Lecture 12 - Technology of Accident Analysis – cont'd

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Nuclear Reactor Safety Course

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Heat Transport System

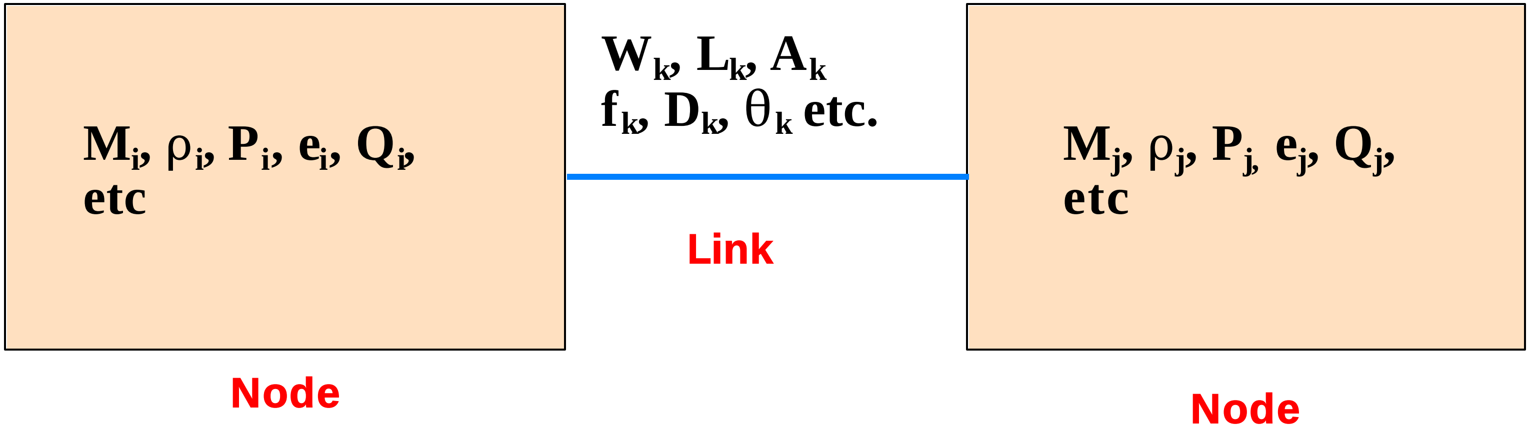
- Equations of mass, energy and momentum conservation for non-equilibrium transient two-phase flow in a network in one-dimension
    - Steam and water
    - Unequal temperature, pressure, flowrate
    - Parallel paths, components connected together

System Thermohydraulic Model

- Equations of state for the various phases
- Component models for steam generators, fuel channels, fuel, headers, secondary side, valves, pumps etc.
- Correlations for pressure-drop, heat transfer (including CHF)
- Efficient numerical solution schemes
- Plant controllers

Typical Link-Node Structure

- Break the circuit up into
  - **nodes** containing mass
  - **links** joining the nodes
- Mass & energy conservation equations for nodes
- Momentum equation for links



M_i, ρ_i, P_i, e_i, Q_i, etc

W_k, L_k, A_k
f_k, D_k, θ_k etc.

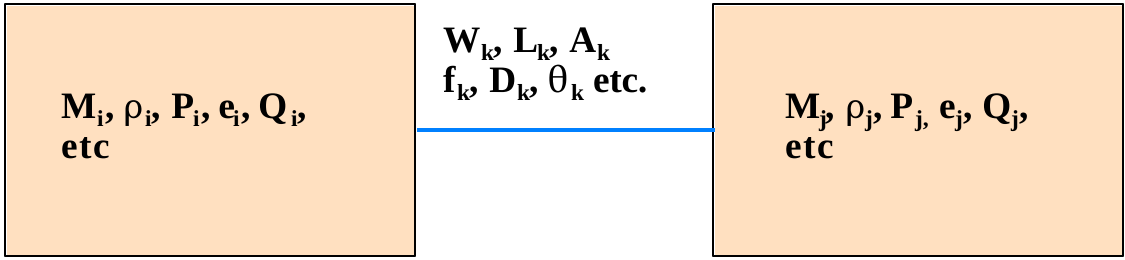
Link

M_j, ρ_j, P_j, e_j, Q_j, etc

Node

Node

1D Flow Level Pipe



M_i, ρ_i, P_i, e_i, Q_i, etc

W_k, L_k, A_k f_k, D_k, θ_k etc.

M_j, ρ_j, P_j, e_j, Q_j, etc

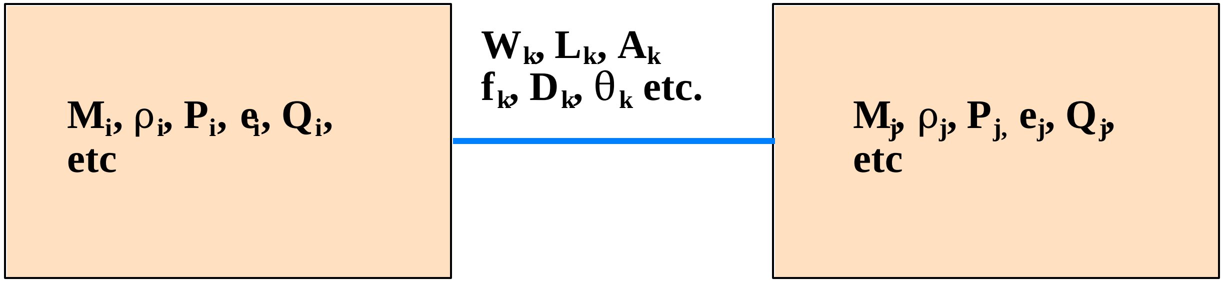
Conservation of Mass

$$\frac{dM_i}{dt} = \sum_k W_k$$

Conservation of Momentum

$$\frac{dW_k}{dt} = \frac{A_k}{L_k}\left[(P_i - P_j) - \left(\frac{f_k L_k}{D_k} + k_k \right) \frac{W_k{}^2}{2 g_c r A_k{}^2} \right]$$

1D Flow – cont'd



M_i, ρ_i, P_i, e_i, Q_i, etc

W_k, L_k, A_k
f_k, D_k, θ_k etc.

M_j, ρ_j, P_j, e_j, Q_j, etc

Conservation of Energy

$$\frac{dU_i}{dt} = \sum W_{in} e_{in} - \sum W_{out} e_{out} + Q_i$$

Equation of State

$$r = f(P,T)$$

Flow Regimes

- Flow stratification:
  - Small LOCA
  - Intact loop
  - Long term ECC
  - Headers

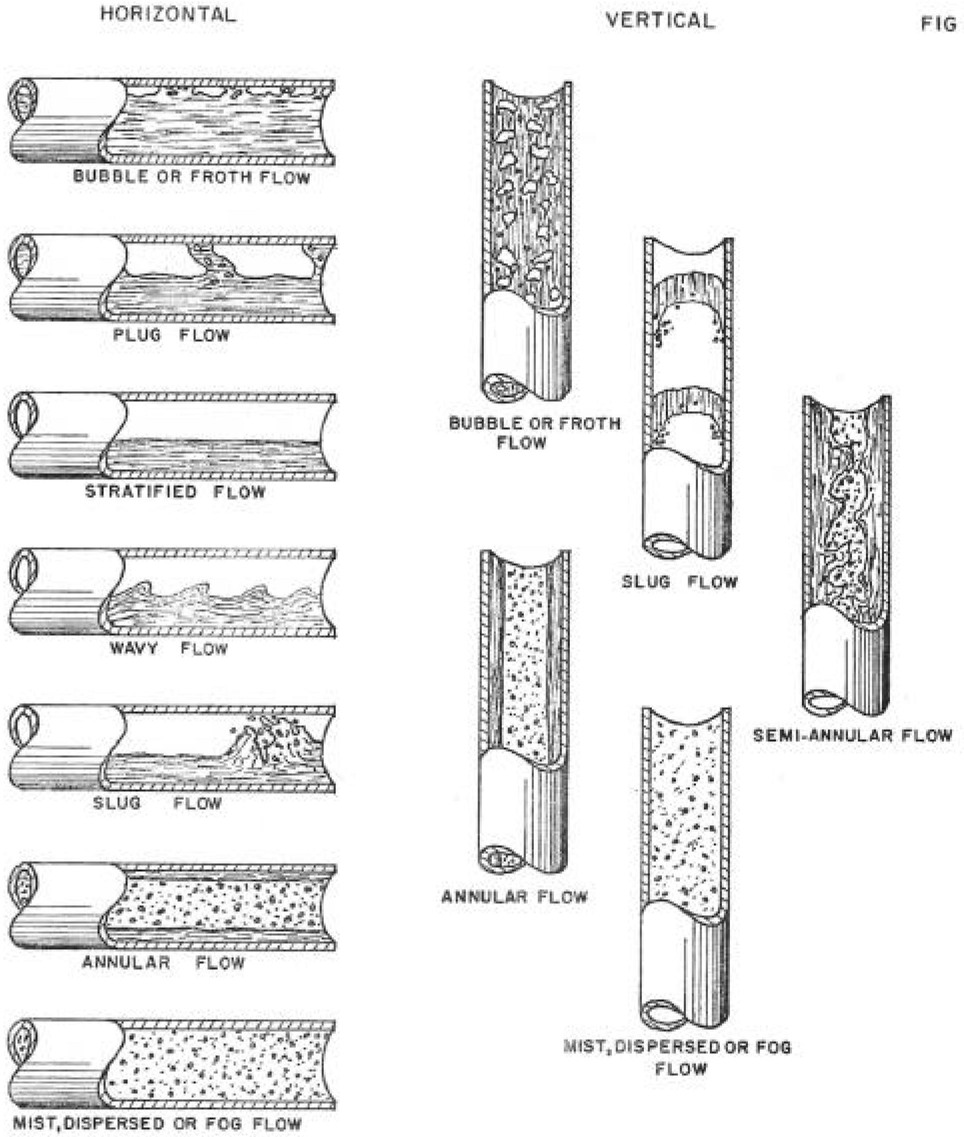


FIG I-

HORIZONTAL & VERTICAL FLOW PATTERN SKETCHES

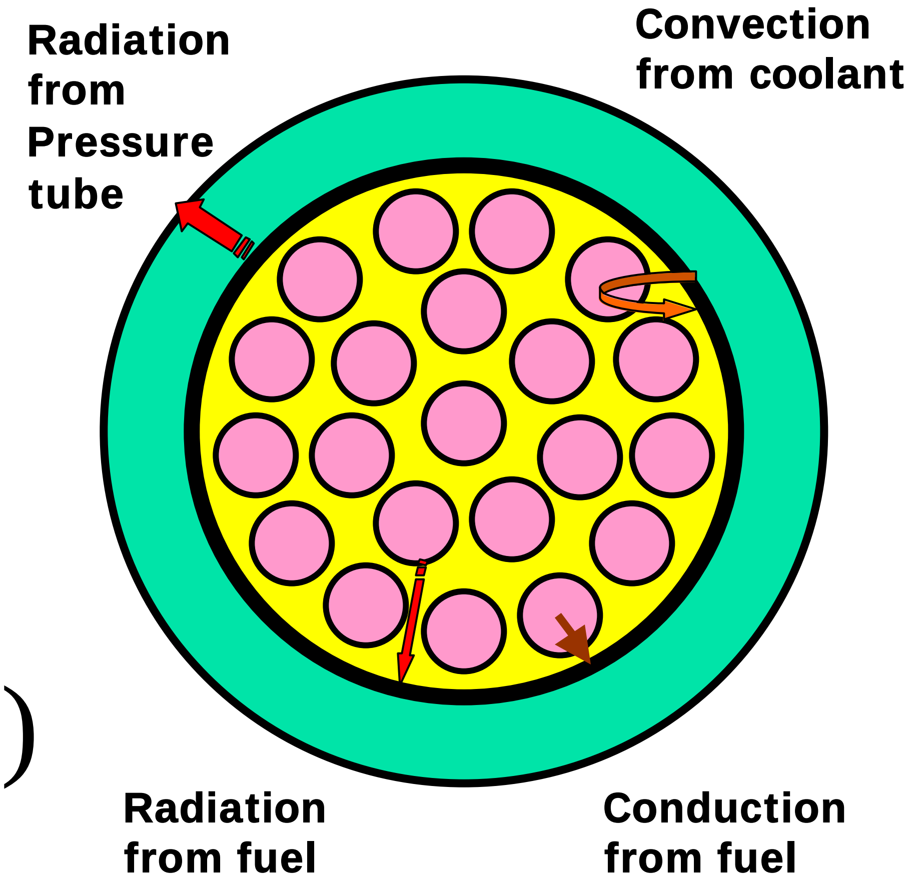
Fuel Channels (in accidents)

- Heat transfer
- Stress-strain behaviour
- Hydrogen chemistry

Heat Transfer

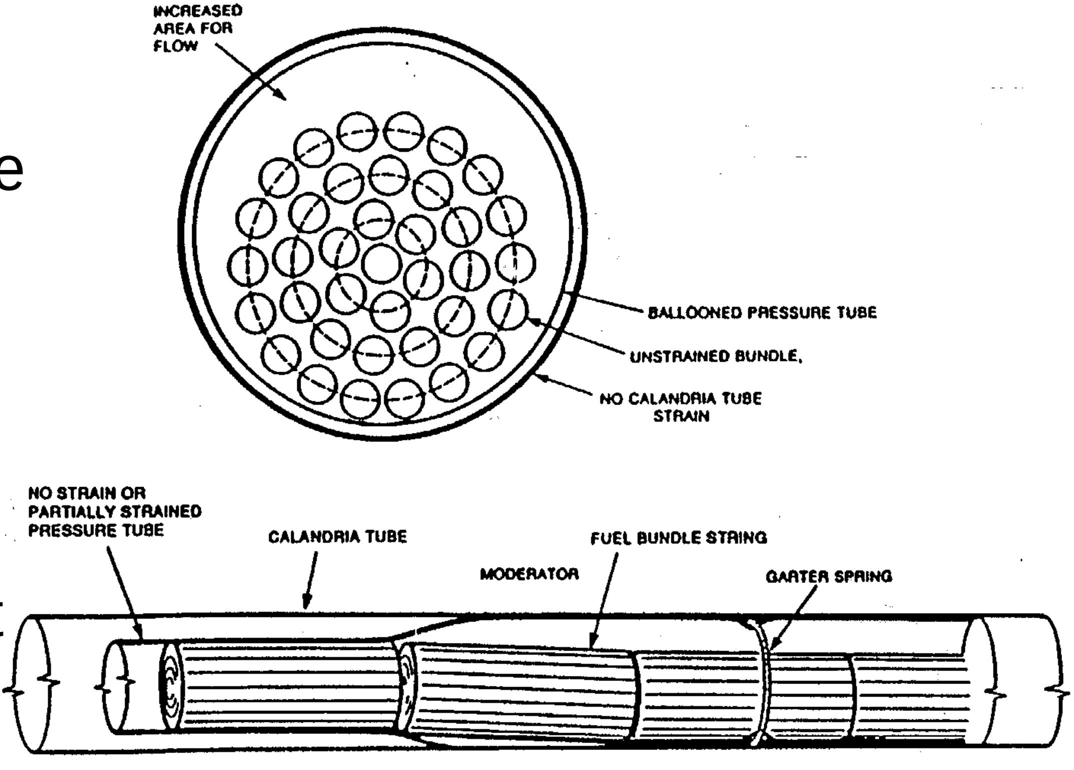
- Convection and conduction from coolant
- Conduction from fuel if in contact
- Radiation from fuel

$$E = e\,s\,(T_f^4 - T_{PT}^4)$$

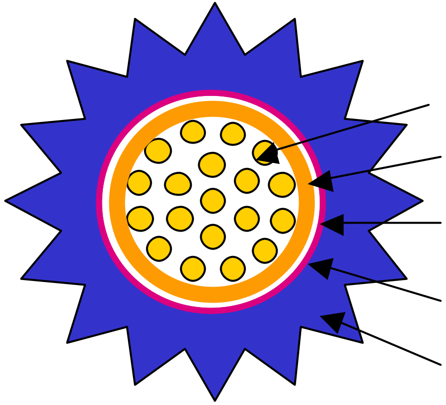


Pressure Tube Strain (>600C)

- Strain to contact calandria tube at moderate pressure (>1MPa)
- Sag to contact calandria tube at low pressure (<1MPa)
- Strain to failure at high pressure (>6MPa)



Modes of Heat Rejection



Fuel

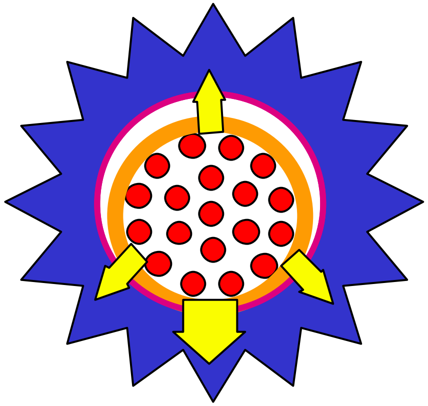
Pressure tube

Gas Annulus

Calandria Tube

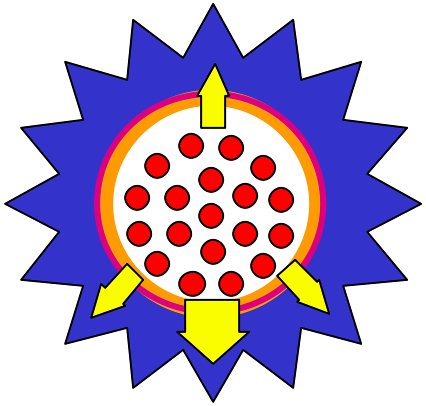
Moderator

Normal



Low Pressure (Sag)

⇨ **Heat flow**



High Pressure (Expand)

Hydrogen – quadruple threat

- Oxygen embrittlement of sheaths & PT
- Heat increases fuel & PT temperatures
- Effect of non-condensables on ECC
- Collects in containment & can burn
  - >4% - burn
  - >10% - detonate (depends on steam fraction)

At high fuel temperatures:

$$Zr + 2H_2O \Rightarrow ZrO_2 + 2H_2 + heat$$

In the long term:

$$H_2O + radiation \longrightarrow H_2 + O$$

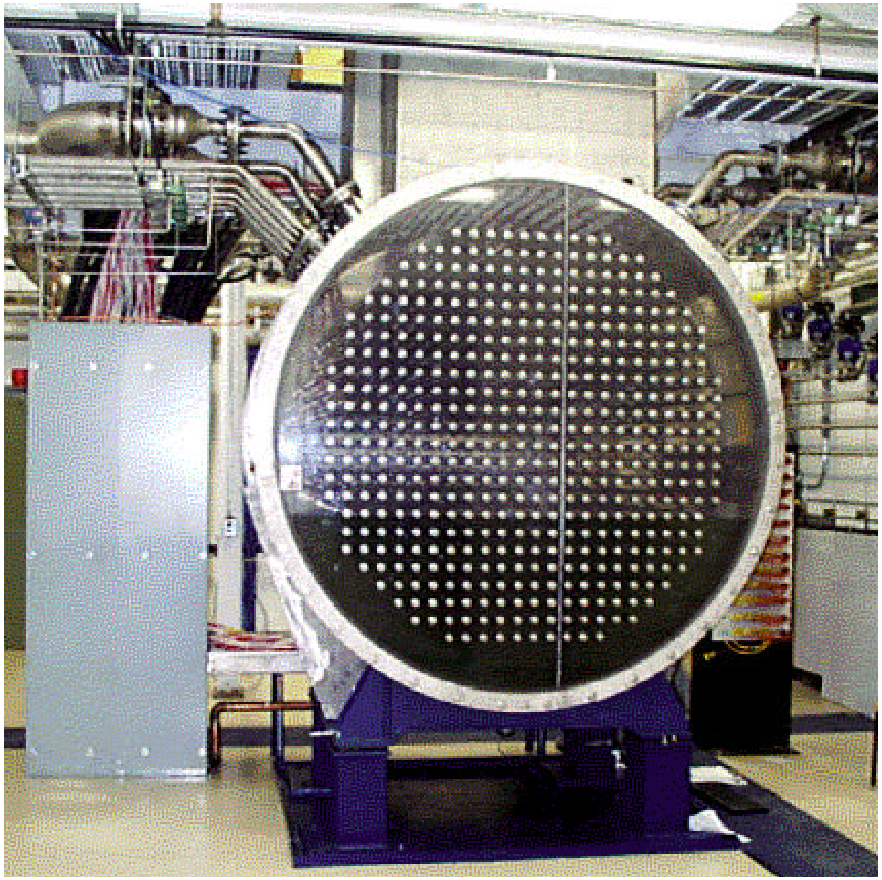
$$O + O \longrightarrow O_2$$

Limits to hydrogen generation

- For T_S~1500C, auto-catalytic
  - For LWRs, no place for heat to go except to fuel nearby
    - Put limit on sheath temperature of 1200C
  - For CANDU, <3 inches from any fuel element to pressure tube
    - Put limit on amount of predicted oxidation

Moderator – Transient Local Temperature

- Solve 3D fluid flow with heat addition in a porous medium
- Mass, momentum & energy equations generalized to 3D
- Need experimental validation because of complex geometry



Moderator – Chemistry

- Formation and recombination of deuterium gas
- Changes in chemistry can cause rapid evolution of D_2

$$2D_2O + radiation \longleftrightarrow 2D_2 + O_2$$

- Can also cause Gd precipitation

Containment

- Same physics as heat transport system, but:
  - Containment volume compartmentalized
  - Flow within the larger compartments is 3D
- Fluids coexist: air, steam/water, & hydrogen
- Heat is added by
  - Steam and hot water
  - Radioactive decay of any fission products
  - Motors, lights
- Heat is removed by
  - Dousing (water sprays)
  - Condensation on walls & surfaces; conduction through wall (slow)
  - Containment air coolers
  - Mass transport (leakage / venting)

Containment Pressure

- Set by heat addition vs. removal and mass transport:
  - Vacuum building (in multi-unit plants)
  - Leakage from containment through cracks
  - Deliberate venting through filters or sand beds

Fission Product Source Term

$$\text{Fission rate} = \text{P MW x } \frac{10^6\text{joule}}{\text{MW}-\text{sec}} \text{ x } \frac{\text{fissions}}{200\,\text{Mev}} \text{ x } \frac{\text{Mev}}{1.60\text{x}10^{-13}\text{joule}} \qquad (1)$$

$$= 3.13 \text{ x } 10^{16} \text{ P fissions/sec.}$$

If yield of *i*th. fission product is g_i per fission:

$$\text{rate of production} = 3.13\text{x}10^{16} \text{ P } ?_i \text{ atoms/sec.} \qquad (1)$$

Activity in core is:

$$a_i = 3.13\text{x}10^{16} \text{ P } ?_i\left(1 - e^{-?_i t}\right) \text{disintegrations/sec.} \qquad (1)$$

Source Term in Fuel

In Curies:

$$a_i = \frac{3.13 \mathrm{x} 10^{16}\ P\ ?_i}{3.7 \mathrm{x} 10^{10}} \left(1 - e^{-?_i t}\right) \text{ disintegrations/sec.} \qquad (1)$$

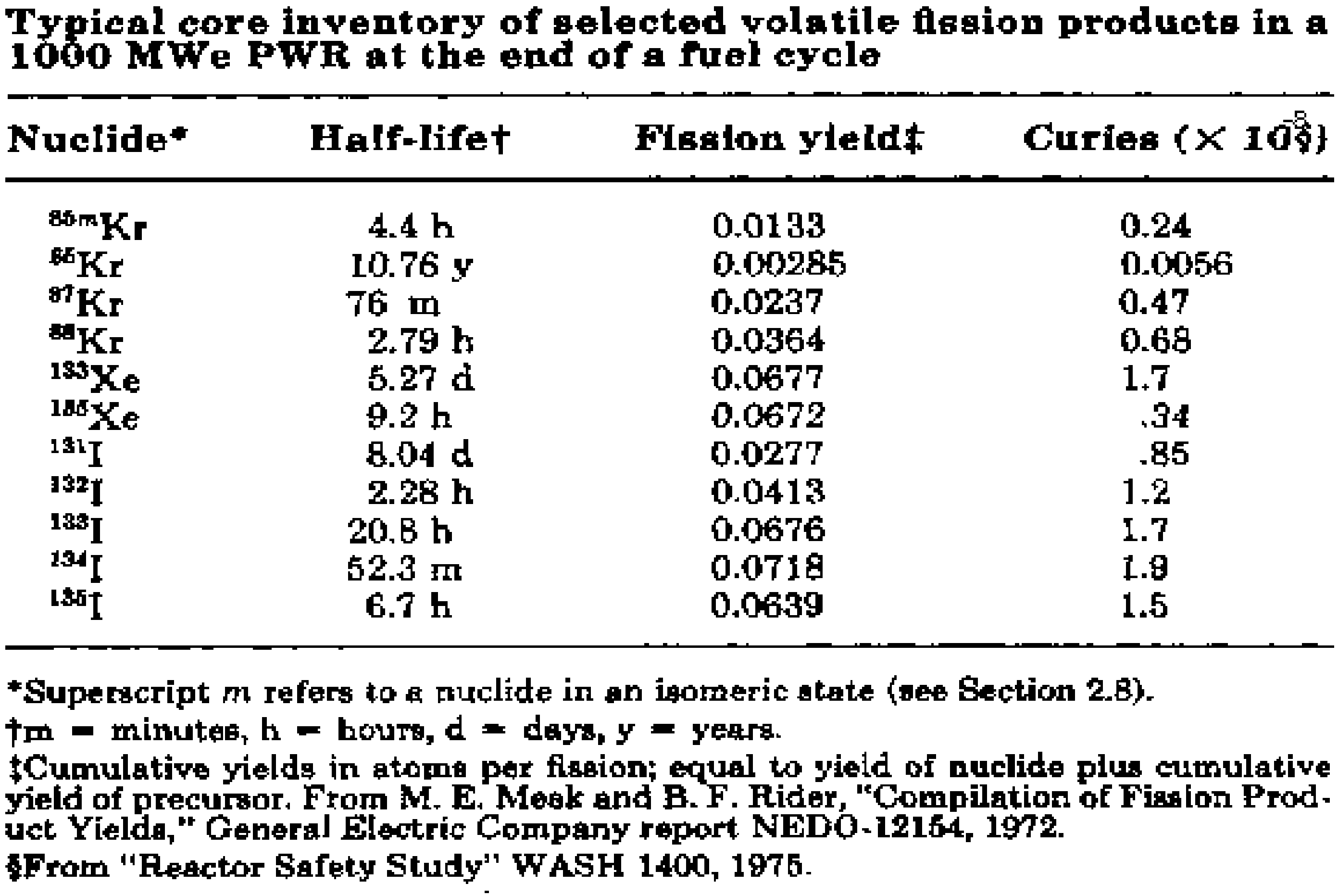
$$= 8.46 \text{ x } 10^5\ P\ ?_i \left(1 - e^{-?_i t}\right) \text{ Ci}$$

If activity saturates:

$$a_i = 8.46 \text{ x } 10^5\ P\ ?_i \text{ Ci} \qquad (1)$$

This is the amount available for release from the fuel

FP Inventories 1000MWe PWR



Typical core inventory of selected volatile fission products in a 1000 MWe PWR at the end of a fuel cycle

Nuclide*	Half-life†	Fission yield‡	Curies (× 10^8)§
^{85m}Kr	4.4 h	0.0133	0.24
^{85}Kr	10.76 y	0.00285	0.0056
^{87}Kr	76 m	0.0237	0.47
^{88}Kr	2.79 h	0.0364	0.68
^{133}Xe	5.27 d	0.0677	1.7
^{135}Xe	9.2 h	0.0672	.34
^{131}I	8.04 d	0.0277	.85
^{132}I	2.28 h	0.0413	1.2
^{133}I	20.8 h	0.0676	1.7
^{134}I	52.3 m	0.0718	1.9
^{135}I	6.7 h	0.0639	1.5

*Superscript *m* refers to a nuclide in an isomeric state (see Section 2.8).

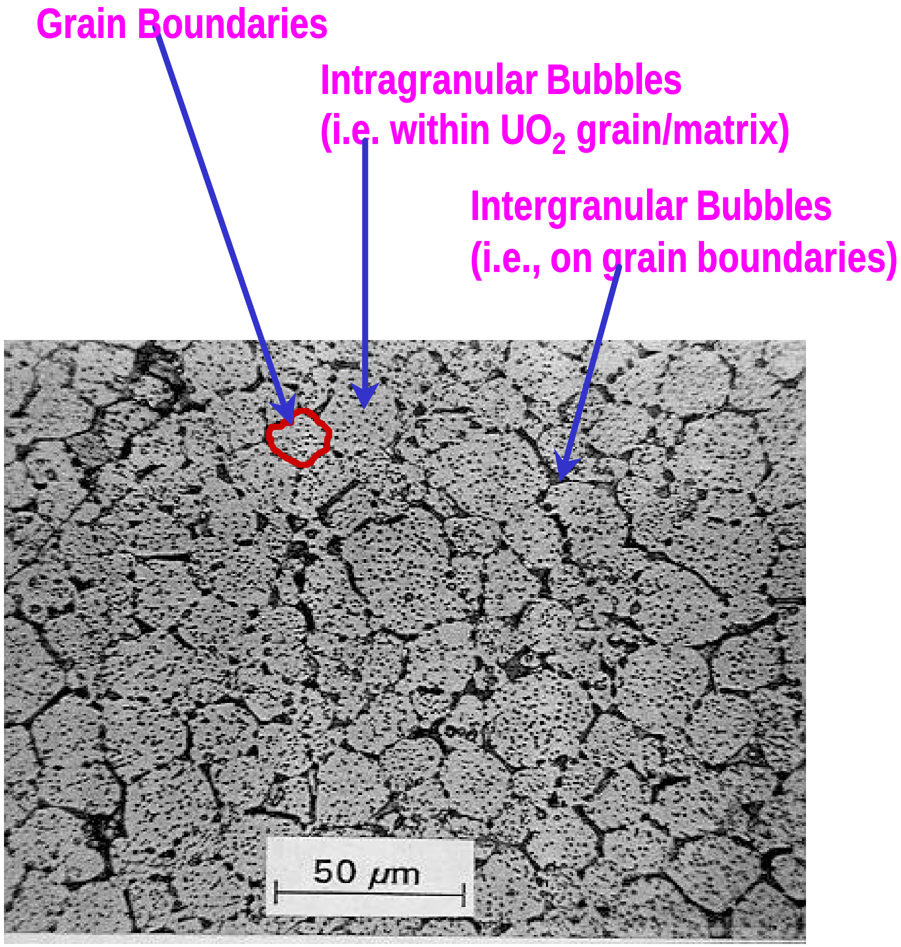
†m = minutes, h = hours, d = days, y = years.

‡Cumulative yields in atoms per fission; equal to yield of nuclide plus cumulative yield of precursor. From M. E. Meek and B. F. Rider, "Compilation of Fission Product Yields," General Electric Company report NEDO-12154, 1972.

§From "Reactor Safety Study" WASH 1400, 1975.

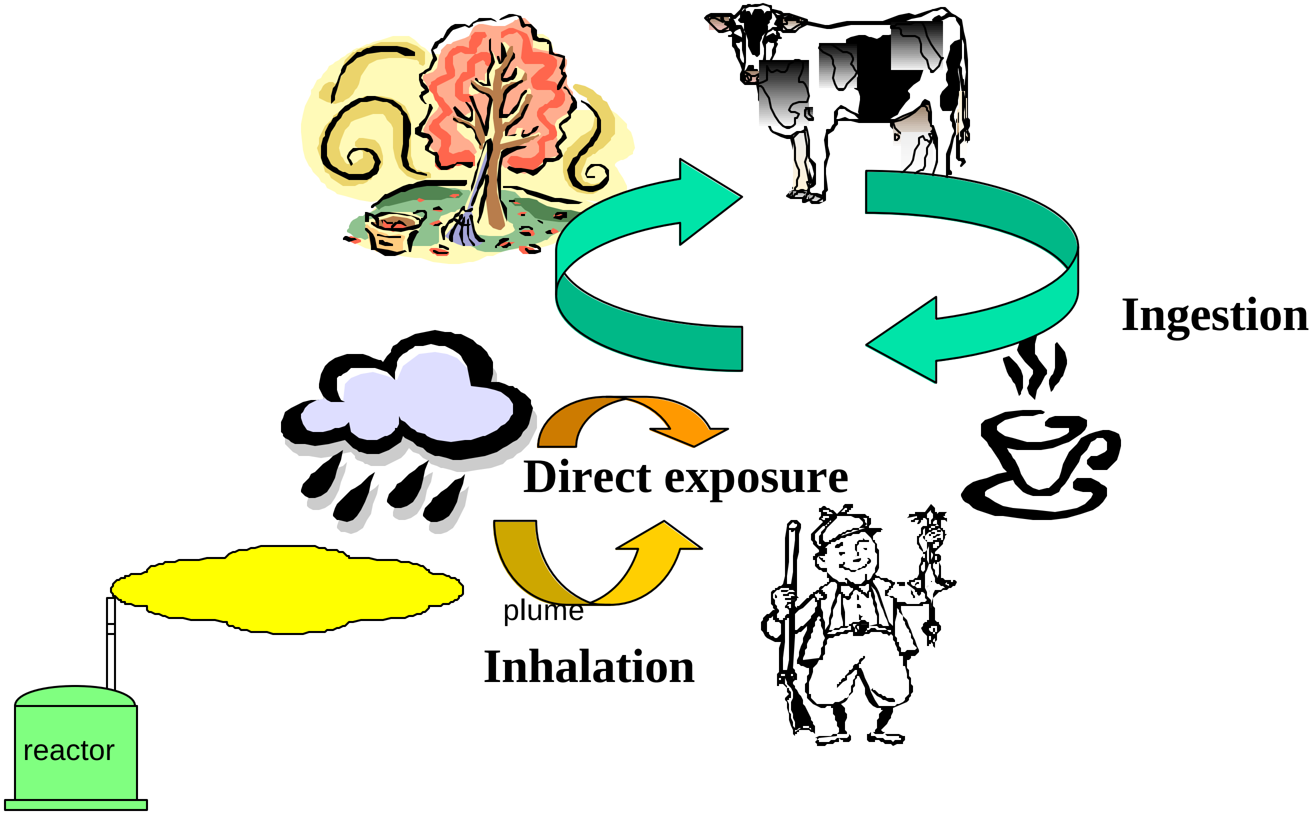
Fission Product Transport

- Noble gases
  - Little interaction with water or surfaces
- Tritium oxide
  - Behaves like steam & water
- Iodine, caesium, strontium, etc.
  - Interact strongly with water (dissolve) and tend to plate out on surfaces;
- Actinides (plutonium)
  - released from the fuel only if core is destroyed.



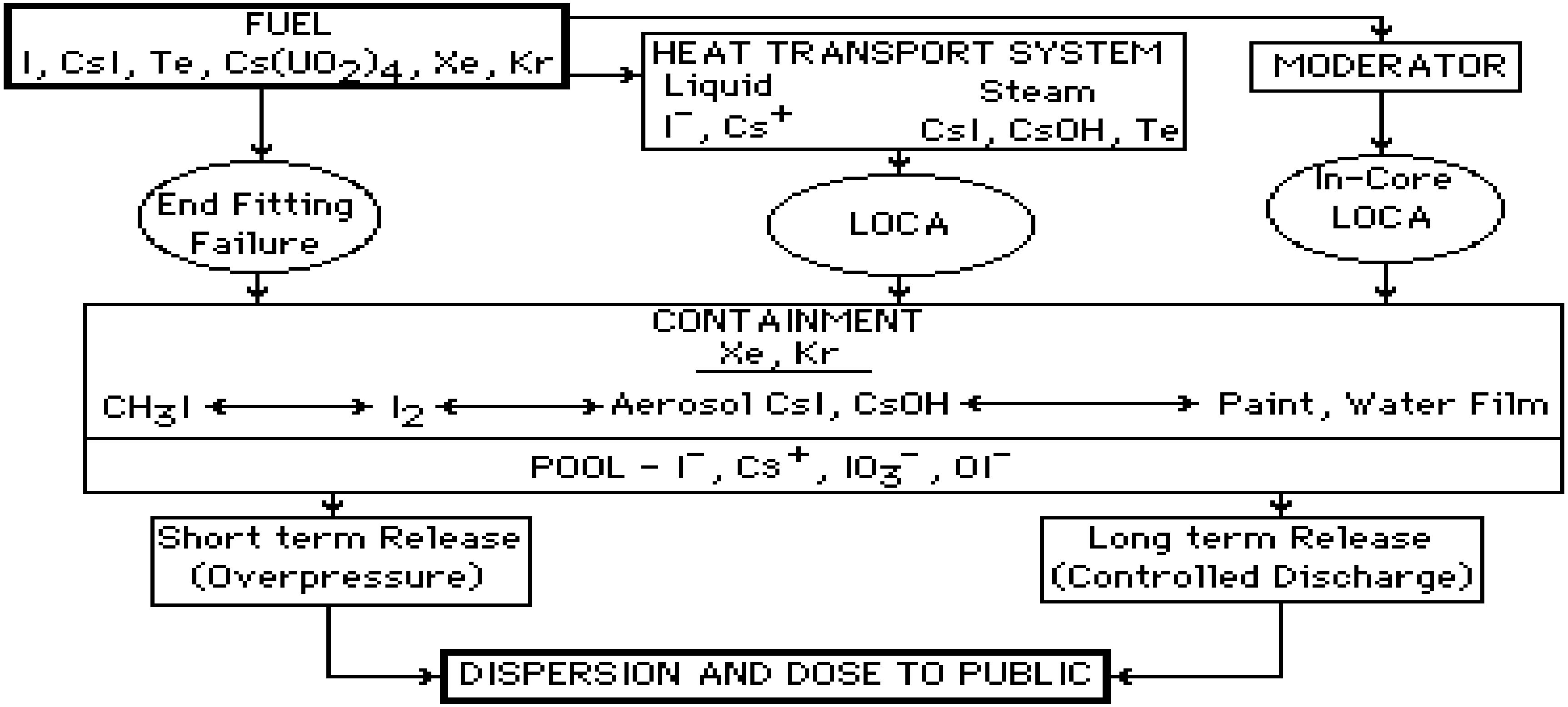
Iodine-131

- Dose from:
  - Ingestion
  - Inhalation
  - External
- Control via high pH in containment water
  - Tri-sodium phosphate



FP Transport - Summary

FIGURE 1.1 – Fission Product Behaviour under Accident Conditions



FUEL

I, CsI, Te, $Cs(UO_2)_4$, Xe, Kr

HEAT TRANSPORT SYSTEM

Liquid

I^-, Cs^+

Steam

CsI, CsOH, Te

MODERATOR

End Fitting Failure

LOCA

In-Core LOCA

CONTAINMENT

Xe, Kr

CH_3I ↔ I_2 ↔ Aerosol CsI, CsOH ↔ Paint, Water Film

POOL – I^-, Cs^+, IO_3^-, OI^-

Short term Release (Overpressure)

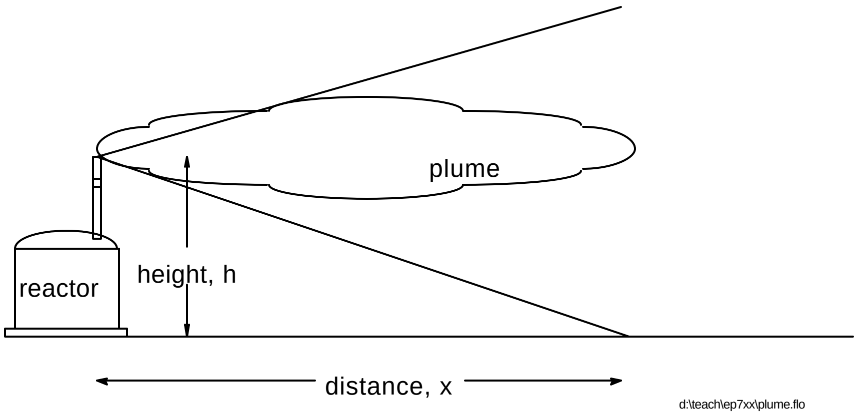
Long term Release (Controlled Discharge)

DISPERSION AND DOSE TO PUBLIC

Atmospheric Dispersion

- Assume release of nuclide
  - concentration *C*
  - leak rate *V*
  - height *h*
- Release rate *Q* :

$$Q=CV$$



Gaussian Dispersion Model

Concentration c **at distance *x* is:**

$$? = \left(\frac{2}{p}\right)^{1/2} \frac{Q}{s_z \bar{u}} \frac{f}{?x} e^{-h^2/2s_z^2} \qquad (1)$$

where ? is the sector-averaged long-term concentration in Bq/m^3 a distance x metres from the source, and will be uniform through the sector

Q is the release rate in Bq/s from a source h metres in height

s_z is the vertical diffusion coefficient in metres

? is the angle subtended by the sector [radians]

f is the fraction of time the wind blows into the sector

u is the mean wind velocity in m/s.

Dose

Given Q, χ, geometry of release etc., the dose at the point *x* is found from:

$$\boxed{\text{Dose} = \chi \text{ times (Dose conversion factor)}}$$

e.g., for Ar^{41}, 1 Bq/m^3 gives a dose of 2.3×10^{-10} Sv/hr