

Fission product transport and the source term

Joint ICTP-IAEA Essential Knowledge Workshop on Deterministic Safety
Assessment and Engineering Aspects Important to Safety

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IAEA

International Atomic Energy Agency

APoS

Safety Fundamentals SF-1

IAEA Safety Standards

for protecting people and the environment

Fundamental Safety Principles

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Safety Fundamentals

No. SF-1



The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation.

Measures to be taken:

- a) To control the radiation exposure of people and the release of radioactive material to the environment;
- b) To restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation;
- c) To mitigate the consequences of such events if they were to occur.

Principle 8: Prevention of accidents

All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.

- To prevent the loss of, or the loss of control over, a radioactive source or other source of radiation.

Source Term Consideration in Design of NPP

IAEA Safety Standards

for protecting people and the environment

Safety of Nuclear Power Plants: Design

Specific Safety Requirements

No. SSR-2/1



- 2.14. A relevant aspect of the implementation of defence in depth for a nuclear power plant is the provision in the design of a series of physical barriers, as well as a combination of active, passive and inherent safety features that contribute to the effectiveness of the physical barriers in confining radioactive material at specified locations. **The number of barriers that will be necessary will depend upon the initial source term in terms of amount and isotopic composition of radionuclides, the effectiveness of the individual barriers, the possible internal and external hazards, and the potential consequences of failures.**

IAEA Safety Standards for protecting people and the environment

Safety Assessment for Facilities and Activities

General Safety Requirements Part 4
No. GSR Part 4



4.19. The possible radiation risks associated with the facility or activity include the level and likelihood of radiation exposure of workers and the public, and of the possible release of radioactive material to the environment, that are associated with anticipated operational occurrences or with accidents that lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation.

Topics for Discussion

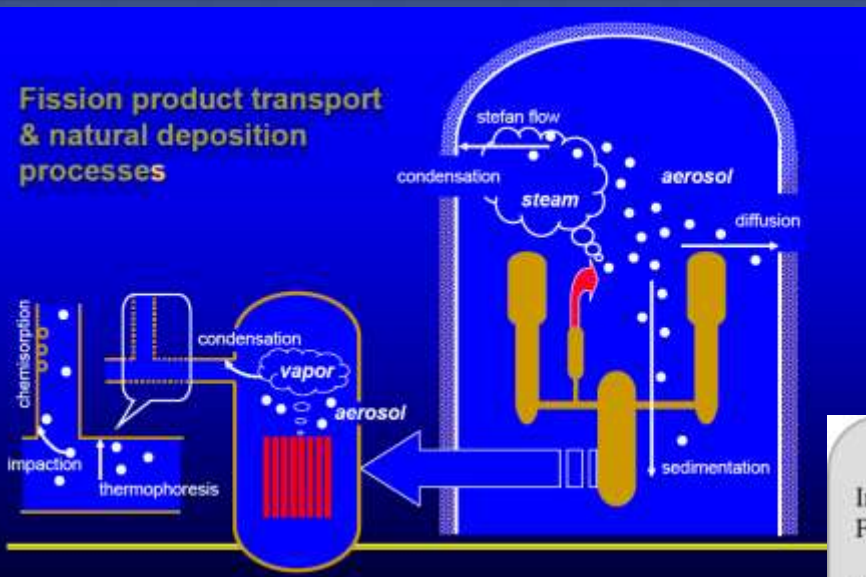


- Fission product release from the Fuel
 - Gap release
 - Fuel degradation release
 - Ex-vessel release
- Fission product transport to the containment
 - Aerosols
 - Vapors
- Engineered safety features to deposit fission product

Fission product transport & natural deposition processes



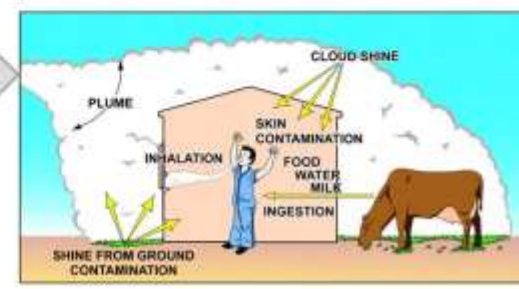
Fission product transport & natural deposition processes



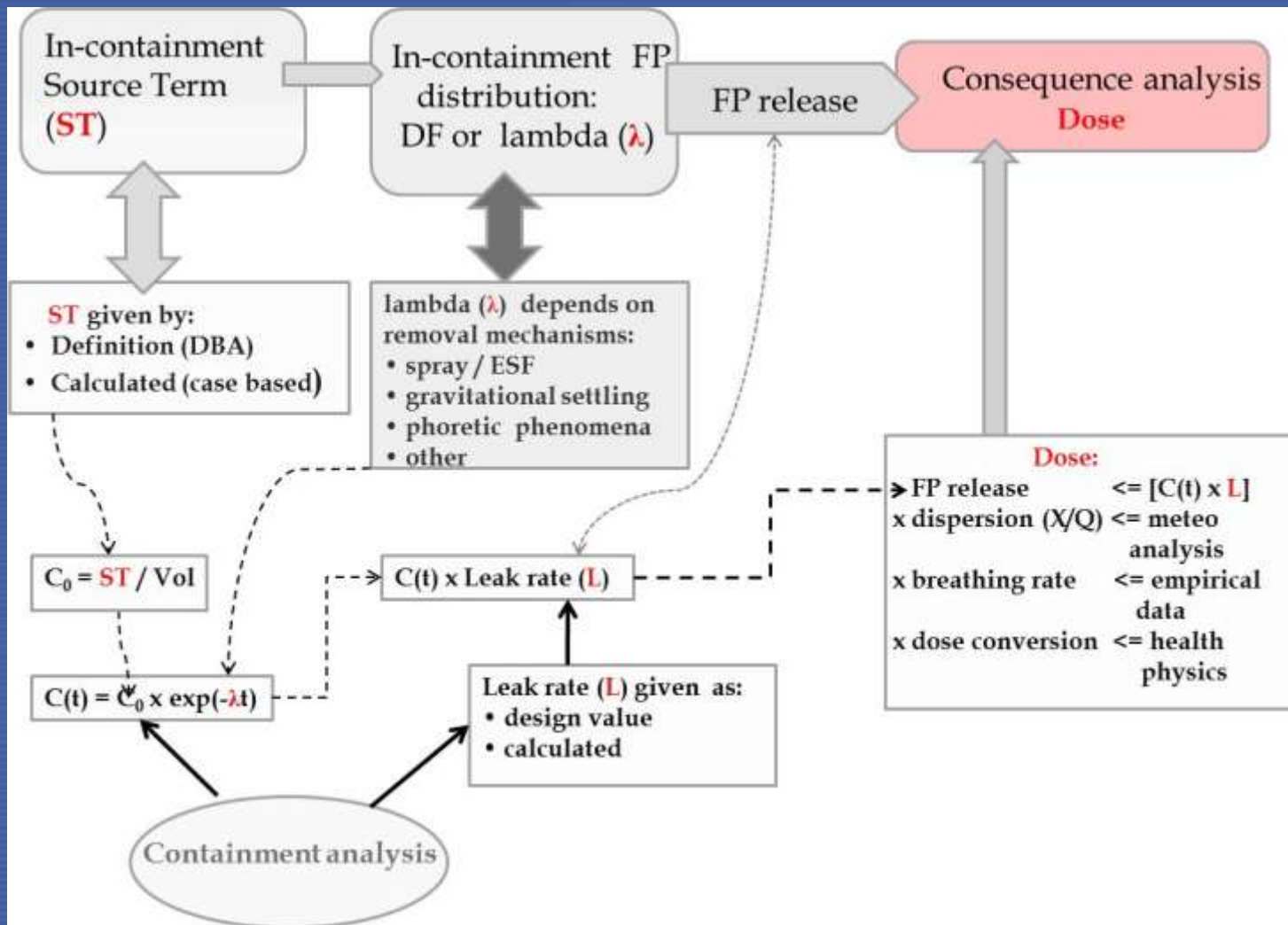
In-containment
FP airborne concentration:
 $C(t) = ST / \text{Volume}$

Containment
leak rate = $L(t)$

Release = $C(t) \times L(t)$

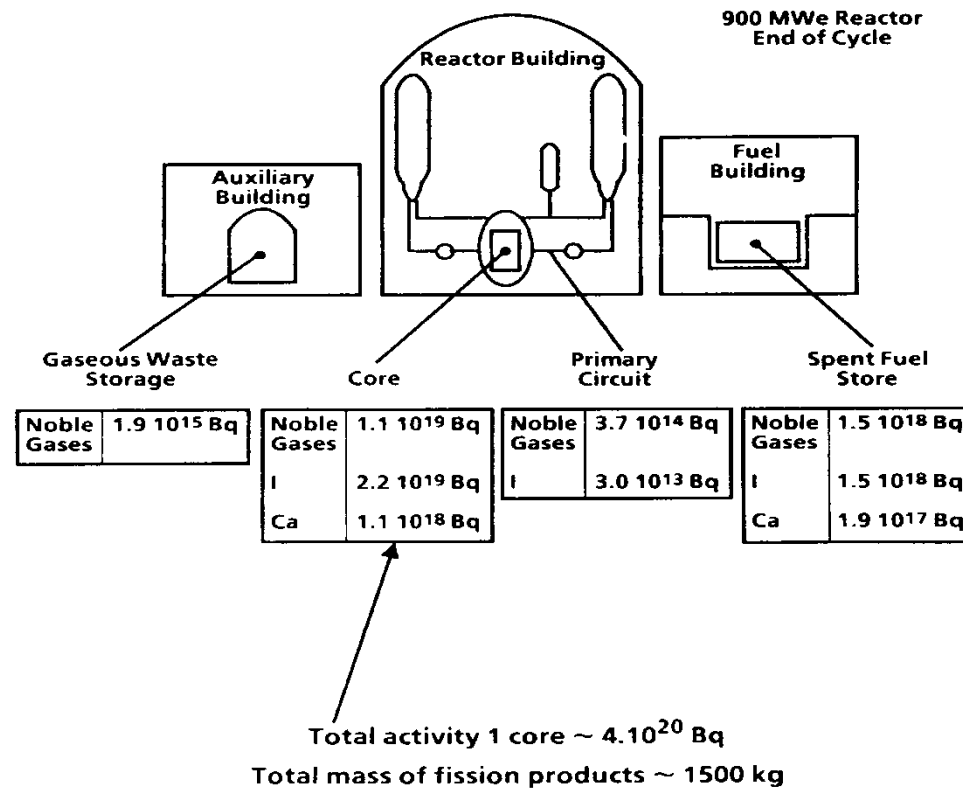


Fission product transport & natural deposition processes



Location of fission products (FP)?

Fission Product Release and Transport in the Reactor System Sources of Radioactivity



Fission product inventory in the core



- The inventory of fission products and other radionuclides in the reactor fuel and core depends on a number of factors:
- **Quantity of fissile material**, reactor type and design
- **Fuel power and burn-up**: for isotopes with **long half life (years)** inventory increases **with burn-up**, for isotopes with **short half life** depends mainly on reactor power, after reaching certain value no further increase
- **For conservative estimates the values for large burn-up should be used**
- Neutron flux distribution in core, operational power history (including transients), fuel management
- **Decay time** after shutdown;
- Usually the information on fission product inventory is available in the plant design documents

Fission product inventory in the core



Example: ORIGEN Calculations

- The ORIGEN computer code generate the tables of the initial fission product inventories and their decay heat powers (i.e.ten days)
- The decay heat power is computed by the relative mass of each element in the class given by the ORIGEN calculations

Fission product inventory in the core

	PWR 3500 MWth		WWER 1000, 3000 MWt 50000 MWd/teU	AP 1000 3415 MWt	US EPR 4612 MWt
	30000 MWd/teU	49000 MWd/teU		Max average burnup of unloaded fuel 62,000 (MWd/teU)	
Kr-85m	8.71 E+17	7.65 E+17	7.69E+17	9.73 E+17	1.66 E+18
Kr-87	1.88 E+18	1.64 E+18	1.53E+18	1.88 E+18	3.34 E+18
Kr-88	2.51 E+18	2.17 E+18	2.14E+18	2.64 E+18	4.74 E+18
Xe-133	7.16 E+18	7.13 E+18	7.21E+18	7.03 E+18	10.7 E+18
Xe-135	1.60 E+18	1.49 E+18	1.60E+18	1.79 E+18	3.43 E+18
I-131	3.27 E+18	3.38 E+18	2.92E+18	3.56 E+18	5,14 E+18
I-132	5.07 E+18	5.13 E+18	3.99E+18	5.18 E+18	7.47 E+18
I-133	7.15 E+18	7.11 E+18	6.79E+18	7.36E+18	10.7 E+18
I-134	8.08 E+18	8.01 E+18	7.50E+18	8.07 E+18	11.8 E+18
I-135	6.68 E+18	6.71 E+18	6.08E+18	6.88 E+18	9.95 E+18
Cs-134	2.82 E+17	5.71 E+17	5.07E+17	7.18 E+17	2.40 E+18
Cs-137	2.29 E+17	3.37 E+17	3.15E+17	4.18 E+17	9.14 E+17

Example: Design Bases Analyses

Source Term from FSAR

Table 5-1

Fuel and Rod Gap Inventories (Curies) – Core = 121 assies
(End of Equilibrium Cycle)

Isotope	Core Fuel Inventory	Gap Fraction	Gap Inventory
Kr-83m	7.262E+06	0.10	7.262E+05
Kr-85	5.207E+05	0.30	1.562 E+05
Kr-85m	1.576E+07	0.10	1.576E+06
Kr-87	3.064E+07	0.10	3.064E+06
Kr-88	4.320E+07	0.10	4.320E+06
Kr-89	5.322E+07	0.10	5.322E+06
Xe-131m	6.017E+05	0.10	6.017E+04
Xe-133	1.098E+08	0.10	1.098 E+07
Xe-133m	3.467E+06	0.10	3.467E+05
Xe-135	2.752E+07	0.10	2.752E+06
Xe-135m	2.143E+07	0.10	2.143E+06
Xe-138	9.482E+07	0.10	9.482E+06
I-131	5.375E+07	0.12	6.450E+06
I-132	7.810E+07	0.10	7.810E+06
I-133	1.122E+08	0.10	1.122E+07
I-134	1.240E+08	0.10	1.240E+07
I-135	1.049E+08	0.10	1.049E+07

Table 6-5

Maximum Inventory in the Gas Decay Tank

Isotope	Activity (curies)
Kr-83m	1.35E+01
Kr-85	2.58E+04
Kr-85m	9.44E+01
Kr-87	2.13E+01
Kr-88	1.43E+02
Kr-89	9.76E-02
Xe-131m	4.76E+02
Xe-133	3.88E+04
Xe-133m	6.39E+02
Xe-135	6.76E+02
Xe-135m	3.66E+01
Xe-137	2.96E-01
Xe-138	3.16E+00
I-131	1.90E-02
I-133	1.76E-02
I-135	8.08E-03

Table 4-1
Secondary Equilibrium Concentrations

Isotope	1% Design Basis Secondary Coolant Concentration	0.05 $\mu\text{Ci/gm DE I-131}$ in Secondary Coolant Concentration
	C_{sg} ($\mu\text{Ci/gm}$)	C_{sg} ($\mu\text{Ci/gm}$)
I-131	1.01E-01	4.32E-02
I-132	5.30E-03	2.28E-03
I-133	9.17E-02	3.94E-02
I-134	1.42E-03	6.09E-04
I-135	2.78E-02	1.19E-02

Activity in the primary/secondary coolant during normal operation



Activity in the primary coolant: depends on the number of failed fuel rods, the type and size of failures, burn-up and power level, materials used in the RCS, the total amount and composition of RCS coolant and the removal rate of the fission products by RCS purification systems

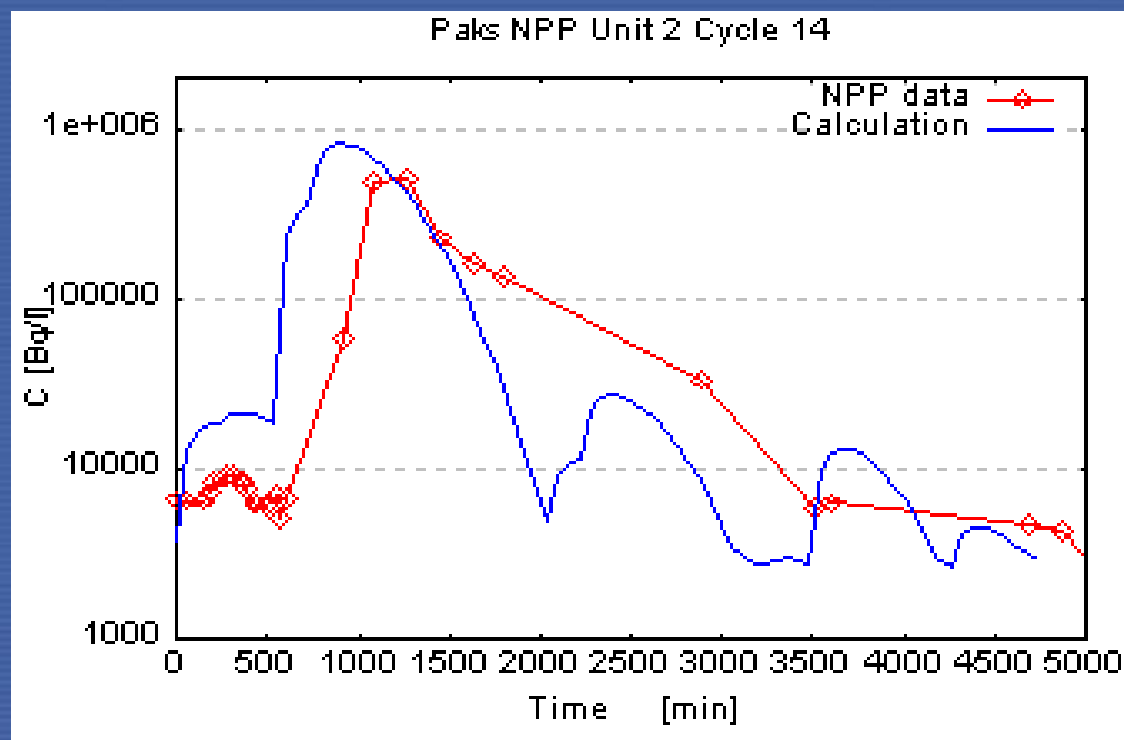
Components of radioactive substances:

- Products of activation of the coolant or additives – C14, O15, H3 (tritium), N 16, Cu164, K42, Ar41, Cl38, Na24
- Corrosion products - ^{60}Co , ^{58}Co , to less extent isotopes of Fe, Ni, Mn
- Fission products – mainly isotopes of iodine, caesium, krypton, xenon
- **Usually total activity of the primary coolant is set up to the maximum values (safety limits) prescribed by the plant limits and conditions**
- Interpretation of maximum values may cause problems – need to understand how the maximum values are measured
- For WWER-440 reactors, operational limits are 1.85 MBq/kg for I-131 and 14.8 MBq/kg for all iodine isotopes. Safe operation limits are 9.25 MBq/kg and 74 MBq/kg, correspondingly. For WWER 1000 reactors, operational limits are 3.7 MBq/kg for I-131, 37 MBq/kg for all iodine isotopes, and safe operation limits are 18.5 MBq/kg and 185 MBq/kg. Operational data are typically 100-times lower than the limits.

Activity of the secondary coolant: Depends on the activity of primary coolant and on operational leakages between primary and secondary side of the SGs, as well as on capacity of SG blowdown system.

Activity in the primary/secondary coolant during normal operation

- **Spiking:** coolant activity during transients sharply increases, as the temperature and pressure changes in the fuel drive the gaseous and volatile fission products from fuel pellets into the pellet -cladding gap and through microscopic cladding fissures into the coolant.
- The range of spiking factor SF for iodines is from about 5 to 100





Spike activity in the coolant – EUR recommendations

- EUR: In the absence of specific evaluations, an I131 equivalent concentration of activity in the primary coolant shall be assumed as less than 11,1 MBq/kg before the accidents and an iodine spike of 740 MBq/kg
- This means increase of activity of iodine about 67 times
- In AP1000 analysis, the values were 37 MBq/kg before the accident and 2220 MBq/kg (3-times higher than EUR values), increase 60-times
- More appropriately, the iodine and other isotopes spiking should be the result of detailed calculation of releases through micro-cracks in the fuel cladding
- Weight of the isotope for calculation of I131 equivalent
 - I-131 1
 - I-132 0.00933
 - I-133 0.1867
 - I-134 0.00173
 - I-135 0.038

Fission product release in the fuel matrix

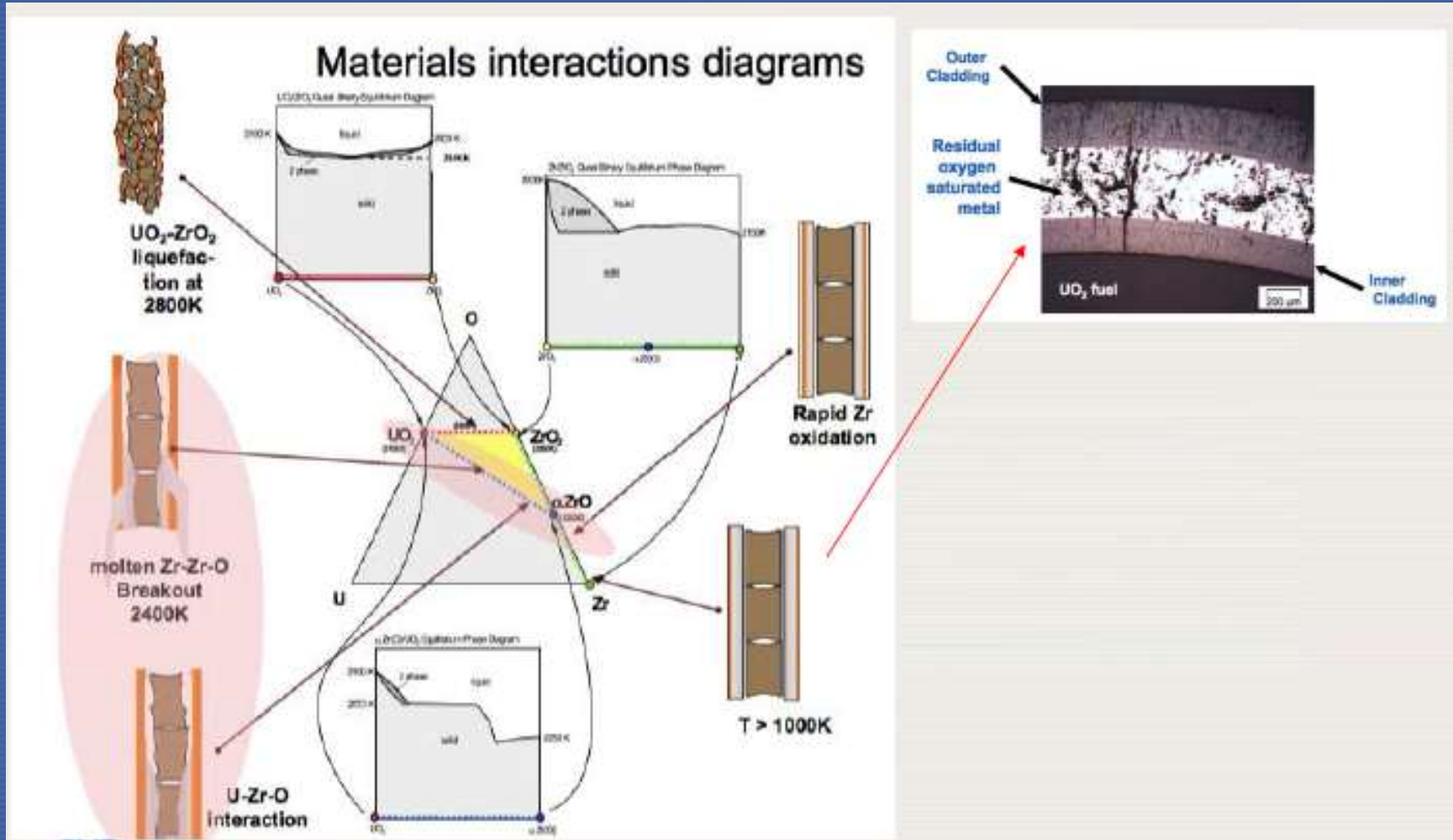


- Burst release
- Diffusion release of the pellet-to-cladding gap inventory
- Grain boundary release
- Diffusion from the UO_2 grains
- Release from molten material

**Severe
Accident
mechanisms**

Each mechanism becomes predominant at a **certain temperature**

Fission product release in the fuel matrix

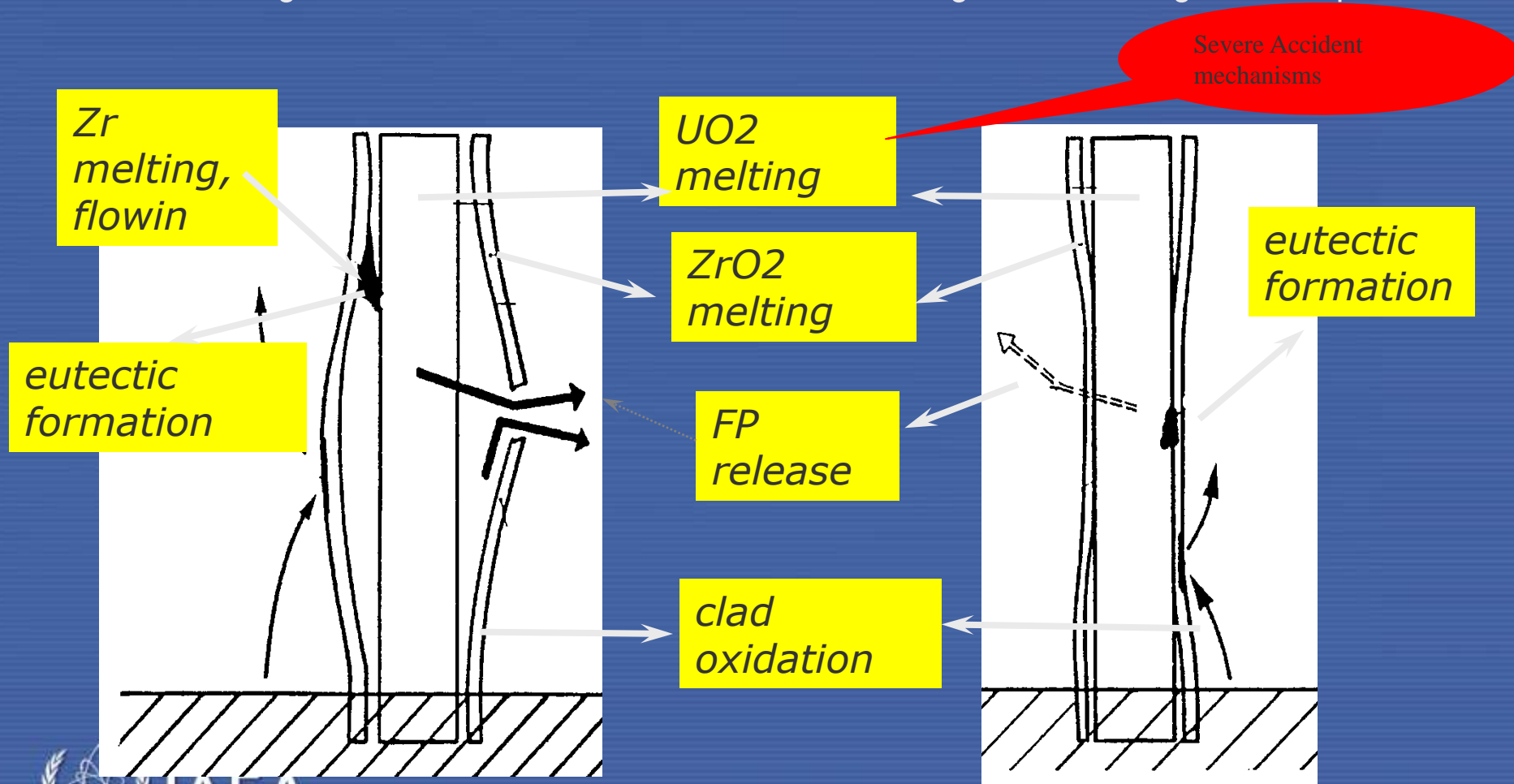


Fission product release in the fuel matrix



Low pressure in primary vessel => swelling of the clad

High pressure in the primary vessel => crushing of the clad against the pellet



Fission product release in the fuel matrix

Fission product releases from fuel depend on various factors :

- accident sequence
- fraction of core affected
- fuel type, characteristics, geometry
- fuel temperature
- fuel environment (e.g. oxidising vs. reducing)
- fuel burn-up
- rate of heat up
- fission product chemistry

Fission product release in the fuel matrix

CORSOR-Booth model

- The release rate of fission product during a time interval t to $t+\Delta t$ from the fuel grain is calculated as:

$$\text{Release Rate}_{\text{Cs}} = \frac{[f(\sum D' \Delta t)_{t+\Delta t} - f(\sum D' \Delta t)_t] V \rho}{F \Delta t}$$

- where
 - ρ is the molar density in the fuel
 - V is the fuel volume,
 - F is the fraction of the radio nuclide (i.e. Cs) inventory remaining in the fuel grain
- the summations are done over the time steps up to time $(t+\Delta t)$ and t , respectively

Fission product release in the fuel matrix

- The release fraction at time t is calculated from an approximate solution of Fick's law for fuel grains of spherical geometry

$$f = 6 \sqrt{\frac{D't}{\pi}} - 3D't \quad \text{for } D't < 1/\pi^2 \quad (2.3.4)$$

$$f = 1 - \frac{6}{\pi^2} \exp(-\pi^2 D't) \quad \text{for } D't > 1/\pi^2 \quad (2.3.5)$$

where

$$\begin{aligned} D't &= D t / a^2 \text{ (dimensionless)} \\ a &= \text{equivalent sphere radius for the fuel grain} \end{aligned}$$

D = effective diffusion coefficient

Fission product release in the fuel matrix

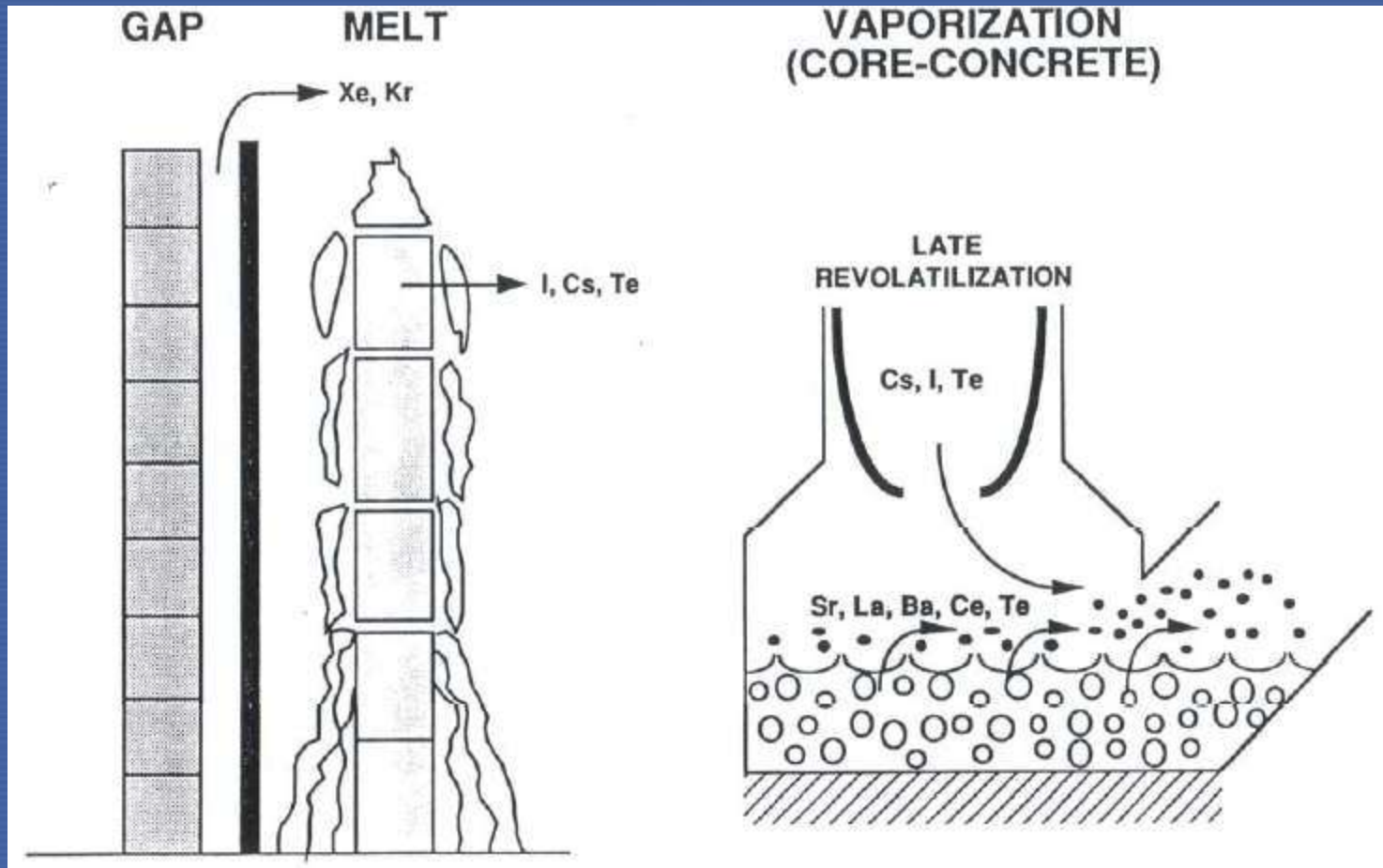
- The classical or effective diffusion coefficient for radio nuclide in the fuel matrix is given by

$$D = D_0 \exp(-Q/RT)$$

- where
 - R is the universal gas constant
 - T is the temperature
 - Q is the activation energy
 - D_0 is the pre-exponential factor as a function of the fuel burn-up

$$\text{Release Rate}_{\text{Cs}} = \frac{[f(\sum D' \Delta t)_{t+\Delta t} - f(\sum D' \Delta t)_t] V \rho}{F \Delta t}$$

Fission product release during accident



Fission product release during accident (Design ST)

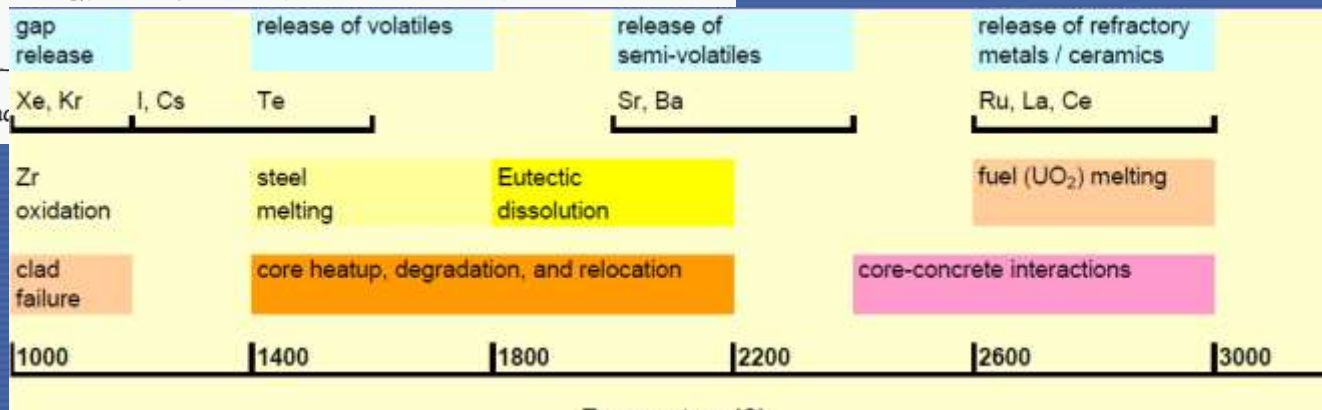
SAND94 - 2, 1994

Table 1. Source Terms to the Containment

Release	Req. Guide*** 1.3, 1.4 (1,2,3)	NUREG-1465* Boiling Water Reactors (6)				NUREG-1465* Pressurized Water Reactors (6)			
		gap	in-vessel	ex-vessel	late in-vessel	gap	in-vessel	ex-vessel	late in-vessel
Duration(s)	0	3600	5400	10800	36,000	1800	4680	7200	36,000
Radionuclide									
Xe, Kr	100	5	95	0	0	5	95	0	0
Iodine									
-gas	23.75	0.25	1.1	1.8	0.4	0.2	1.75	1.4	0.4
-particle	1.25	4.75	20.9	35.2	6.6	4.8	33.25	27.6	6.6
-total	25	5	22	37	7	5	35	29	7
Cesium	0	5	15	45	3	5	25	39	6
Tellurium	0	0	11	38	1	0	15	29	2.5
Strontium	0	0	3	24	0	0	3	12	0
Barium	0	0	3	21	0	0	4	10	0
Ruthenium	0	0	0.7	0.4	0	0	0.8	0.4	0
Cerium	0	0	0.9	1.0	0	0	1.0	2.0	0
Lanthanum	0	0	0.2						

*Releases are given as percent of core inventory.

**Reference 1 calls for release of 1 percent of other rad



Radionuclide Groups & Typical Inventory

- Source AP-600

Group No.	Name (representative element)	Elements Contained in Group	End-of-Cycle Mass in Core (kg)
			PWR
1	Noble gases	Xe, Kr	412
2	Iodine	I, Br	18
3	Cesium	Cs, Rb	238
4	Tellurium	Te, Sb, Se	34
5	Strontium	Sr	71
6	Ruthenium	Ru, Rh, Pd, Mo, Tc	612
7	Lanthanum	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y	567
8	Cerium	Ce, Pu, Np	201
9	Barium	Ba	108

Fission product release during accident (Regulatory ST)



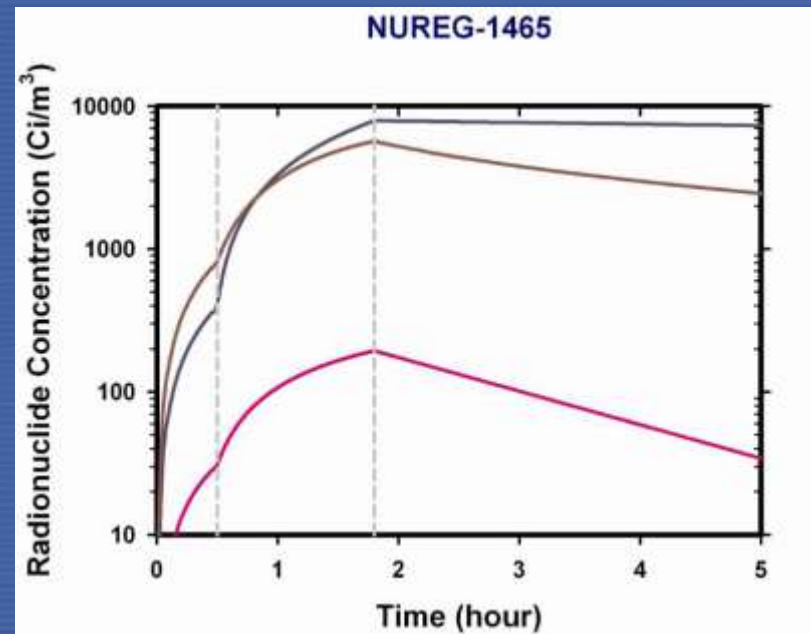
PWR

	Gap**	Early In-Vessel	Ex-Vessel	Late in-Vessel
Duration (Hours)	0.5	1.3	2.0	10.0
Noble Gases: Xe, Kr	0.05	0.95	0	0
Halogens: I, Br	0.05	0.35	0.25	0.01
Alkali Metals: Cs, Rb	0.05	0.25	0.35	0.01
Tellurium Group: Te, Sb, Se	0	0.05	0.25	0.005
Barium, Strontium: Ba, Sr	0	0.02	0.1	0
Noble Metals: Ru, Rh, Pd, Mo, Tc, Co	0	0.0025	0.0025	0
Lanthanides: La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am	0	0.0002	0.005	0
Cerium Group: Ce, Pu, Np	0	0.0005	0.005	0

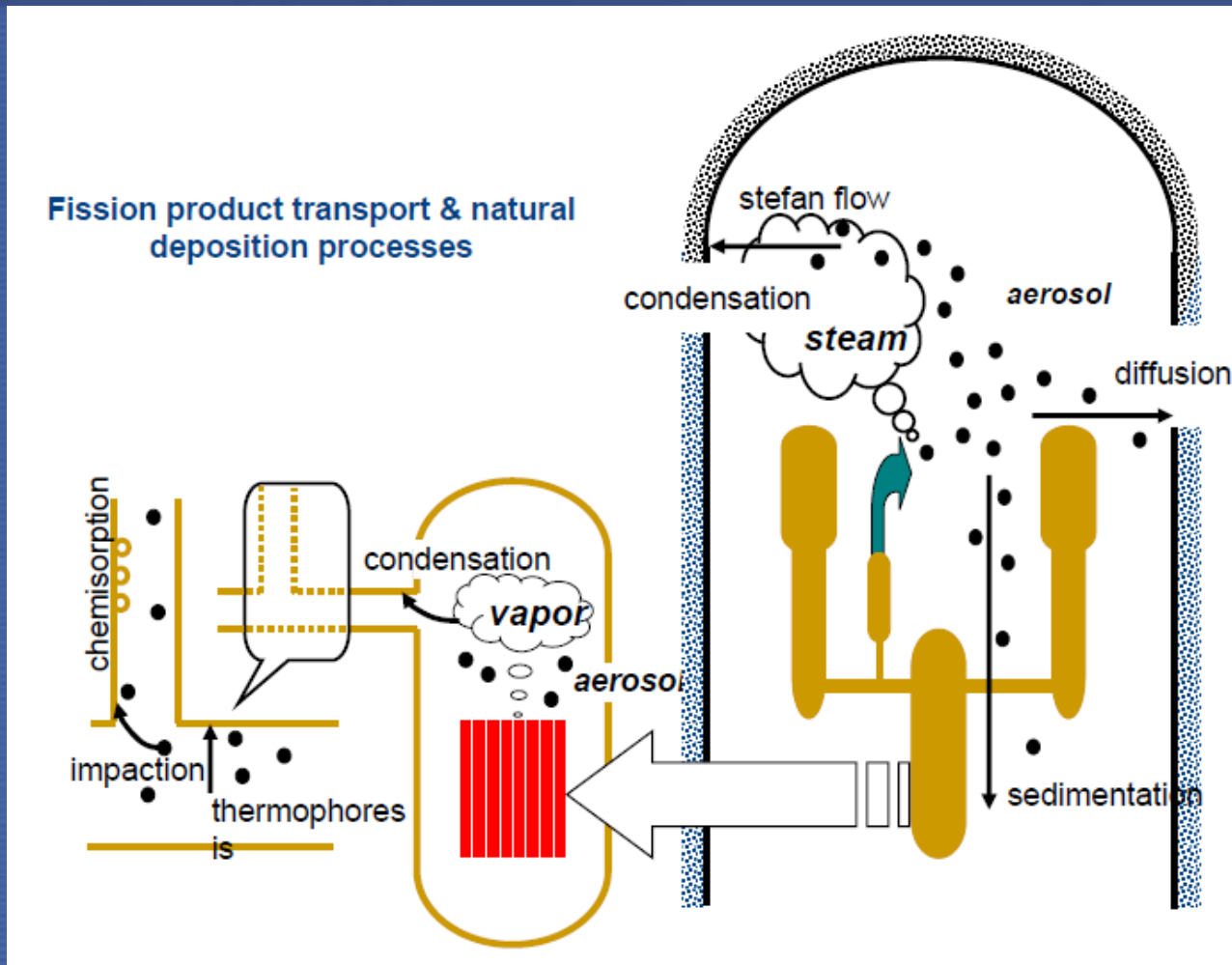
BWR

	Gap**	Early in-Vessel	Ex-Vessel	Late In-Vessel
Duration (Hours)	0.5	1.5	3.0	10.0
Noble Gases: Xe, Kr	0.05	0.95	0	0
Halogens: I, Br	0.05	0.25	0.30	0.01
Alkali Metals: Cs, Rb	0.05	0.20	0.35	0.01
Tellurium group: Te, Sb, Se	0	0.05	0.25	0.005
Barium, Strontium: Ba, Sr	0	0.02	0.1	0
Noble Metals: Ru, Rh, Pd, Mo, Tc, Co	0	0.0025	0.0025	0
Lanthanides: La, Zr, Nd, Am, Eu, Nb, Pm, Pr, Sm, Y, Cm	0	0.0002	0.005	0
Cerium Group: Ce, Pu, Np	0	0.0005	0.005	0

NUREG-1465 releases into containments



Fission product transport & natural deposition processes



- Fission products are combined with the vapor or gas and are transported in the containment
- This is called an aerosol which is a colloid of fine solid particles or liquid droplets, in air or another gas. Examples of natural aerosols are fog and geyser steam. Examples of artificial aerosols are dust, particulate air pollutants and smoke

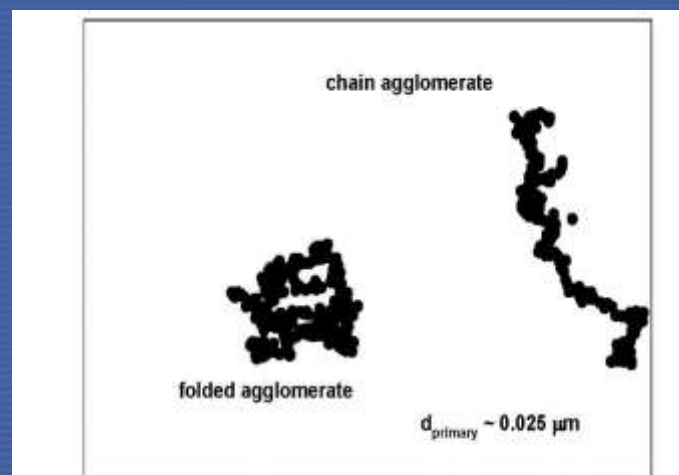


Fig. 10.2-2 Sketches of branched chain and folded agglomerates

Aerosols size distribution correction

Aerosol Mechanics and Transport (Introduction and Overview)

- ♦ Particle Size (how measured for irregular shaped particles?)

$$D_{\text{aerodynamic}} = D_{\text{equivalent-volume}} \left(\frac{\rho}{\chi \rho_0} \right)^{1/2}$$

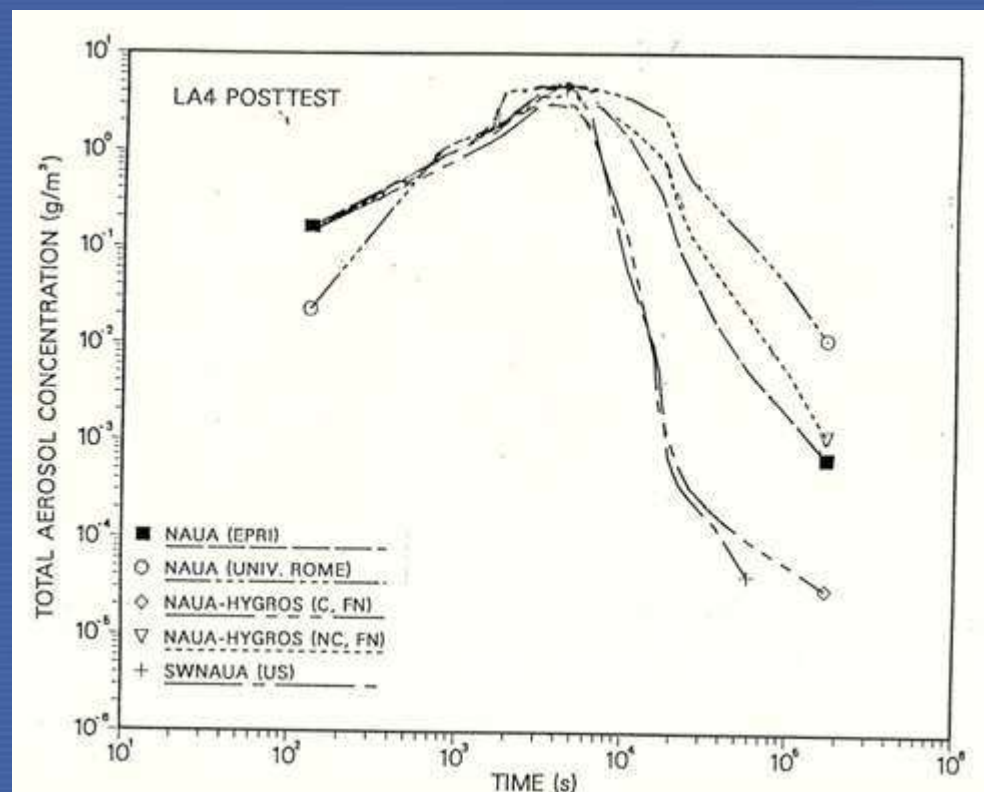
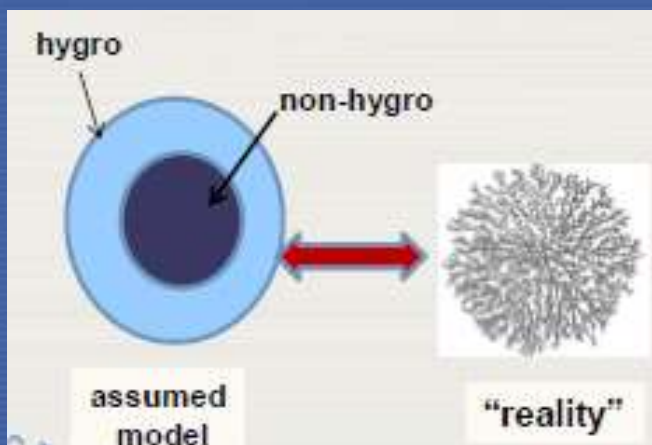
(Diameter of sphere with material density of 1 g/cm³ that settles at the same velocity of particle. Respirable for $D_a < 20$ microns.)

- $\rho_0 = 1 \text{ g/cm}^3$
- $\rho =$ particle-material density in g/cm³
- $\chi =$ dynamic shape factor (Hinds, 1982)
 - * 1.00 sphere
 - * 1.08 cube
 - * 1.12 two-sphere chain
 - * 1.27 three-sphere chain

Hygroscopic Correction

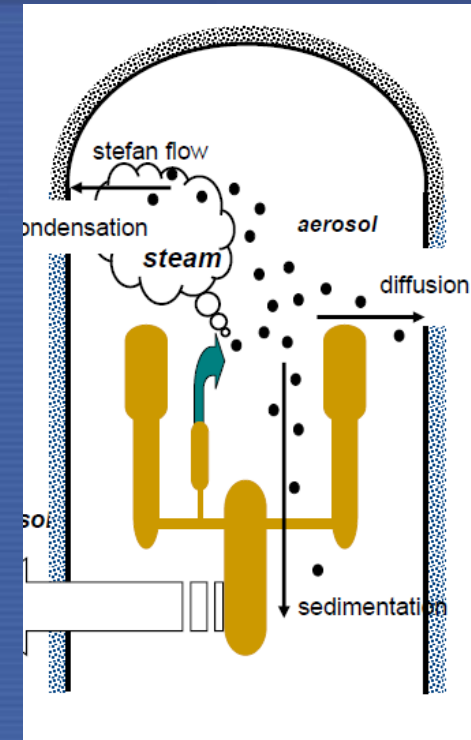
$$r \frac{dr}{dt} = [S - K_H \cdot \text{Exp}(A)] / B$$

- S = SATURATION INDEX = $P_p / P_s(t)$
- A, B = THERMODYNAMIC FUNCTIONS
- K_H = HYGROSCOPIC CORRECTION
- P_s , SOLUTION, FLAT
- = $\frac{P_s, \text{ SOLUTION, FLAT}}{P_s, \text{ PURE WATER, FLAT}}$



Aerosol agglomeration and growth

- Agglomeration is a process that two aerosol particles collide and they can combine to form a larger particle.
- There are four agglomeration processes
 - Brownian diffusion (random motion)
 - Differential gravitational settling
 - Turbulent agglomeration by shear and inertial forces



Aerosol agglomeration and growth

- Q_t is defined as the total mass of aerosol per unit volume of fluid in section H at time t.

$$Q_t(t) = \sum_{k=1}^s Q_{t,k}(t)$$

- where $Q_{t,k}(t)$ is the mass of component k and s is the total number of components.
- These sectional coefficients correspond to the following mechanisms:

Aerosol agglomeration and growth

Brownian

$$\beta = 2 \pi (D_i + D_j) (\gamma_i d_i + \gamma_j d_j) / F$$

$$D_i = \frac{k T}{3 \pi d_i \mu \chi_i} C_i$$

$$C_i = 1 + Kn_i [c_{s,i} + 0.4 \exp(-1.1 / Kn_i)]$$

$$F = \frac{d_i + d_j}{d_i + d_j + 2 g_{ij}} + \frac{8 (D_i + D_j)}{v_{ij} (d_i + d_j) c_2}$$

$$g_{ij} = (g_i^2 + g_j^2)^{1/2}$$

$$v_{ij} = (v_i^2 + v_j^2)^{1/2}$$

$$g = \frac{1}{3 d_i l_i} \{ (d_i + l_i)^2 - (d_i^2 + l_i^2)^{1/2} \} - d_i$$

$$l = \frac{8 D_i}{\pi v_i}$$

$$v = \left(\frac{8 k T}{\pi m_i} \right)^{1/2}$$

$$Kn_i = 2 \lambda / d_i$$

$$\lambda = \frac{\mu}{p_0} (1.89 \times 10^{-4} M_{w,g} / T)^{1/2}$$

$$p_0 = 1.21 \times 10^{-4} P M_{w,g} / T$$

μ - values for air; from the Material Properties (MP) package

Gravitational

$$\beta = c_0 \frac{\pi}{4} c_s (\gamma_i d_i + \gamma_j d_j)^2 |v_{Ti} - v_{Tj}|$$

$$v_{Ti} = \frac{\rho_{p,i} g d_i^2 C_i}{18 \mu \chi_i}$$

$$c_0 = 1.5 \left\{ \frac{\min(d_i, d_j)}{(d_i + d_j)} \right\}^2$$

Turbulent

$$\beta = c_s (\beta_{T1}^2 + \beta_{T2}^2)^{1/2}$$

$$\beta_{T1} = \left(\frac{\pi \epsilon_T \rho_g}{120 \mu} \right)^{1/2} (\gamma_i d_i + \gamma_j d_j)^2$$

$$\beta_{T2} = \frac{0.04029 \rho_g^{1/4} \epsilon_T^{3/4}}{\mu^{3/4}} (\gamma_i d_i + \gamma_j d_j)^2 \left| \frac{\rho_{p1} C_i d_i^2}{\chi_1} - \frac{\rho_{p2} C_j d_j^2}{\chi_2} \right|$$

Nomenclature

$c_{s,i}$	= particle slip coefficient
c_s	= particle sticking coefficient
c_2	= thermal accommodation coefficient
C	= particle mobility
d	= particle diameter
D	= diffusion coefficient
k	= Boltzmann constant
k_p/k_s	= ratio of thermal conductivity of the gas over that for the particle
Kn	= Knudsen number
m	= particle mass
M_w	= molecular weight
P	= pressure
T	= temperature
V	= volume

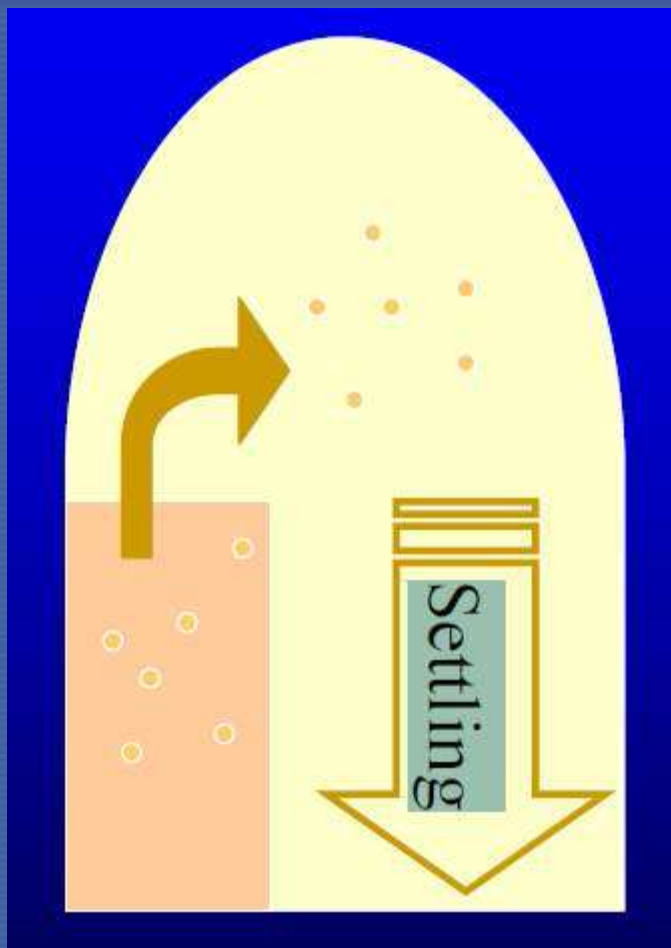
Greek

β	= coagulation kernel (m^3/s)
ϵ_T	= turbulence dissipation density
ρ	= density
μ	= viscosity
λ	= mean free path
γ	= agglomeration shape factor
χ	= dynamic shape factor

Subscripts

b	= bulk
g	= gas (air assumed)
ij	= particle identifier
p	= particle
s	= steam

Gravitation sedimentation/settling



Aerosol Mechanics and Transport (Gravitational Settling)

♦ Assumptions/Approximations

- Well-mixed cell of volume V and projected settling area A
- Particles settle at velocity $v = (\rho D^2 g / 18 \eta \chi)$
 - * g = gravitational constant, η = gas viscosity
 - * Let Q = mass concentration in a section

$$\frac{dQ}{dt} = -\frac{vA}{V} Q$$

$$\tau_{\text{settle}} = \frac{V}{vA}$$

Gravitation sedimentation/settling

- Gravitational deposition is effective only for upward-facing surfaces (i.e., floors and water pools) and flow through to lower control volumes; for downward-facing surfaces (i.e., ceilings).
- The gravitational deposition velocity is given by

$$v_{\text{grav}} = \frac{d_p^2 \rho_p g C_m}{18\mu\chi} \quad (2.4.10)$$

where

- v_{grav} = the downward terminal velocity (m/s);
- d_p = the particle diameter (m);
- ρ_p = the particle density (kg/m³);
- g = acceleration of gravity = 9.8 m/s²;
- C_m = the particle mobility, or Cunningham slip correction factor, which reduces the Stokes drag force to account for noncontinuum effects.

Gravitation sedimentation/settling

- The particle mobility, or Cunningham slip correction factor, in the equation above is expressed as:

$$C_m = 1 + \frac{2\lambda}{d_p} [F_{\text{slip}} + 0.4 \exp(-1.1d_p/2\lambda)] \quad (2.4.11)$$

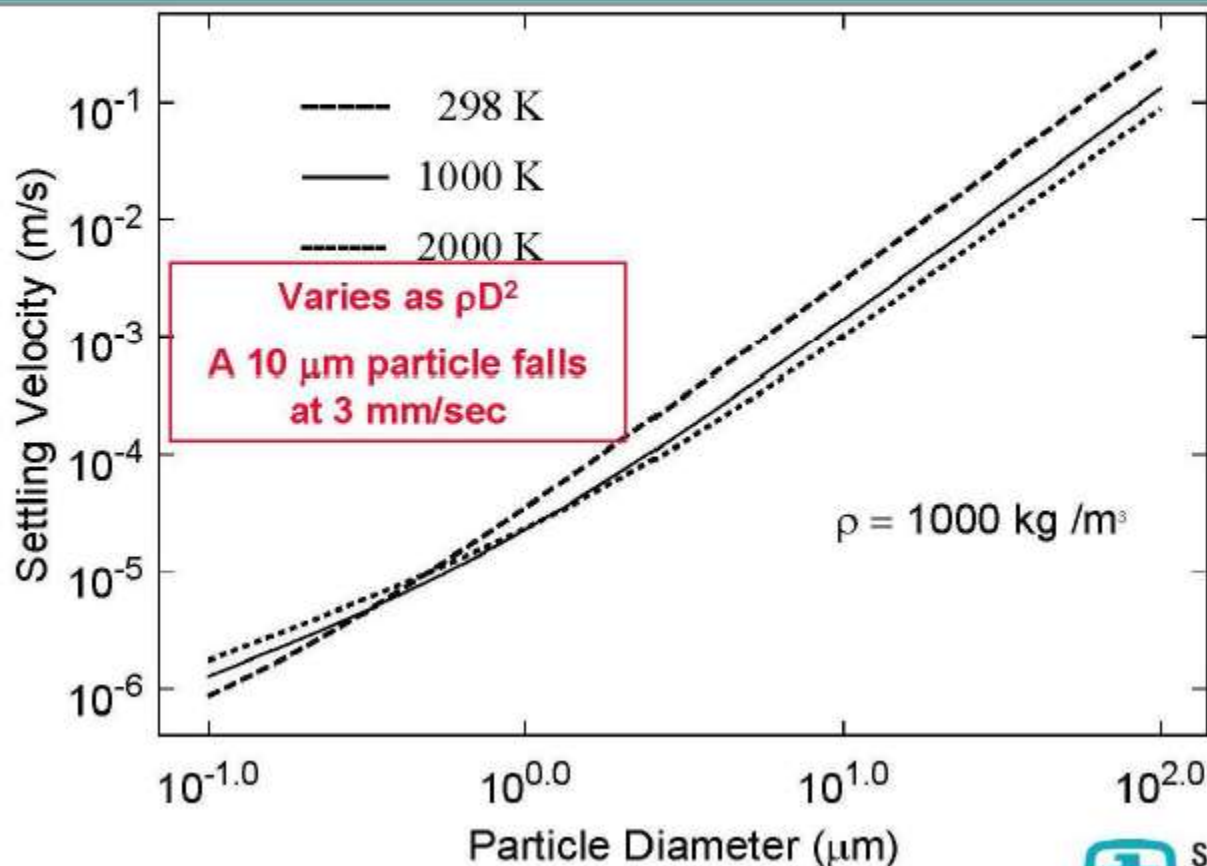
where

- λ = mean free path of air at 298K ($\sim 0.069 \cdot 10^{-6}$ m);
- F_{slip} = slip factor specified on input record RNMS000 (default value of 1.257);
- μ = viscosity of air at 298K ($\sim 1.8 \cdot 10^{-5}$ (N·s/m²)); and
- χ = dynamic shape factor.

$$V_{\text{grav}} = \frac{d_p^2 \rho_p g C_m}{18\mu\chi}$$

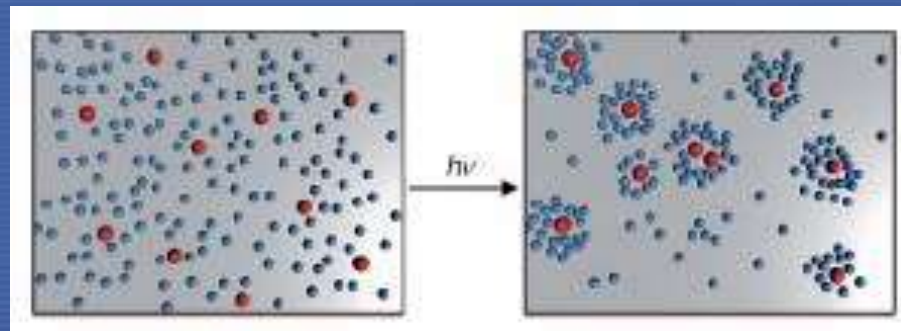
Gravitation sedimentation/settling

Aerosol Mechanics and Transport (Gravitational Settling)

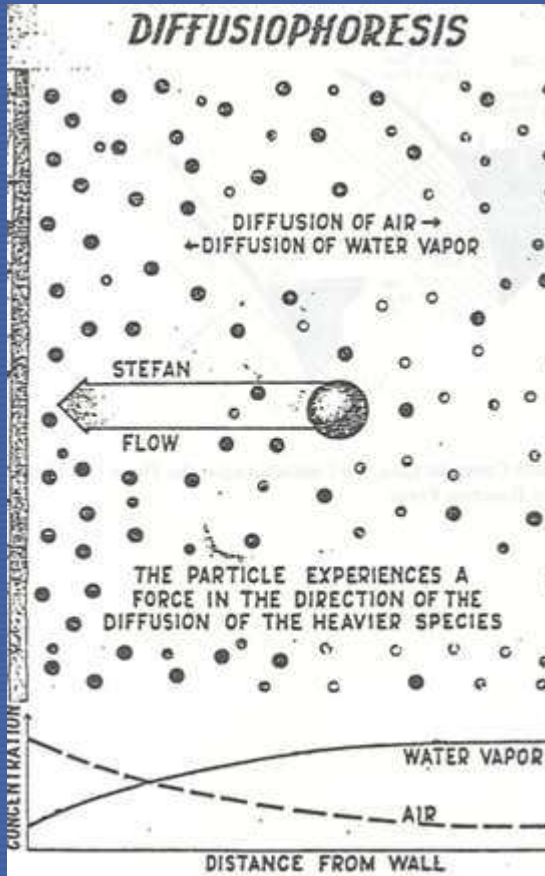


Diffusiophoresis

- Diffusiophoresis is a spontaneous motion of dispersed particles in a fluid induced by a diffusion gradient (also called "concentration gradient") of molecular substances that are dissolved in the fluid.
- A net molar flux of gas toward the condensing (evaporating) surface called the Stefan flow will tend to move aerosol particles with it.



Diffusiophoresis



Stefan flow

$$v_{\text{diffusio}} = \left(\frac{\sqrt{M_s}}{X_s \sqrt{M_s} + X_{\text{NC}} \sqrt{M_{\text{NC}}}} \right) \left(\frac{W_{\text{cond}}}{\rho_b} \right) \quad \text{if } W_{\text{cond}} \geq 0 \quad (\text{condensation})$$

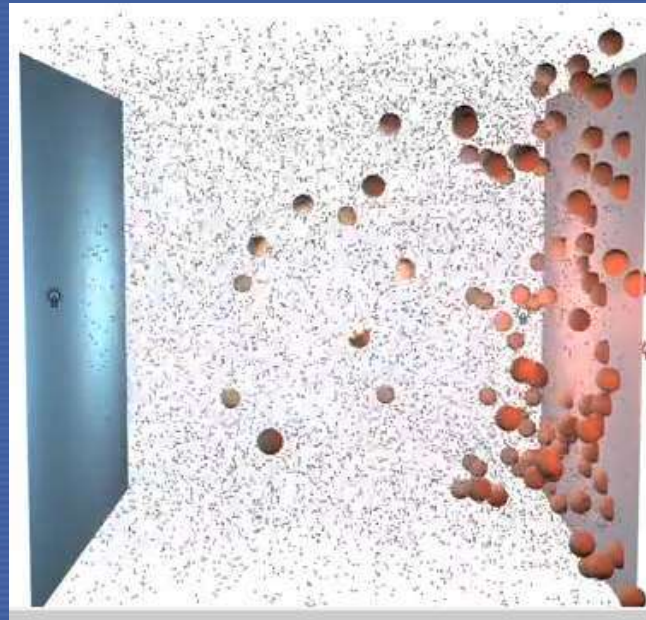
$$v_{\text{diffusio}} = W_{\text{cond}} / \rho_s \quad \text{if } W_{\text{cond}} < 0 \quad (\text{evaporation})$$

where

- M_s = molecular weight of water (kg/kgmole);
- M_{NC} = molecular weight of noncondensable gases (air)
- W_{cond} = condensation mass flux to the surface (kg/s-m²);
- ρ_b = density of bulk gas (kg/m³);
- ρ_s = saturation density of water vapor (kg/m³);
- X_s = mole fraction of water vapor in the bulk gas; and
- X_{NC} = mole fraction of noncondensable gases in the bulk gas.

Thermophoresis

- Thermophoresis' (also thermomigration, thermodiffusion) is a phenomenon observed in mixtures of mobile particles response to the force of a temperature gradient.
- Thermophoresis: associated with aerosol deposition due to temperature gradient



Deposition Rate by Thermophoresis

- Rate at which aerosol concentration Q changes in volume V :

$$\frac{dQ}{dt} = - \frac{\int |-\bar{v}_t \cdot d\bar{A}|}{V} Q$$

where: v_t = deposition velocity, dA = surface area normal to Q

- Deposition velocity for thermophoresis:

$$v_t = \frac{3\mu C_m (c_t Kn + k_{gas} / k_p) \nabla T}{2\chi \rho_{gas} T (1 + 3 \cdot 1.257 Kn) (1 + 2c_t Kn + k_{gas} / k_p)}$$

$$C_m = 1 + \frac{2\lambda}{d_p} [1.257 + 0.4 \exp(-0.55d_p / \lambda)]$$

Thermophresis

where:

- T = pipe temperature,
- ∇T = temperature gradient from the gas to the wall,
- dp = particle diameter,
- ct = constant,
- g = gravitational constant,
- $Kn = 2\lambda/dp$ (Knudsen number),
- k_{gas}/k_p = ratio of gas to particle thermal conductivity,
- λ = mean free path of gas,
- μ = gas viscosity,
- ρ_p = particle material density,
- ρ_{gas} = gas density, and
- χ = dynamic shape factor; and

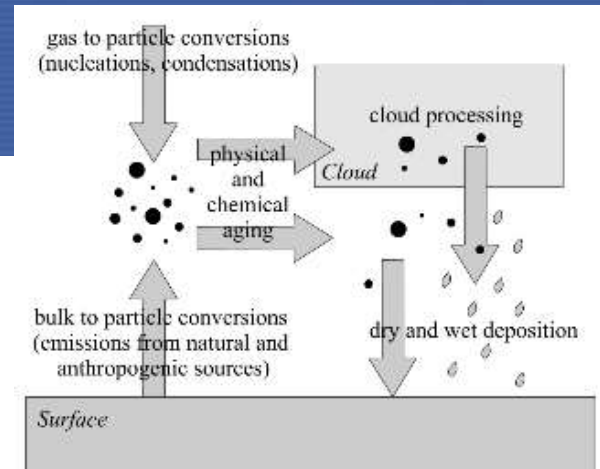
Brownian Diffusion

- Deposition can also result from diffusion of aerosols in a concentration gradient from a higher to a lower concentration region.
- The diffusive deposition velocity is given by

$$v_{\text{diff}} = \frac{\sigma T C_m}{3\pi\mu\chi d_p \Delta}$$

where

- v_{diff} = diffusion deposition velocity (m/s);
- σ = Boltzmann Constant = $1.38 \cdot 10^{-23}$ (J/s-m²K⁴);
- T = atmosphere temperature (K);
- μ = viscosity (N·s/m²);
- χ = dynamic shape factor; and
- Δ = user-specified diffusion boundary layer thickness specified on input record RNMS000 (default value of 10^{-5} m);



Aerosol Mechanics and Transport (Vapor Condensation)

Condensation growth rate of a particle of mass m is given by Mason's Eq.

$$\frac{dm}{dt} = \frac{2\pi D D Q_{eq} \left\{ \frac{Q_{steam}}{Q_{eq}} - a_w \exp \left[\frac{4\sigma}{RT\rho_w D} \right] \right\}}{1 + \frac{D Q_{eq} \Delta H}{KT} \left[\frac{\Delta H}{RT} - 1 \right]}$$

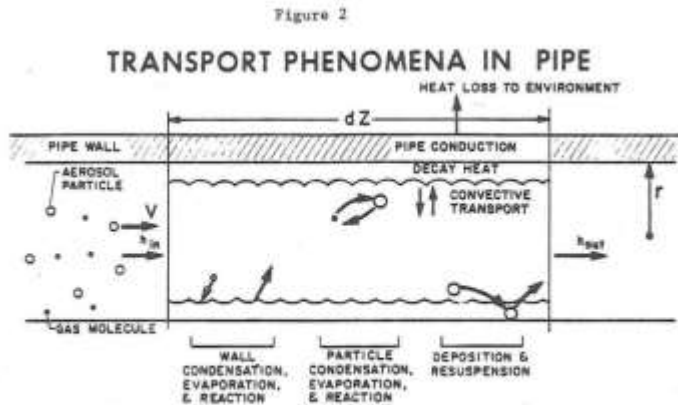
For water condensation on inert particles

$$T = 373 \text{ K}$$

$$P = 1.013 \times 10^5 \text{ Pa}$$

1% supersaturation (with Kelvin and hygroscopic effects)

$\tau \sim 3 \text{ sec}$ for 1 μm diameter particle and varies as D^2



Processes affecting aerosol behavior in complex geometry:

1. Gravity
2. Turbulence
3. Brownian Motion
4. Thermophoretic
5. Vapor Deposition
6. Inertia (Bends)
7. Irregularities
8. Re-entrainment

Figure 3

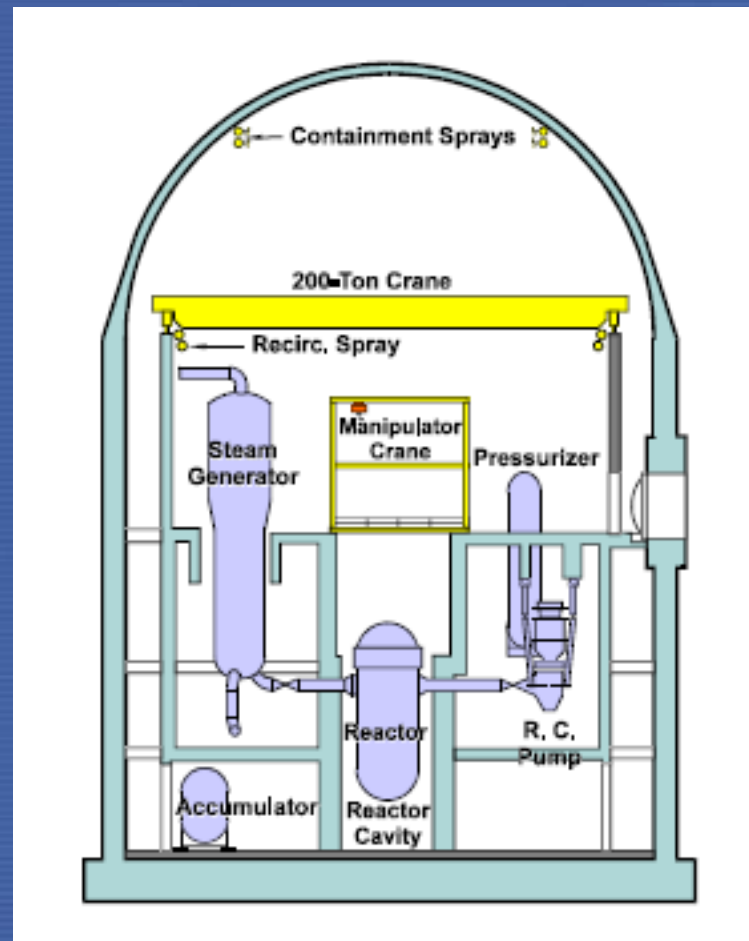
OBSERVATIONS

VELOCITY	HIGH	<p>AEROSOL: INERTIAL DEPOSITION</p> <p>GAS: VERY LOW CONCENTRATION & TRANSFER RATES</p> <p>STRUCTURE: THIN FILM (& HIGH RESUSPENSION RATE)</p> <p>MELTING PT. DEPRESSION</p>	<p>AEROSOL: SIGNIFICANT STRIPPING (OR CONDENSATION)</p> <p>GAS: ABILITY FOR HIGH CHEMICAL POTENTIAL DRIVEN TRANSFER WITH WALL & AEROSOL</p> <p>STRUCTURE: THIN FILM (& HIGH RESUSPENSION RATE)</p>
	LOW	<p>AEROSOL: BROWNIAN DEPOSITION</p> <p>GAS: VERY LOW CONCENTRATION & TRANSFER RATES</p> <p>STRUCTURE: POTENTIALLY THICKEST FILM, BUT SLOWEST GROWTH</p> <p>MELTING PT. DEPRESSION</p>	<p>AEROSOL: SIGNIFICANT STRIPPING (OR CONDENSATION)</p> <p>GAS: ABILITY FOR HIGH CHEMICAL POTENTIAL DRIVEN TRANSFER WITH WALL & AEROSOL</p> <p>STRUCTURE: THICK FILM</p>
		LOW	HIGH
		TEMPERATURE	

Engineered safety features to deposit fission product

CONTAINMENT SPRAYS

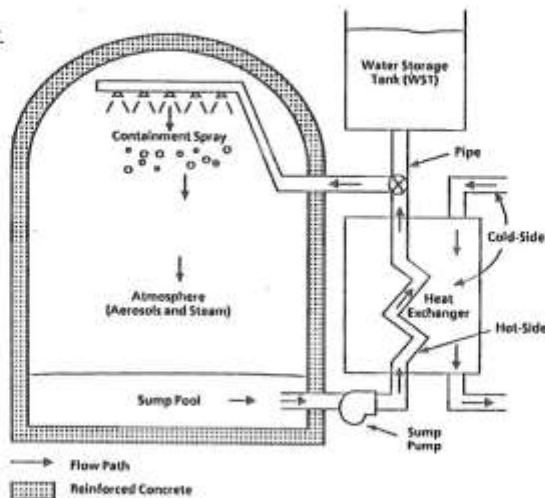
- Most effective in large-dry & subatmospheric containments
- Reduce airborne aerosol concentrations to negligible levels given sufficient time (e.g., delayed containment failure)
- For shorter periods
 - less effective, but
 - substantial mitigative effect



Engineered safety features to deposit fission product

Engineering Safety Features Model

Containment Spray Model

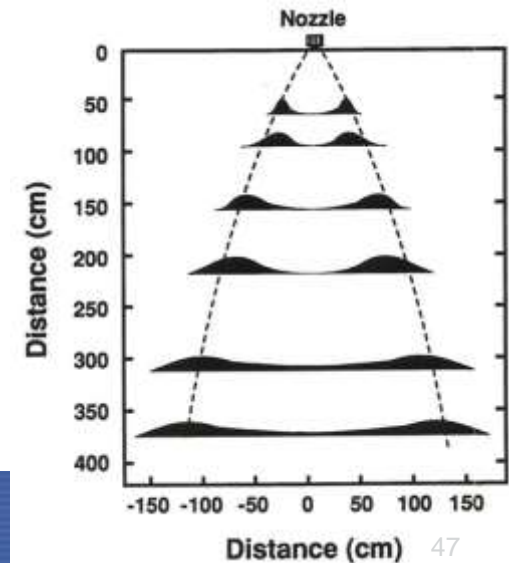
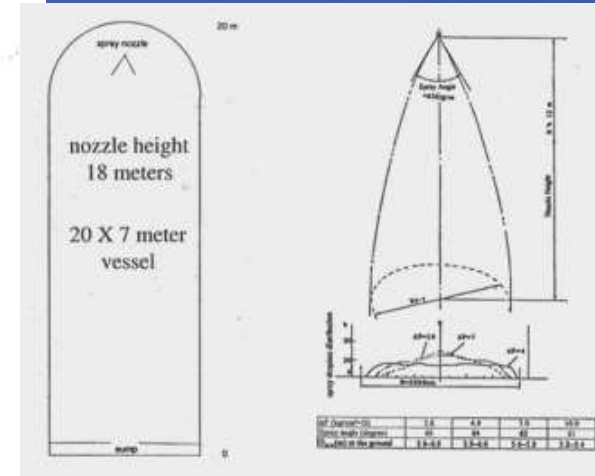


- Forced convection around falling sphere of diameter D

$$N_{Ns} = 2.0 + 0.60(N_{Re})^{0.5} (N_{Fr})^{0.33}$$

- Drop falls at terminal velocity (residence time in atmosphere)
- Condensation/Evaporation by HMTA method
- No fall through stacked cells
- Collected in sump
- Includes other sub-models water storage tank, pumps, heat exchangers, etc.

JAERI 1-nozzle spray test



Engineered safety features to deposit fission product

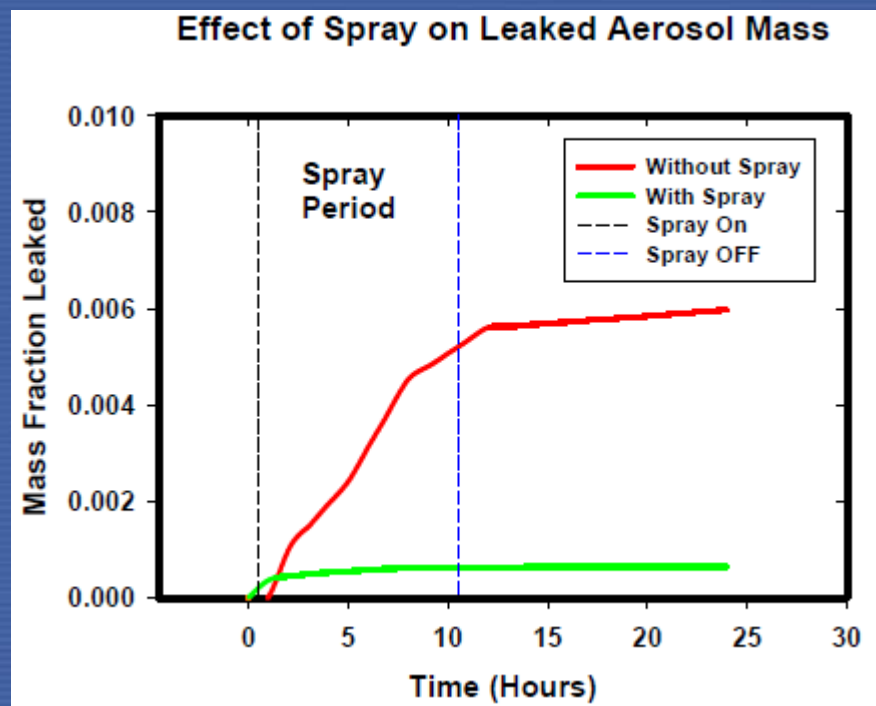
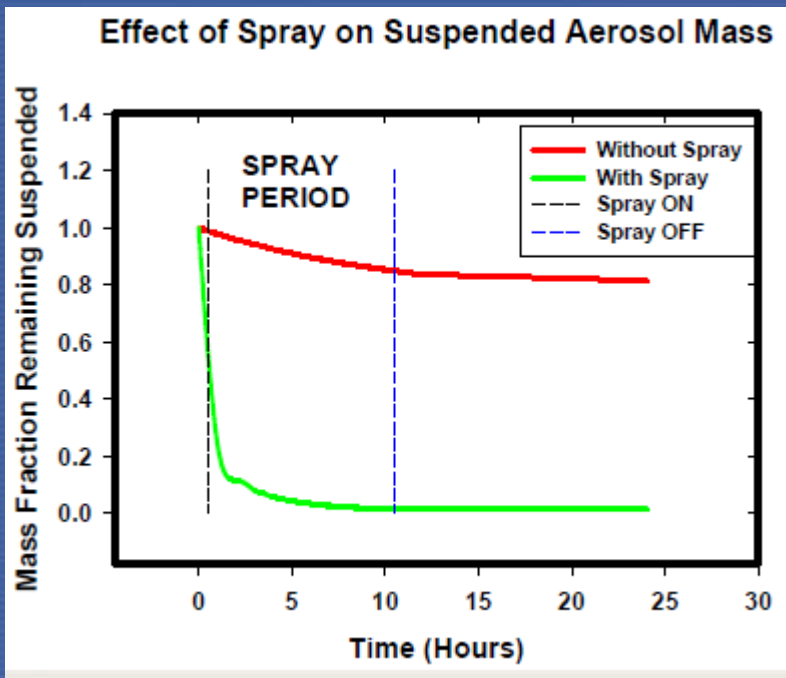


CONTAINMENT SPRAYS

- Falling water droplets capture aerosol particles by:
 - Gravitational impaction (large aerosol particles > 5 microns)
 - Interception/capture of particles following streamlines of flow around falling droplet (> 0.5 microns)
 - Diffusion to falling droplet (small particles < 0.1 microns)
- Leads to a capture efficiency depends on droplet size
 - Smaller droplets more efficient at aerosol capture

Engineered safety features to deposit fission product

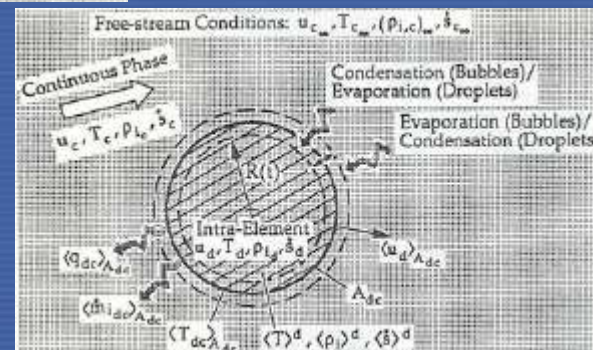
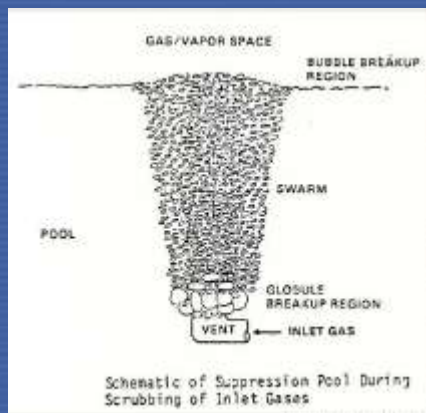
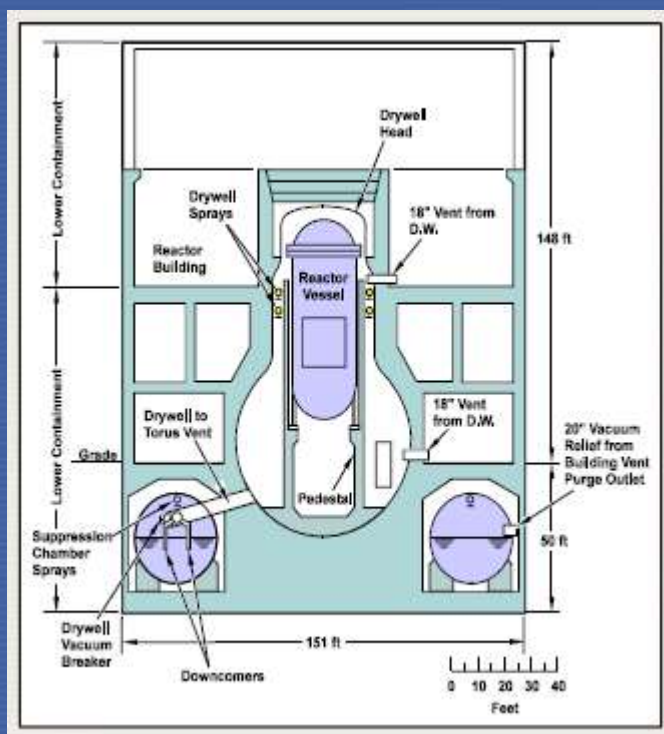
CONTAINMENT SPRAYS



Engineered safety features to deposit fission product

POOL SCRUBBING

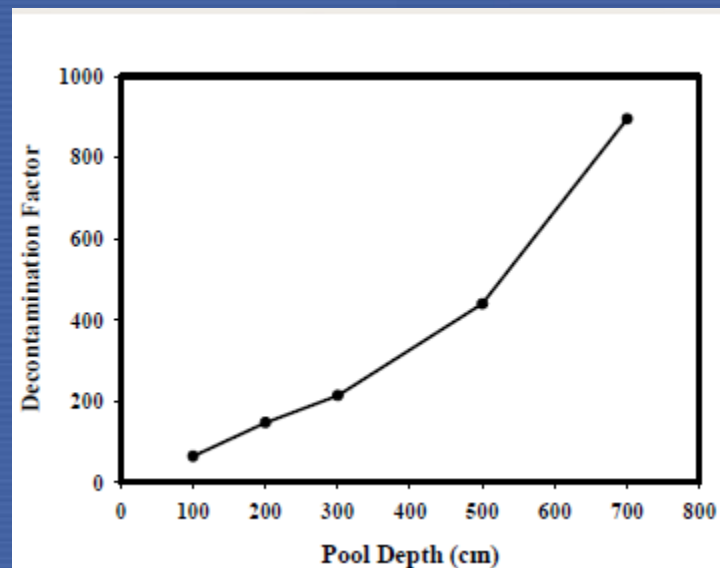
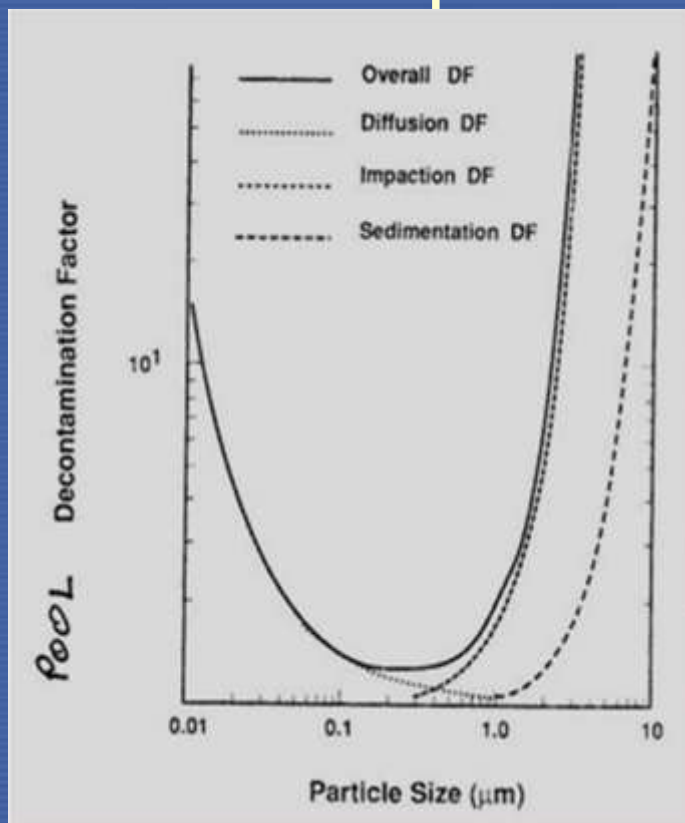
- Growth or decay of dispersed bubble or droplet in the steam of continuous phase (liquid or gas)



Engineered safety features to deposit fission product

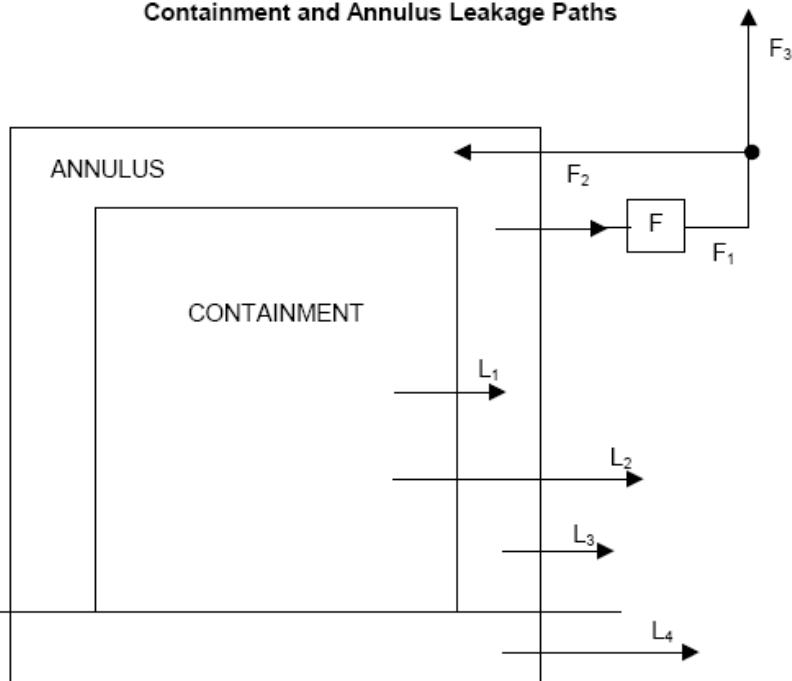
POOL SCRUBING

- Decontamination Achieved by a Suppression Pool As a Function of the Pool Depth



Example: DBA Containment Leakage Model

Containment and Annulus Leakage Paths

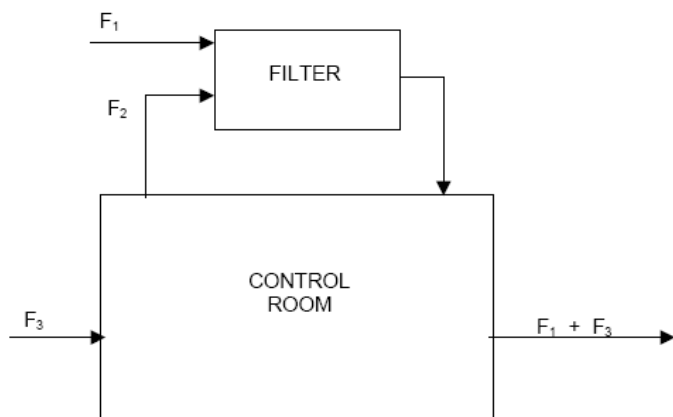


- L_1 : Containment leakage to annulus (% / day)
- L_2 : Containment leakage to environment (% / day)
- L_3 : Annulus leakage to environment (% / day)
- L_4 : Sump/ESF leakage to environment (% / day)
- F_1 : Total annulus filter capacity (cfm)
- F_2 : Annulus recirculation flow (cfm)
- F_3 : Annulus exhaust flow (cfm)

LOCA Analysis Parameters/Assumptions - Radiological Consequences (Cont'd)

Parameter	Analysis Value
Annulus filter efficiencies	
elemental iodine (charcoal)	95%
organic iodine (charcoal)	95%
particulate iodine (HEPA)	99%
Effective time for annulus recirculation	after 1200 s
Form of iodine activity in containment available for release	
elemental iodine	91%
organic iodine	4%
particulate iodine	5%
Spray removal coefficients (Reference 8.24)	
elemental iodine	20.4 hr ⁻¹
organic iodine	0 hr ⁻¹
particulate iodine	4.6 hr ⁻¹
Maximum decontamination factors	
elemental (time to reach max DF)	100 (0.79 h)
particulate (time to reach max DF)	50 (1.31 h)
Containment leak rate	0 – 24 h 1 – 30 d
	0.2% per day 0.1% per day
Containment leak rate which bypasses annulus	0 – 1200 s 1200 s and beyond
	All leakage 10% of above leakage
Engineered safeguards leakage (ECCS leakage - sump)	2 x operational leakage (USAR Table 6.3-6)
	3026 cc/h
Meteorology	Table 4-5
Breathing rate	USNRC Regulatory Guide 1.4
RCS fission and corrosion product activity	SSR-NEK-7.10.1
Dose conversion factors and other physical parameters	Table 4-6

Example: DBA Main Control Room Model for Habitability Analyses



- F_1 : Filtered makeup = 1550 m³/h
- F_2 : Filtered recirculation = 40,000 m³/h
- F_3 : Unfiltered inleakage = 300 m³/h

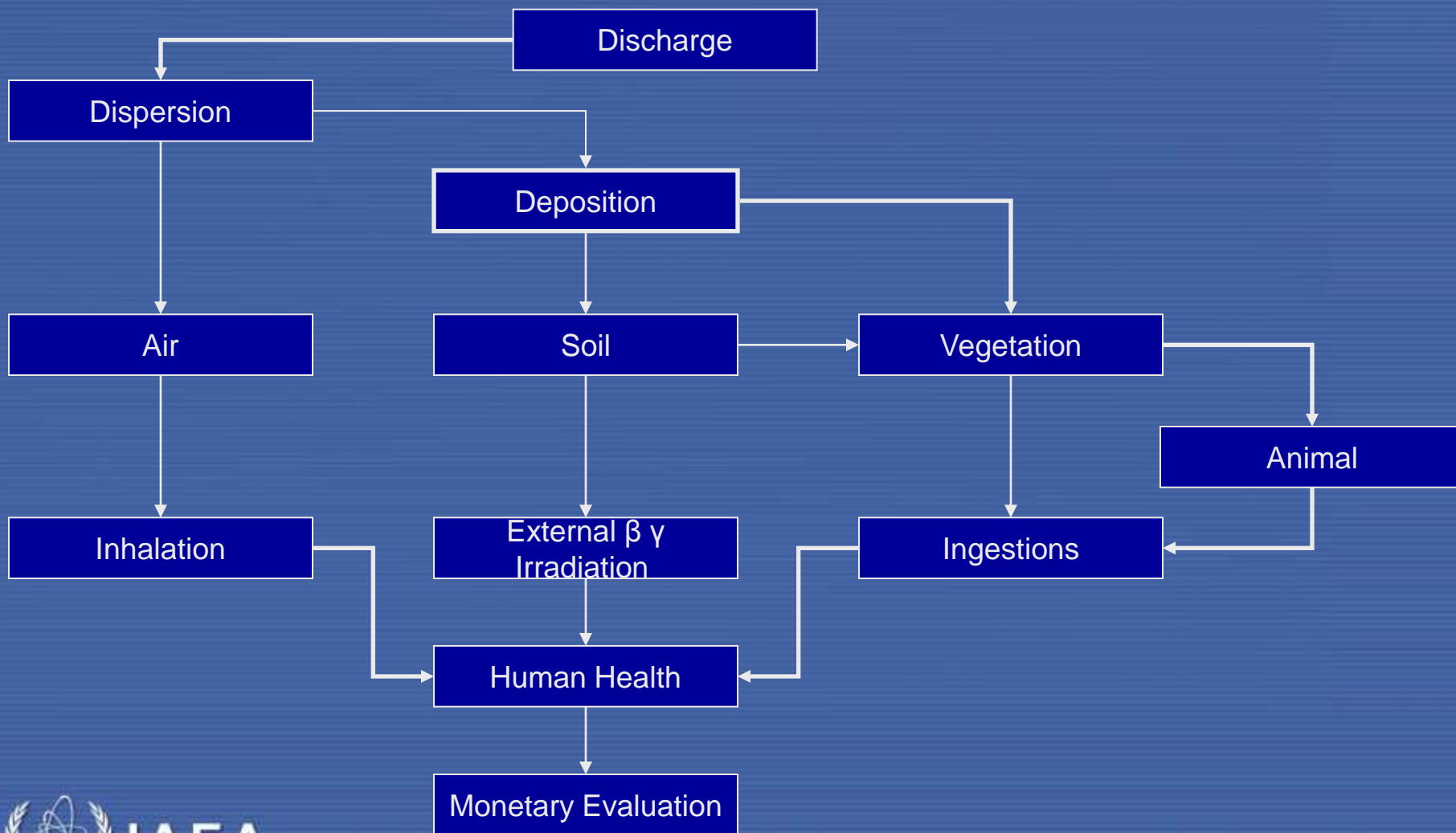
NOTE:

- F_1 - includes damper leakage, make-up, and filter recirculating flow
- F_2 - includes 0.9 x filter flow less filter recirculating flow
- F_3 - includes miscellaneous control room volume leakage and door opening/closing leakage.

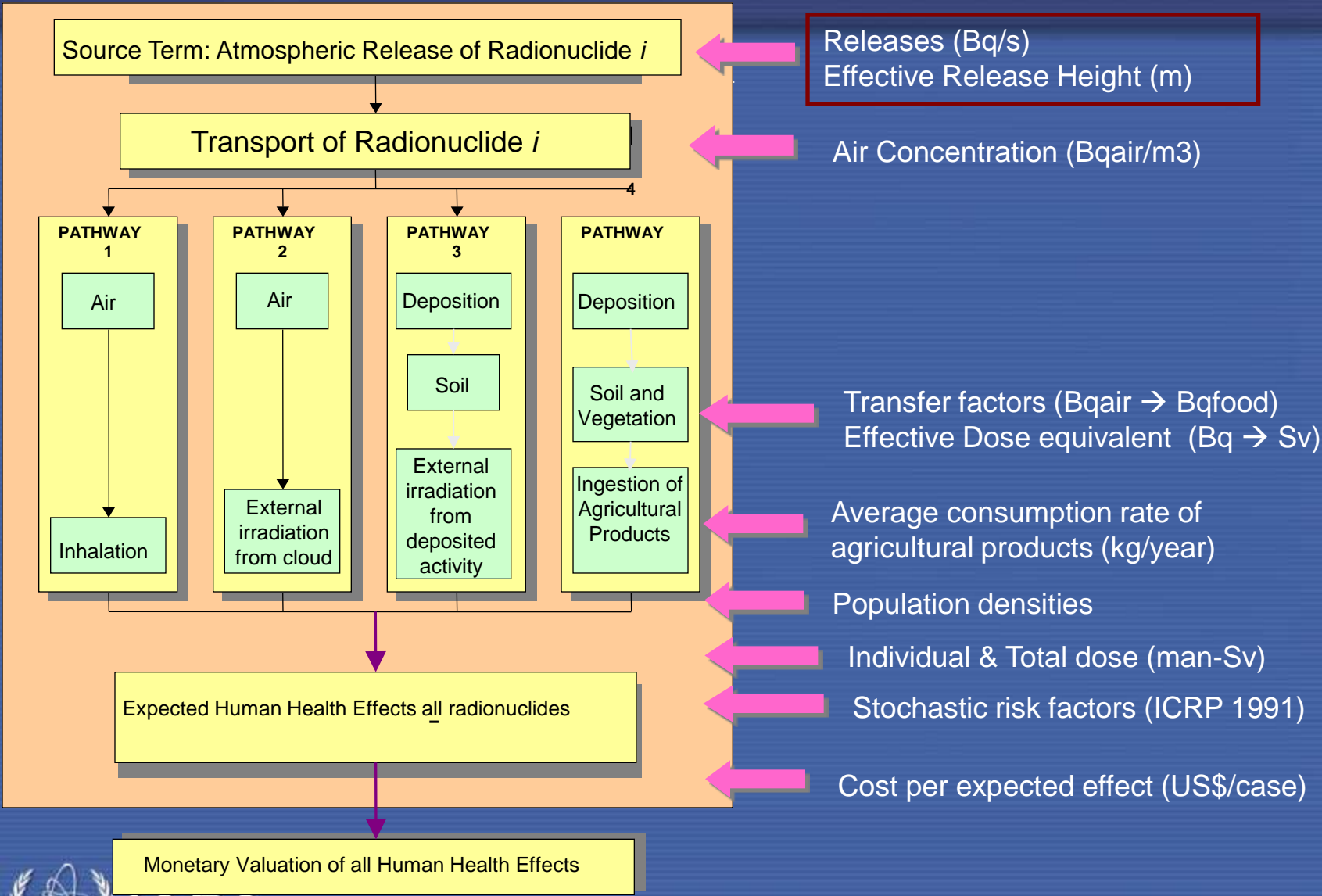
LOCA Control Room Dose Analysis Parameters/Assumptions

Parameter	Analysis Value
Control room volume	4700 m ³ (166000 ft ³)
Control room unfiltered inleakage	300 cmh (175 cfm)
Doors	17 cmh
Unidentified	282 cmh (0.06 air changes per hour)
Control room filtered make up airflow	1550 cmh (912 cfm)
Control room recirculation air flow	40000 cmh (23529 cfm)
Control room filter efficiencies	
Elemental iodine (charcoal)	95%
Organic iodine (charcoal)	95%
Particulate iodine (HEPA)	99%
Meteorology	USAR section 15.6.5.4.3
Breathing rate (0 – 30 days)	3.47E-4 m ³ /s (0.012 ft ³ /s)
Occupancy factors	USAR section 15.6.5.4.3
RCS fission and corrosion product activity	SSR-NEK-7.10.1
Dose conversion factors and other physical parameters	Table 4-6

Pathways for the Atmospheric Releases of Radionuclides



Atmospheric Release of Radionuclide



Impact Pathway for the Atmospheric Discharge of NPP

Radionuclide Released in the air from a PWR

Source



Radionuclide	Half-life	Radionuclide	Half-life
Kr-85	10.7 y	I-134	52.6 min
Kr-87	76.3 min	I-135	6.6 h
Kr-88	2.8 h	Cs-134	2.1 y
Xe-133	5.2 d	Cs-136	13.1d
Xe-135	9.2 h	Cs-137	30 y
Xe-138	14.0 min	Co-58	71 d
I-131	8.1 d	Co-60	5.3 y
I-132	2.3 h	C-14	5710 y
I-133	21 h	H-3	13.3 y

Transport & Dispersion

Deposition

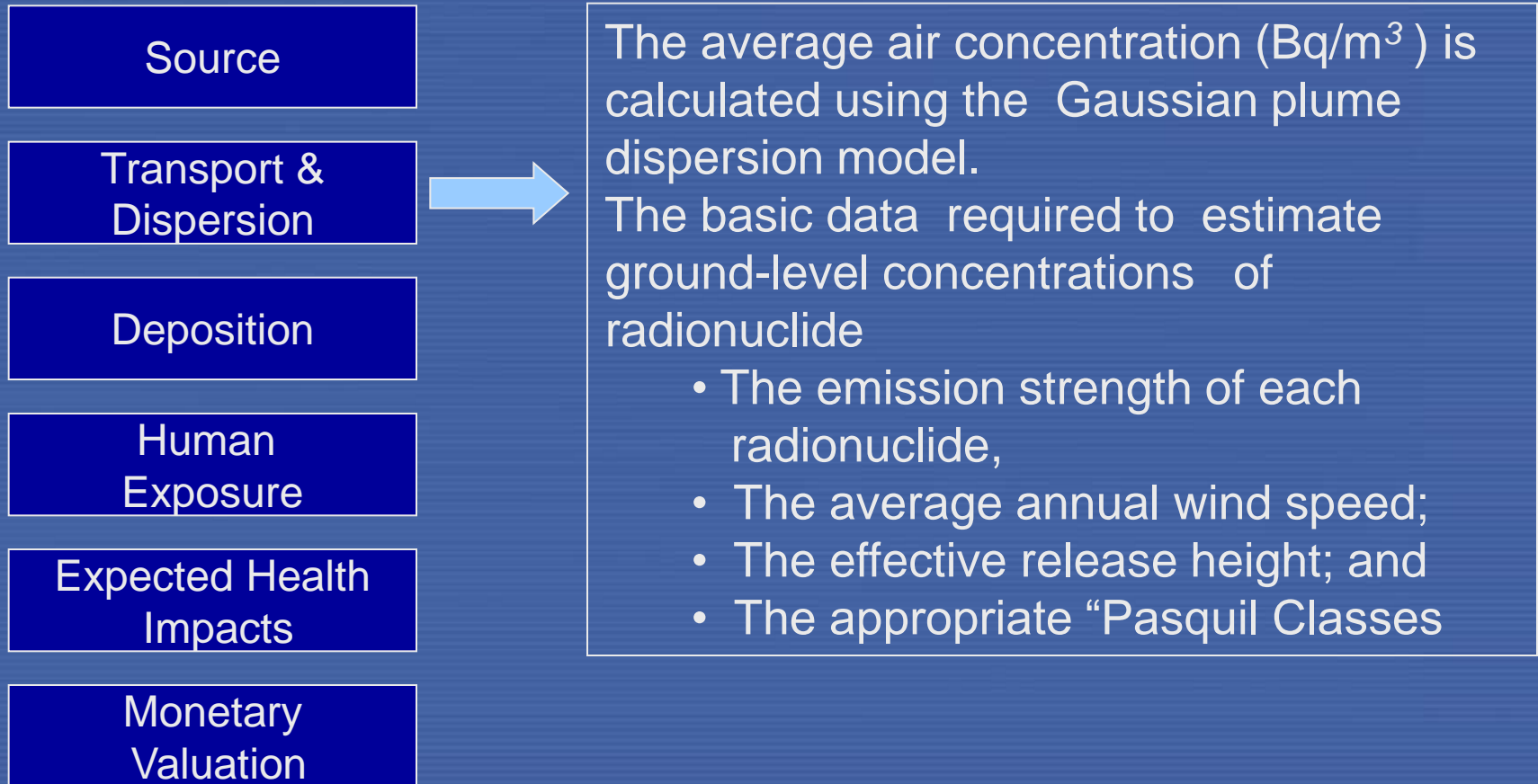
Human Exposure

Expected Health Impacts

Monetary Valuation



Impact Pathway for the Atmospheric Discharge of NPP



Effect of height of release

- **Ground releases** (few meters or few tens of meters) versus elevated releases from the NPP stack at the height of more than 100 m.
- The **effect of elevated release** can also be strengthened by **sensible heat**
- Ground releases lead to much higher radiological consequences due to the fact that in case of elevated release radioactivity is disseminated on larger area.
- For ground release contribution to doses from different isotopes typically leads to results 2-20 times higher than an elevated release (depend on the distance).

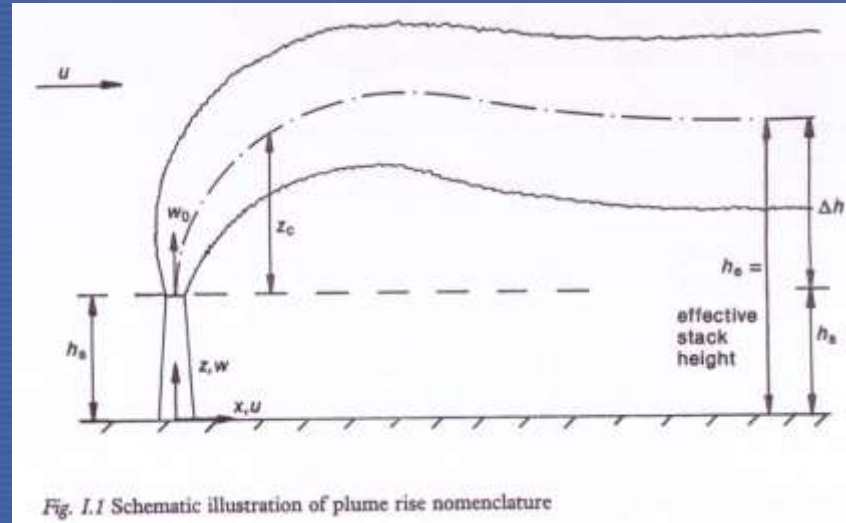


Fig. 1.1 Schematic illustration of plume rise nomenclature

Schematic illustration of plume rise nomenclature

Effect of height of release

- EUR document accepts ~15-times higher elevated releases for the same consequences
- Long term land contamination at the distance 5-10 km from the point of release could be up to 2-5 times lower in case of elevated release
- In **case of elevated release** through the stack the results are even much **more optimistic** since many isotopes (except noble gases) could be **captured by filters**.
- For **conservative analysis** the release should be assumed at **ground level and sensible heat should be zero** or conservatively estimated unless a justification is made for an elevated release (ventilation stack, vented containment)

Example of effect of height of release for DBA (direct release of primary coolant to the environment)

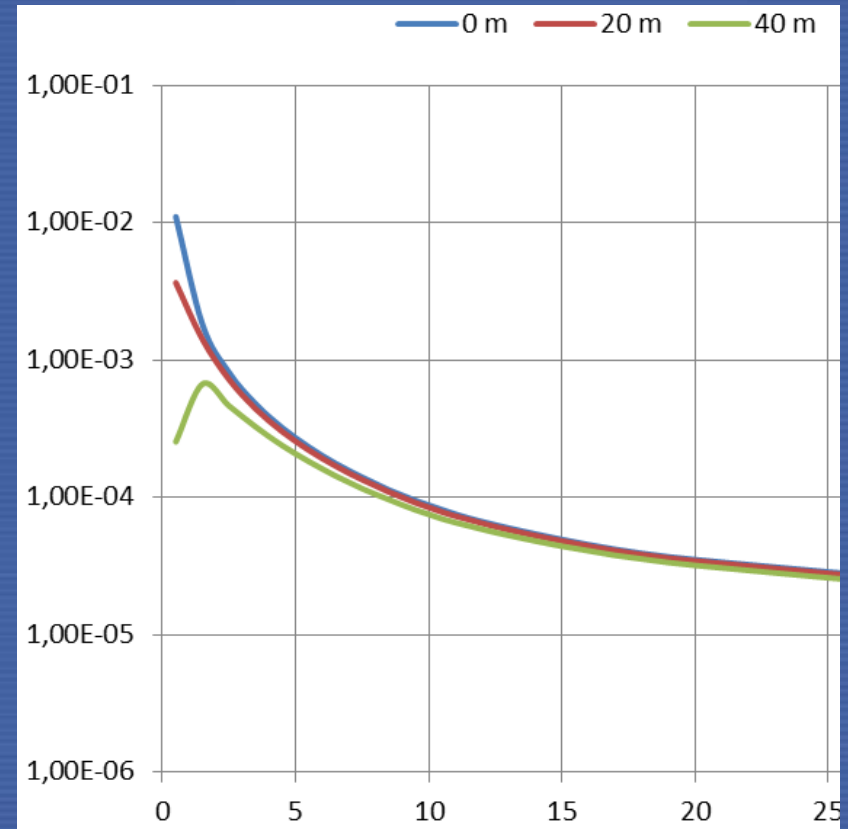
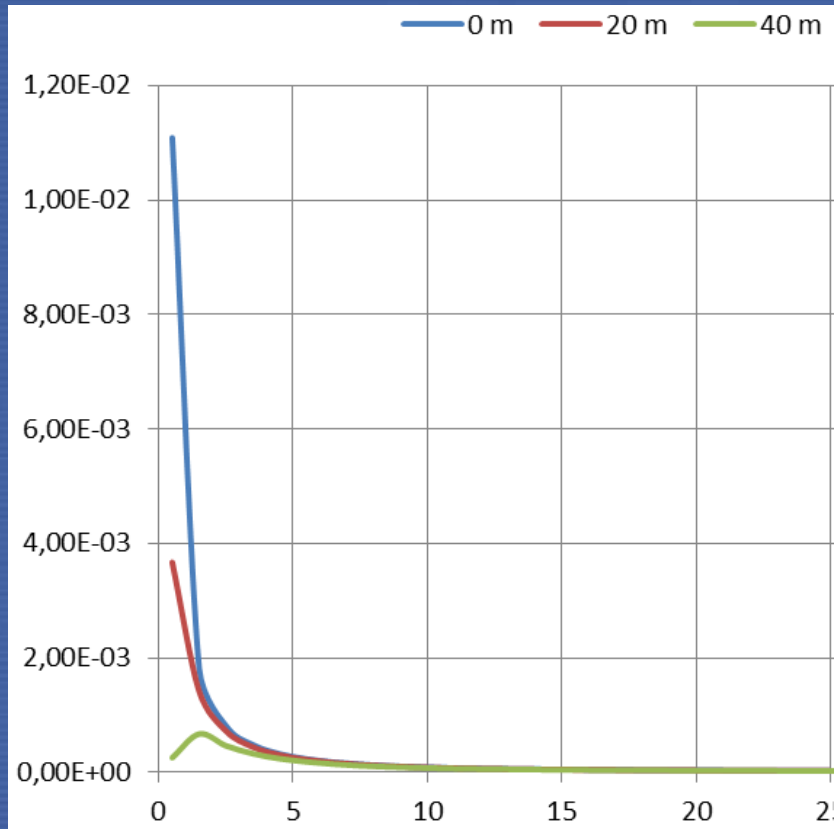


Height of release

Logarithmic scale

Linear scale

Effective dose, mSv/year

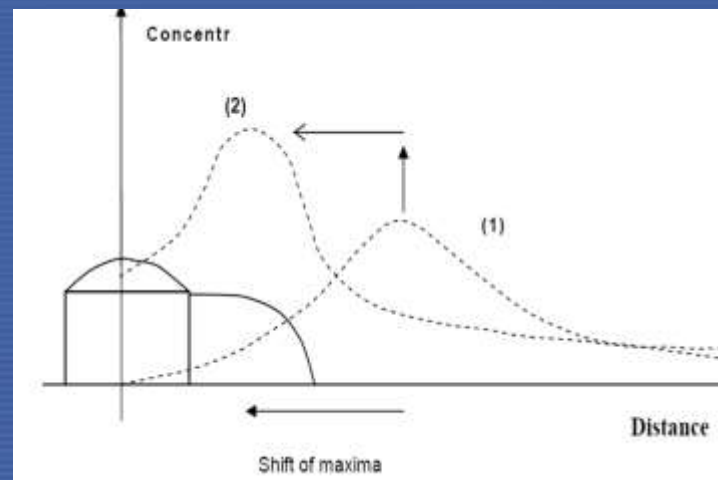
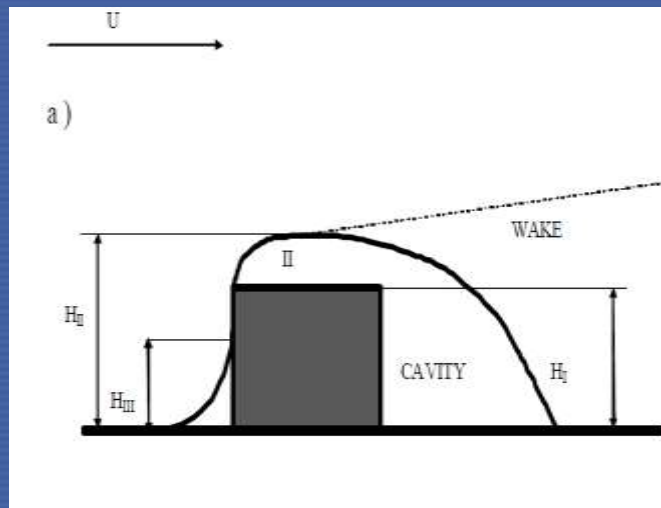


Distance, km



Effect of a building

- The effect of a building is effectively increasing the height of the releases
- Consideration of a building leads to increased plume dispersion and consequently to lower concentrations in the plume. Therefore at larger distance the doses are lower
- Reduction of effective doses at the exclusion area boundary is significant, several times
- Maximum concentration is shifted closer to the building
- If the height of the release is sufficiently higher than the height of the building (about 1.4 times) the effect of the building is negligible



Dilution Coefficients

Dilution coefficients for ground level release can be calculated as follows:

$$(a) \quad X/Q(x) = \frac{1}{(\pi \cdot \sigma_y \cdot \sigma_z + \frac{A}{2}) \cdot u}$$

$$(b) \quad X/Q(x) = \frac{1}{\pi \cdot \sigma_y \cdot \sigma_z \cdot u}$$

$$(c) \quad X/Q(x) = \frac{1}{\pi \cdot SY \cdot \sigma_z \cdot u}$$

- X/Q is dilution coefficient,
- u is mean scalar wind speed at 10m,
- σ_y and σ_z is lateral and vertical plume spread (dispersion parameters),
- A is the smallest vertical-plane cross-sectional area of the reactor building,
- SY is lateral plume spread with meander effect.

The X/Q values should be calculated using Equation a, b and c. The values from Equation a and b should be compared and the higher value selected. This value should be compared with the value from Equation c and the lower value of these two should be selected as the appropriate X/Q value:

$$X/Q = \text{low}(c, \text{high}(a, b))$$

Impact Pathway for the Atmospheric Discharge



$W_i = C_i \times V_d$
 W_i = average flux of radionuclide i (Bq/m².s)
 C_i = average air concentration of radionuclide i (Bq/m³), determined by Gaussian Plume model
 V_d = average wet and dry deposition velocity (m/s)

Impact Pathway for the Atmospheric Discharge



The most important pathways for health of the general public resulting from atmospheric releases are :

- i. The inhalation of radionuclides in the air;
- ii. The external irradiation from cloud exposure;
- iii. The external irradiation from ground deposition, and
- iv. The ingestion of radionuclides in food.

Impact Pathway for the Atmospheric Discharge

Source

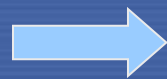
Transport & Dispersion

Deposition

Human Exposure

Expected Health Impacts

Monetary Valuation



Dose-response relationship
 The key risk factors are the following
 (cases per man Sv)

Fatal cancer	0.05
Non-fatal cancer	0.12
Severe hereditary effects	0.01

Source: (ExternE 1995, ICRP 1991)

References

- Powers, D. A., Fission Product Behavior During Severe LWR Accidents: Modeling Recommendations for the MELCOR Code System, Vol 1: Fission Product Release from Fuel. NUREG/CR-4481, Sandia National Laboratories (September, 1988).
- D. E. Bennett, SANDIA-ORIGEN User's Manual. NUREG/CR-0987, SAND79-0299, Sandia National Laboratories, Albuquerque, NM (October 1979).
- Ostmeyer, R. M., An Approach to Treating Radionuclide Decay Heating for Use in the MELCOR Code System. SAND84-1404, NUREG/CR-4169, May 1985.
- Kuhlman, M. R., D. J. Lehmicke, and R. O. Meyer (1985), CORSOR, User's Manual., BMI-2122, NUREG/CR-4173, March 1985
- M.Ramamurthi, M.R.Kuhlman, Final Report on Refinement of
- CORSOR – An Empirical In-Vessel Fission Product Release Model, Battelle Memorial Institute, October 31,1990.

References

- K. Manwong, IAEA, ANSN Regional Workshop on Severe Accident Analysis for Nuclear Power Plants from 18 to 22 May, 2015, Tokyo, Japan
- I. Bašić, APOSS, Safety Training Program Deterministic Safety Analysis, DSA 4.1, Assessment of Radioactive Release Consequences, AFColenco, 2009