mol^{-1}), e_i and e_a are the vapour pressures in the intercellular spaces and in the ambient air, respectively (Pa), p is the atmospheric pressure (Pa), D is the molar vapour concentration gradient between the intercellular space and the air (mol m^{-3}), A_n and A_g are the net and gross CO_2 assimilation rates, respectively (mol $m^{-2}s^{-1}$), R_d is the respiration rate (mol $m^{-2}s^{-1}$), g_{sc} is the stomatal conductance (m s^{-1}), C_s and C_i are the molar CO_2 concentrations at the leaf surface and in the leaf interior, respectively (mol m^{-3}).

There are many approaches describing the stomatal resistance and recently, a review (Damour et al., 2010) was published. In the Jarvis approach (Jarvis 1976), the environmental factors such as: light, temperature, vapour pressure deficit, abbreviated as VPD, and soil water deficit are uncorrelated and behave as modifying factors (between 0 and 1) for a minimal canopy resistance. This represents actually the main inconvenience of this approach. The basic equation of Jarvis approach is:

$$R_c = \frac{R_{c\_\min}}{LAI \times F1 \times F2 \times F3 \times F4} \tag{13}$$

where: R_{c_min} is the minimal leaf resistance, which is a plant characteristic (s m^{-1}), F1 is a factor depending on photosynthetic active radiation (PAR), F2 is factor depending on air temperature (heat stress), F3 is factor depending on air humidity (dry air stress), F4 is factor depending on soil moisture (dry soil stress).

In a different model (Ball et al., 1987), abbreviated as BWB (Ball-Woodrow-Berry) model, the stomatal conductance to CO_2, g_{sc}, is dependent: (i) directly on the CO_2 concentration at the leaf surface, C_s; (ii) directly on the relative humidity at the leaf surface, h_s; and (iii) indirectly on temperature and radiation, via photosynthesis. The stomatal conductance is:

$$g_{sc} = g_0 + \frac{a * A_n * h_s}{C_s} \tag{14}$$

where: g_0 is minimal stomatal conductance (m s^{-1}), a is an empirical coefficient

The main limitation of BWB model is that the “a” coefficient in equation (14) is an empirical factor.

An improved version of BWB model (Leuning 1990) (herein referred as Leuning model) considers the compensation point for CO_2, Γ (the CO_2 concentration for which CO_2 uptake equals the CO_2 production) and replaces the relative humidity at leaf surface, h_s, with a function dependent on VPD.

A different approach (Cowan 1977) suggested that the stomata operate to minimize the evaporative cost of plant carbon gain. This condition is met if the marginal water cost of assimilation is constant in time, but it is not the general case.

In the laboratory experiments, C_i is often found to be a fraction of C_s. For sufficiently high levels of solar radiation, it appears that the ratio between C_i and C_s is only a function of VPD (Goudriaan et al., 1985; Jacobs 1994). This formulation (Jacobs 1994) has some difficulties for low light situations, but recently, a better approach (Ronda et al., 2001) has been proposed for stomatal conductance:

$$g_{sc} = g_0 + \frac{a_1 A_g}{(C_s - \Gamma)(1 + \frac{D_s}{D_*})} \tag{15}$$

where D_s is VPD at plant level (Pa), a_1 and D_* (Pa) are parameters derived from the closure relationship of C_i:

$$\frac{(C_i - \Gamma)}{(C_s - \Gamma)} = f_0 - a_d D_s \tag{16}$$

where f_0 and a_d are empirical parameters found as regression coefficients of experimental data and are given in Table 2 based on complex studies (Steeneveld 2002)

Table 2. Experimental values of the empirical parameters f_0 and a_d for different types of vegetation (Steeneveld 2002)

Vegetation type	**f_0**	**a_d (kPa^{-1})**
Low vegetation C3	0.89	0.07
Low vegetation C4	0.85	0.015
Lobos	0.093	0.12
Rice and phalaris grass	0.89	0.18
Forest temperate	0.875	0.06
Boreal forest	0.4	0.12

In equation (15), the key parameter, D_* also depends on the mesophyll conductance, g_m.

In a recent paper (Melintescu and Galeriu, in press), it was tested the dependence of D_* on g_m and it was found that this dependence is weak. Melintescu and Galeriu (in press) found for D_* an average value of 1.2 kPa (range 1.09 – 1.3) for C3 plants and 8 kPa (range 7.8 - 8.33) for C4 plants. The details on C3 and C4 plants are given elsewhere (Goudriaan et al., 1985; Steeneveld 2002). The CO_2 assimilation rate can be seriously affected by the soil water stress, especially during the summer time, when the water supply is low. Using a correction for the water stress (Ronda et al., 2001), the gross CO_2 assimilation rate is given by:

$$A_g = A_g^*[2\beta(\bar{\theta}) - \beta^2(\bar{\theta})] \tag{17}$$

$$\beta(\bar{\theta}) = \max[0, \min(1, \frac{\bar{\theta} - WP}{FC - WP})] \tag{18}$$

where A_g^* is the unstressed assimilation (mol $m^{-2}s^{-1}$), $\bar{\theta}$ is the average soil water content in root zone, WP is the wilting point, FC is the field capacity

For the physiological approaches, the scaling from leaf to canopy involves the integral of the photosynthetic rate for over the canopy the canopy height (*i.e.* LAI). For example, starting with the eq. (15), the canopy conductance is given by:

$$g_{c,w} = \int_0^{LAI} \left[g_0 + \frac{a_l A_g}{(C_s - \Gamma)(1 + \frac{D_s}{D_*})} \right] dL = g_0 LAI + \frac{a_l \int_0^{LAI} A_g dL}{(C_s - \Gamma)(\Gamma + \frac{D_s}{D_*})} \tag{19}$$

The physiological approaches are based on photosynthesis rate. There are many models describing the photosynthesis, from the simple to very complex models, some of them reported below.

The assimilation rate depends on the environmental conditions (temperature, CO_2 concentration, light intensity, humidity, and oxygen concentration). For the assimilation rate many approaches are used. The most comprehensive approach (Farquhar et al., 1980), a biochemical model (herein referred as Farquhar model), considers CO_2 assimilation as a process limited by a number of factors, each of them controlling different sub-processes, such as rubisco-limited carboxylation, light-limited electron transport, carboxylase–oxygenase production. Each limiting factor gives a maximum allowable assimilation rate and the minimum of these allowable rates is considered as the realized assimilation. At leaf scale, the model needs about eleven parameters and six of them are plant dependent. In practice, the plant characteristics depend on fertilization and plant age.

Another approach (Collatz et al., 1991) ignores the limitation coming from the carboxylase–oxygenase production for C3 plants and considers as possible a combination of both rubisco-limited carboxylation and light-limited electron transport limiting processes (co-limitation). A simplified biokinetic model for C4 plants was reported (Collatz et al., 1992) with parameters adapted for a maize cultivar from Southern USA. A simplified biochemical model (Kim and Verma, 1991) was carefully fitted with the experimental data for three C4 grass species.

The biochemical model (Farquhar et al., 1980, de Pury and Farquhar 1997) was intensively used with the stomatal conductance defined in BWB model (Ball et al., 1987) for land-atmosphere interaction modelling purposes, despite the limitation concerning the drought conditions.

The leaf-level photosynthesis model (Thornley and Johnson, 1990) (herein abbreviated as TJ (Thornley-Johnson)) featuring simplified gas exchange, but emphasizing stomatal control of assimilation, received less attention in the literature. Recently, the field data (Gao et al., 2004) had been obtained for eleven plant species, helping to fix the model parameters for two models: Farquhar and TJ model. Then, the performances of both models had been compared, and the results showed that the Farquhar model explained on average 66 % and 82 % of the observed net photosynthesis rates variations for the C3 and C4 plants, respectively, comparing with TJ model which explained 72 % and 76 % of variations, respectively. The more mechanistic, detailed approaches of the biochemical processes in the biochemical photosynthesis models did not offer significant advantages over the simpler leaf photosynthesis models for explaining the field data.

All biochemical model parameters at large scale (biomes) are fixed, but at local scale consisting of specific cultivars of many agricultural crops (around a nuclear facility, for example), the appropriate model parameters are difficult and expensive to obtain.

For practical reasons, another approach (Melintescu and Galeriu, in press) uses the canopy photosynthesis model from the WOFOST crop growth model (Boogaard et al., 1998). The leaf gross photosynthesis rate, A_{Lg}, is:

$$A_{Lg} = A_{\max}(1-\exp(-\frac{\varepsilon \times I_{aL}}{A_{\max}})) \tag{20}$$

where: A_{Lg} is the gross assimilation rate (kg $m^{-2}d^{-1}$), $A_{\max}$ is the maximum photosynthesis rate at light saturation (kg m^{-2} d^{-1}), ε is the initial slope or light use efficiency (kg J^{-1}), I_{aL} is the absorbed photosynthetically active radiation (PAR) (μmol $m^{-2}s^{-1}$)

A_{max} depends on the crop type and age, as well as on the ambient temperature, while ε depends on the crop type, but this week temperature dependency is ignored. A_{max} depends also on C_i (determined by the ambient concentration, boundary and stomatal conductance). A parameter data base for many cultivars of the main agricultural crops in Europe is established and the adaptation for the Romanian conditions was done in the past (Melintescu et al., 2002; Melintescu and Galeriu, 2005). Many plant specific results given by the biochemical models can be reproduced using the simplified WOFOST model. For example, the experimental data for maize (Collatz et al., 1992) are well reproduced (Table 3), as well as the experimental data for grass (Kim and Verma, 1991) (Figure 3), using WOFOST model.

Table 3. Maximum photosynthesis rate (A_{max}) and light use efficiency (ε) at different temperatures (T) for maize using WOFOST parameters

T (°C)	A_{max} (kg CO_2 $m^{-2}h^{-1}$)	ε (kg CO_2 J^{-1})
15	19.0	0.33
20	36.5	0.33
25	55.5	0.32
30	74.0	0.32
35	70.7	0.32

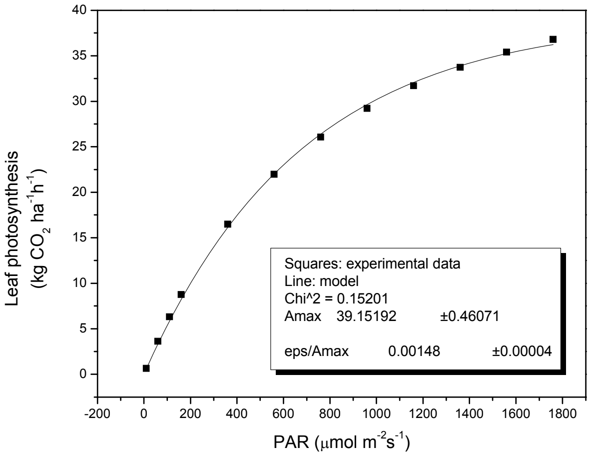

Figure 3. Comparison between WOFOST model and experimental data for Kansas grass at ambient temperature of 40 °C

The Romanian approach (Melintescu and Galeriu, in press) was tested with experimental data for stomatal resistance of different plant types and the comparison between the model and the data are good (see Table 4).

Table 4. Comparison between the experimental and theoretical data for the maximum stomatal resistance

Plant type	**Exp. val. (s m^{-1})**	**Model val. (s m^{-1})**	**References**
Wheat (vegetative stage)	41 – 52	56	Baldocchi (1994)
Wheat (anthesys)	62 - 100	60	Baldocchi (1994)
Maize (vegetative stage)	121 - 131	111	Baldocchi (1994)
Wheat	17 - 20	18	Choudhury and Idso (1985)
Potato	100 - 130	130	Vos and Groenwold (1989)
Alpha-alpha	100 – 120	110–130 (depends on VPD)	Saugier and Katerji (1991)
Soya	66	70	Oliosa et al. (1996)
Grass C3	74	74–120 (depends on VPD)	Knapp (1993)
Grass C4	151	156–178 (depends on VPD)	Knapp (1993)

In order to scale from leaf to canopy, it is necessary to distinguish between sunlit and shaded leaves and also, to take into account the difference between the air temperature (above the crop) and the canopy temperature. In order to explain the experimental data, it is recommended to consider the crop development stage effect on photosynthesis and canopy resistance (aging effect). All these effects are taken into account in this recent approach (Melintescu and Galeriu, in press), using WOFOST model and the bulk canopy energy budget. Melintescu and Galeriu (in press) ignored the difference between temperature and stomata resistance for the shaded and sunlit leaves in field conditions.

V. OBT formation during the daytime

Based on the photosynthesis reaction and stoichiometric relationships, the OBT production during the daytime is linked to the HTO concentration in leaves and the photosynthesis rate. The dynamics of OBT concentration in plant parts (ignoring the OBT production during the night time) (Melintescu and Galeriu, in press) is given by the following equation:

$$\frac{dC_{OBT}}{dt} = \frac{P_D}{Y} * (0.6 * FD * C_{HTO} - C_{OBT}) \tag{22}$$

where C_{OBT} is the OBT concentration in the whole plant (Bq kg^{-1} dry matter (dm)), C_{HTO} is the HTO concentration in leaf water (Bq L^{-1}), P_D is the dry matter net production rate (kg dm m^{-2}s^{-1}) and is time dependent, with $P_D = \frac{30}{44} P_C$, P_C is the CO_2 assimilation rate (net of respiration) (kg m^{-2}s^{-1}), Y is the total plant yield and is time dependent (kg dm m^{-2}), 0.6 is a stoichiometric factor which links the water assimilation in organic molecule with the dry matter production, FD is the discrimination ratio (the ratio between OBT formation and organically bound hydrogen (OBH) formation), with an average of 0.5, but with the range between 0.45 and 0.55.

In eq. (22), it was considered as a first approximation the net dry matter production (gross assimilation minus respiration and the subsequent conversion to dry matter). This simplification cannot reproduce the details of the dynamics next week after the plume passage and an improved approach is in progress.

Some comparisons between the Romanian model results (Melintescu and Galeriu, in press) and the experimental data for wheat (Diabate and Strack, 1997) are given in Table 5. The model results (Melintescu and Galeriu, in press) for potato are given in Table 6.

Table 5. Comparison between the experimental data (Diabate and Strack, 1997) and the model predictions (Melintescu and Galeriu, in press) for relative OBT concentration in wheat at harvest

Time	**Rel. OBT conc. at harvest (%)**		**Exposure conditions**	
	Exp.	**Model**	**Solar radiat. (W m^{-2})**	**Temp. (°C)**
Dawn	0.18	0.29	90-170	11-26
Day	0.25	0.34	400-800	26-36
Dusk	0.20	0.34	26-38	15-24
Night	0.15	0.31	0	12-17

Table 6. Model predictions (Melintescu and Galeriu, in press) for relative HTO uptake, HTO half-time and relative OBT concentration in potato at harvest

Day of year	**DVS** *	**LAI**	**Canopy resistance (s m^{-1})**	**Rel. HTO uptake** # **(%)**	**HTO half-time (min)**	**Rel. OBT** & **(%)**
162	1.02	2	75	43	44	3.6x10^{-3}; 0.03
177	1.16	3.5	60	51	32	0.026; 0.21
193	1.31	4	60	49	52	0.051; 0.42
202	1.4	4	45	50	68	0.075; 0.6
219	1.55	3.4	95	44	62	0.03; 0.25
236	1.71	1.9	125	37	90	0.039; 0.33
177 (night)	1.16	3.5	690	14	600	0.022; 0.23

* DVS represents the development stage of the plant and is 0 at emergence, 1 at anthesis and 2 at harvest;

Relative HTO uptake is the concentration of HTO in leaf water at the end of exposure relative to HTO conc. in air moisture;

& Relative OBT is the OBT concentration at harvest (per kg fw or per L of combustion water, assuming 0.2 g dm in tuber) relative to the HTO conc. in leaf water at the end of exposure.

VI. OBT partition in plant parts

The dynamics of OBT concentration in a plant part also includes the partition factor (fraction of the new produced dry matter translocated to different plant parts). For modelling the continuous harvesting crops, the gross photosynthesis and the respiration must be considered and the dynamics of OBT concentration is more complex. The partition factors depend on the plant cultivar (genotype) and not only on the plant type. The net assimilation rate depends on crop type, development stage

(DVS), leaf area index (LAI), temperature, light, water stress (air vapour deficit and soil water deficit). At each stage of the plant development, the new formed net dry matter is differently distributed to the various plant parts, which means that the initial uptake and the time evolution depends on plant part. Consequently, we must know the partition factors in order to assess the OBT production in the edible plant parts. Even for the leafy vegetables and pastures we must know the partition to roots.

An example of the partition fractions of the new produced dry matter to different plant parts for a Romanian maize cultivar is given in Figure 4 **(Melintescu and Galeriu, 2005)**.

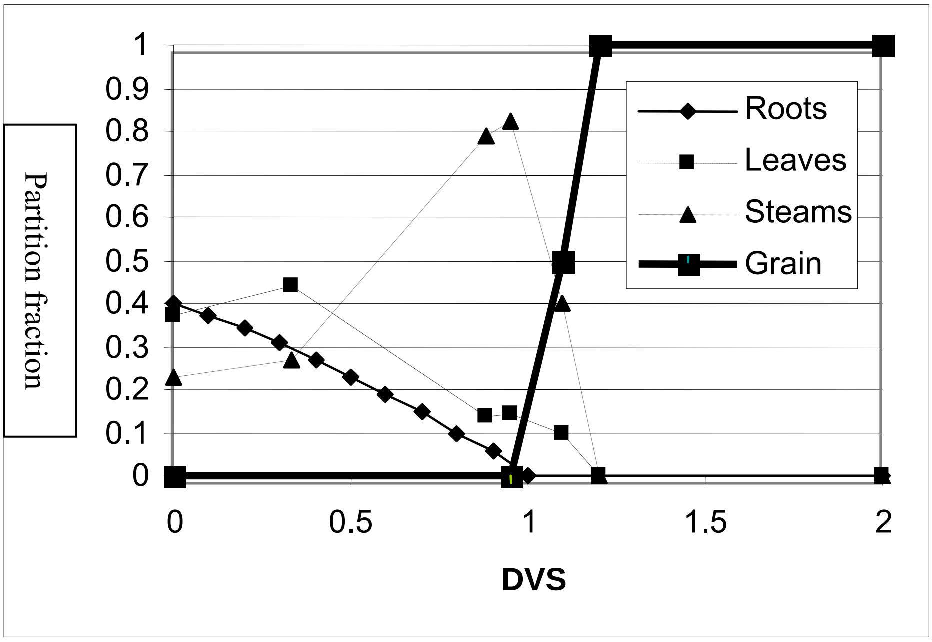

Figure 4. Partition fraction of the new produced dry matter to roots, leaves, stems and edible grains as function of DVS (0-emergence; 1- flowering; 2- full maturity) for a maize cultivar F320 (Southern Romania)

VII. Conclusions and recommendations

The present draft document is a preliminary attempt to analyze the present status in respect to a robust, not very complex model. Models used in EMRAS for accidental tritium emission span a large range of complexity. The simplest models use a constant exchange velocity for both daytime and night time, differing by the average value for the daytime and night time. For OBT production at harvest, the integrated HTO concentration in leaves is multiplied by a coefficient. The most complex models use a layered canopy, full dynamics of HTO in leaves, and a combination between BWB model and a generic Farquhar model for photosynthesis. OBT formation and dynamics is based on the carbohydrate formation and translocation in a single plant, *Beta Vulgaris*.

Up to now there was no attempt to analyze the available models form the point of view of their transparency, user friendly and robustness of the predictions. A too complex model is difficult to apply in practice, needing too much input parameters for which a data base does not exist or is too expensive to be obtained. A very simple model cannot cover the variability of the environmental condition and crop specific properties. A quality assurance procedure for the environmental models does still not exist for accidental tritium models. It is needed more research, open collaboration and interaction with the nuclear regulators and utilities, in order to have an operational model which will be able to satisfy the requirements of transparent, easy to use and moderate conservatism. The work done in WG7 must continue until such model will be developed and the harmonization between views and approaches will be attained.

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