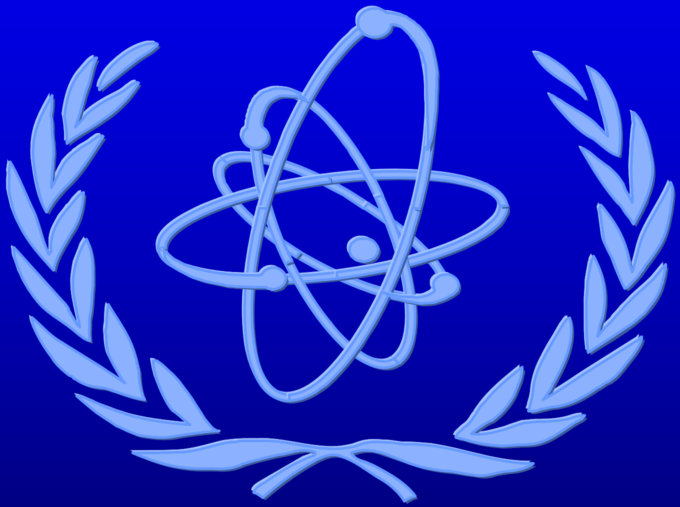
IAEA Training in Level 2 PSA

MODULE 3:

Source Term Phenomena



Outline of Discussion

- Review basic fission product release and transport processes
- Simple calculation methods
- Major uncertainties
  - Examples from active research

  - Computer code modeling and applications to Level 2 PSA discussed later (M7)

Fission Product Inventory

- Level of detail needed to define core inventory depends on objective of PSA
  - Full-scope (Level 3): Complete isotopic inventory
  - Typical “IPE” study: concentrate on key radio-elements
- Computer codes and PSA models work with ‘groups’ of radio-elements
  - Similar chemical behavior

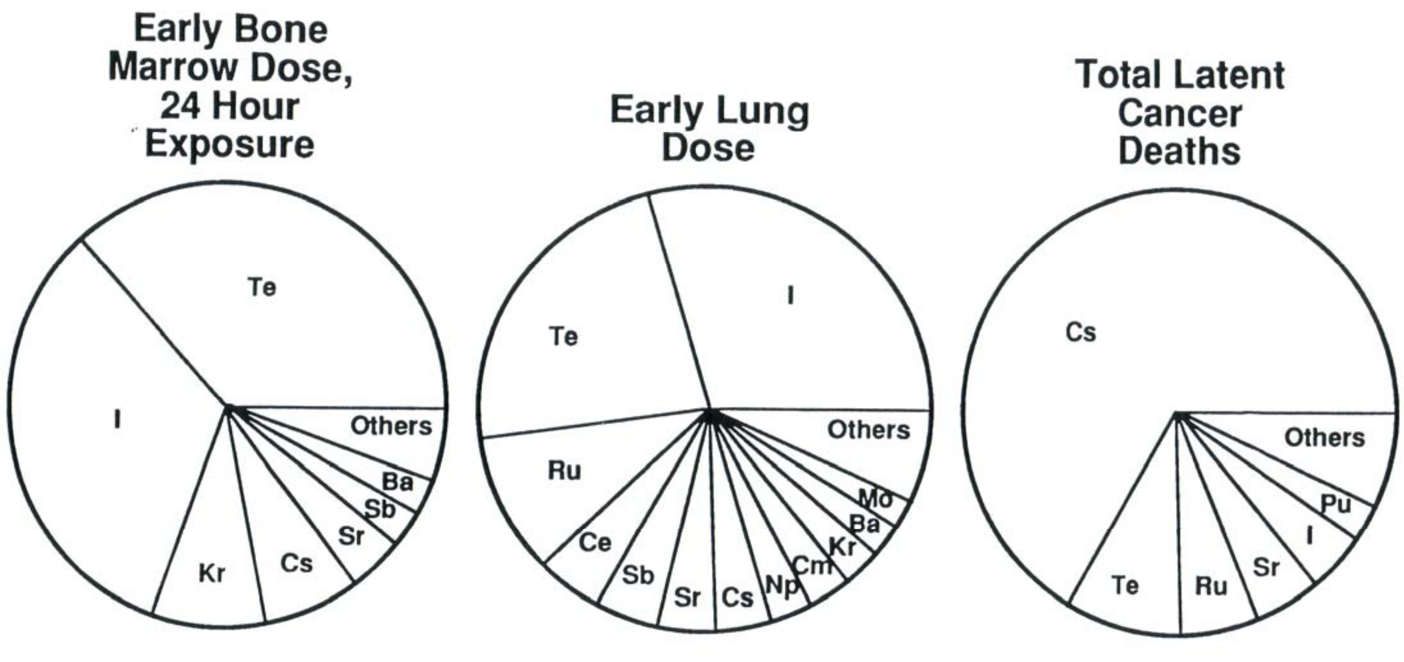
Radionuclide Groups & Typical Inventory

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

Source: AP-600

Isotopes of Some Elements More Important than Others

- Relative importance of radio-elements to various human health consequences [Ref: NUREG/CR-4467, U.S. NRC, 1986]



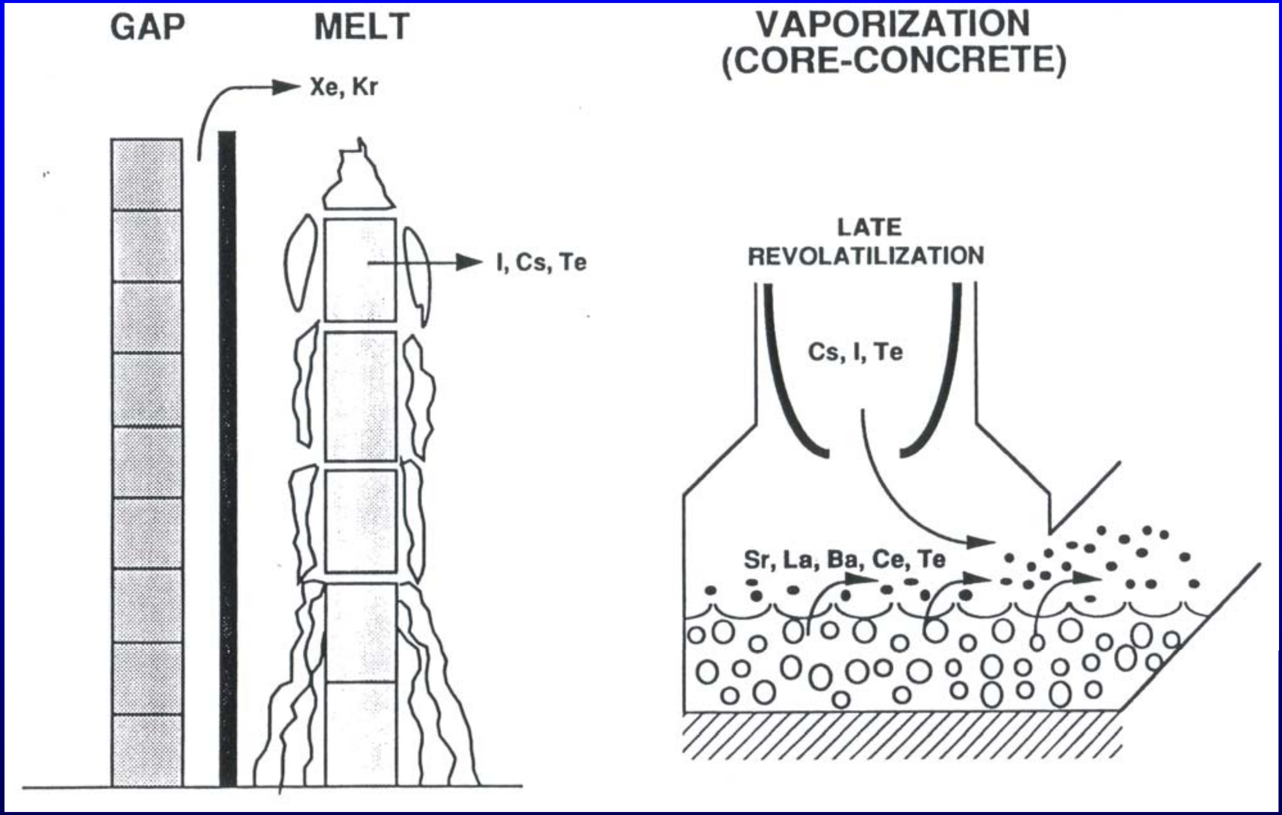
Early Bone Marrow Dose, 24 Hour Exposure

Early Lung Dose

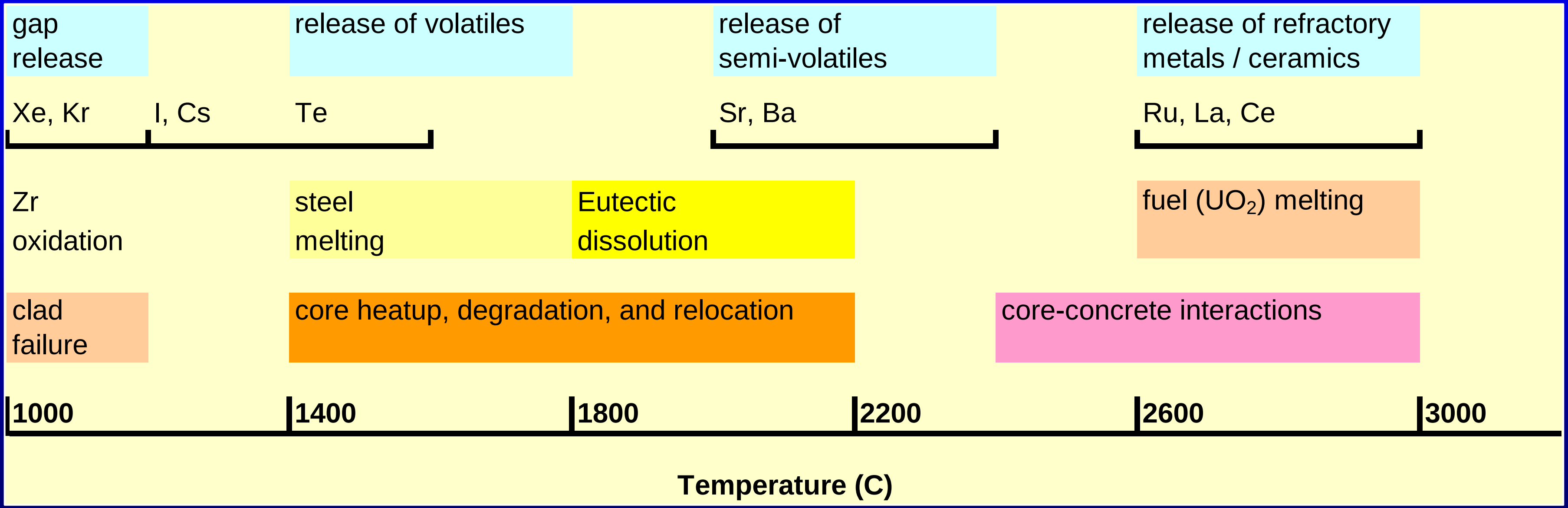
Total Latent Cancer Deaths

Assumes unit release of each element.

F.P. Release occurs at Different Times During an Accident



Fission Product Release a Strong Function of Temperature



gap release

release of volatiles

release of semi-volatiles

release of refractory metals / ceramics

Xe, Kr

I, Cs

Te

Sr, Ba

Ru, La, Ce

Zr oxidation

steel melting

Eutectic dissolution

fuel (UO_2) melting

clad failure

core heatup, degradation, and relocation

core-concrete interactions

1000

1400

1800

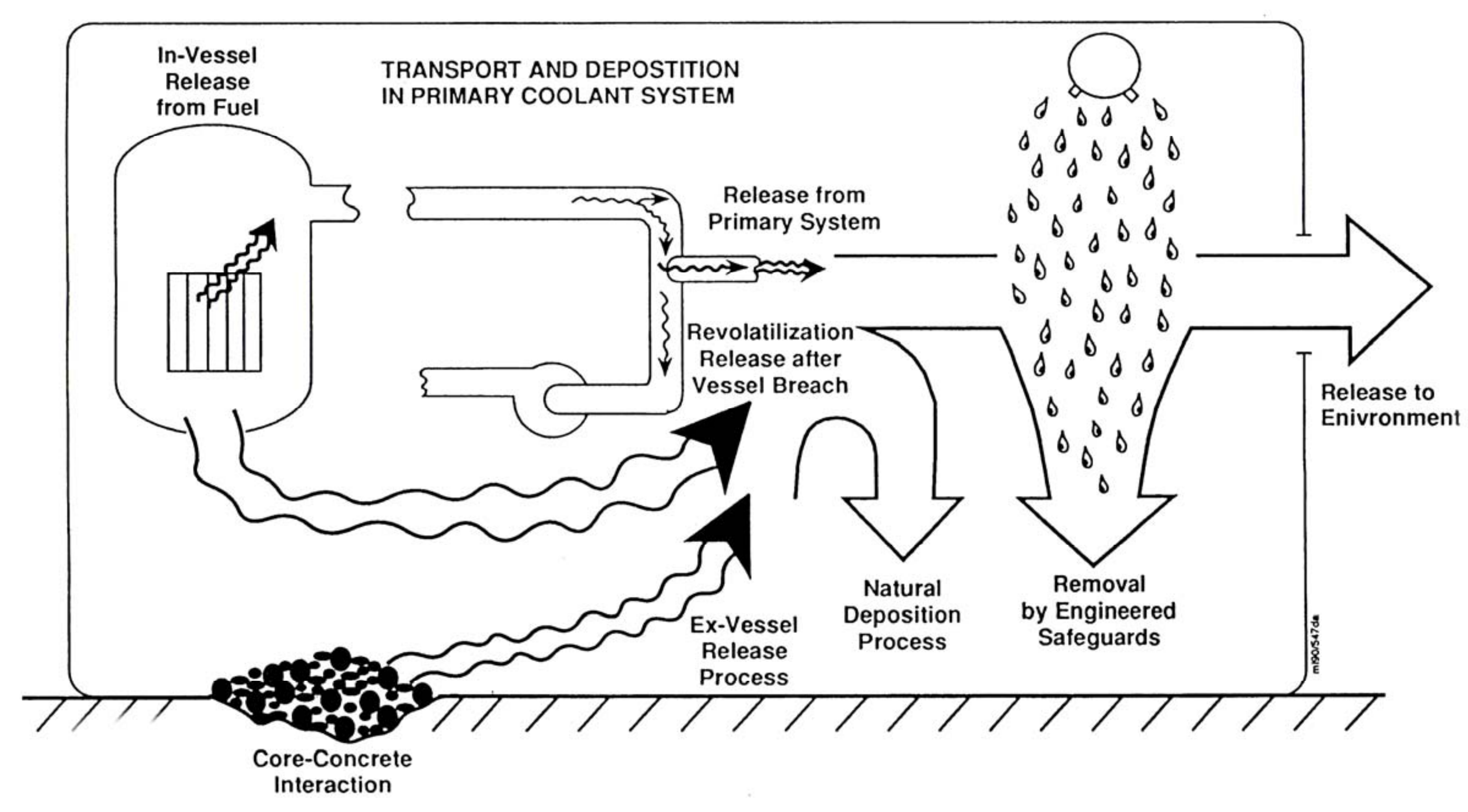
2200

2600

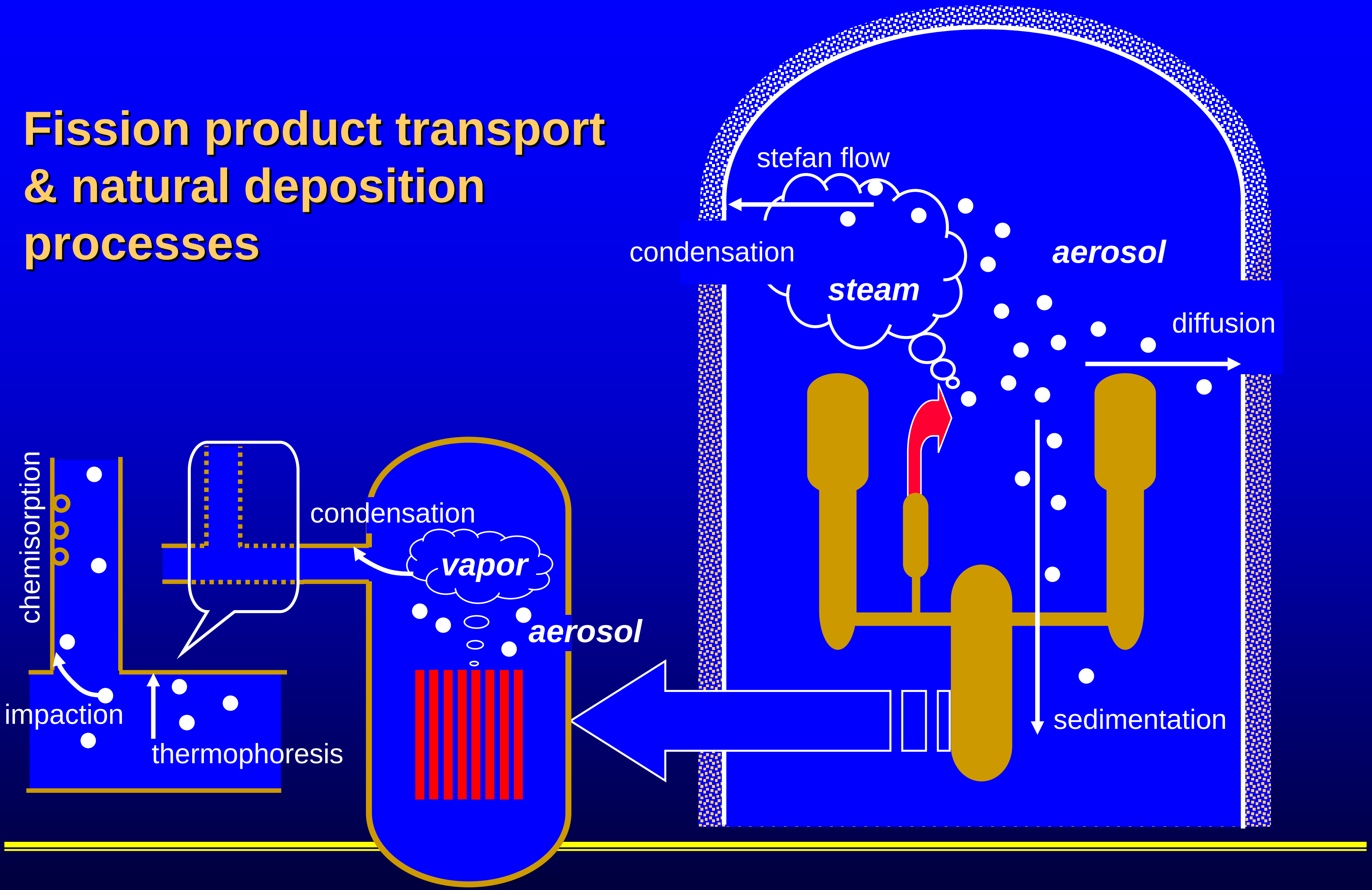
3000

Temperature (C)

Deposition Along Transport Path Reduces Inventory Available for Release to Environ.

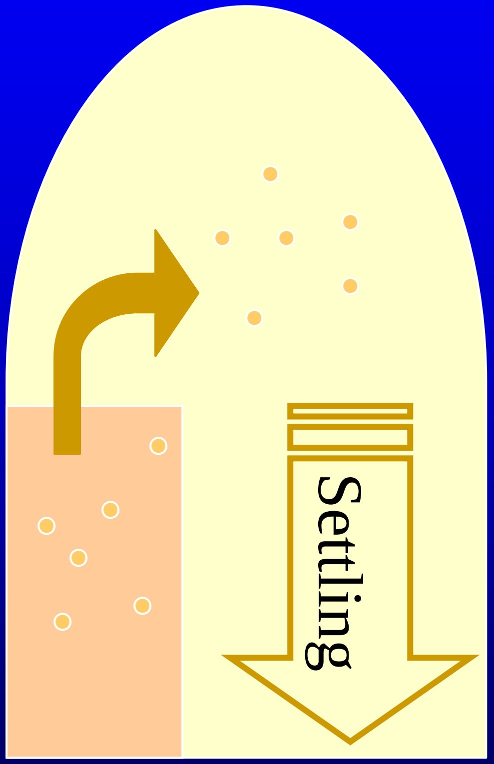


Fission product transport & natural deposition processes



Calculation Methods

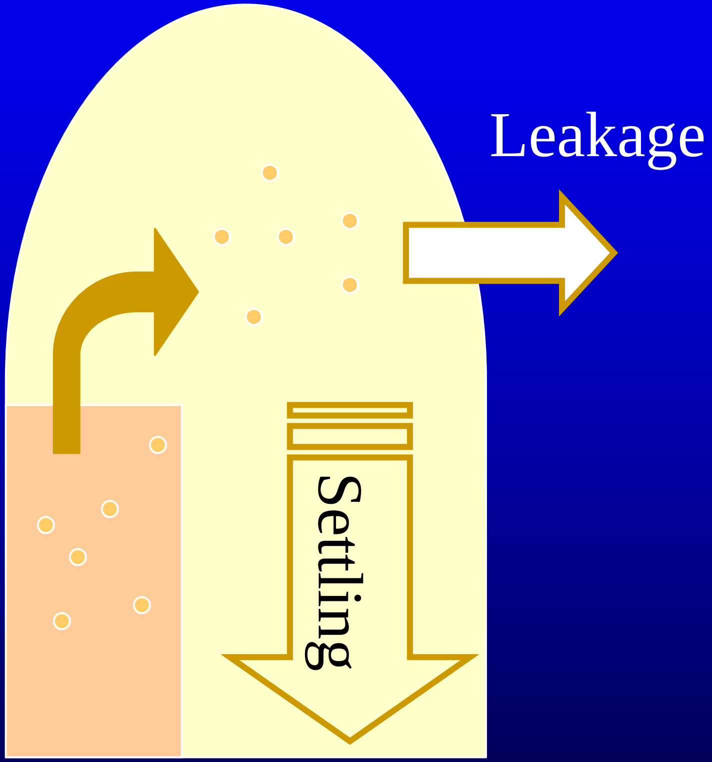
- Detailed source term assessment requires integrated computer code (discussed later)
- Simpler methods useful to examine broad issues
  - Gravitational settling (sedimentation) often dominates behavior in containment
  - Hand calculations can provide estimates of the importance of deposition in the RCS

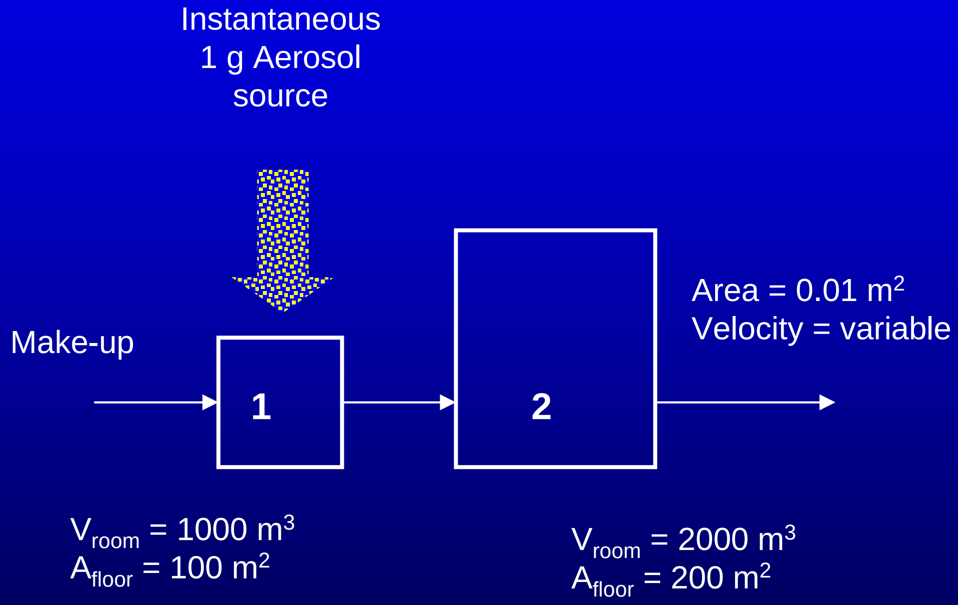


Two examples of hand-calculations

- Airborne aerosol depletion by gravitational settling
  - Estimate the amount of time needed to reduce airborne concentrations
- Aerosol deposition on reactor coolant system surfaces at very high temperatures
  - Determine if thermophoresis is important

Control Volume Approach to Estimating Aerosol Settling Rate





Area = 0.01 m^2
Velocity = variable

V_{room} = 1000 m^3
A_{floor} = 100 m^2

V_{room} = 2000 m^3
A_{floor} = 200 m^2

Control Volume Mass Balance

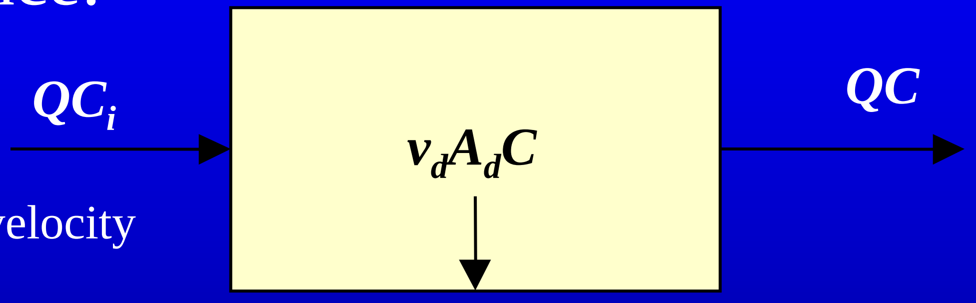
Steady state flow balance:

Q = flow rate

C = particle concentration

v_d = particle deposition (settling) velocity

A_d = deposition (settling) area



$$v_d A_d C = Q\,(C_i - C)$$

Release Fraction (RF):

$$RF = \left(\frac{QC}{QC_i}\right) = \frac{C}{C_i} = \frac{1}{1 + \dfrac{v_d\, A_d}{Q}} = \frac{1}{1+\alpha}$$

Deposition by Gravitational Settling

$$v_d = \frac{d_p^2 \, \rho_p \, g \, C_m}{18 \, \mu \, \chi}$$

where

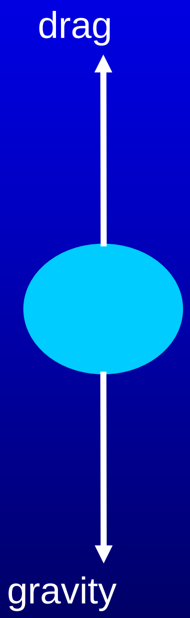
v_d = particle settling velocity

d_p, ρ_p = particle diameter, density

C_m = slip correction factor

μ = viscosity of air

χ = dynamic shape factor



Settling (terminal) velocity is proportional the square of particle diameter: ($v_d \propto d^2$)

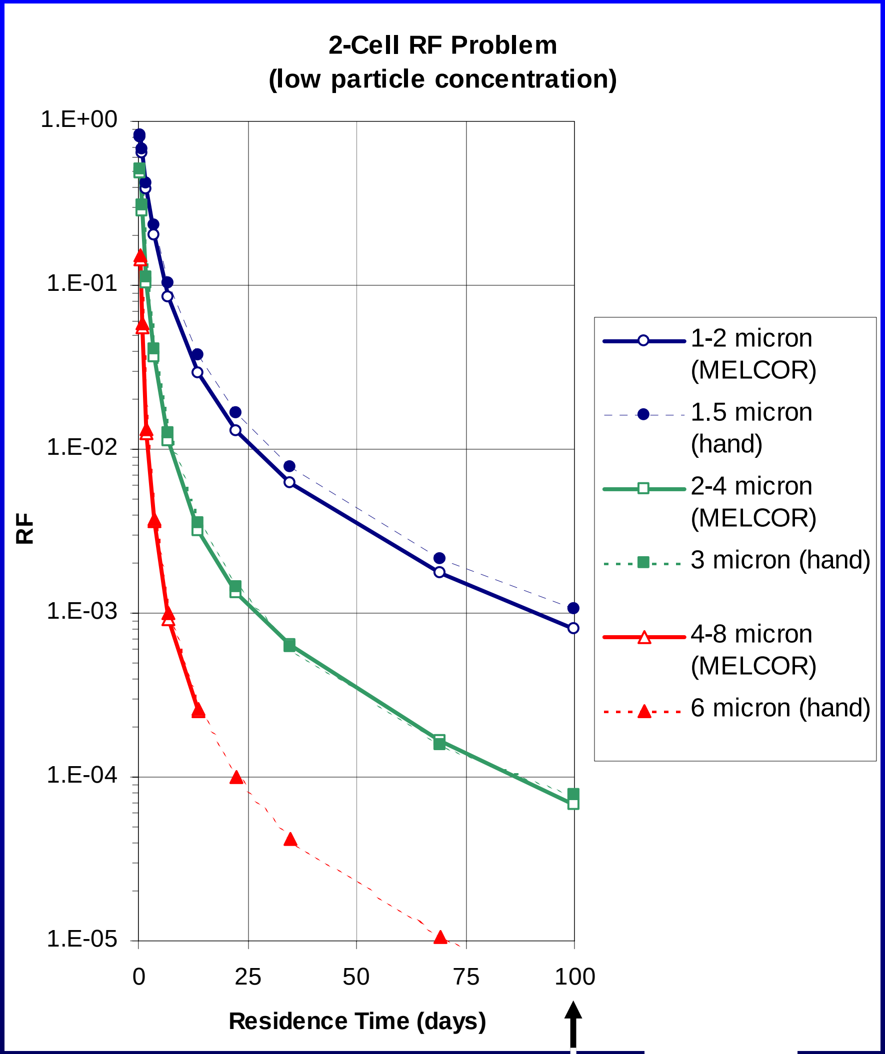
Diameter (μm)	Terminal Velocity (cm/s)
1.0	3.0E-3
2.0	1.2E-2
4.0	4.7E-2
8.0	1.9E-1

Results

- Release Fraction (RF) as function of residence time in containment:

$$\mathit{Residence\ Time} = \mathit{Volume} \Big/ \mathit{Leak\ Area} * \mathit{Velocity}$$

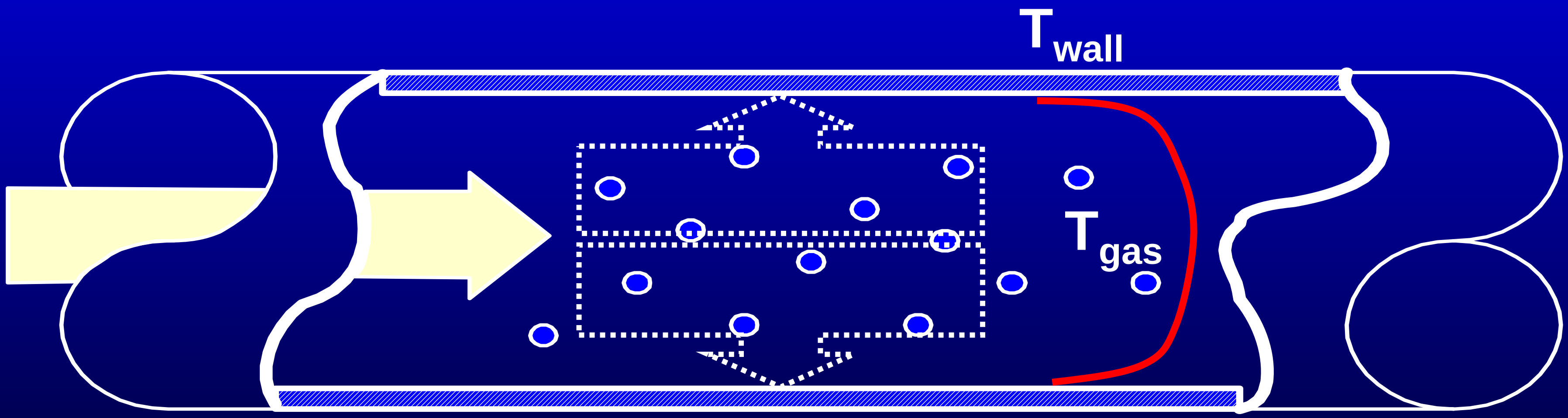
- Settling much more efficient for large particles
- Hand calculations for ‘simple’ problems reproduce code results



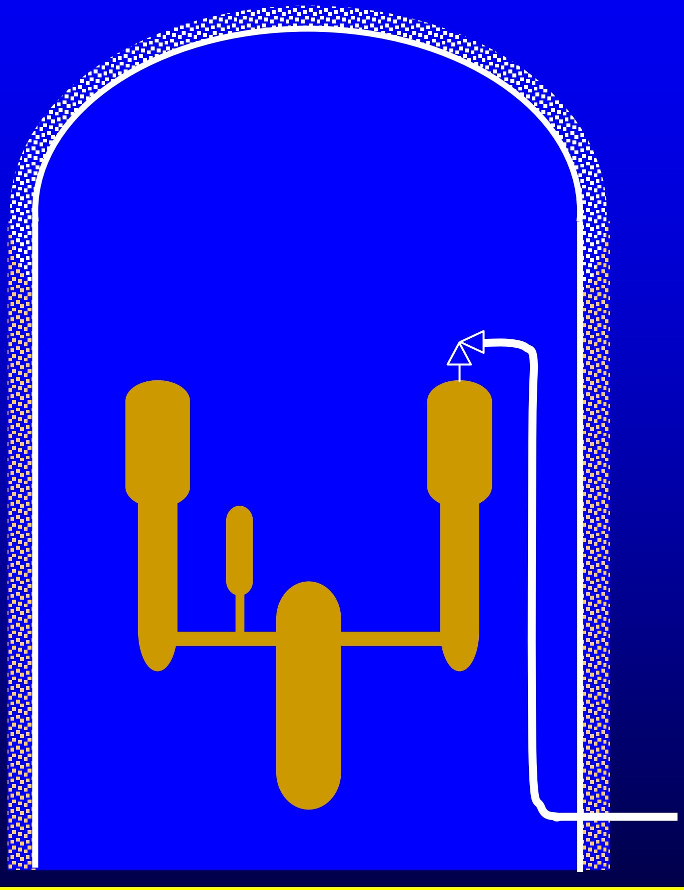
1% / day

Example 2: Aerosol Deposition on an RCS Pipe by Thermophoresis

- Thermophoresis: movement of an aerosol particle due to a local temperature gradient.
- dT/dr creates a net force from a hot gas toward a cooler surface.



Estimating Thermophoretic Deposition



- Example: Steam generator relief valve discharge line during a tube-rupture accident sequence
- Objective: Estimate aerosol deposition in the discharge line by thermophoresis
- Gas effluent temperatures (during core damage) can be very high (~900K)
- Pipe wall temperatures may be cooler if valve opens late in time

Deposition Rate by Thermophoresis

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

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

where: v_t = deposition velocity

dA = surface area normal to Q

Deposition velocity for thermophoresis:

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

where:

T = pipe temperature,

∇T = temperature gradient from the gas to the wall,

dp = particle diameter,

c_t = constant (2.25),

g = gravitational constant,

Kn = 2λ/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,

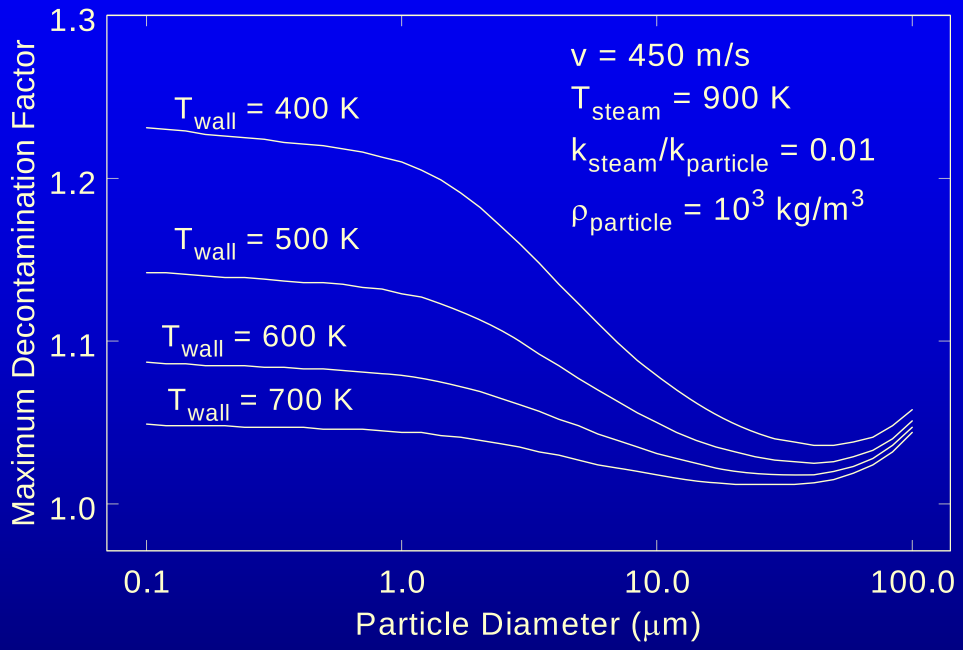
ρ_{gas} = gas density, and

χ = dynamic shape factor; and

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

Results for sample SGTR RV discharge line deposition

- Assume T_{gas} in the pipe ~900K
- T_{wall} is a function of time spanning range of 400K to 700K
- Gas velocities near sonic (~450 m/s)



Result: Deposition significant only for:
Very small aerosols and ΔT > 300°C

Simplified methods -- summary

- Simple, “hand” calculations provide useful information on
    - the time-scale for major deposition mechanisms to operate, and
    - the importance of deposition mechanisms under specific conditions.
- A summary of simplified source term estimation methods can be found in: IAEA-TECDOC-1127.
- BUT -- Simple calculations can not completely replace fully-integrated computer codes calculations of accident source terms
    - However, they help define the level of detail required in modeling plant behavior

Source Term Uncertainties

- Focus of Recent Research -

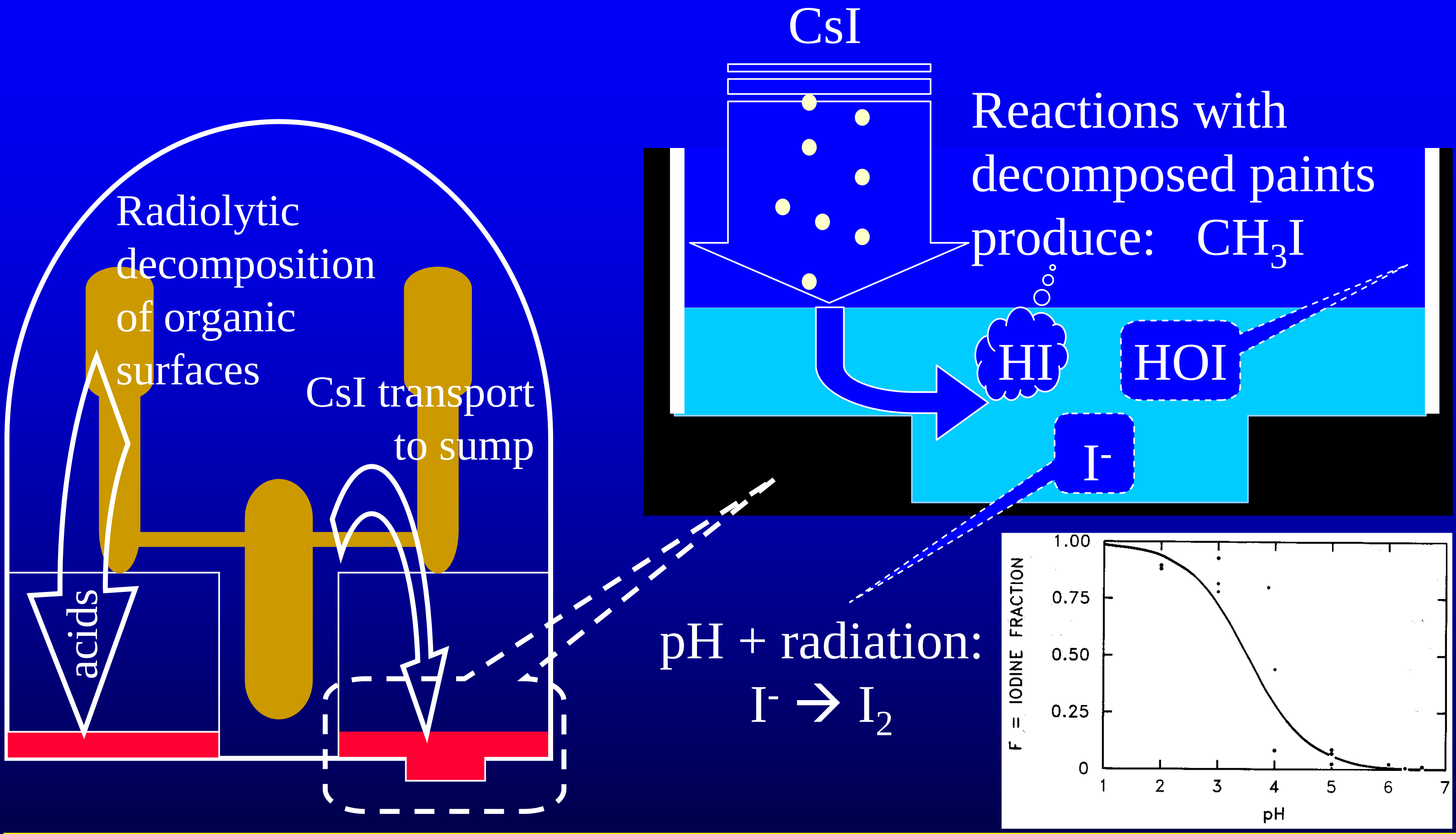
- Chemical form of iodine
  - Phase and chemical transformations occur in containment atmosphere and aqueous solutions
  - Leads to late re-evolution of iodine from pools of water
- Chemical reactions with cesium in the RCS
  - CsI reaction well established
  - Recent evidence from PHEBUS suggests additional reactions with molybdenum ($Cs \rightarrow Cs_2MoO_4$)
  - Challenging historical assumption that most cesium is transported as an oxide ($CsOH$)

- Published validation of source term computer code models for these effects is very limited

Iodine Behavior in Containment

- Cesium iodide (CsI) is the dominant form of iodine transported to containment
- CsI is highly soluable
  - Tendency to collect in pools of water
- Chemical and radiolytic environment enhances reactions that yields volatile forms of iodine
  - Effect is to increase long-term release to environment

Iodine Chemistry



CsI

Reactions with decomposed paints produce: CH_3I

Radiolytic decomposition of organic surfaces

CsI transport to sump

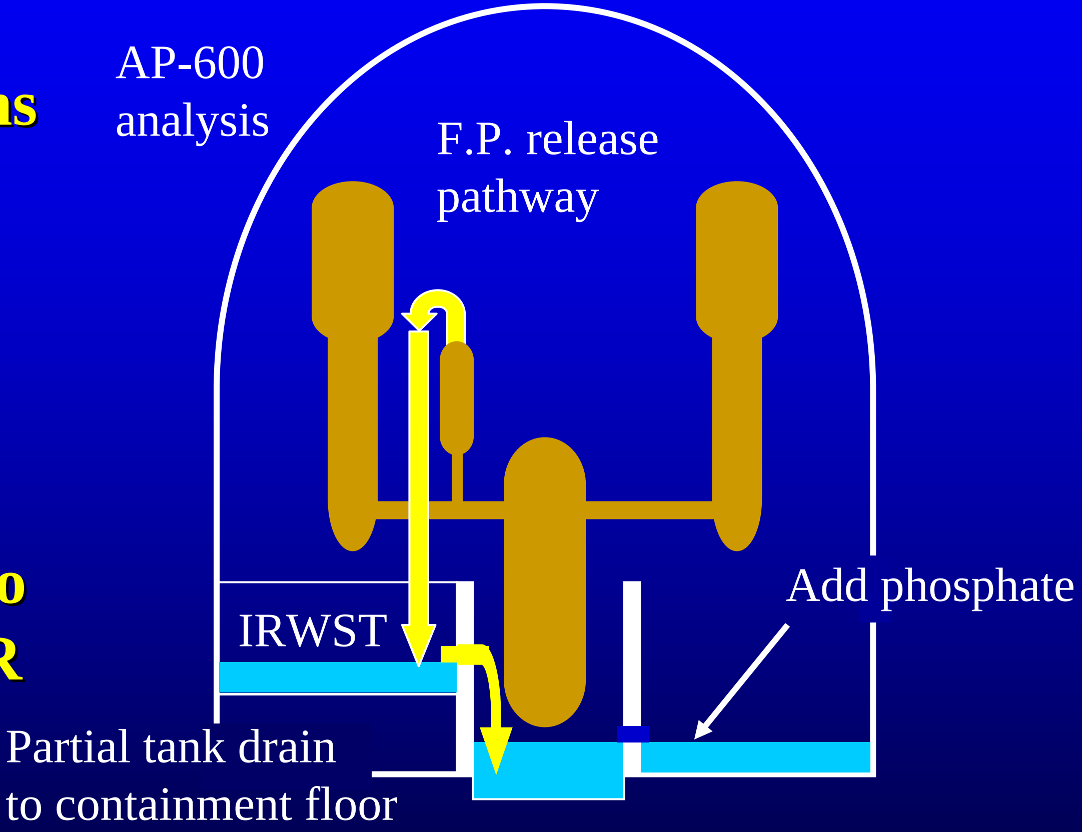
pH + radiation:

$I^- \rightarrow I_2$

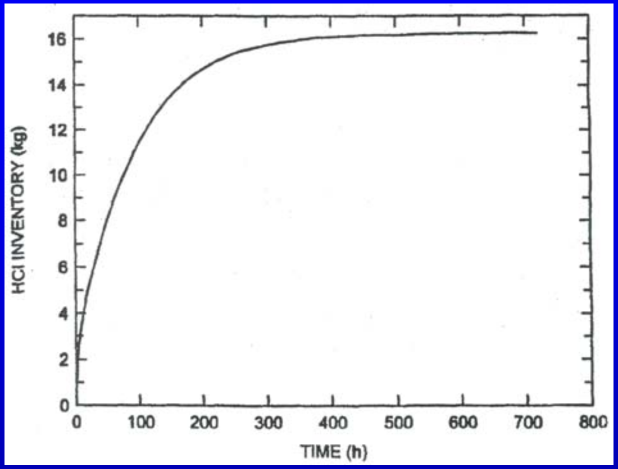
Example Calculation of Long-term Iodine Release

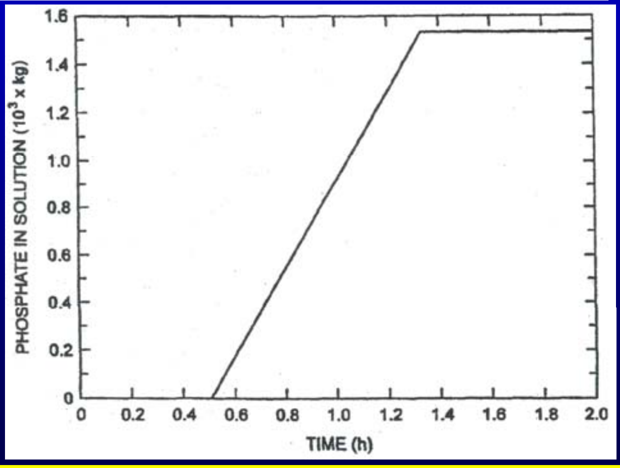
- **Detailed calculations of chemical transformations for representative PWR and BWR**
  - **Evaluate needs for post-accident pH control**

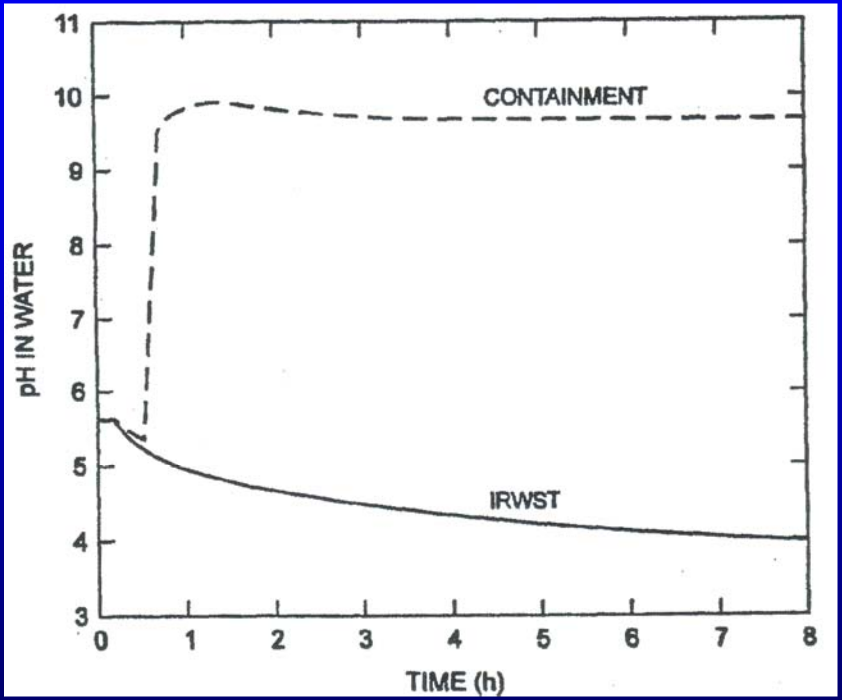
- **Models recently added to TRENDS and MELCOR codes**



Example Calculation: AP-600

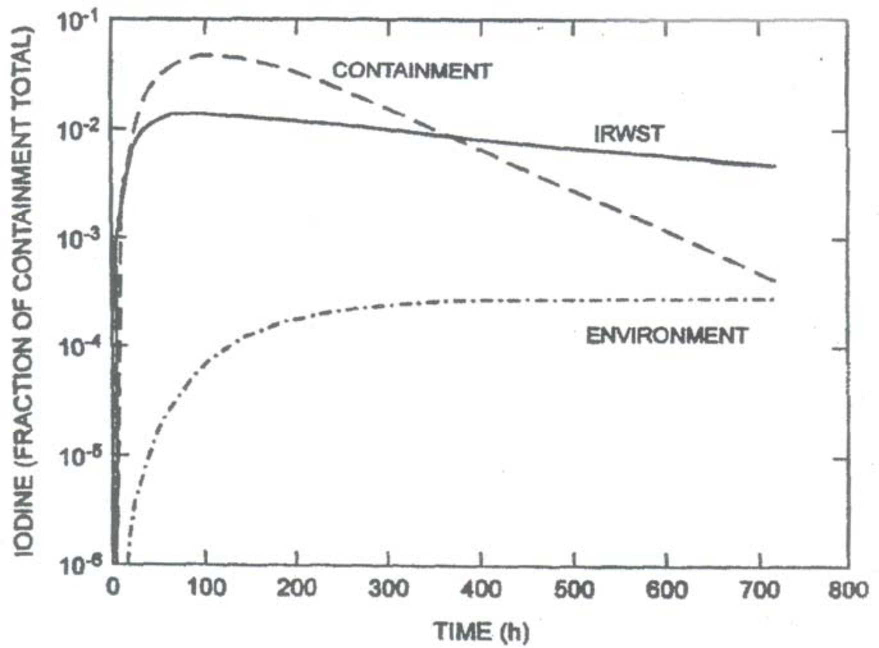


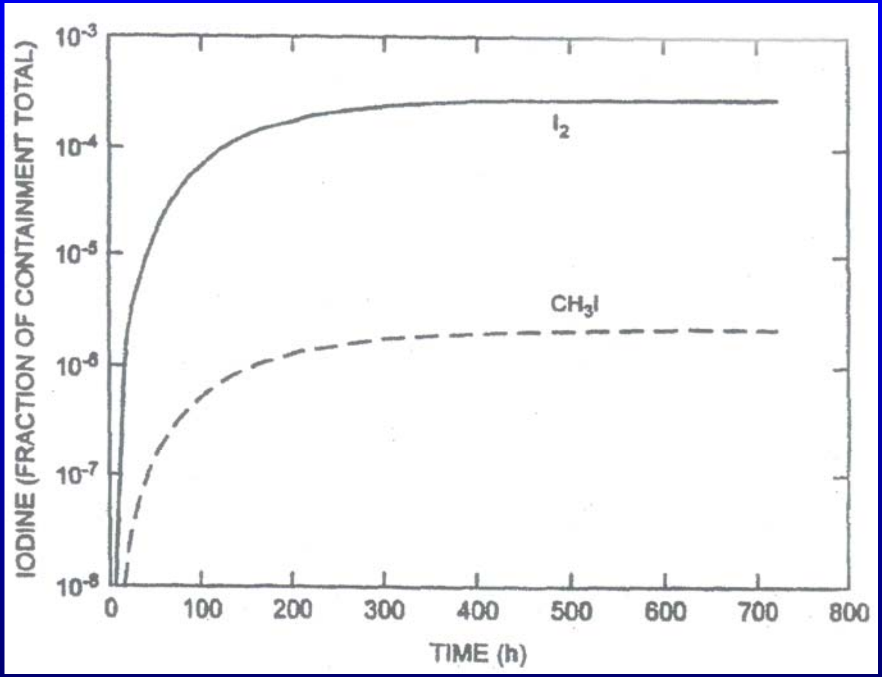




Ref: TRENDS analysis in NUREG/CR-6599, Oct 1998

AP-600 example (2)





Ref: NUREG/CR-6599, Oct 1998

Source Term Phenomena: Summary

- Dominant phenomena for fission product release & transport have substantial data base to support code calculations
  - Well established models exist for fission product release from fuel, aerosol growth and major deposition processes
  - Simple calculation methods are useful for first-order evaluations of major issues
  - Fully-integrated, computer simulations are necessary for a comprehensive source term assessment
- Substantial uncertainties remain
  - Must account for code modeling limitations in defining source terms for Level 2 PSA