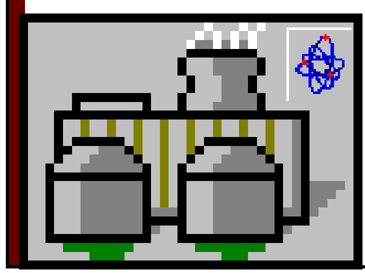
RADIOLOGICAL EMISSIONS II



Workshop on the use of the SIMPACTS model for estimating human health and environmental damages from electricity generation

ICTP, Trieste

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Externalities and Nuclear Power

- Nuclear power's economic competitiveness could improve significantly if *externalities* are taken into account.
- Initial studies suggest that the external costs associated with nuclear electricity generation are much smaller than those associated with other electricity generating options, especially fossil ones.
- Requires political will to implement.

The Competitiveness of Nuclear Power. A Fad of the Day or the Key to Survival? Presentation of Hans-Holger ROGNER and Lucille LANGLOIS, Planning and Economic Studies Section, Department of Nuclear Energy, IAEA.

Climate Change and Nuclear Power

- The potential need for Greenhouse Gas Mitigation and its climate benefits should create a substantial market pull for nuclear power.
- The tide appears to turn for nuclear - Member States of IAEA increasingly wish to keep the option open.
- Ultimately, mitigation strategies will depend on economics.
- Lately, climate change damage estimates and the costs of non-nuclear mitigation have been revised downward - controversial.
- Nuclear cannot count on Kyoto - rather it must become competitive in its own right.

Main impacts of nuclear cycle

- Normal operation:
  - atmospheric radiological releases (health impacts)
  - liquid waste disposal
- Hypothetical accidents:
  - health impacts
  - relocations
  - food ban
  - risk aversion
- Solid waste disposal

ATMOSPHERIC RADIOLOGICAL RELEASES

VALUING THE HUMAN HEALTH EFFECTS OF ROUTINE ATMOSPHERIC RELEASES FROM NUCLEAR FACILITIES, - OCTOBER 2002
Prepared by A. Markandya (University of Bath), L. Hudson, A. Hunt and T. Taylor (Metroeconomica Ltd)
Prepared for IAEA

Exposure routes for atmospheric radiological releases:

- direct inhalation of radionuclides in the air;
- external irradiation from radionuclides immersed in clouds;
- external irradiation from deposited radionuclides;
- ingestion of radionuclides in agricultural products.

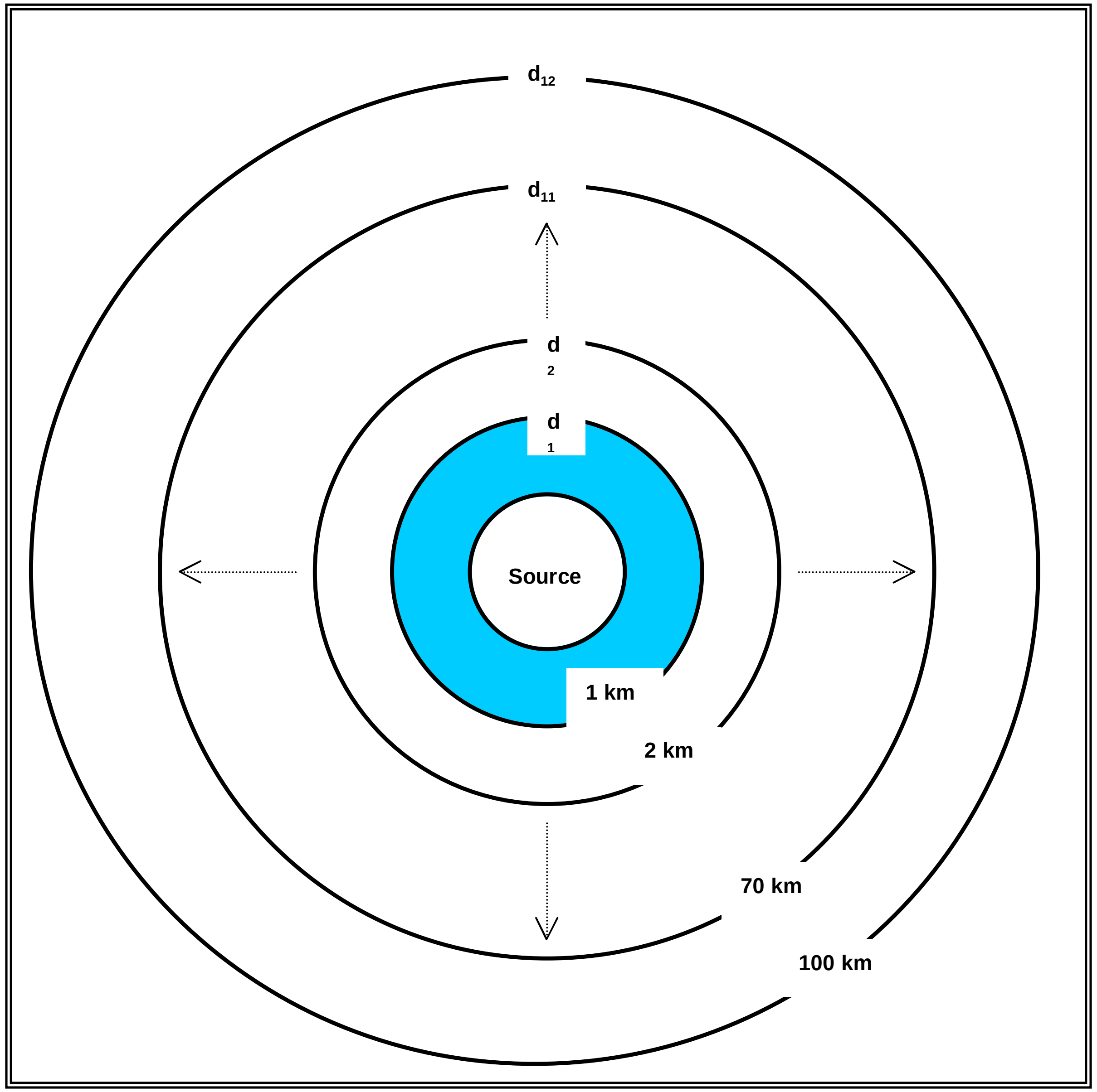
Key Stages of the Impact Pathways for Atmospheric Releases

Stage of Pathway	Description	Units
Source	Releases reported	Bq/year
Air Transport	Gaussian-plume (air)	Bq/m^3
Deposition	Deposition velocity	m/s
Contamination	Transfer coefficients and models to determine the concentration in: ♦ food consumed ♦ ground surface area ♦ air	 Bq/kg Bq/m^2 Bq/m^3
Human Exposure	Standard characteristics of man: ♦ inhalation rates ♦ consumption of food ♦ effective dose equivalent	 m^3/year Kg/year Sv, man Sv
Health Effects	Dose-response functions	cancer non-fatal cancer severe hereditary effects
Monetary Valuation	Willingness-to-pay studies Loss of utility, food ban, etc.	US $

Spatial dimension

- **Local Domain**
  - Zero to 100 km from the emission source
- **Regional Domain**
  - 100 to 1,000 km from the emission source;
- **Global Domain**
  - Greater than 1,000 km from the emission source.

Local Domain



Defined by distance bands dj of radio
j=1, 2, 3, ……., 12
d_1 = 0 to 1 km;
d_2 = 1 to 2 km;
d_3 = 2 to 3 km;
d_4 = 3 to 5 km;
d_5 = 5 to 7 km;
d_6 = 7 to 10 km;
d_7 = 10 to 15 km;
d_8 = 15 to 20 km;
d_9 = 20 to 35 km;
d_{10} = 35 to 50 km;
d_{11} = 50 to 70 km;
d_{12} = 70 to 100 km.

Temporal dimension

- Temporal dimension is allowed for by integrating effects over relevant time scale

- Due to the long life of some radionuclides, the temporal dimension is very important for environmental impact. For this reason the collective dose should be integrated over a period of 100000 years, enough time to consider all possible impacts.

Assumptions and input data

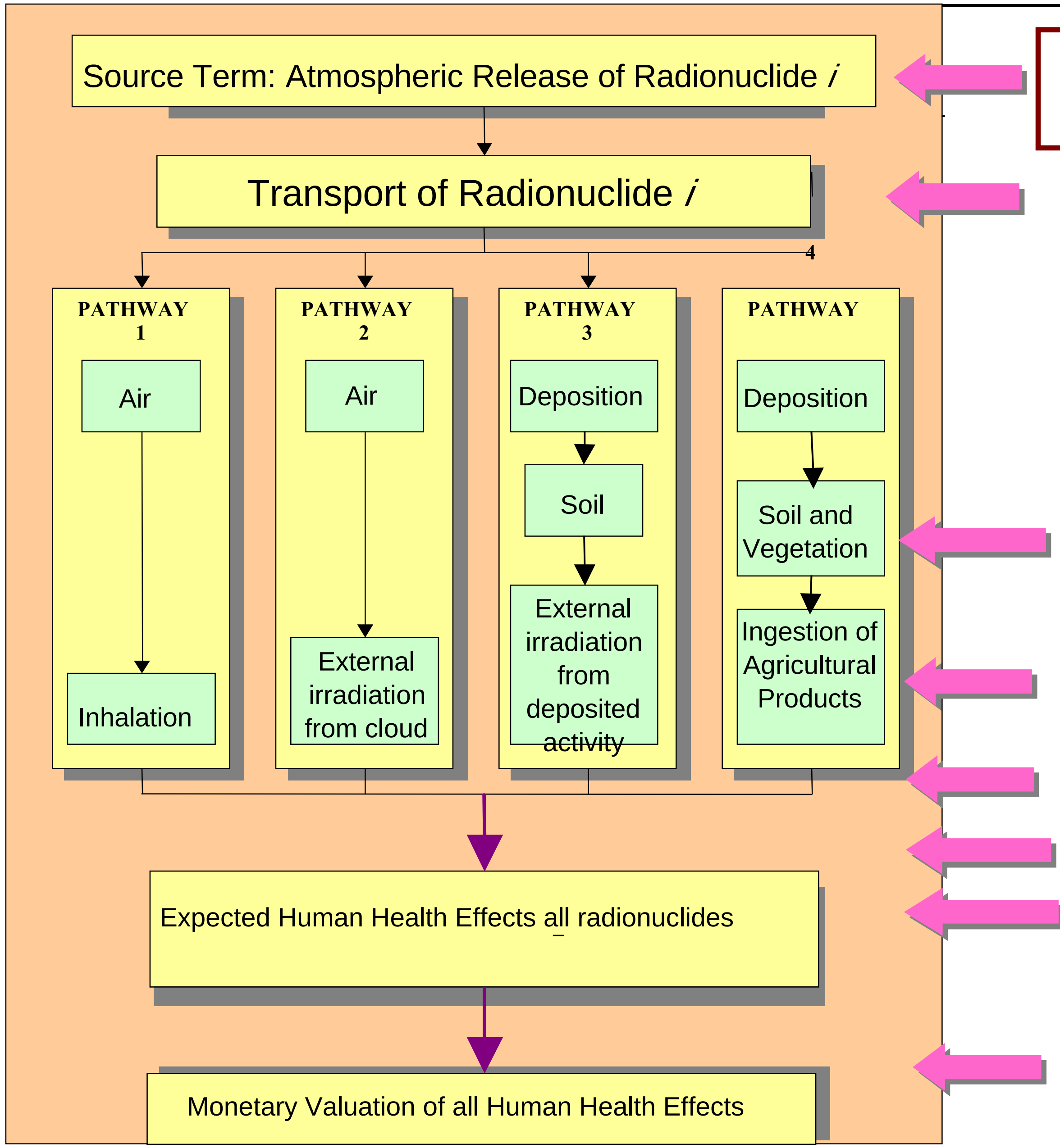
- Uniform local and regional population densities
- Uniform wind rose
- Mean meteorological data:
  - Wind speed
  - Pasquill stabilities categories
- Total depletion factor function of:
  - Radioactive decay constant of radionuclide *i* (1/s),
  - Wet removal coefficient (1/s),
  - Deposition velocity (m/s).

Input data

- Stack parameters and radionuclides inventory,
- Population data,
- Meteorological data,
- Average consumption rate of agricultural products
- **Transfer factors ($Bq_{air} \rightarrow Bq_{food}$)**
- **Effective Dose equivalent ($Bq \rightarrow Sv$)**

Note: subsequent slides are a bit busy. However, this information is important as there is no manual at the moment.

NukPacts program – Air component



Releases (Bq/s)
Effective Release Height (m)

Air Concentration (Bq_{air}/m^3)

Transfer factors ($Bq_{air} \rightarrow Bq_{food}$)
Effective Dose equivalent (Bq → Sv)

Average consumption rate of agricultural products (kg/year)

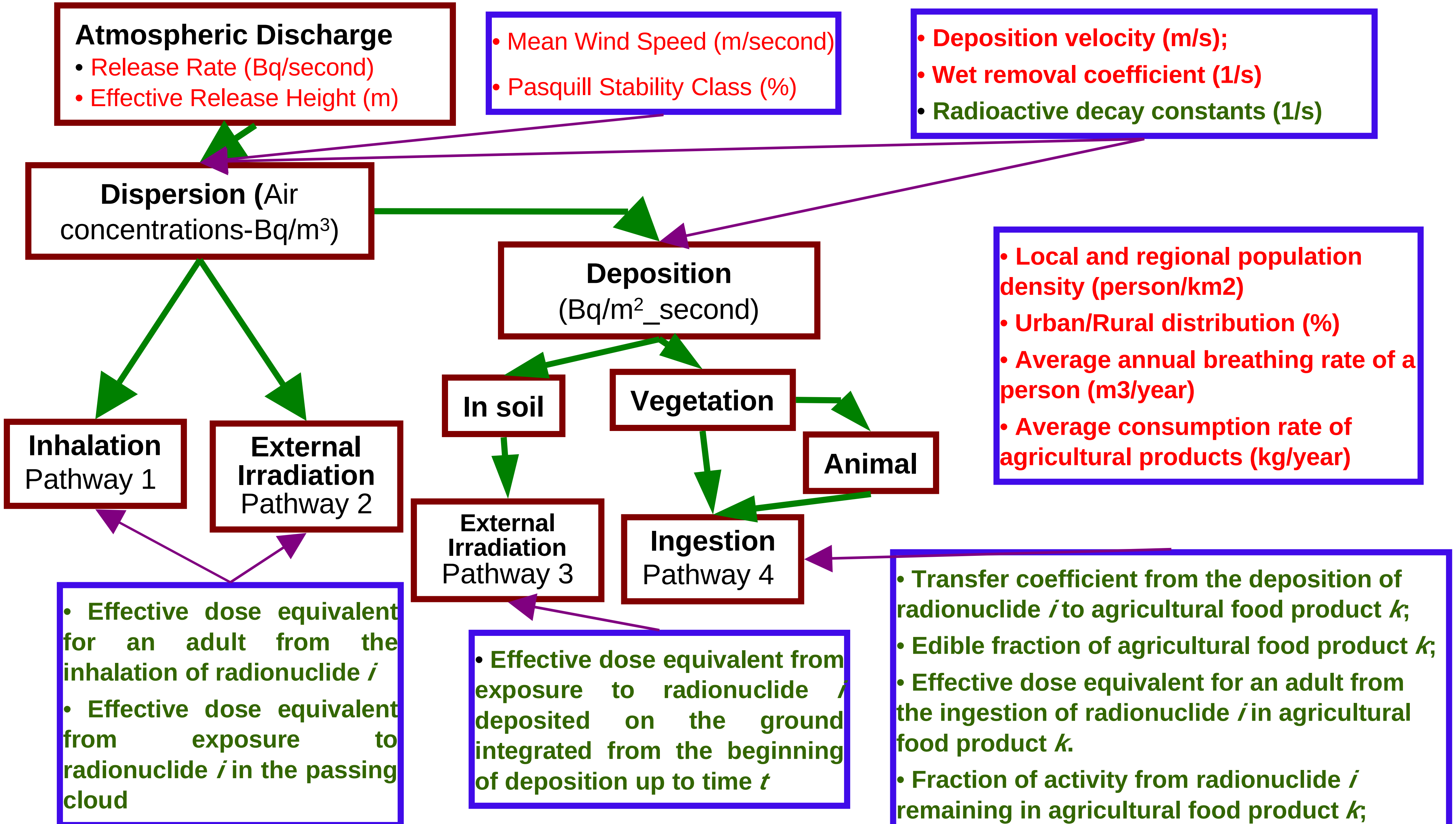
Population densities

Individual & Total dose (man-Sv)

Stochastic risk factors (ICRP 1991)

Cost per expected effect (US$/case)

Steps, Mandatory Input data, Default values



Pathway 1: Inhalation of radionuclides in the air

$$I_{inh}(i, d_j)\left[\frac{Bq}{year}\right] = C(i, d_j)\left[\frac{Bq}{m^3}\right] \times Br\left[\frac{m^3}{year}\right]$$

$C(i,j)$	•Atmospheric concentration of radionuclide i at distance from source	•Bq/m3
Br	•Average annual breathing rate of a person •Default value 7,500 m3/year)	•m^3/person_year
$I_{inh}(i,d_j)$	•Average annual individual intake of radionuclide i in d_j	•Bq/year

$$H_{inh}^{AID}(i, d_j)\left[\frac{Sv}{year}\right] = I_{inh}(i, d_j)\left[\frac{Bq}{year}\right] \times EDE_{inh}(i)\left[\frac{Sv}{Bq}\right]$$

$EDE_{inh}(i)$	•**Effective dose equivalent** over 50 years for an adult from the inhalation of radionuclide i	•Sv/ Bq
$H_{inh}^{AID}(i,d_j)$	•Average individual dose from the inhalation of radionuclide i in d_j	•Sv/year

Pathway 1: Inhalation of radionuclides in the air

$$H_{inh}\left(d_j\right)\left[\frac{Sv}{year}\right]=\sum_i H_{inh}^{AID}\left(i,d_j\right)\left[\frac{Sv}{year}\right]$$

$H_{inh}(d_j)$	•Average individual dose from the inhalation of all radionuclides in d_j	•Sv/year

$$H_{inh}^{TCD}\left[\frac{man\_Sv}{year}\right]=\sum_j H_{inh}\left(d_j\right)\left[\frac{Sv}{year}\right]\times P\left(d_j\right)[person]$$

$H_{inh}{}^{TCD}$	•Total annual collective dose for all 12 distance bands	•man_Sv/year

Pathway 2: External irradiation from radionuclides immersed in clouds

$$H_{ext,c}^{AID}\left(i,d_j\right)[Sv] = C\left(i,d_j\right)\left[\frac{Bq}{m^3}\right] \times EDE_{ext,c}(i)\left[\frac{Sv}{Bq/m^3}\right]$$

$EDE_{ext,c}(i)$	•**Effective dose equivalent** from exposure to radionuclide *i* in the passing cloud	•Sv/(Bq/m^3)
$H_{ext,c}^{AID}(i,d_j)$	•Average individual dose from external exposure to radionuclide *i* in the passing cloud d_j	•Sv

Pathway 2: External irradiation from radionuclides immersed in clouds

$$H_{ext,c}\left(d_j\right)[Sv] = \sum_i H_{ext,c}^{AID}\left(i, d_j\right)[Sv]$$

$H_{ext,c}(d_j)$	•The average individual dose from exposure to all radionuclides in the passing cloud over d_j	•Sv

$$H_{ext,c}^{TCD}\left[\frac{man\_Sv}{year}\right] = \sum_j H_{ext,c}\left(d_j\right)[Sv] \times P\left(d_j\right)[person]$$

$H_{ext,c}^{TCD}$	•The total annual collective dose for all 12 distance bands	•man_Sv/year

Deposition of Radionuclides

$$w(i,d_j)\left[\frac{Bq}{m^2\_sec}\right] = C(i,d_j)\left[\frac{Bq}{m^3}\right] \times V_d^{w,d}\left[\frac{m}{sec}\right]$$

• $W(i,d_j)$	•Average deposition rate of radionuclide *i* at distance d_j from the emission source	•Bq/m^2_second
$V_d^{w,d}$	•Average wet and dry deposition rate	•m/s

- $V_d^{w,d}$ *is function of:*
  - Wet removal coefficient,
    - default value: 9.0x10^{-6} 1/s
  - Deposition velocity,
    - default value: 0.005 m/s

$$V_d^{w,d}\left[\frac{m}{s}\right] = Deposition\_velocity \times Wet\_removal\_coefficient \times 800$$

Pathway 3: External irradiation from deposited radionuclides

$$H_{ext,g}^{AID}(i,d_j)[Sv] = w(i,d_j)\left[\frac{Bq}{m^2\_sec}\right] \times EDE_{ext,g}(i)\left[\frac{Sv}{Bq/m^2\_sec}\right]$$

$EDE_{ext,g}(i)$	•**Effective dose equivalent** from exposure to radionuclide *i* deposited on the ground integrated from the beginning of deposition up to time *t* (*t=100,000 years)*	$\left[\frac{Sv}{Bq/m^2\_sec}\right]$
$H_{ext,g}^{AID}(i,d_j)$	•Average individual dose from external exposure to radionuclide *i* integrated from the beginning of deposition in d_j up to time *t*	•Sv

Pathway 3: External irradiation from deposited radionuclides

$$H_{ext,g}\left(d_j\right)[Sv] = \sum_i H_{ext,g}^{AID}\left(i, d_j\right)[Sv]$$

$$H_{ext,c}^{TCD}\left[\frac{man\_Sv}{year}\right] = \sum_j H_{ext,c}\left(d_j\right)[Sv] \times P\left(d_j\right)[person]$$

$H_{ext,g}(d_j)$	•Average individual dose from exposure to all radionuclides deposited on the ground within d_j	•Sv
$H_{ext,g}^{TCD}$	•Total collective dose for all 12 distance bands (man Sv per year of releases).	•man_Sv/year

Pathway 4: Ingestion of radionuclides in agricultural products

Categories of food products considered:

- beef,
- lamb,
- cereals: *oats, barley, rye, wheat, rice, corn*.
- root vegetables: *carrot, turnip, beet*
- green vegetables: *bean, cabbage, pepper*
- milk

$$CR_k\left(i,d_j\right)\left[\frac{Bq}{kg}\right] = w\left(i,d_j\right)\left[\frac{Bq}{m^2\_sec}\right] \times f_k(i)\left[\frac{Bq/kg}{Bq/m^2\_sec}\right]$$

t=100,000 years

$f_k(i)$	•Transfer coefficient for product k integrated over 100,000 years	$\left[\frac{Bq/kg}{Bq/m^2\_sec}\right]$
$CR_k(i,d_j)$	•Contamination rate of product k by radionuclide i in d_j	•Bq/kg

Pathway 4: Ingestion of radionuclides in agricultural products

$$H_{ing_k}^{TCD} = \sum_j (CR_k(i,d_j)\, x\; EDE_{ing}(i)\, x\; Cons(k)\, x\; F_{cp}(k)\, x\; D(k))$$

Cons(k)	•Annual average consumption of product k	•kg/year
Fcp(k)	•Edible fraction of the product	•%
D(k)	•Fraction of Radioactivity Remaining in the Food at the Time of Consumption: it takes into account the radioactive decay during the delay between harvest (or animal slaughter) and consumption	•%
$EDE_{ing,k}(i)$	•Effective dose equivalent for radionuclide *i* ingested in agricultural food products	•Sv/Bq
$H_{ing,k}^{TCD}$	•Total collective dose from ingestion of agricultural product *k* all 12 distance bands (local area)	•man_Sv/year

$$H_{ing}^{TCD} = \sum_k H_{ing_k}^{TCD}$$

Pathway 4: The Special Case of Tritium and Carbon–14

- The transfer of H – 3 (tritium) between the atmosphere and the terrestrial environment is particularly complex because it mixes directly into the hydrogen cycle in biological systems. As a result, the assessment of the collective dose due to the ingestion of H – 3 in ‘locally’ produced food products differs slightly from the approach used for other radionuclides. Likewise, the assessment of ingested C – 14 is also treated slightly differently.
- The assessment is not conducted for individual agricultural products, but rather for the acumulated ingestion of contaminated food products.

Pathway 4: The Special Case of Tritium and Carbon–14

$$H_{ing}\left(H-3, C-14; d_j\right) = C\left(H-3, C-14; d_j\right) \times f\left(H-3, C-14\right)$$

$C(d_j)$	• Concentrations of H – 3 and C – 14 in d_j.	•Bq/m³
f	•Transfer coefficient from contaminated air to food products: •H –3 8.10E-01 •C –14 5.81E+05	•(Bq/year)/ (Bq/ m³)
$Hing(d_j)$	• Accumulative radioactivity ingested by an average individual from food products exposed to the ambient air concentrations of H–3 and C–14	•Bq/year

$$H_{ing}^{AID}\left(H-3, C-14; d_j\right) = H_{ing}\left(H-3, C-14; d_j\right) \times EDE_{ing}\left(H-3, C-14\right)$$

EDE_{ing}	•**Effective dose equivalent** committed over 50 years from the ingestion of food products contaminated with H–3 and C–14	•Sv/Bq
$H_{ing}^{AID}\left(d_j\right)$	•Average individual dose from the acumulated radioactivity associated with the ingestion of H–3 and C–14	•Sv/year

Pathway 4: The Special Case of Tritium and Carbon – 14

$$H_{ing}^{TCD}(H-3, C-14) = \sum_{j} H_{ing}^{AID}\left(H-3, C-14; d_j\right) \times P\left(d_j\right)$$

H_{ing}^{TCD}	Total collective dose from the ingestion of H–3 and C–14 for all 12 distance bands	Man_Sv/year of releases
$P(d_j)$	Total population	•persons

- Basic data requirements include:
  - Transfer coefficient from contaminated air to food products,
  - effective dose equivalent for an adult from the ingestion of H – 3 and C – 14 in food products.

Transfer Coefficients for Selected Agricultural Products Integrated Over 100,000 Years

Edible fraction

Fraction of Radioactivity Remaining in the Food at the Time of Consumption

	Beef	Lamb	Cereals	Green Vegetab.	Root Vegetab.	Milk
Co – 58	6.95E+03	1.62E+04	5.22E+04	9.09E+04	3.30E+01	5.12E+04
Co – 60	2.93E+04	4.34E+06	6.86E+04	1.15E+05	5.16E+03	7.08E+04
I – 131	2.47E+04	3.17E+04	4.21E+04	4.12E+04	1.09E+04	5.82E+04
I – 133	1.11E+03	5.76E+03	5.29E+02	6.17E+03	3.50E+00	3.79E+03
Cs – 134	7.93E+05	1.26E+06	4.75E+05	1.32E+05	9.40E+02	1.59E+05
Cs – 137	9.14E+05	1.91E+06	5.25E+05	1.48E+05	1.63E+05	1.79E+05
Edible fraction	80.0	80.0	100.0	70	70	100.0
H – 3	99.9	99.9	95.9	98.7	98.8	99.2
Co – 58	93.4	93.4	7.3	58.2	58.1	98.1
Co – 60	99.7	99.8	90.8	97.1	97.2	98.1
I – 131	54.7	54.7	0.0	35.4	26.2	1.1
I – 133	0.4	0.4	0.0	2.1	0.1	0.0
Cs – 134	99.4	99.4	77.9	92.7	32.2	95.3
Cs – 137	100.0	100.0	98.3	99.5	99.5	99.7
All others	100.0	100.0	100.0	100.0	100.0	100.0

Effective Dose equivalent

		•Pathway1	Pathway2	Pathway3	Pathway4
• Nuclide	• Half-life	•$EDE_{inh}(i)$	$EDE_{ext,c}(i)$	$EDE_{ext,g}(i)$	$EDE_{ing,k}(i)$
		•(Sv/Bq)	•Sv/(Bq/m^3)	$\left[\frac{Sv}{Bq/\frac{sec\_m^2}{100,000years}}\right]$	•(Sv/Bq)
• H – 3	• 12.3 years	•1.73E-11	•1.10E-11		•1.80E-11
• C – 14	• 5710 years	•5.60E-10			•5.60E-10
• Co – 58	• 71.0 days	•2.90E-09	•1.40E-06	•1.70E-01	•1.00E-09
• Co – 60	• 5.3 years	•5.60E-08	•4.40E-06	•6.84E+00	•7.20E-09
•Kr – 85			•4.40E-09		
•Xe – 133			•5.50E-08		
• I – 131	• 8.1 days	•1.30E-08	•4.90E-07	•8.60E-03	•2.20E-08
• I – 133	• 21.0 hours	•2.30E-09	•1.00E-06	•1.50E-03	•4.20E-09
• Cs – 134	• 2.1 years	•1.20E-08	•2.80E-06	•2.28E+00	•1.90E-08
• Cs – 137	• 30.0 years	•1.30E-08	•9.20E-07	•4.10E+00	•1.30E-08

Regional effects

Regional effects are modelled as:

- 15% of local effects (first versions)
- mean concentration of each radionuclide across the regional domain, then the regional impacts can be calculated

$$C_R = \frac{Q_R}{A_R V_d^{w,d}}$$

Qr is not the emission rate, rather it is the amount of pollutant remaining in the plume at a distance of 100 km.

Qr = emission at source – locally depleted pollutant.

Global Impacts bases

- Tritium (H – 3), with a half-life about 12 years, rapidly mixes into the global hydrogen cycle
- Carbon – 14, with a half-life over 5,700 years, mixes with the global carbon cycle
- Krypton – 85, a noble gas with a half-life of about 10 years, does not deposit and consequently is able to disperse throughout the global atmosphere

Global Impacts equations

$$H^{TCD}_{global}\left(H-3, C-14, Kr-85\right) = Q\left(H-3, C-14, Kr-85\right) \times EDE_{global}\left(H-3, C-14, Kr-85\right)$$

H^{TCD}_{global}	•**Total global collective dose,** integrated over 100,000 years, from the release of H–3, C–14 and Kr–85 to the atmosphere.	•Man_Sv/year of releases
Q	•Release rate of H – 3, C – 14 and Kr – 85.	•MBq/year
EDE_{global}	•**Collective effective dose equivalent**, integrated over 100,000 years, resulting from the release of 1 M Bq of H – 3, C – 14 and Kr – 85 into the atmosphere. •H–3 9.42E-09 •C–14 1.42E-04 •Kr–85 9.30E-11	•Man_Sv/ (MBq/year)

HEALTH EFFECTS

- Stochastic nature and delay time in its manifestation at low levels of exposure
- Latent or long-term stochastic effects (cases/man Sv)
  - Fatal cancer 5.00E-02
  - Non-fatal cancer 1.20E-01
  - Severe hereditary effects 1.00E-02
    - ICRP 1991 numbers
- Impacts vary linearly with dose, with no threshold value.

Monetary Valuation

•Approach	•Fatal Cancers	•Non-fatal Cancers	•Sever Hereditary Effects
	•US $^{2000}/case	•US$^{2000}/case	•US$^{2000}/case)
•VOSL	•1,500,000	•500,000	•1,500,400
•VLYL	•670,000		

- Value of a Statistical Life (VOSL)
- Value of a Life Year Lost (VLYL)

- Transfer from EU and US studies

$$Unit\_Cost\ in\ a\ country = Unit\_Cost\ REf\_Study\ \frac{PPP\ GNP_{Country}}{PPP\ GNP_{REF\ \ STUDY}}$$

Monetary Valuation

- Damage should be calculate using national values for local impacts
- National values should also be used for regional impacts is the country is large enough, otherwise mean regional values should be used
- For global impacts, the PPP of the worlds should be used, around 6000 USD/cap

Case study, Mandatory Input data, Default values

Atmospheric Discharge

- Release Rate (Bq/second)
  - H - 3 **1.88E+05**
  - C - 14 **2.09E+02**
  - Co - 58 **4.75E-02**
  - Co - 60 **1.67E-02**
  - Kr - 85 **1.94E+05**
  - I - 131 **7.25E+02**
  - I - 133 **1.01E+03**
  - Xe - 133 **2.78E+07**
  - Cs - 134 **4.92E-01**
  - Cs-137 **1.77E+00**
- Effective Release Height 147.3 m, using Airpats

- Mean Wind Speed (2.9 m/s)
- Pasquill Stability Class (%)
  - A 3%
  - B 13%
  - C 11%
  - D 27%
  - E 7%
  - F 40%

- **Local and regional population density (45.6 and 15person/km2)**
- **Urban/Rural distribution (%)**
- **Average annual breathing rate of a person (7500 m3/year)**
- **Average consumption rate of agricultural products (kg/year)**

•Beef	•2
•Sheep	•2
•Grain	•80
•Green vegetable	•80
•Root vegetable	•80
•Fresh milk	•45
•Other milk*	•45

- **Deposition velocity (m/sec);**
- **Wet removal coefficient (sec^{-1})**
- **Radioactive decay constants (sec-1)**
- **Effective dose equivalent**
- **Transfer coefficient**
- **Edible fraction**

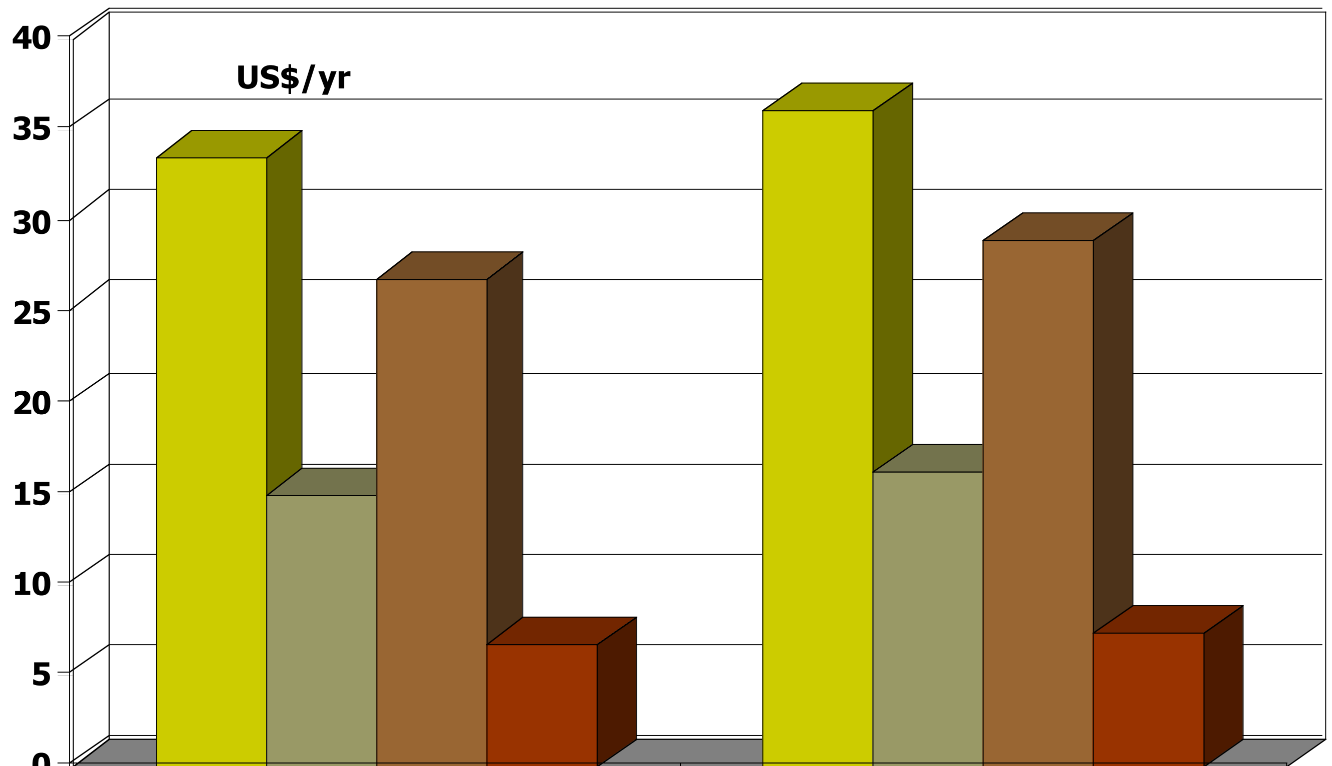
Effective stack height, I

- $h_E = H_S$ stack height + Δh plume rise
- Δh plume rise is a function of:
  - Pasquill stability class,
  - Exhaust gas temperature,
  - Exit velocity
  - Stack inner diameter.
  - Note: For typical Paris and Stuttgart weather conditions and for exhaust gas velocity, temperature and exit stack diameter of 14 m/s, 413 K and 2.9 m, respectively, the plume rise is approximately equal to 130 meters for neutral atmospheres (Pasquill class D) and 70 meters for stable conditions (Pasquill classes E and F)
- AIRPACTS could be used to estimate h_E

Effective stack height, II

•Parameter	•Formula
•Briggs Buoyancy Flux	$$F_B = gV_E D_E^2 \left(\frac{\Delta T}{4T_E} \right)$$
•Plume rise for unstable (Pasquill classes A, B and C) •or neutral (Pasquill class D) atmospheric conditions	•*if FB < 55* $$\Delta H = 21.425 \frac{F_B^{0.75}}{U}$$ *if FB ≥ 55* $$\Delta H = 38.71 \frac{F_B^{0.60}}{U}$$
•Plume rise for stable dispersion (Pasquill classes E and F)	$$\Delta H = 2.6 \left(\frac{F_B T_A}{U \, g \, \partial\theta / \partial z} \right)^{0.33}$$ •∂θ/∂z = 0.020 K/m for Class E •∂θ/∂z = 0.035 K/m for Class F

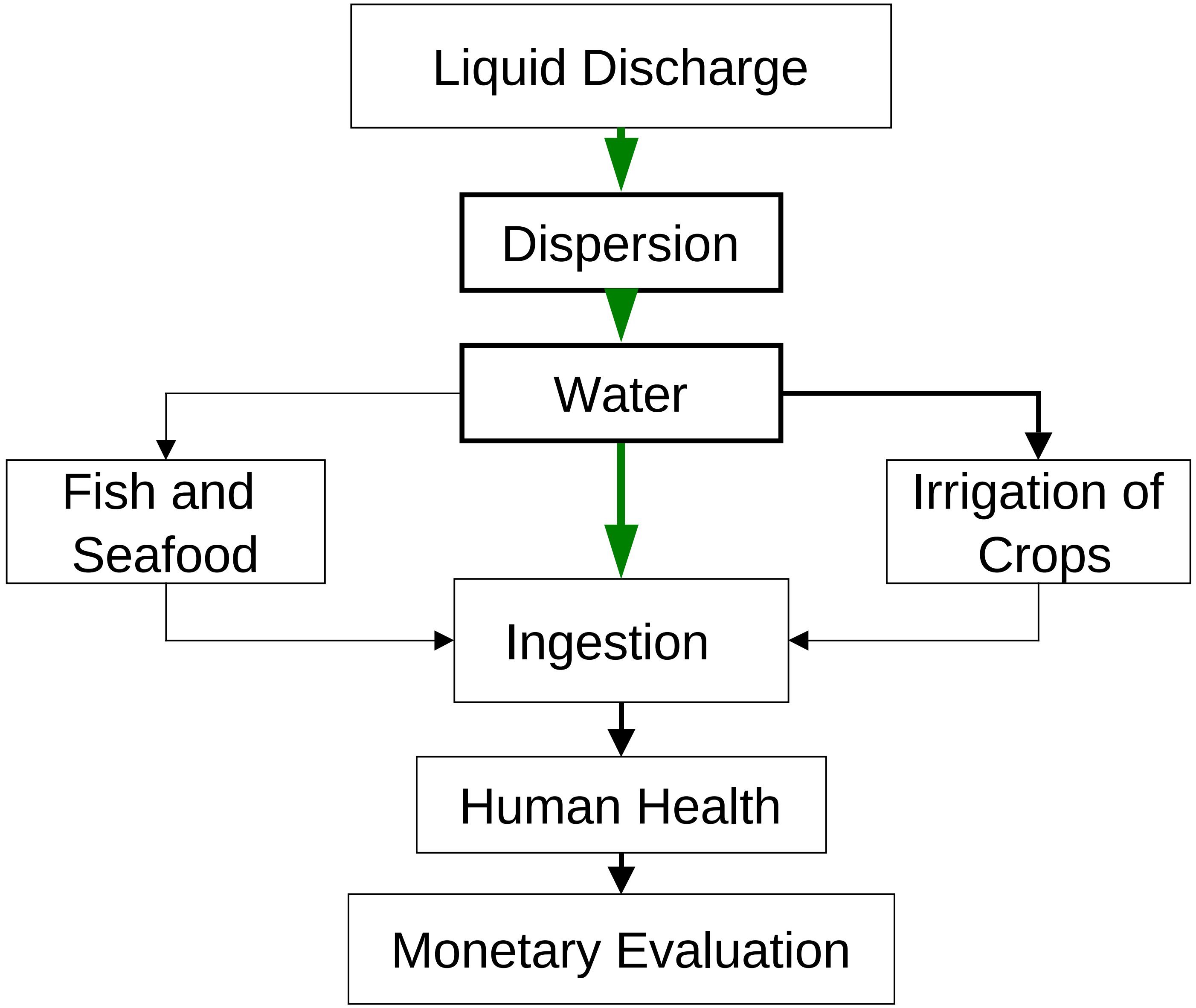
Impacts of atmospheric releases, results



	Local Impact	Regional Impact
Fatal cancer (VOSL)	3.34E+01	3.61E+01
Fatal cancer (YOLL)	1.49E+01	1.61E+01
Non fatal cancer	2.67E+01	2.89E+01
Severe hereditary effect	6.68E+00	7.22E+00

LIQUID WASTE DISPOSAL

Impacts Pathways for the Liquid Discharge of Radionuclides into Aquatic Environment



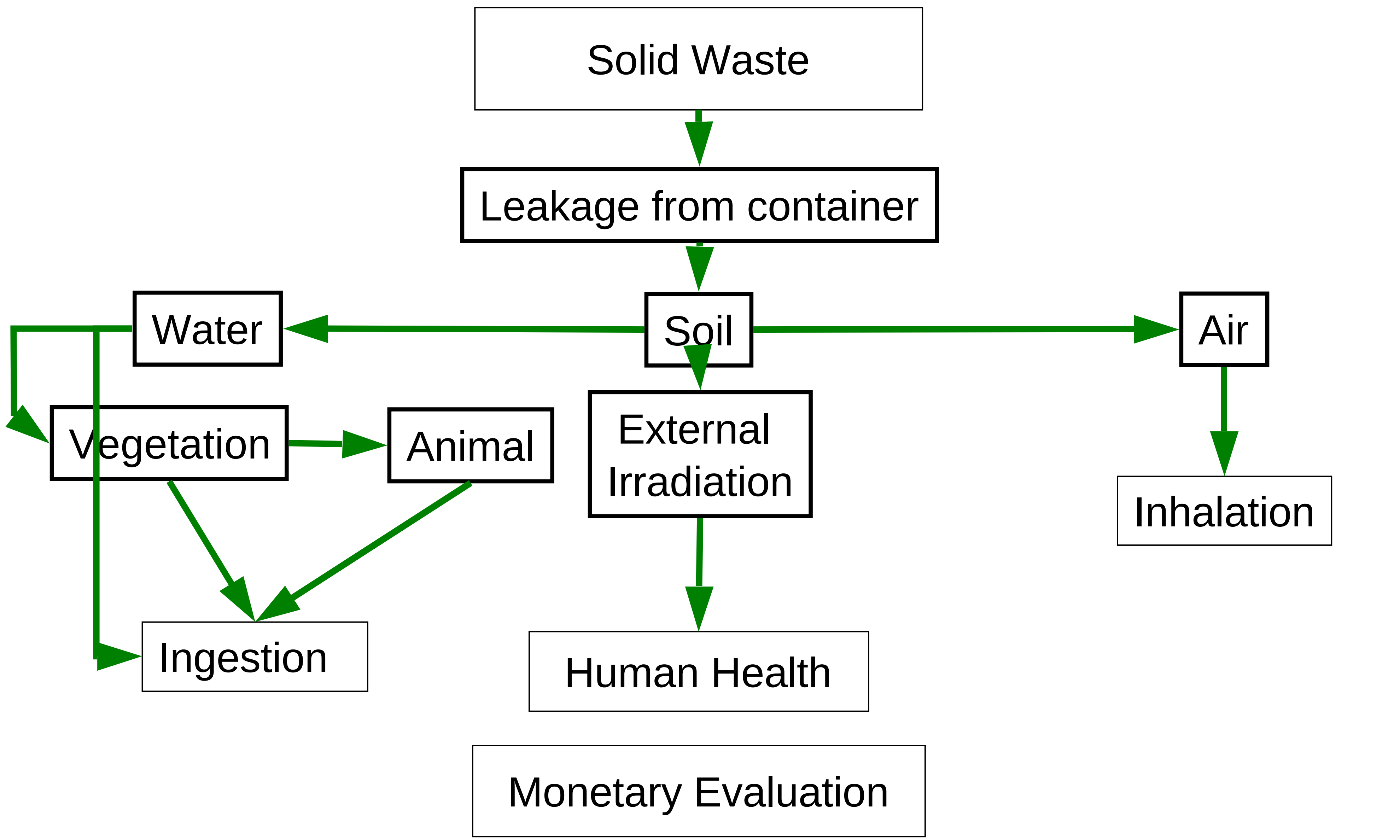
Key considerations

- There is not simplified methodologies to evaluate the impacts pathways of radionuclides in aquatic environment
- Aquatic environment:
  - Rivers
    - River-specific characteristics such as flow rate of water and sediments
    - Transfer factor for water/sediments and water/fish
    - Water use for irrigation and consumption
    - Fish consumption
  - Sea
    - Volume interchanges between compartments, in which is divides the sea,
    - sedimentation and the radionuclide transfer factors between the water, sediments, fish, mollusks, etc.

RADIOACTIVE WASTE DISPOSAL

ESTIMATING THE EXTERNAL COSTS OF RADIOACTIVE WASTE DISPOSAL, *Prepared by*
A. Markandya (University of Bath) and R. Boyd (Metroeconomica Ltd) for IAEA, JUNE 1999.

Impacts Pathways for of Radionuclides to the ground from a waste disposal site



Some considerations

- Potential impacts from waste are very large
- Time over which impacts can occur is very long - up to 100,000 years
- Local impacts: 5 km
- Regional impacts: more than 5 km
- Impact prediction requires use of sophisticated flow and solute transport models, they are not easily replicated.
  - There is not simplified methodology ready

Key concepts

- Waste classified into low, intermediate and high.
- Low and intermediate waste further classified into long lived (with α emitters) and short lived
- Disposal is either near surface or deep geological

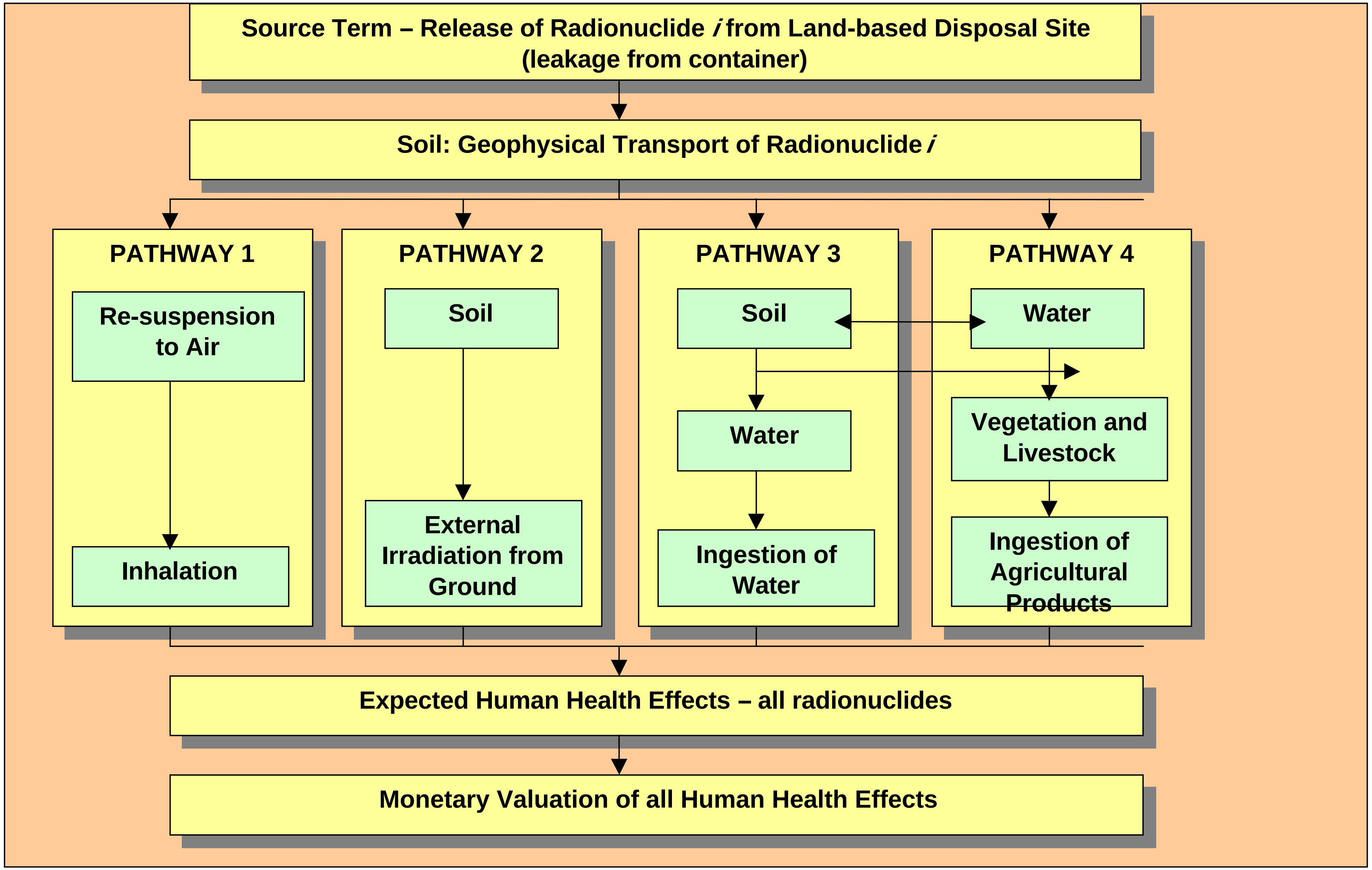
Radioactive isotopes in waste

- Low level waste disposal
  - Solid: H-3, C-14, Co-58, Co-60, Ni-59, Ni-63, Sr-90, Nb-94, Mo-93, Tc-99, Pd-107, I-129, Cs-135, Cs-137, U-234, U-238, Pu-239, Pu-241, Am-241, Np-237
- High level waste disposal
  - Solid: Se-79, Zr-73, Tc-99, Pd-107, Cs-135, U-233, Am-241, Np-237

Impact Pathway

1. The ingestion of radionuclides in contaminated water
2. The ingestion of radionuclides in agricultural product irrigated/watered by contaminated water
3. Inhalation of re-suspended radionuclides in the air
4. External irradiation from radionuclides in contaminated soil

Priority Impact Pathways for Radionuclide Releases to Ground



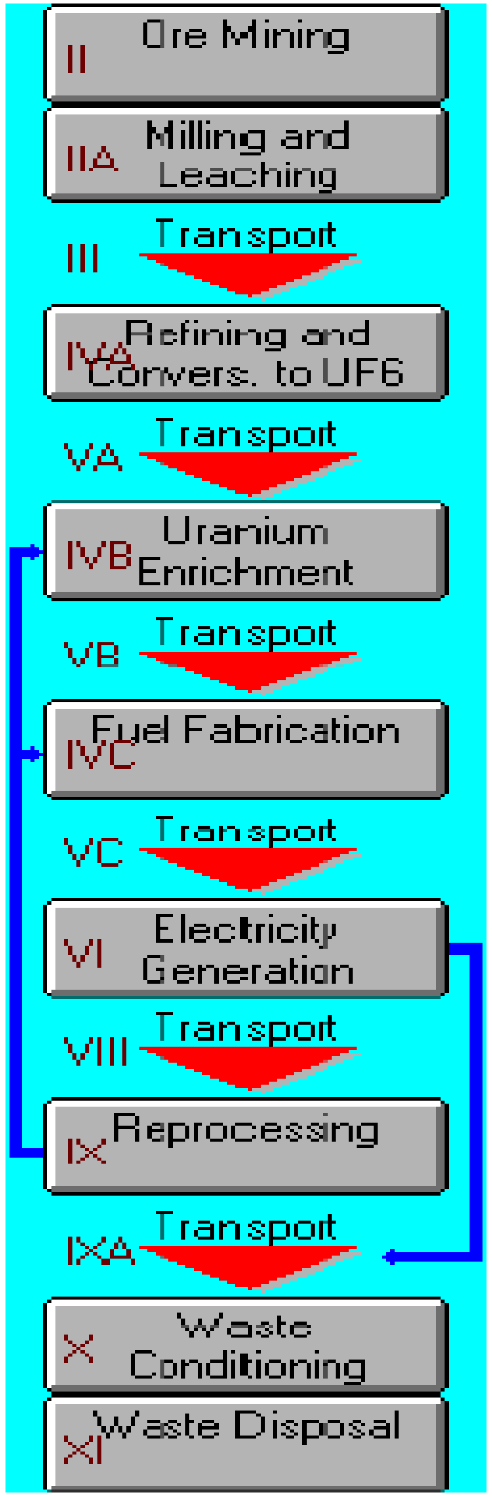
ExternE Project, Nuclear fuel cycle

- **Definition of cycles**
- **Burdens and impacts**
- **Results**

http://externe.jrc.es /All-EU+Nuclear.htm

Nuclear fuel cycle

- Steps
  - Mining and milling
  - Refining and Conversion
  - Enrichment
  - Fuel fabrication
  - Power Generation
  - Reprocessing
  - Storage and final disposal
- Open or closed fuel cycle,
  - Closed cycle: part of the fuel is from reprocessing
- Power generation
  - The technology considered was PWR.



Burdens and impacts

- The major burdens of the nuclear fuel cycle are:
  - the radioactive emissions from the mining and milling activities,
  - the risk of accidents,
  - the air pollutant emissions from energy used for other stages, such as enrichment and reprocessing.
- Regarding the risk of accidents, the methodology for assessing this impact was improved, incorporating risk aversion through an expected utility approach.
- The assessment of impacts was focused on:
  - radiological impacts on both workers and the general public, including
    - fatal and non-fatal cancers and hereditary effects.
    - occupational accidents leading to deaths
    - major and minor injuries
  - non-radioactive pollutants emitted from the nuclear fuel cycle. The priority pathways identified for the fossil fuels were analyzed, including effects on:
    - public health,
    - crops,
    - materials,
    - ecosystems,
    - and global warming

Results of the nuclear fuel cycle, I

- Damages are quite low, especially for the power generation stage.
- For other fuel cycle stages, damages are larger, mostly due to:
  - radioactive emissions of abandoned mill tailings,
  - global warming effects associated with the energy used for reprocessing and enrichment.
- Regarding the impact of radioactive emissions from mill tailings, the quantification of its impacts is quite uncertain, due to difficulties in transferring dose-response functions to low doses, since average individual doses are very small.
- For the global warming impacts, they may be largely diminished if the energy consumed for this stages comes from nuclear plants, as happens with the French installations.

Results of the nuclear fuel cycle, II

- The critical point of the assessment was the choice of the discount rate because the results were very sensitive to these.
  - In the long time horizon of the radiological effects, the discounted damage is much lower and dominated by the non-radiological impacts due to emissions of non-radioactive pollutants from the fuel cycle. When 3% discount rates are used, results range from 0.1 to 3.3 mECU/kWh, depending on the study case.
- External costs of accident risk are very small, even though the assessment methodology incorporate the effects of risk aversion.
- However, much controversy still exists on how public perception of risk should be incorporated to the analysis. Due to the complexity of this fuel cycle, it seems that further research is still needed to estimate with a sufficient reliability the damages

mECU/kWh

			Power generation			Other fuel cycle stages			
	Site, size	Technology	Human health	Accidents	Other	Human health	Global warming	Other	SUB-TOTAL
BE	Doel	PWR, open	0.4	0.001-0.35	-	3.5	0.02-0.7	0.1	4.0-4.7 (4.1-4.3)
BE	Doel	PWR, closed	0.4	0.001-0.35	-	3.5	0.02-0.6	02.1	3.9-4.6 (4.0-4.2)
DE	SW Germany, 1375 MW	PWR	0.18	0.003	-	4.2	0.1-2.7	-	4.4-7.0 (4.7-5.2)
FR	1300 MW	PWR							2.5
NL	Borssele, 449 MW	PWR	0.11	-	-	7.2	-	-	7.3

- 0% discount rate, and 10,000 years,
- France and Dutch, damages were calculated for 100,000 years and it have not been included the risk aversion and the quantification of non-radiological effects.

Sub-total of quantifiable externalities for different energy sources, (global warming, public health, occupational health, material damage): cent/kWh

Country	Coal & lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
AUT				1-3		2-3	0.1		
BE	4-15			1-2	0.5				
DE	3-6		5-8	1-2	0.2	3		0.6	0.05
DK	4-7			2-3		1			0.1
ES	5-8			1-2		3-5*			0.2
FI	2-4	2-5				1			
FR	7-10		8-11	2-4	0.3	1	1		
GR	5-8		3-5	1		0-0.8	1		0.25
IE	6-8	3-4							
IT			3-6	2-3			0.3		
NL	3-4			1-2	0.7	0.5			
NO				1-2		0.2	0.2		0-0.25
PT	4-7			1-2		1-2	0.03		
SE	2-4					0.3	0-0.7		
UK	4-7		3-5	1-2	0.25	1			0.15

ExternE limitations:

- **Highs uncertainties in the monetary valuation of mortality effects**
- **Omission of impacts on ecosystems due to acidification, eutrofication[1] and global warming**
- **Not taking into account the contamination of water and soil**
- **Unbalanced treatment of severe accidents**
  - It was very much focused on accidents in the nuclear fuel chain, while neglecting severe accidents from other energy sources, as oil spills on the water body and ground.

1 Enrichment of the environment in nutrients resulting in undesirable effects such as alga growth

NewExt: **New Elements for the Assessment of External Costs from Energy Technologies**

- to improve the assessment of externalities by providing new methodological elements for integration into the existing external costs accounting framework that reflect the most important new developments in the assessment of external costs

Objectives

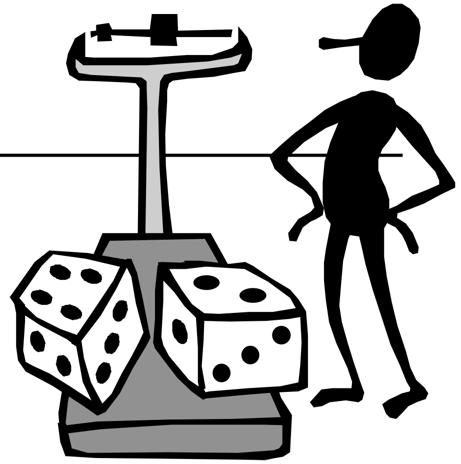
- **Monetary valuation of mortality impacts**
- **Monetary valuation of ecological and CO_2 impacts based on preferences revealed in political negotiations (standard-price approach)**
  - evaluation of acidification and eutrophication on the ecosystem and biodiversity;
- **Assessment of environmental impacts and resulting externalities from multi-compartment (air/water/soil) impact pathways**
- **Effects of major accidents in non-nuclear fuel chains (such as oil spills)**
- **Methodology testing and revision of ExternE results**
- **Dissemination**

ACCIDENT ASSESSMENT

ACCIDENT ASSESSMENT

- Why?
  - To provide estimates of external costs of nuclear accidents that take account of risk and public perception of accident probabilities
  - Traditionally valuation has been based on expected values of accidents -- i.e. Probability of estimated damages.
  - Value emerging are very low and have been criticized as not reflecting WTP to avoid such accidents

Risk assessment



- Proposed methodology is based on expected utility model. This is widely used to model risky decisions
- Concavity of utility function is measured by coefficient of risk aversion. Empirical estimates indicate values between 0.5 and 2.5

User input data

- ACCIDENT´s characteristics:
  - Accident type
  - PROBAILITY
  - estimated dose, local and regional due to the accident
- NUMBER OF PERSONS AFFECTED
  - Local population (~100km)
  - Regional population (~1000 km)
- ESTIMATES OF CONSEQUENCES
  - Number of fatal events (Cancer and severe hereditary defects)
  - Number of non fatal events
  - Population relocated
- VALUES OF CONSEQUENCES
  - Food ban costs
  - Evacuation costs
  - Value of statistical life (VSL)
  - Value of non fatal injury,
  - % Indirect costs
- RELATIVE RISK AVERSION COEFFICIENT
- AVERAGE INDIVIDUAL WEALTH
- PPP_GDP

Output data

- Total cost of accident
- Expectation value of Total cost
  - (Total cost × probability)
- Normalized cost ($/kWh)
  - excluding and including risk aversion (WTP to avoid the accident)

SOME RESULTS for France plant

- Accident probability: 1.9e-6
- 3000 deaths,
- 9000 non fatal cancers,
- 600 severe hereditary diseases
- 10,000 individuals relocated.
- Total costs are around 18 billion dollars.
- Expected damages for plant which produces 7.6 TWh are around 0.0044 mills/kwh.
- Risk aversion (1) adjusted costs are around 0.087 mills/kwh.

mills = 0.1 cents

- Increasing of damage costs for taking in account risk aversion is around 20.

Analysis of results

- Estimates are sensitive to risk aversion parameter
- Estimates are very sensitive to accidents probability
- Public perception is that probability is many times higher than technical or scientific risk.