KEY MECHANISMS

It is not the purpose of this paper to review the large volume of literature that describes the processes of transport between the different compartments of the environment. However, this section deals with the key mechanisms and definitions for understanding tritium transfer and its fate in plants.

In the situation of accidental release, tritium can be released as a gas (HT) or as tritiated water vapor (HTO).

I HT

Nevertheless, it has to be noted that HT is not transferred to plant, has a low dry deposition velocity, furthermore, it is not washed by rain and has a low dose par unit intake by inhalation. Then the only pathway of interest is the chemical transformation by microorganisms of the small deposit on the soil into tritiated water, and the following use of the water by plants.

In practice, it is necessary to have about a one kilogram release of tritium HT to reach a significant impact, delivered in some weeks. As this quantity is difficult to reach in any existing factory the case of HT does not need to be developed. Nevertheless, in a real accident, it is important to know the fraction of HT in the release, as its contribution to impact is negligible compared to tritiated water.

II HTO AIR TO PLANT

Pathways for tritiated water are more complex and operate on different scales of time.

It is well-known that the **main pathway** for HTO is **consumption of food** with a large contribution of tritiated organic molecules, OBT (Organically Bound Tritium).

Nevertheless, Models take interest in the definition of instantaneous concentration in the different compartments which is useful to interpret the measurements but often forget the second objective of the purpose which is to propose efficient countermeasures. This is why it is interesting to analyze in detail the different mechanisms, their time of occurrence and contribution to the total dose.

During the accident, many mechanisms of transfer operate depending on a lot of interconnected parameters:

The first one is the direct transfer **from air to leaves** by exchange between air vapor and free water of the leaves through the stomata and also through the cuticle. It depends on the Leaf Area Index, (m^2 of leaves per m^2 of soil) and on the stomatal resistance which characterize the opening of the stomata.

It depends on many environmental factors such as light, temperature, relative humidity of air and soil and internal factors such as number of stomata, location, sugar concentration, age of the plant…In practice, these data will never be available at the moment of accident.

Stomata are cellular structures which constitute doors through which the different gas of the photosynthesis (CO_2, O_2 and water vapor) exchange between air and the internal medium of the plant. Cuticle is a layer more or less impervious which cover the epithelium.

Stomata control the flux of transpiration. They are open when there is light and sufficient water coming from soil and some internal regulation (absisic acid for water stress). Photosynthesis and transpiration will occur when fluxes of CO_2 and water are possible.

To quantify this pathway, it is interesting to give some idea of the different contents. The absolute humidity of air is of the order of 5 - 25 $g.m^{-3}$. The quantity of water in 1 m^2 of vegetable covering the soil is between 500 and 5000 $g.m^{-2}$; and the quantity of water released by transpiration is between 50 and 250 $g.h^{-1}.m^{-2}$. It needs few hours to reach the equilibrium between plant free water and air vapor. As a part of the free water comes from the soil, the equilibrium is not 1 but about 40%.

This also shows that the turnover of the free water of the plant is rapid and of the order of the day.

Exchange velocity

In leaves charge and discharge of HTO from air are fast phenomena. The air HTO dose contribution occurs during the first day for vegetable gathered that day (fresh garden vegetable).

It increases and decreases with a biological period of the order of an hour, except during the night where the period can reach many hours. In that condition, the real time of the release is important as the decrease phase will occur in the morning in day conditions.

The activity of leaves increases from zero at the beginning to maximum at the end of the release and come back to nearly zero some hours later). Now if we suppose that the **exchange velocity** between free water of the plant and air vapor remains the same, then the integrated activity is less sensitive to this exchange rate.

L’absorption d’eau par les feuilles se fait rapidement pendant le jour et à une vitesse plus réduite pendant la nuit. En effet, les échanges de vapeur d’eau s’effectuent principalement à travers les orifices stomatiques des feuilles, dont l’ouverture est contrôlée par la pression interne des cellules de garde. Selon que cette pression est forte ou faible, il y a ouverture ou fermeture des stomates.

Les facteurs externes à la plante qui influencent l’état des stomates sont l’humidité relative de l’air (HR) et la luminosité.

- Un air humide (HR = 80 %) favorise l’ouverture des stomates alors qu'un air plus sec (HR = 50 %) conduit à leur fermeture. C’est la différence de pression entre cellules de garde et cellules voisines qui provoque l’ouverture ou la fermeture stomatique.
- La lumière joue aussi un rôle direct dans l’ouverture des stomates. En effet, elle entraîne une forte augmentation de la pression osmotique des cellules de garde (la pression passe de 12 à 18 bars) alors que les cellules voisines sont à une pression de 15 bars. D’après les connaissances actuelles, il y aurait dans les cellules de garde, accumulation de potassium avec contre-transport de protons. Cette « pompe à protons » serait stimulée par la lumière, en particulier le rayonnement dans le bleu. On rappelle que c’est également la lumière qui fournit l’ATP nécessaire aux transformations biochimiques. L’ATP est la source d’énergie cellulaire et est produit par photosynthèse.

Du côté des facteurs internes à la plante, l'acide abscissique joue un rôle prépondérant. En cas de déficit hydrique, sa teneur augmente considérablement, ce qui provoque la fermeture rapide des orifices stomatiques. L'acide abscissique agit comme une hormone de détresse et permet une réaction vigoureuse des végétaux.

$$V_c = \frac{IF}{r}$$

avec : V_c : vitesse d'échange de l'eau entre l'air et les feuilles ($m.s^{-1}$)
IF : indice foliaire du végétal à son stade végétatif (sans dimension)
r : résistance stomatique de la surface foliaire ($s.m^{-1}$)

La résistance stomatique de la surface foliaire r vaut en moyenne 300 $s.m^{-1}$ pendant le jour lorsque les stomates sont pleinement ouverts et 3000 $s.m^{-1}$ pendant la nuit lorsqu'ils se ferment. Connaissant l'indice foliaire pour différentes catégories végétales, on peut en déduire une estimation de la vitesse d'échange de l'eau entre l'air et les feuilles.

Comment [pG1]: to be confirmed

A physiological approach is needed to integrate stomata resistance and leaf area index. It would be the best approach, if it is possible to evaluate stomata resistance from available data at the moment of accident.

From the point of view of countermeasures, if there is no consumption of leaf or fruits vegetable during 2 or 3 days, then, this pathway will be avoided.

III HTO AIR TO SOIL

The second one is the transfer from **air to soil**, which occurs by diffusion of air vapor through the surface. It appears like a deposition, and can be modelized with a deposition velocity which will depends mainly on the soil humidity. It is often indicate that about half of the maximal deposition is released to air after the end of the accident.

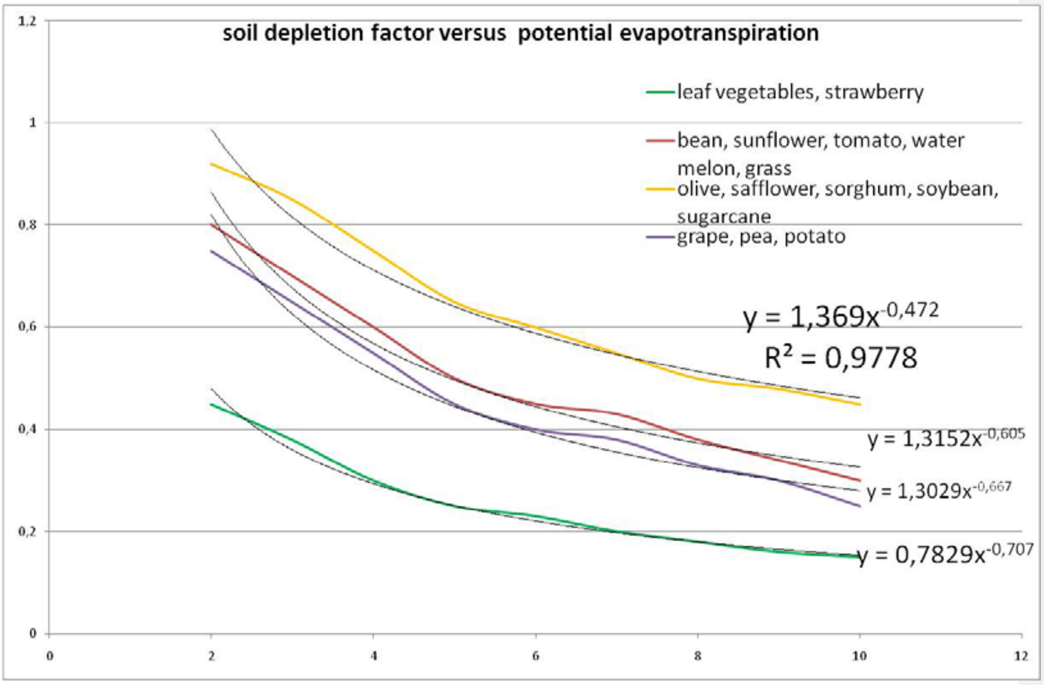
To give some quantitative idea of this mechanism, an assessment of the vapor exchange between air and soil in a temperate climate has been done in the environment of Dijon France, 300L.y^{-1} of air vapor is incorporated in the soil, compared to 700L.Y^{-1} of rain. Considering that average air vapor content is 8g.m^{-3}, this gives an average deposition velocity of air of 1.2 10^{-3} $m.s^{-1}$ (generally supposed to be between 10^{-3} and 10^{-2} $m.s^{-1}$. The average deposition in one hour is 30 to 300 $g.h^{-1}.m^{-2}$.

Comment [pG2]: Other measures ?

IV HTO SOIL TO PLANT

At a given moment, the relative humidity of soil is between 10 and 30%, corresponding to 50,000 and 150,000 g.m^{-2} for the rooting zone (It can be more in deep soils).This means that soil water concentration will be, for a short release of 1h, less than 0.1-1% of air vapor. This is small compared to air transfer, which is of some percents in the same time in day time, Nevertheless, the halftime in the soil will be of some weeks instead of some hours for free water in leaves, then the integration time is important and doses from the soil pathway is not negligible. Considering the fast turnover of free water in the plant, the equilibrium between plant and soil will be reached in 2 or 3 days. Then the plant free water concentration will decrease with the same halftime as the soil concentration. From the point of view of countermeasures, this pathway needs to be taken into account during the first week and will be confirmed by measurements.

From spring to autumn water evapotranspiration is of the order of some liters per square meter and per day, compared to 50 150L contained in the soil. The decrease of activity in temperate climate will then have half-lives between 10 and 100 days. The longest period corresponds to the biggest soil content and so on the lowest concentration. Then the dose which is bound to integrated activity won't be very different from one case to another.



Relationship beetween potential evapotranspiration and real evapotranspiration

$$Rws= 1/(1-p) . (\theta-\theta wp)/(\theta fc-\theta wp)$$

Potential Evapotranspiration
State of soil water content humidity
Real Evapotranspiration : give a correcting factor, by a factor of max 5.
To use directly for incorporation factor in organic matter

V HTO AIR TO RAIN AND SOIL

- Concentration of rain about 3 to 5 times lower than air moisture. (except at the foot of the stack)
- Dilution in the soil water about 100.
- Question of the direct leaves transfer.
    - Time of input = time of release + Time of evaporation.

Comment [pG3]: to discuss with Luca travailler avec Luc

VI OBT

A part of HTO is transformed in OBT, with practically no decrease up to harvest. Depending on the part of the vegetable eaten, the air-OBT may be translocated in totality to the accumulation organ after flowering or very little before. The influence of the date of accident is then important in terms of dose for vegetable which are stored and eaten during a long period like wheat or potatoes. At some critical period of the year (like in June under European climate) the total dose may be quite reduced by stopping the culture and by replacing it (if possible) by a new one. Simultaneously some deposition occurred on the ground and also contributes to the contamination of the plants by root pathway and incorporation of tritium in organic material. Soil concentration in HTO is much smaller than that in vapor, but the soil HTO has a much smaller turnover and will lead to a continuous production of OBT up to harvest. Rain may increase quite a lot the deposition to the soil and is a particular point to take into account.

The organic compounds of a plant are produced by photosynthesis from sun light. The general reaction produces a C3 molecule $(H\text{-}C\text{-}OH)_3$ $+O_2$ from CO_2 and H_2O. We can see that each carbon corresponds to a molecule of H_2O and may suppose this equivalence as a basic approach.

From continuous normal release, the average incorporation rate can be calculate from the yield of dry matter at harvest divided by the time of growth multiplied by a ratio of 0.53 which corresponds to the proportion of H_2O in C3 molecule corrected by a discrimination factor of 0.95.

$$\tau_{inc} = 0{,}53 \frac{\tau_{dm}^{veg}\ Y}{86400\ \Delta t_{growth}}$$

avec :	τ_{inc}	:incorporation rate of tritium in organic matter	$(kg_{FW}.m_{soil}^{-2}.s^{-1})$
	0,53	: water equivalence of dry organic matter	$(kg_{water}.kg_{dry\ vegetal}^{-1})$
	τ_{dm}^{veg}	: dry matter content in the vegetable	$(kg_{dry\ vegetal\ \cdot\ fresh\ vegetal}^{-1})$
	Y	: Yield at harvest	$(kg_{fresh\ vegetal}.m_{soil}^{-2})$
	86400	: conversion factor	$(s.d^{-1})$
	Δt_{growth}	: growth duration of the vegetable	(d)

This type of very simple approach does not make any difference between day and night and between cold, warm and hot weather. It should be at least corrected by the ratio daylight per day, as there is no incorporation by the light reactions during the night (dividing by about 0.6 for summertime).

As the effect of temperature is relatively important for incorporation, it is important to refine equation to include this parameter. The simplest approach is then to considerate general case and to characterize the extreme cases.

As soon as sun arises, the photosynthetic mechanisms operate. Light is then never the limiting factor of this process. As it is a chemical process, temperature plays an important game in the speed of the reactions. In the same time, respiration is minimal for temperature around 20°C and increases for low temperature and high temperature. The net photosynthesis becomes null when temperature of leaf reaches about 35°C. At cold temperature, the balance becomes positive above a given temperature depending on the crop considered. Values of 0°C, 5 and 7.5 °C are often used (depending on the geographical origin of the plant, exple. grass-wheat-maize). A first order relationship may be considered, for temperature between 10°C and 30°C.

A very useful concept for expressing heat units is “total day degrees”: that is, the accumulated number of days (or sometimes hours) above the crop base temperature.

Considering that air temperature is an available data, and considering that in the general case incorporation rate is proportional to temperature, then it is possible taking the previous equation to introduce temperature and total day degrees, instead of growth duration.

$$\tau_{inc} = 0,53 \frac{\tau_{dm}^{veg}\, Y.\theta}{24.TDD_{harvest}}$$

avec : τ_{inc} : incorporation rate of tritium in organic matter $(kg_{FW}.m_{soil}^{-2}.s^{-1})$

0,53 : water equivalence of dryorganic matter $(kg_{water}.kg_{dry\ vegetal}^{-1})$

τ_{dm}^{veg} : dry matter content in the vegetable $(kg_{dry\ vegetal} \cdot {}_{fresh\ vegetal}^{-1})$

Y : Yield at harvest $(kg_{fresh\ vegetal}.m_{soil}^{-2})$

24 : conversion factor $(s.d^{-1})$

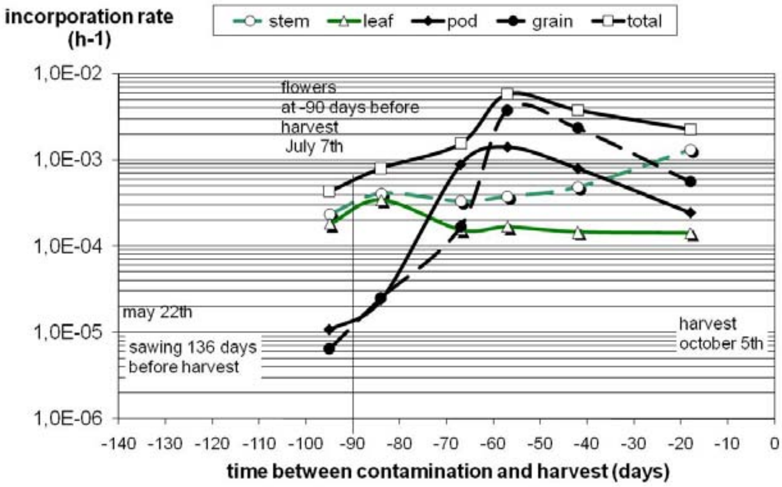
θ : average temperature during the accident and following hours (°C)

$TDD_{harvest}$: Total day degree (d°)

It is also possible to get free from the surface by dividing the incorporation rate by the dry matter yield to obtain a mass incorporation rate expressed in kg of water per kg of dry matter per hour.

This permits to calculate the activity integrated inside the whole plant, which is interesting for leaf-vegetable but cannot be used for grains or fruits, as the metabolism of these crops changes during the growth and partitioning occurs between the different organs of the plants.

Figure 1 shows a measured mass incorporation rate for soybean from the IAEA EMRASS soybean scenario. It can be seen that the total incorporation rate reaches a maximum at the beginning of august, best time for photosynthesis/temperature for a well-developed cover. It can be seen that incorporation rate remains relatively stable for leaves after blooming. At the contrary most of incorporation is done by transfer from the leaves to pods and grains. This is typically plant dependant and needs a data base for the physiology of the different plants eaten by the population.



VII SUMMARY

Figure 2 illustrates the evolution of tritium activity in vegetable per square meter in time, considering the two pathways (air and soil) and the two chemical forms (HTO and OBT).

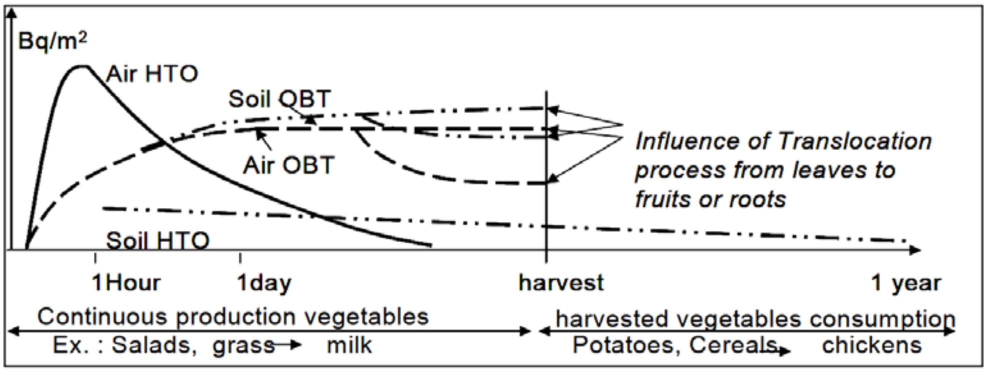


Figure 1 : Contribution to total dose of the different mechanisms versus time

Figure 2 : Evolution of activities by the different pathways.

VIII THE CASE OF THE NIGHT

Exchange velocity for HTO with the stomata resistance (which includes probably cuticle).

Calculation from integrated activity of free water, taking into account decrease in the next morning

Exchangeable OBT occurs quickly even in the night.

Many chemical reactions exist during the night, and some incorporation of hydrogen directly on carbon occurs.

The basic approach for night can be: consider that incorporation rate is the same than in the day, at the night temperature.

IX ANIMALS

See Dan and Anca

The different point to adress

Atmospheric transport and dispersion is similar as for other radionuclides except that HTO is re-emitted

Equilibrium between air moisture and crop relatively fast during daytime but long lasting at night (stomata versus cuticula)

Deposition to top millimetres of soil (HTO several mm; HT 20 mm)

Only in case of rain deeper penetration

Reemission is fast during the day and 50% of the HTO can be re-emitted during one day easily

The Canadian HT release experiment has reported re-emission rates of average 33% during the half hour release time (Tächner et al. 1990)

Root uptake small compared to direct uptake from atmosphere

Typical contribution (%) of the exposure pathways to the maximum dose at 1 km distance for a release of tritium as HTO or HT, calculated with the accidental tritium assessment model UFOTRI (local production and consumption) (inhalation 20% ingestion 80% HT <0.1 inh and >90% ing

Tritium foodchain model

Processes to be considered:

phenological stages of crop development

sowing, emergence, anthesis, harvest

growth of crop based on photosynthesised organic matter

photosynthesis rate

respiration rate

Photosynthzsis

Plant properties

Plant development stage

Photosynthetic active radiation (PAR)

Leaf area index (LAI)

Leaf temperature (air temperature)

Opening of stomata

radiation

air humidity

air temperature

soil water content

Photosynthesis highly dependent on the day of the year and the daytime

Le schéma général d’une contamination de végétaux par de l’eau tritiée est le suivant : la vapeur d’eau de l’air s’échange avec l’eau des feuilles. Ceci s’effectue d’une part à travers les stomates, d’autre part à travers la cuticule

La vapeur d’eau s’échange dans les deux sens, principalement de la plante vers l’extérieur (transpiration) mais également de l’extérieur vers l’intérieur, par diffusion .

Le flux sortant sert au transport les sels minéraux des racines aux parties aériennes de la plante par l’intermédiaire des vaisseaux de la tige et des feuilles.

Les plantes sont des systèmes biologiques ouverts, fonctionnant grâce à l’eau du sol. Un point capital est donc la régulation du flux d’eau sortant dès lors que l’eau vient à manquer.