INTRODUCTION TO THERMAL HYDRAULICS

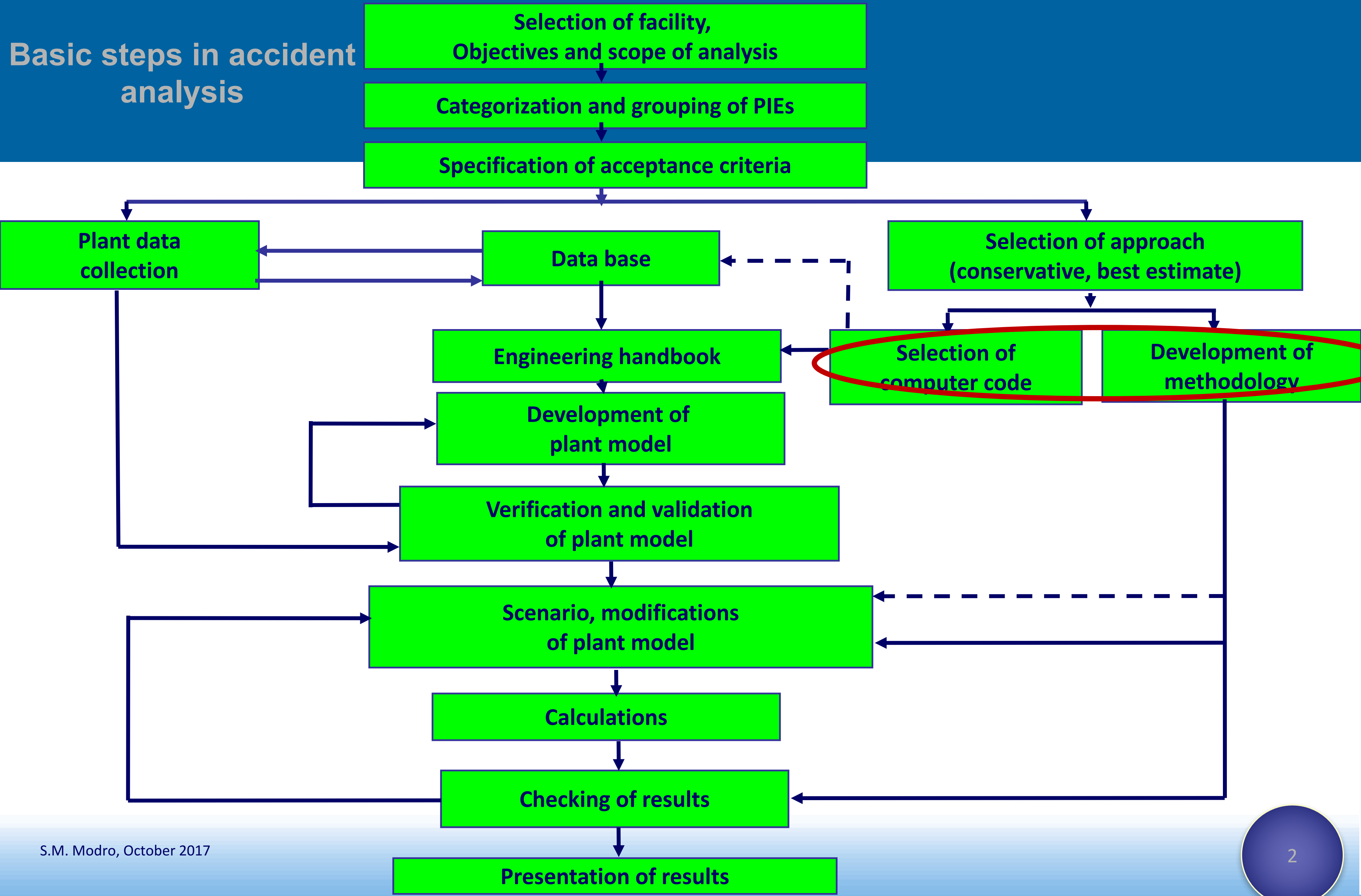
S. Michael Modro

Joint IAEA-ICTP Essential Knowledge Workshop on Nuclear Power Plant Design Safety-Updated IAEA safety Standards

9-20 October 2017

Trieste, Italy

Basic steps in accident analysis



Deterministic Safety Analyses

- Deterministic safety analyses predict the response of an NPP to postulated initiating events.
  - The likelihood of the initiating event is not considered. They apply a specific set of rules and acceptance criteria.
  - Typically, they focus on neutronic, thermal-hydraulic, radiological, thermo-mechanical and structural aspects, which are often analysed with different computational tools.
  - The computations are usually carried out for predetermined operating modes and operational states and include anticipated transients, postulated accidents, selected design extension conditions and severe accidents with core degradation.
  - The results of computations are spatial-time dependencies of physical variables (neutron flux, thermal power of the reactor, pressure, temperature, flow rate and velocity of the primary coolant, stresses in structure materials, physical and chemical compositions, concentrations of radionuclides, etc.) or, in the case of an assessment of radiological consequences, the dose to workers or the public.

Introduction to thermal-hydraulic basis of system codes

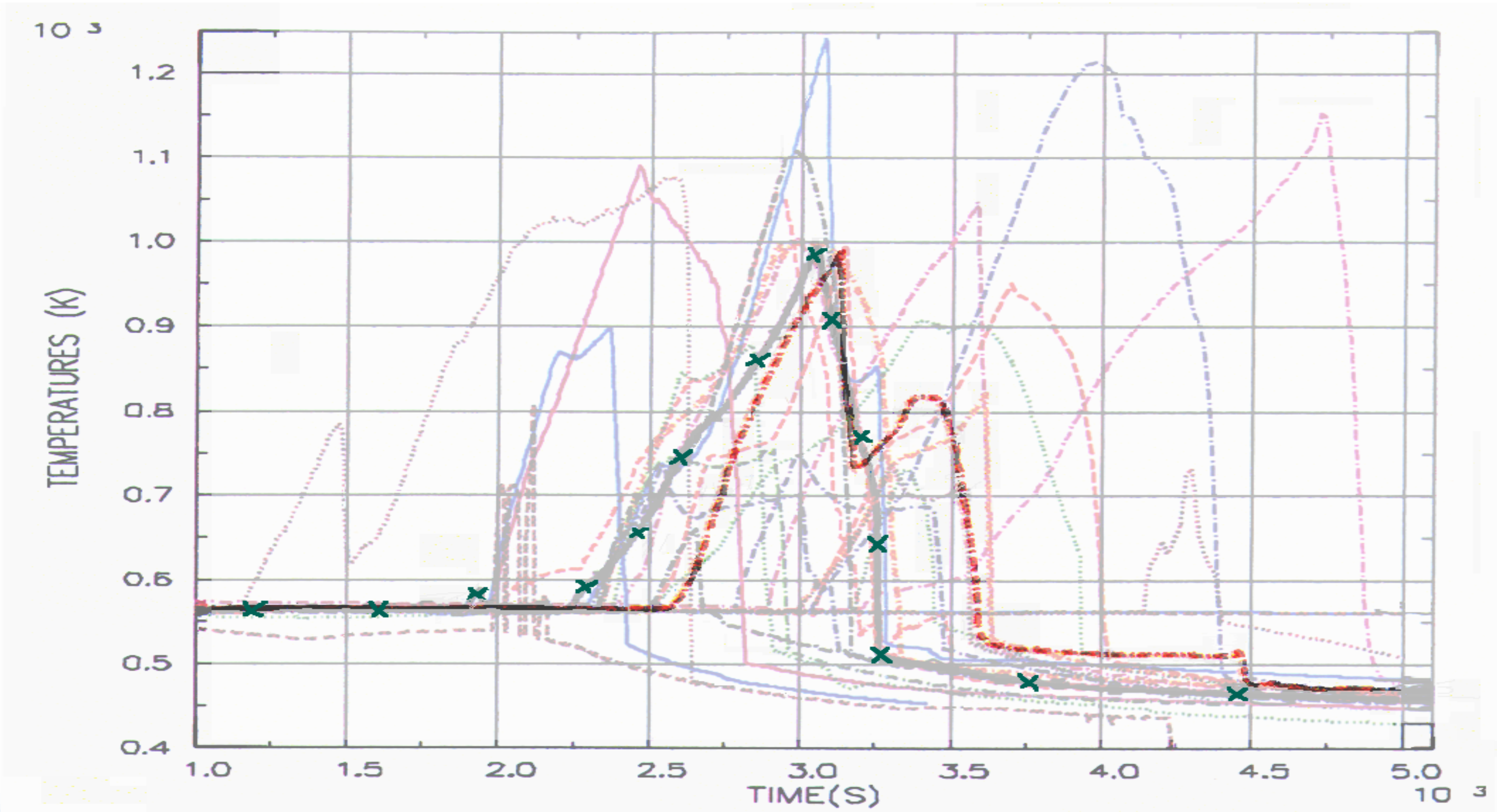
Discuss of the basic modeling concepts underlying system thermal hydraulic codes.

Outline

- **Code uncertainty**
- **Brief discussion of physical process during postulated accidents**
- **Fluid Flow – Basic Concepts**
- **Heat Transfer – Basic Concepts**
- **Special models**
- **Models and inputs**

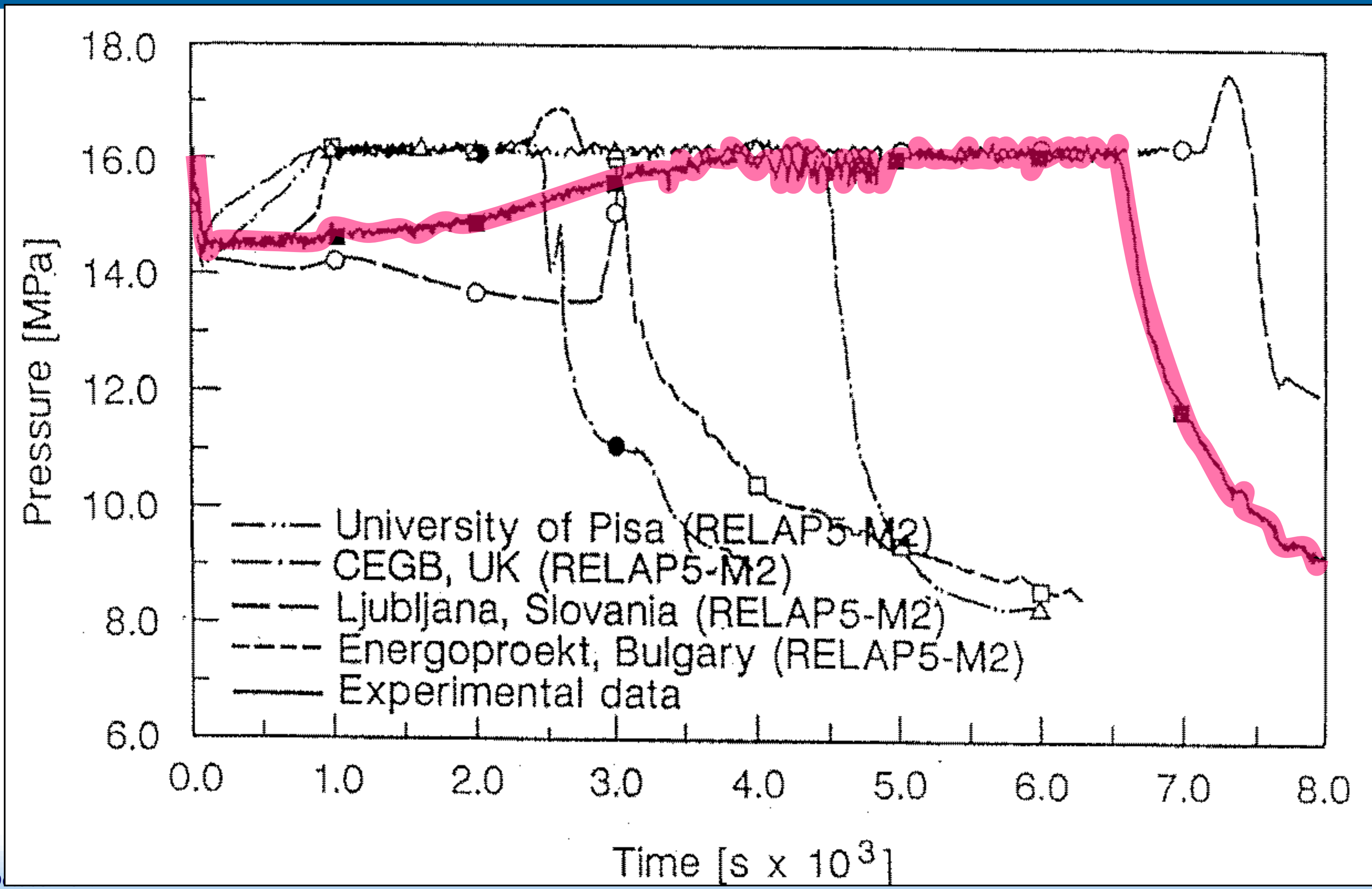
Computer Codes and Applications

Example of code validation: ISP-27



PCT **(**pre-test calculation**):** **x** - experiment, ---- - TRAP (Russia)

Dispersion of results obtained by participants performing "blind" calculations for ISP-22 (SPES facility) by using RELAP5/Mod2 code



Code (analysis) Uncertainty (1/2)

- Code related uncertainties may be related to:
  - Conservation equations
  - Constitutive correlations (equations)
  - Material properties
  - Special process and component models
  - Numerics
- Examples related to balance equations
  - Conservation equations are approximate
  - Only one velocity per phase (for example liquid droplets and film) is considered by the codes.
  - The lack of consideration of the velocity profile (i.e. cross-section averaging).
  - Geometry averaging at a volume scale (only one velocity vector per phase is associated with a hydraulic mesh along its axis).
  - Energy and momentum dissipation associated with vortices are not directly accounted for.

Code (analysis) Uncertainty (2/2)

- Examples related to constitutive equations
  - Range of validity is not fully specified or equations are used outside their range of validation (e.g., wall-fluid friction factors in 2-phase conditions when pipe diameter is of 1 m order).
  - Usually equations are obtained under steady state and fully developed flow conditions, but almost in no region of NPP do these conditions apply during an accident.
  - Equations are obtained from ensembles of experimental data that unavoidably show scatter and are affected by errors or uncertainties.
- Representation related uncertainties originate from setting up the input model as a connection between code and 'physical reality' to be simulated. This process is carried out by code users, and limitation of available resources, lack of data, target of code application, available computer and expertise of users play significant role in this process. This "user effect" may strongly affect the response of code.

History of code development - examples (1/2)

- Development of Computer Code for System T/H Analysis (in US)
  - During the 1960s, Stable Numerical Integration of Conservation Equations for Hydraulic Network (Porshing, Murphy, Redfield; Westinghouse) ☐
  - FLASH Series
    - ✓ FLASH (1966 : Bettis Atomic Power lab.) ☐
    - ✓ WFLASH (W; 1974), CEFLASH (CE; 70s)
      - Commercial LOCA code for vendors (BART,BASH, CEFLASH-4AS, etc) ☐
  - RELAP Series
    - ✓ RELAPSE(1966), RELAP 2,3,4-Series (INEL, 1971,1975,1981)
    - ✓ Final version of RELAP4/MOD7 was released to NESC in 1980
    - ✓ Merged into RETRAN Series (EPRI) Code (Final version RETRAN-03) ☐
    - ✓ Semi-implicit method for two phase fluid dynamics (LANL, 1977)
    - ✓ RELAP5-Series (INEL, since late 1970s)
    - ✓ Last version RELAP5/MOD3.3 , RELAP5-DOE
  - TRAC Series
    - ✓ TRAC-P Series (LANL 1977, 1979, 1981), TRAC-B Series (INEL) ☐ Consolidation program (USNRC 1997)
    - ✓ TRACE (PSU, 2002)

History of safety analysis code development - non US examples

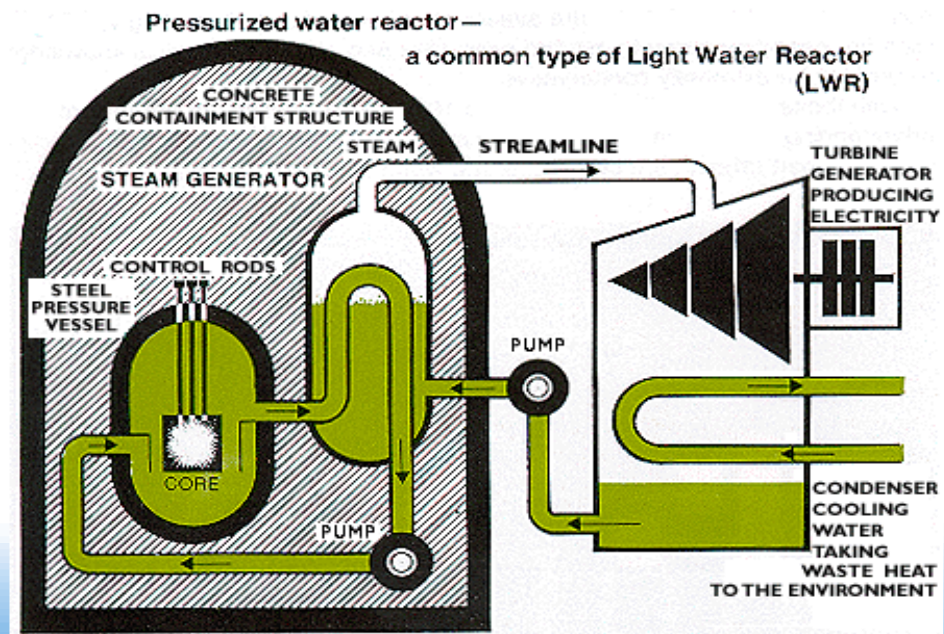
- System analysis codes
  - French Code
    - ✓ ☐ CATHARE (1980s) : two fluid model – test facility : BETHSY ☐
  - German Code
    - ✓ ☐ ATHLET (1980s) : two phase based on drift flux model – test facility: PKL ☐
  - Canadian Code
    - ✓ ☐ CATHENA(1990s) : two fluid – test facility RD14 ☐
    - ✓ Japan, Korea
  - ☐ J-TRAC(1980s, based on TRAC-PF1) – test facility : LSTF
    ☐ MARS(1990s, based on RELAP-COBRA) (test facility : ATLAS)
- ☐ Other Component Analysis Code
  - COBRA-Series, Core Subchannel Code
  - ☐ CONTEMPT-Series; Containment Analysis Code
- ☐ Utilization of GUI (after 2000)
  - ☐ RELAP5-GUI(INEL)
  - ☐ SNAP (USNRC: RELAP, TRAC)
  - ☐ VISA (KAERI; RELAP, MARS, RETRAN)
  - ☐ SIPA (CEA, CATHARE)

- Uncertainty
- Brief discussion of physical process during postulated accidents
- Fluid Flow
- Constitutive relations and special models
  - Flow regimes
  - Heat transfer
- Models and inputs
- Uncertainty

Important physical processes in a light water reactor

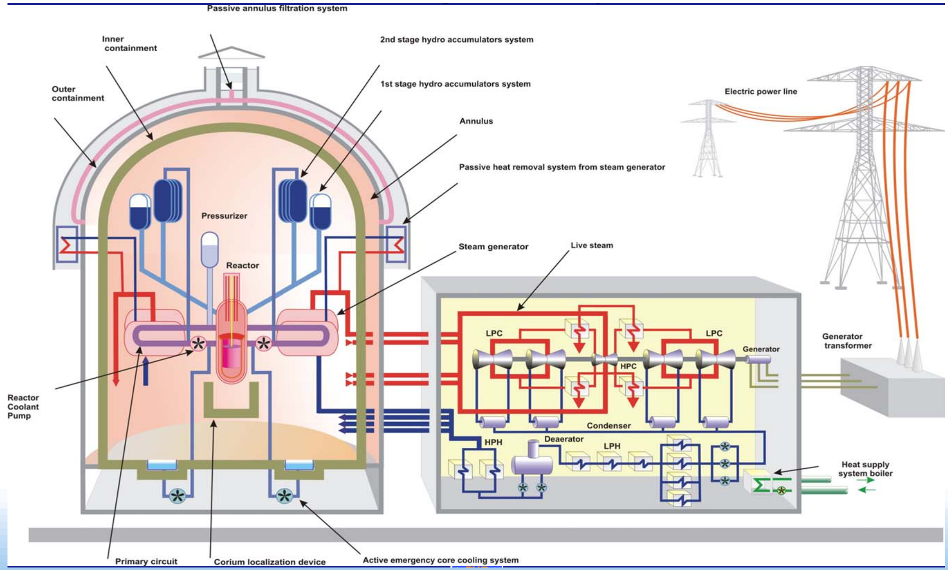
To assess NPP behaviour during accident conditions thermal-hydraulic system codes are used

- Coolant flow and distribution
- Coolant temperatures
- System pressure
- Fuel and structure temperatures
- .
- .



What needs to be modelled?

- All important to safety plant components and systems
  - Reactor core
  - Primary coolant system
  - Secondary coolant system
  - Safety systems
  - Control functions
  - Etc.
- All phenomena occurring during normal and accident conditions having impact on safety parameters.



Transient and accident conditions:

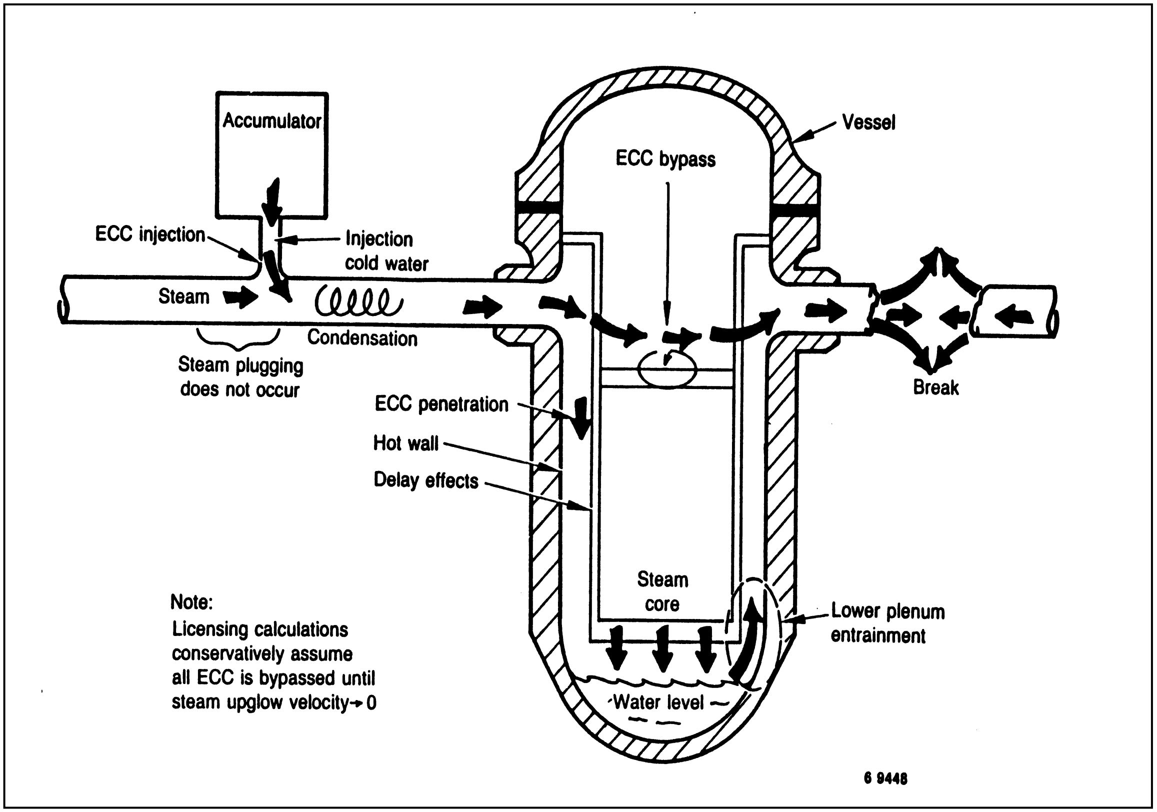
The main issue is mismatch between heat generation and heat removal capability leading potentially to failures of fuel and of protective barriers

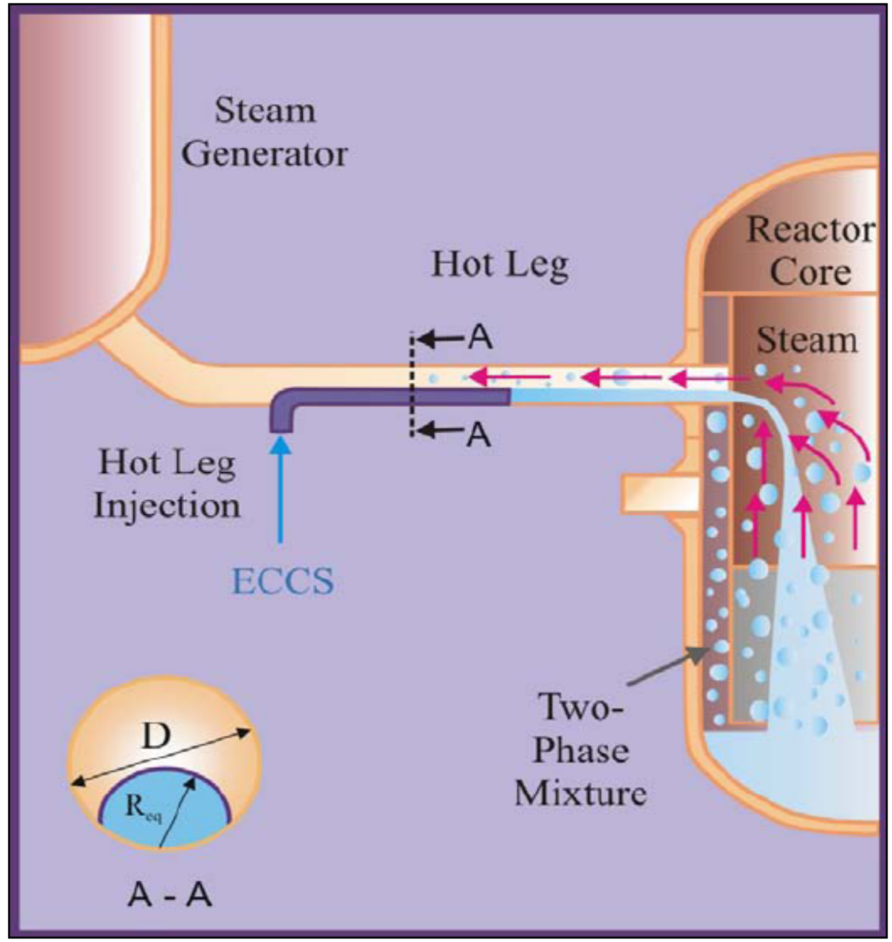
- Type of events to be considered
  - ✓ Anticipated transients
  - ✓ Increase or decrease of power
  - ✓ Loss of flow
  - ✓ Loss of coolant
  - ✓ Anticipated transients without scram
  - ✓ .

Key physical processes to be modelled:

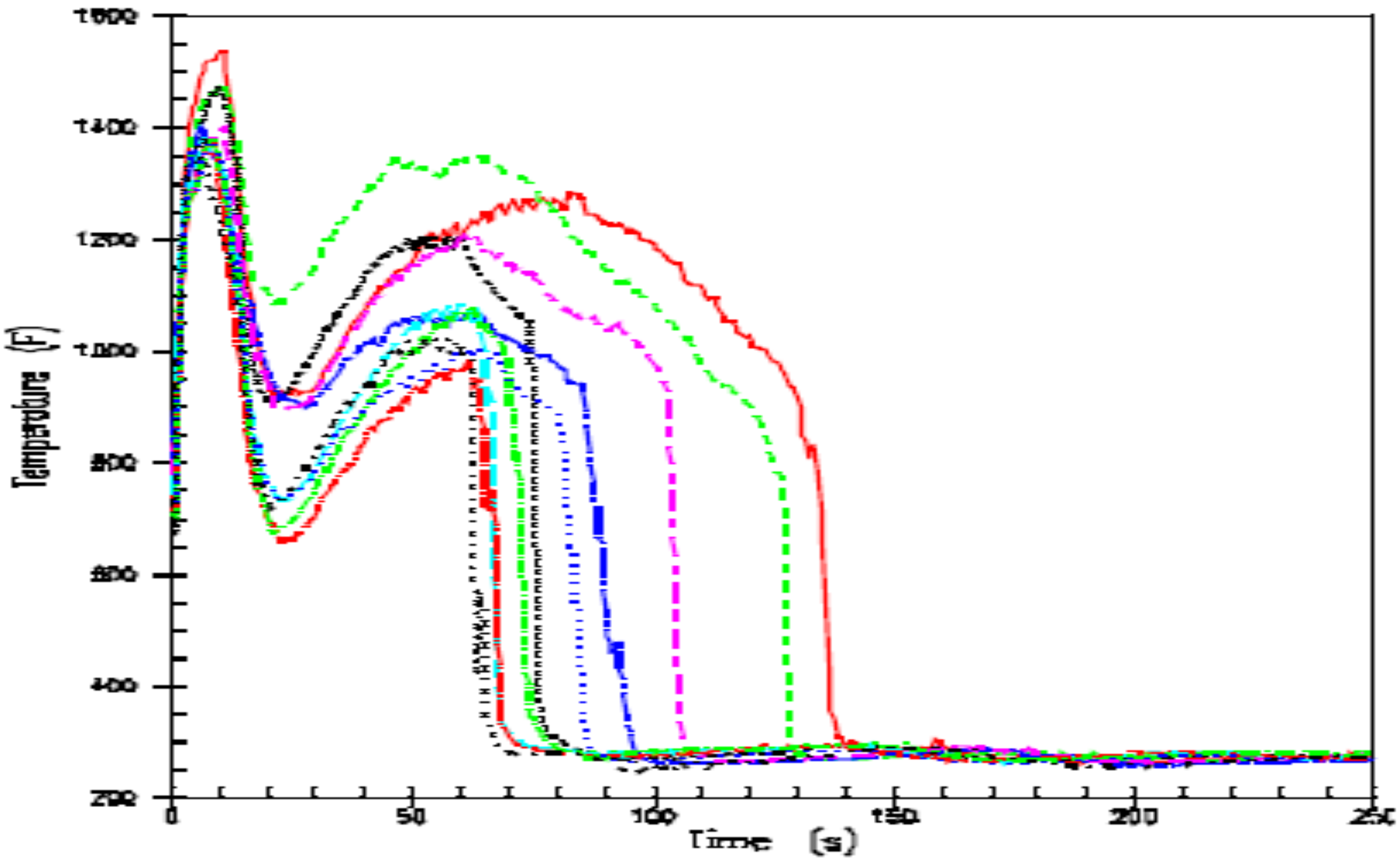
- Mass flow
  - Flow regimes
  - Multiple velocities of phases
  - Fields
  - Momentum and shear between the phases
  - Wall shear
  - Form losses on structures and geometries
  - Break flow/critical flow
  - Entrainment, de-entrainment
  - Condensation
- Heat transfer
  - Single phase to/from structures
  - Between the phases
  - Presence of non-condensable gases
  - Condensation
  - Special heat transfer processes such as reflux condensation
  - Radiation heat transfer

Examples of phenomena during accidents





Phenomena example: Large Break LOCA, fuel cladding temperature



Outline

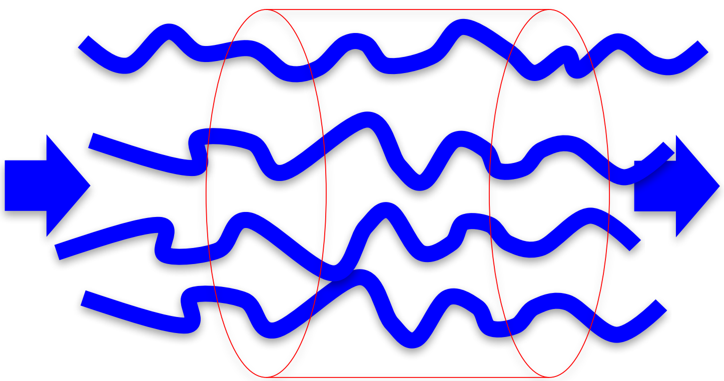
- Uncertainty
- Brief discussion of physical process during postulated accidents
- **Fluid Flow – Basic Concepts**
- Constitutive relations and special models
  - Flow regimes
  - Heat transfer
- Models and inputs
- Uncertainty

How is the complexity of the phenomena, component geometries, process interactions and control modelled in current system codes?

Current approach to system modeling: **discretization** – volumes, junctions, heat slabs, special components with analytical solutions.

Control Volume

Control volume is a fixed region in space where one studies the masses and energies crossing boundaries of the region



Basic assumptions:

- The properties of each phase within a control volume are uniform
- The pressures of each phase are equal to each other
- The liquid and gas phases may move at different velocities
- All thermodynamic state combinations are possible:

THE BASICS:

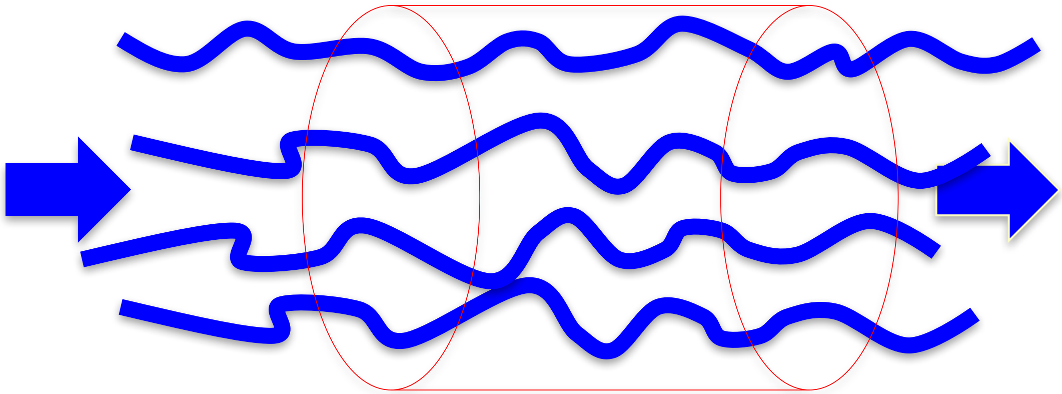
The principles of the flow of a substance are governed by the basic physical laws of **conservation of mass, momentum and energy**.

- Consider mass, momentum and energy within the control volume

Conservation of mass

- All mass flow rates into a control volume are equal to all mass flow rates out of the control volume plus the rate of change of mass within the control volume

$$\dot{m}_{in} = \dot{m}_{out} + \Delta m / \Delta t$$



Conservation of momentum

- Newton's Second Law of Motion: The acceleration of an object is directly proportional to the net force and inversely proportional to its mas.

$$F = ma$$

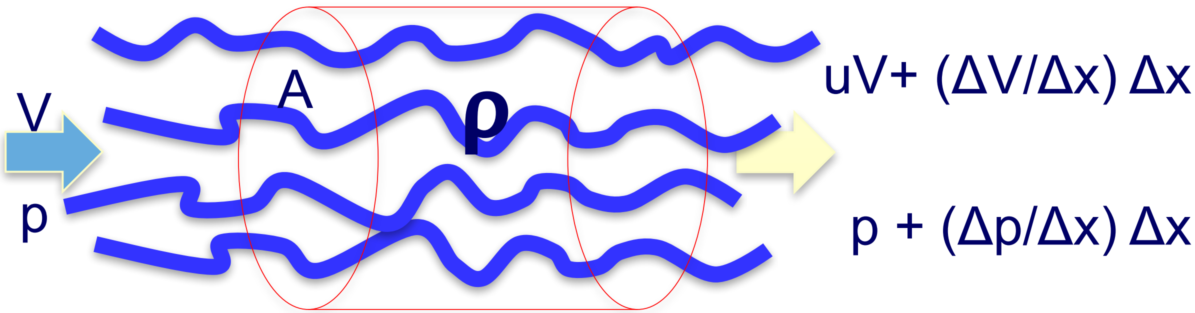
- Or: the amount of momentum remains constant – momentum is neither created nor destroyed, but only changed through the action of forces.

Conservation of momentum (cont'd)

- The momentum equation states that the sum of all forces applied on the control volume is equal to the sum of the rate of change of momentum inside the control volume and the net flux of momentum through the control surface.

$$\Sigma F = d(mV)/dt$$

- F = sum of forces on fluid system ($F_{gravity}$, $F_{pressure}$, F_{fric})
- mV = momentum

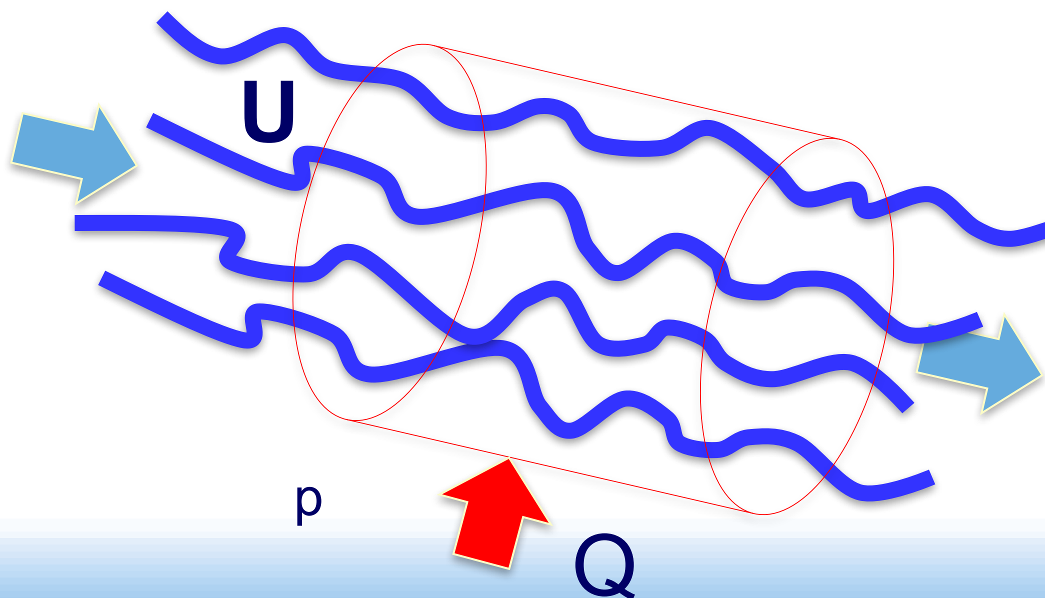


Conservation of energy

- The conservation of energy principle states that energy can be neither created nor destroyed.

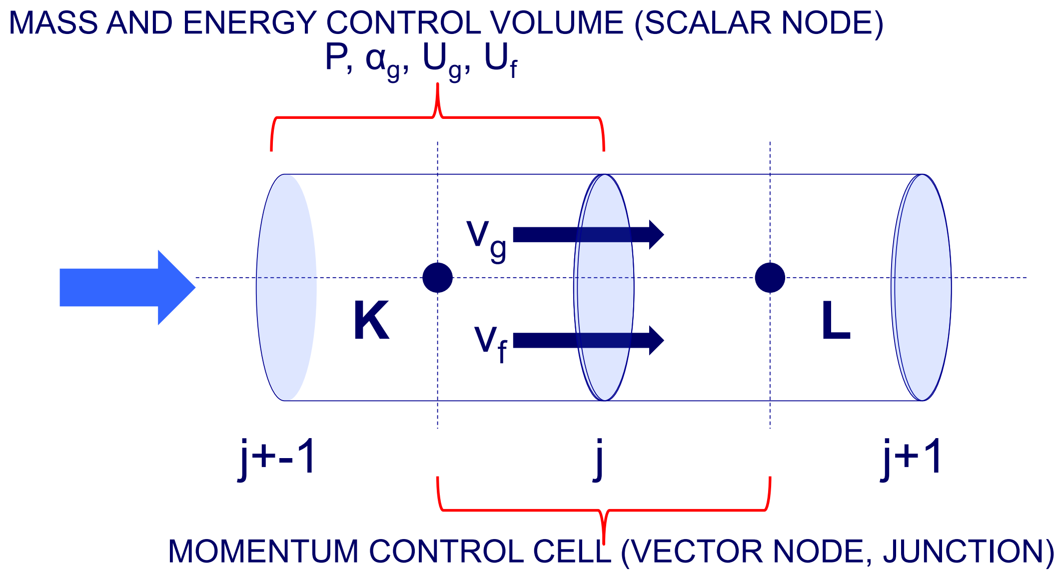
$$Q+(U+PE+KE+PV)_{in} =$$
$$W + (U+PE+KE+PV)_{out} + (U+PE+KE+PV)_{stored}$$

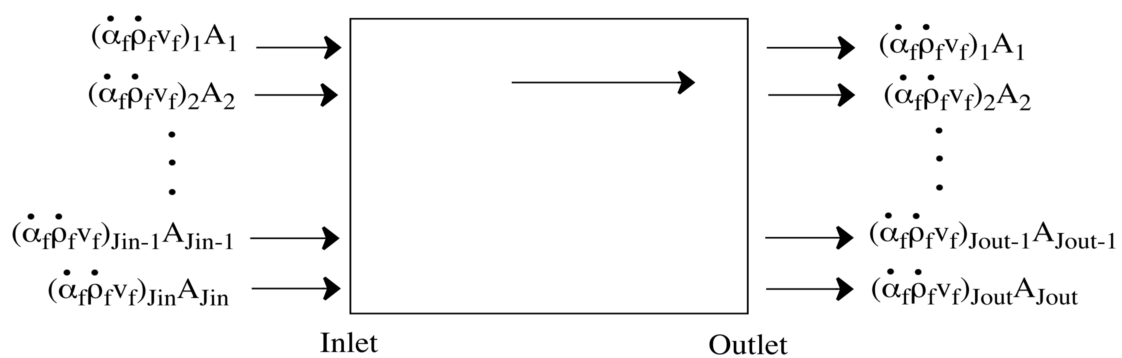
Q – Heat
U – Internal energy
PE – Potential energy
KE – kinetic energy
P – pressure
V – volume
W - work



Concept of control volume in a code

2 phases (liquid and vapor) need to be considered





RELAP5 conservation equations (1/2)

Mass:

$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_g \rho_g v_g A) = \Gamma_g$$

$$\frac{\partial}{\partial t}(\alpha_f \rho_f) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_f \rho_f v_f A) = \Gamma_f$$

Momentum:

$$\alpha_g \rho_g A \frac{\partial v_g}{\partial t} + \frac{1}{2}\alpha_g \rho_g A \frac{\partial v_g^2}{\partial x} = -\alpha_g A \frac{\partial P}{\partial x} + \alpha_g \rho_g B_x A - (\alpha_g \rho_g A) FWG(v_g)$$
$$+ \Gamma_g A(v_{gI} - v_g) - (\alpha_g \rho_g A) FIG(v_g - v_f)$$
$$- C \alpha_g \alpha_f \rho_m A \left[\frac{\partial (v_g - v_f)}{\partial t} + v_f \frac{\partial v_g}{\partial x} - v_g \frac{\partial v_f}{\partial x}\right]$$

$$\alpha_f \rho_f A \frac{\partial v_f}{\partial t} + \frac{1}{2}\alpha_f \rho_f A \frac{\partial v_f^2}{\partial x} = -\alpha_f A \frac{\partial P}{\partial x} + \alpha_f \rho_f B_x A - (\alpha_f \rho_f A) FWF(v_f)$$
$$- \Gamma_g A(v_{fI} - v_f) - (\alpha_f \rho_f A) FIF(v_f - v_g)$$
$$- C \alpha_f \alpha_g \rho_m A \left[\frac{\partial (v_f - v_g)}{\partial t} + v_g \frac{\partial v_f}{\partial x} - v_f \frac{\partial v_g}{\partial x}\right] .$$

RELAP5 conservation equations (2/2)

Energy:

$$\frac{\partial}{\partial t}(\alpha_g \rho_g U_g) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_g \rho_g U_g v_g A) = -P\frac{\partial \alpha_g}{\partial t} - \frac{P}{A}\frac{\partial}{\partial x}(\alpha_g v_g A) + Q_{wg} + Q_{ig} + \Gamma_{ig} h_g^* + \Gamma_w h_g' + DISS_g$$

$$\frac{\partial}{\partial t}(\alpha_f \rho_f U_f) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_f \rho_f U_f v_f A) = -P\frac{\partial \alpha_f}{\partial t} - \frac{P}{A}\frac{\partial}{\partial x}(\alpha_f v_f A) + Q_{wf} + Q_{if} - \Gamma_{ig} h_f^* - \Gamma_w h_f' + DISS_f \ .$$

Mass conservation for noncondensable component:

$$\frac{\partial}{\partial t}(\alpha_g \rho_g X_n) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_g \rho_g X_n v_g A) = 0$$

- The noncondensable component is assumed to move with the same velocity and have the same temperature as the vapor phase,
- all properties of the vapor/gas phase (subscript g) are mixture properties of the vapor/noncondensable mixture.

Mass conservation for dissolved boron:

$$\frac{\partial \rho_b}{\partial t} + \frac{1}{A}\frac{\partial(\rho_b v_f A)}{\partial x} = 0$$

- Liquid (solvent) properties are not altered by the presence of the solute.
- Solute is transported only in the liquid phase (solvent) and at the velocity of the liquid phase (solvent).
- Energy transported by the solute is negligible.
- Inertia of the solute is negligible.

Outline

- Uncertainty
- Brief discussion of physical process during postulated accidents
- Fluid Flow – Basic Concepts
- **Constitutive relations and special models**
  - **Flow regimes**
  - Heat transfer
- Models and inputs
- Uncertainty

- The field equations are expressions only of conservation principles, they describe neither
  - the thermodynamic properties of the materials involved, nor
  - the interactions between the phases, nor
  - the interaction between each phase and the medium in which the flow occurs.
- To complete the field equations, mass, momentum and energy fluxes of one phase must be connected across the interface to the corresponding fluxes of the other phase through constitutive relations

Constitutive Models

Constitutive models describe the interactions of the phases with each other and the system boundaries including

- Wall Heat Transfer -Convective heat transferred to or from the wall and each phase
- Interfacial Drag -The drag force each phase imposes on the other
- Interfacial Heat/Mass Transfer -The transfer of energy and mass accompanying vaporization or condensation
- Wall Friction -The wall drag force imposed on each phase
- Form Loss -Irreversible losses due to contractions, expansion, elbows, tees, etc.

Two- Phase Flow Regimes

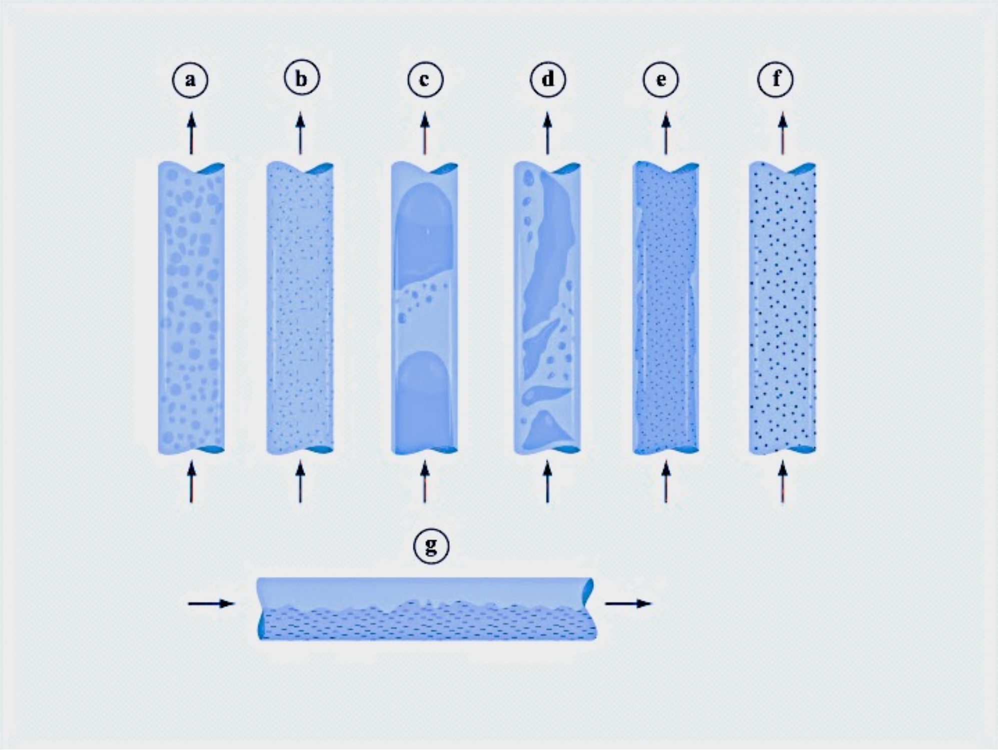


Image by MIT OpenCourseWare.

Typical configuration of

(a) bubbly flow,

(b) dispersed bubbly (i.e. fine bubbles dispersed in the continuous liquid phase),

(c) plug/slug flow,

(d) churn flow,

(e) annular flow,

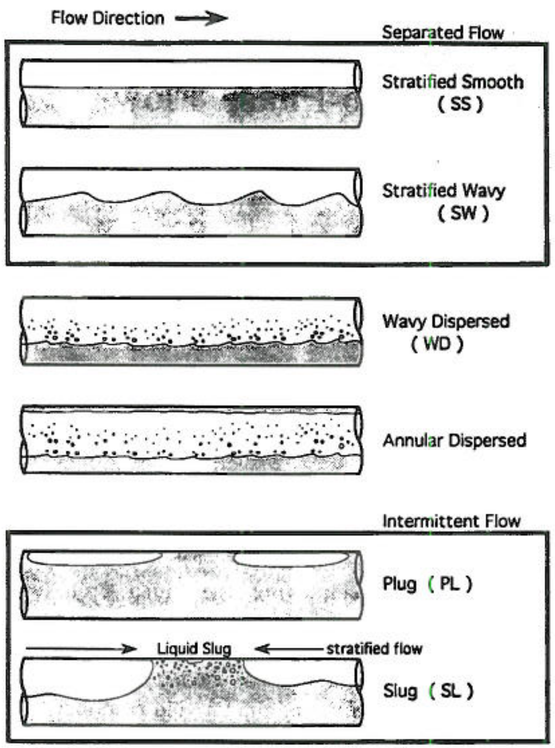
(f) mist flow (i.e. fine droplets dispersed in the continuous vapor phase) and

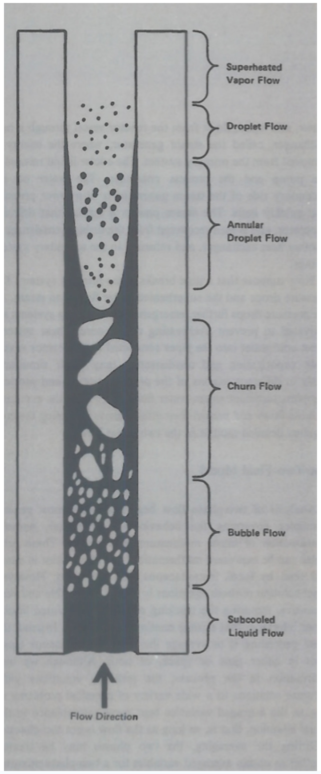
(g) stratified flow.

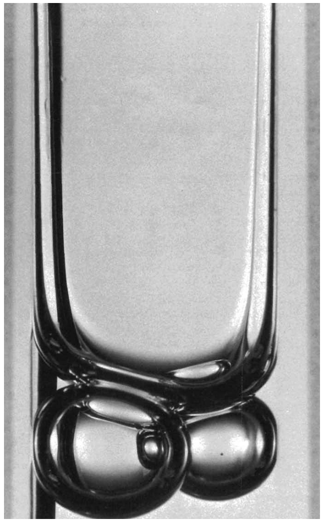
Note: mist flow is possible only in a heated channel; stratified flow is possible only in a horizontal channel.

Two- Phase Flow Regimes

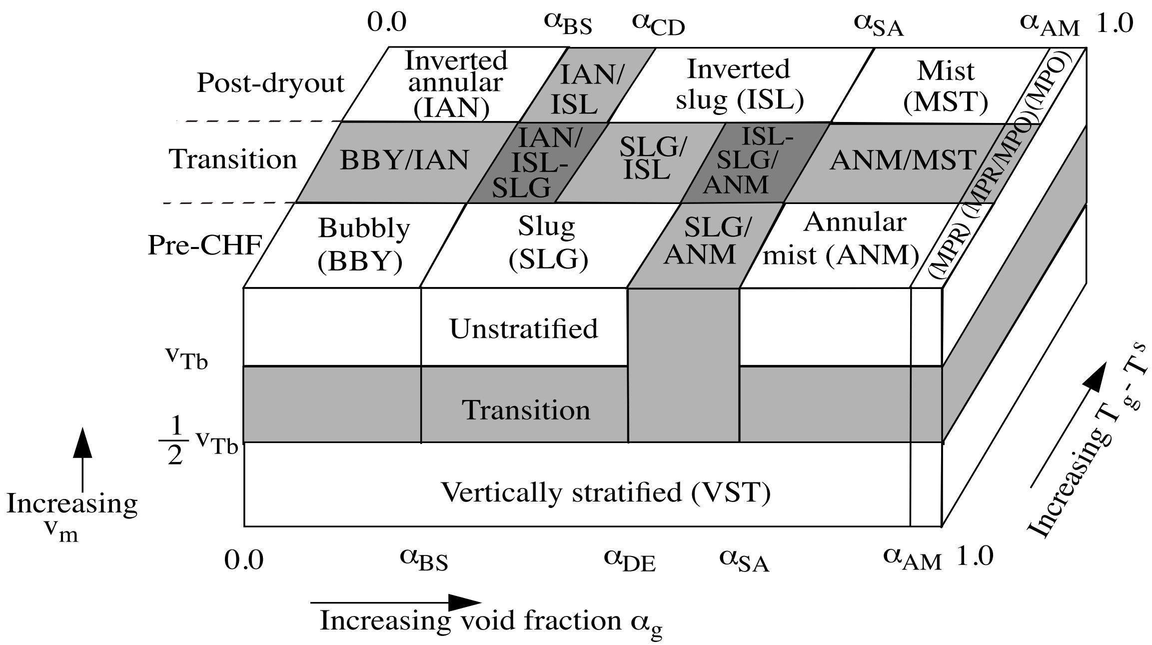
- The interfacial topology constantly changes and the phases interact exchanging, energy momentum and mass
- Two-phase flow exhibits various flow regimes



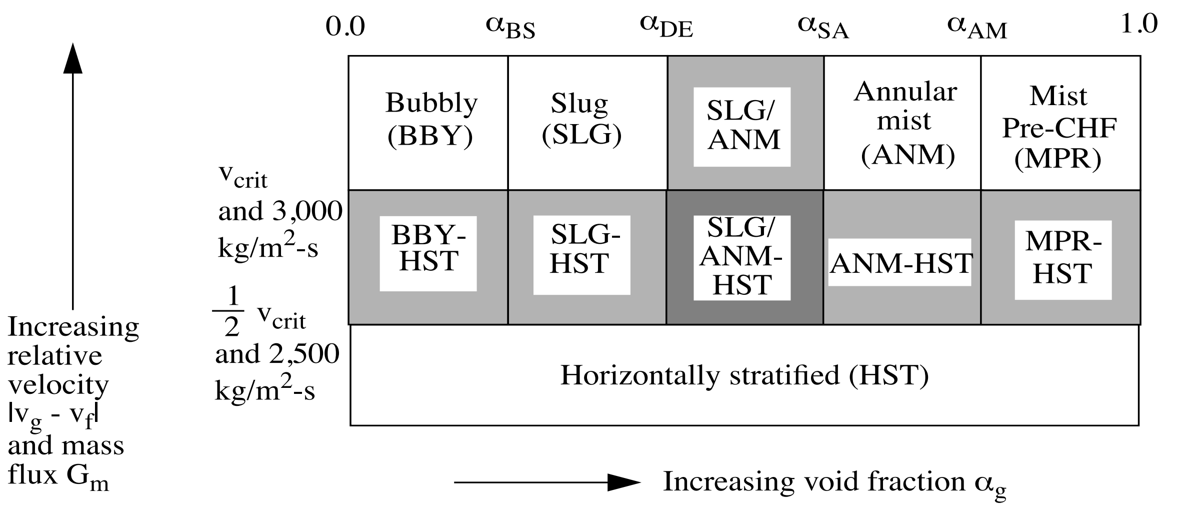




Vertical flow-regime map (RELAP5-3D)



Horizontal flow-regime map (RELAP5-3D)



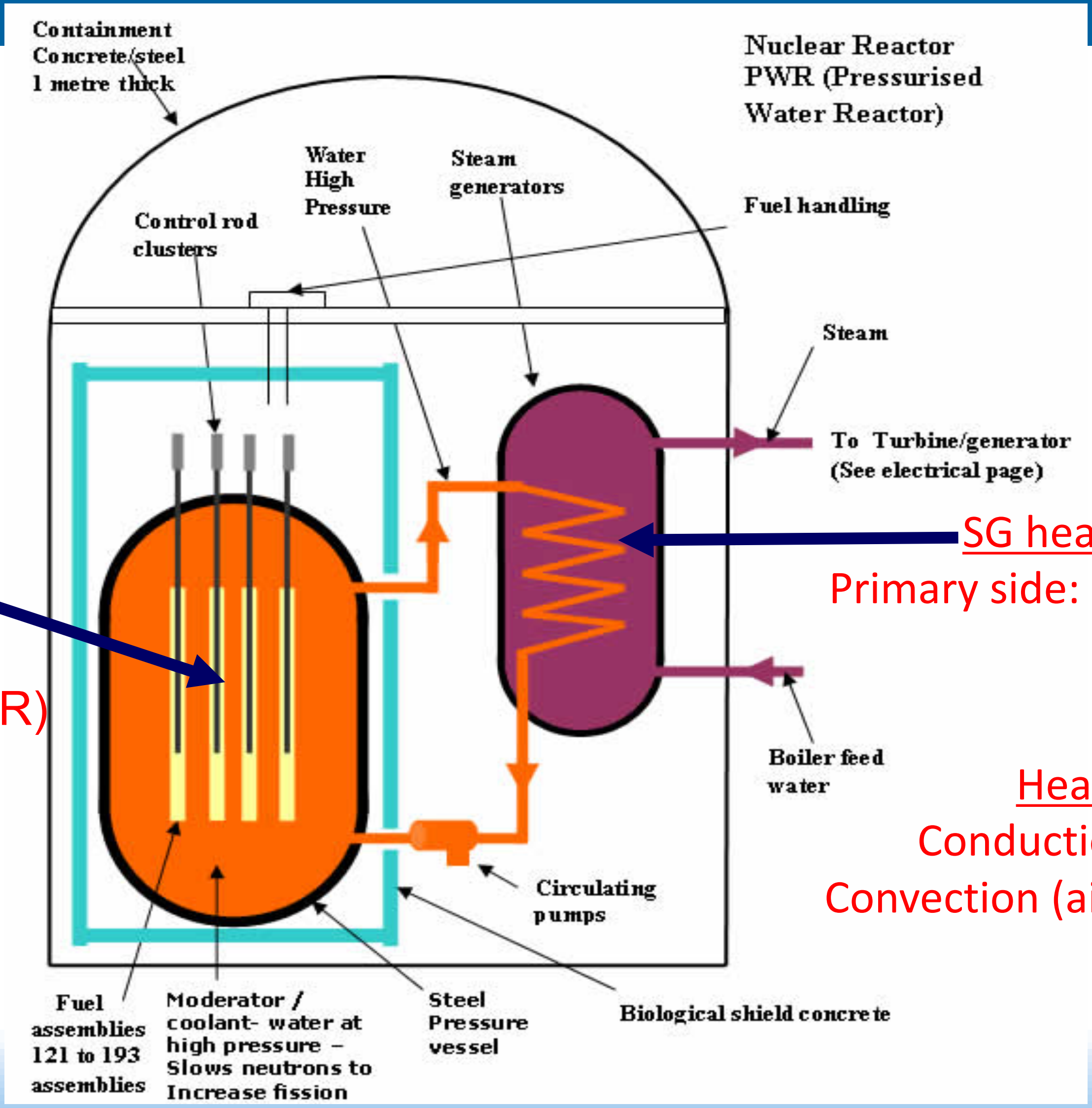
Special Hydro Process Models

- Choking (critical flow)
- Countercurrent flow limiting (flooding)
- Abrupt area change
- Form loss
- Two-phase mixture level
- Thermal-stratification
- Phase separation at tees

Outline

- Uncertainty
- Brief discussion of physical process during postulated accidents
- Fluid Flow – Basic Concepts
- **Constitutive relations and special models**
  - Flow regimes
  - **Heat transfer**
- Models and inputs
- Uncertainty

Heat transfer processes during NPP operation (1/2)

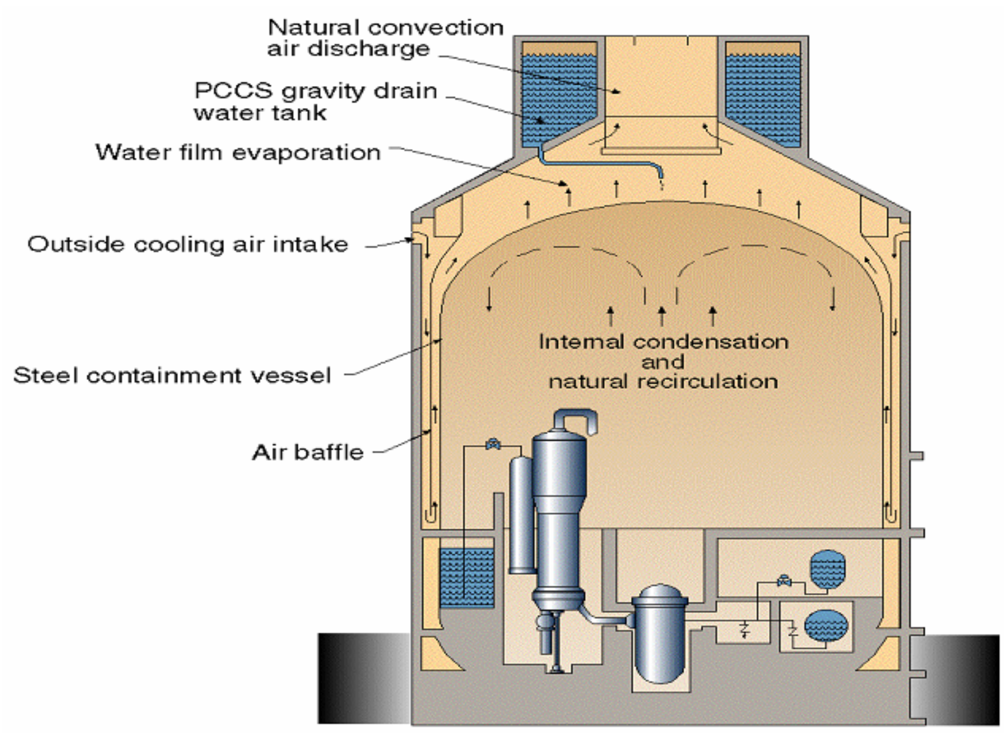


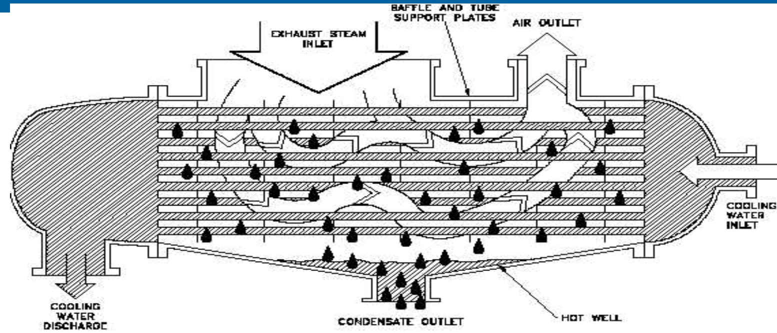
Fuel element
Internal conduction
Cladding/coolant (PWR)

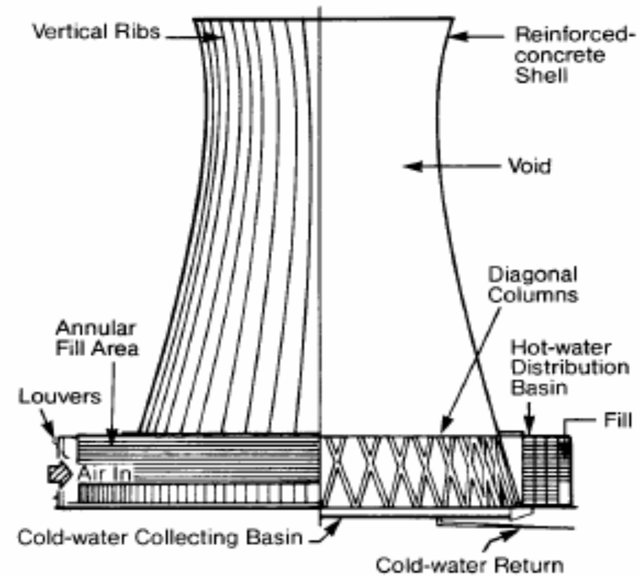
SG heat exchange
Primary side: coolant/ pipe wall

Heat losses
Conduction (isolation)
Convection (air of containment)

Heat transfer processes in NPP operation (2/2)





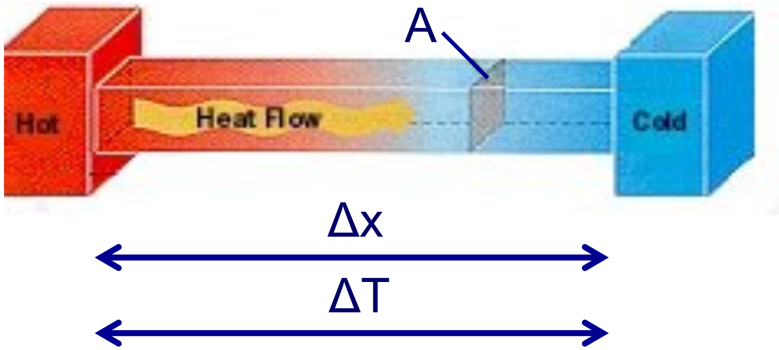


Heat transfer modes

- **Conduction**
  - Performs the transfer of heat by the interactions of atoms or molecules of a material through which the heat is being transferred.
- **Convection**
  - Performs the transfer of heat by the mixing and motion of macroscopic portions of a fluid.
- **Radiation**
  - Performs the transfer of heat by electromagnetic radiation that arises due to the temperature of a body.

Conduction

- **According to the SECOND LAW of thermodynamics**
  "…heat is transferred from a body to another (or from part of a body to another part of the same body) when there is a temperature difference between them…"
- Heat transfer by conduction is dependent upon the driving "force" of temperature difference and the resistance to heat transfer. The resistance to heat transfer is dependent upon the nature and dimensions of the heat transfer medium. All heat transfer problems involve the temperature difference, the geometry, and the physical properties of the object being studied.

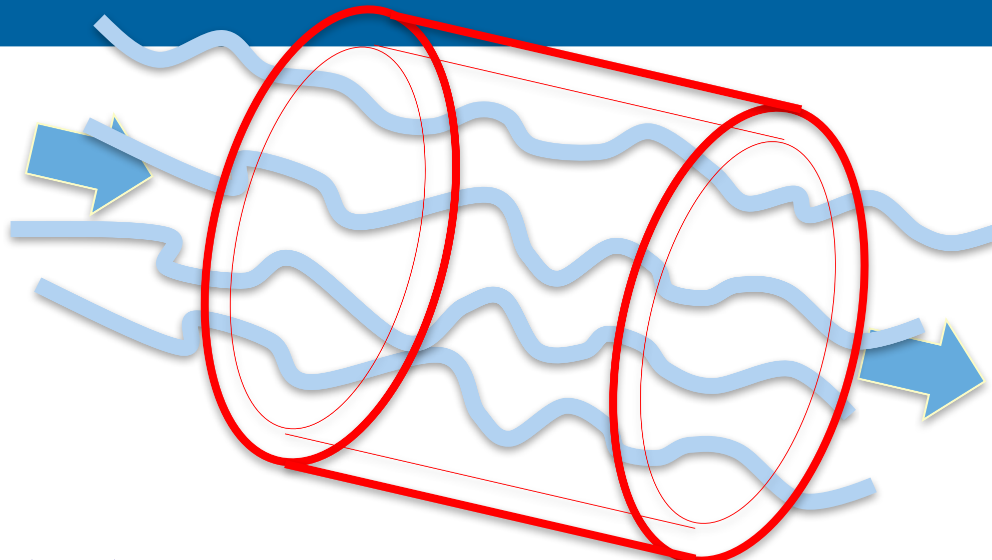


Based on the Fourier's law of conduction the heat transfer rate is:

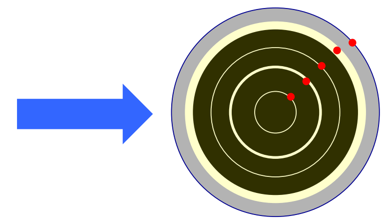
$$\mathbf{Q = k\,A\,(\Delta T/\Delta x)}$$

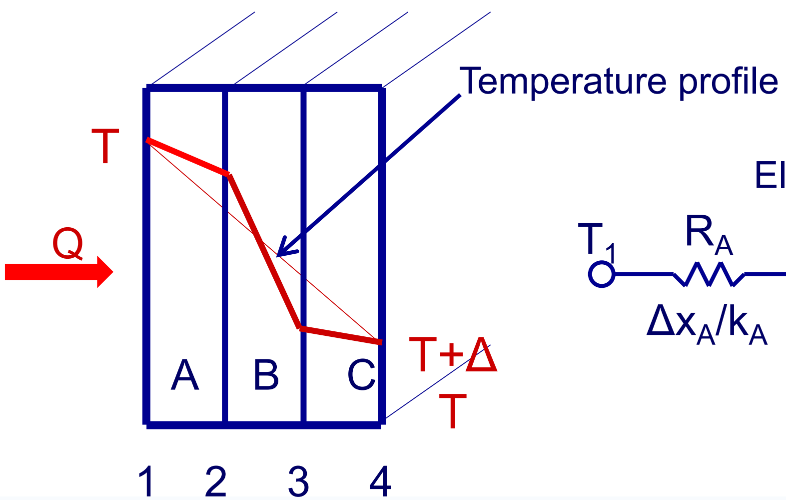
Where k is the thermal conductivity of the material and A is the heat transfer area

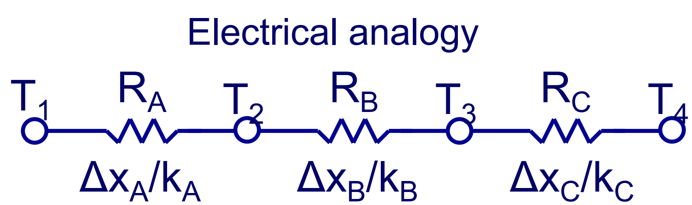
Heat slab concept



Modelling fuel







Convection (1/3)

- Convection involves the transfer of heat by the motion and mixing of "macroscopic" portions of a fluid.
  - The term natural convection is used if this motion and mixing is caused by density variations resulting from temperature differences within the fluid.
    - ✓ The transfer of heat from a hot water radiator to a room is an example of heat transfer by natural convection.
  - The term forced convection is used if this motion and mixing is caused by an outside force, such as a pump.
    - ✓ The transfer of heat from the surface of a heat exchanger to the bulk of a fluid being pumped through the heat exchanger is an example of forced convection.

Convection (2/3)

- Heat transfer by convection is more difficult to analyze than heat transfer by conduction because no single property of the heat transfer medium, such as thermal conductivity, can be defined to describe the mechanism.
- Heat transfer by convection varies from situation to situation (upon the fluid flow conditions), and it is frequently coupled with the mode of fluid flow (regimes).

- Basic correlation:

$$Q = h\ A\ \Delta T$$

Where: Q = heat transfer rate, h = convective heat transfer coefficient, A = surface area for the heat transfer, ΔT = temperature difference

Convection (3/3)

- Despite the simple formula the heat transfer coefficient (h) is practically unknown, depending among the other things by:
  - Fluid velocity
  - Fluid viscosity
  - Heat flux
  - Surface roughness
  - Type of flow (single-phase/two-phase)
  - …
- In single phase there are two basic flow regimes, laminar and turbulent (Osborne Reynolds, 1883)
  - In a laminar flow regime the fluid layers flow side by side in an orderly manner. In a turbulent flow pieces of fluid are transported by the turbulent motion in all directions and mix with other parts of the flow in a chaotic way.
  - Heat transfer is higher for turbulent flow than for laminar flows

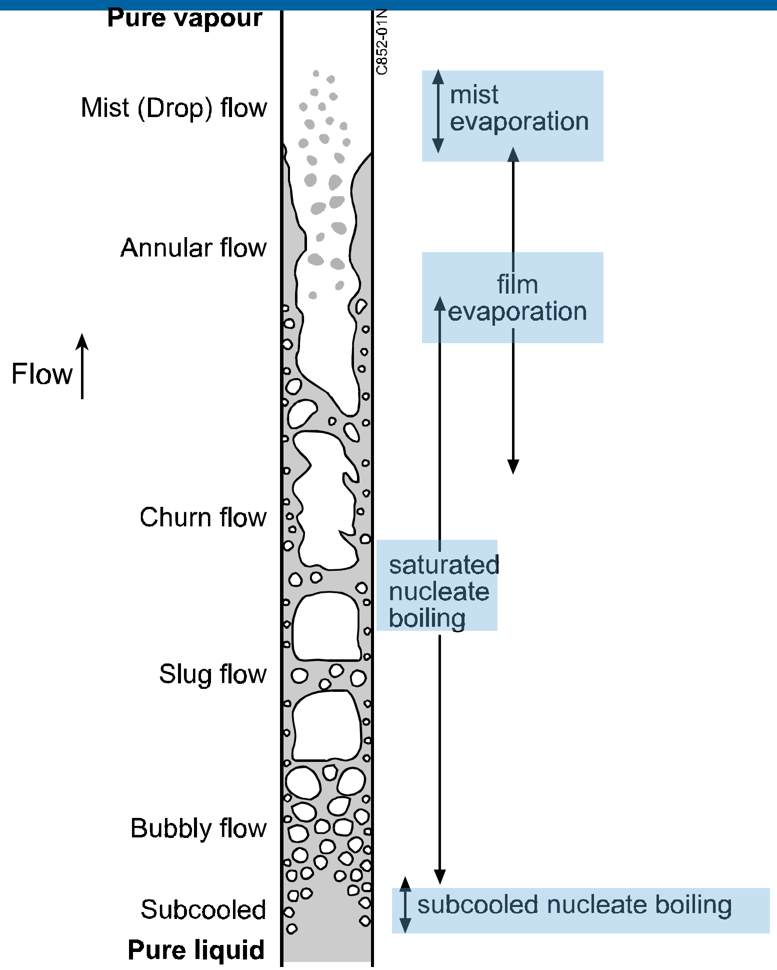
Two-phase heat transfer: Relevance in NPP (1/2)

- Two-phase heat transfer mechanisms (basically BOILING and CONDENSATION) are commonly encountered in a NPP and are of great relevance to its design and safety. Examples:
- Normal operation conditions
  - Convective boiling in coolant channels is the normal way heat is transferred from the nuclear fuel to the working fluid in a BWR
  - Boiling in the steam generators of a PWR
  - A little amount of boiling is admitted also in PWR coolant channels
  - Condensation in condenser after turbines
  - Condensation/evaporation in pressurizer (spray/heaters intervention)
  - Condensation in pre-heaters, deaerators
  - Evaporation in cooling towers

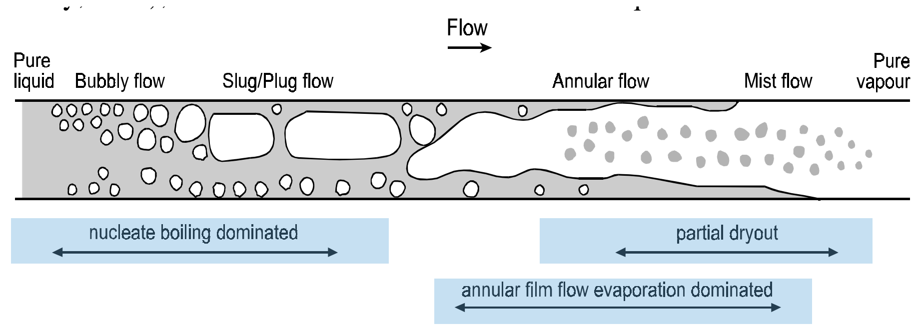
Two-phase heat transfer: Relevance in NPP (2/2)

- **Abnormal/accidental conditions**
  - Extensive boiling in PWRs in case of power excursion
  - Flashing due to rapid depressurization (e.g. following LOCAs)
  - Direct contact condensation at ECC injection into water/steam mixture
  - Steam condensation in containment (wall cond.; sprays)
  - Steam condensation in containment water pools (pressure suppression)
  - Cavitation in valves/pumps

Two phase heat transfer

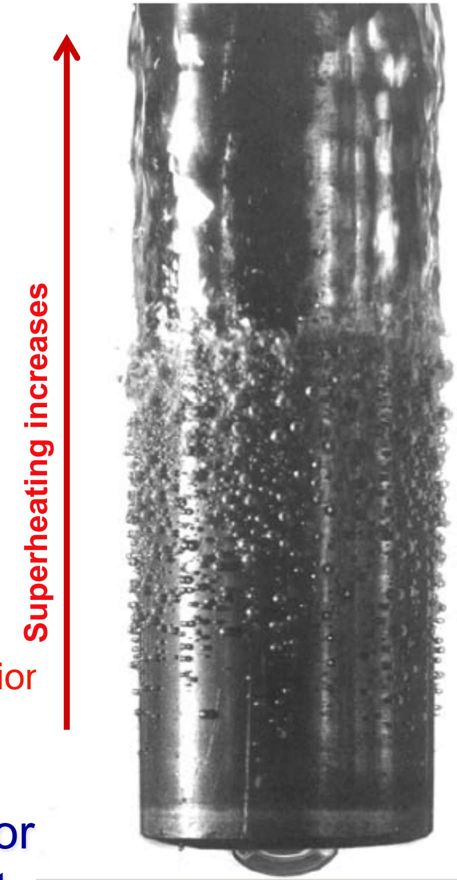


In nuclear system analysis special consideration needs to be given to flow regimes and boiling phenomena



Two-phase heat transfer: Pool Boiling

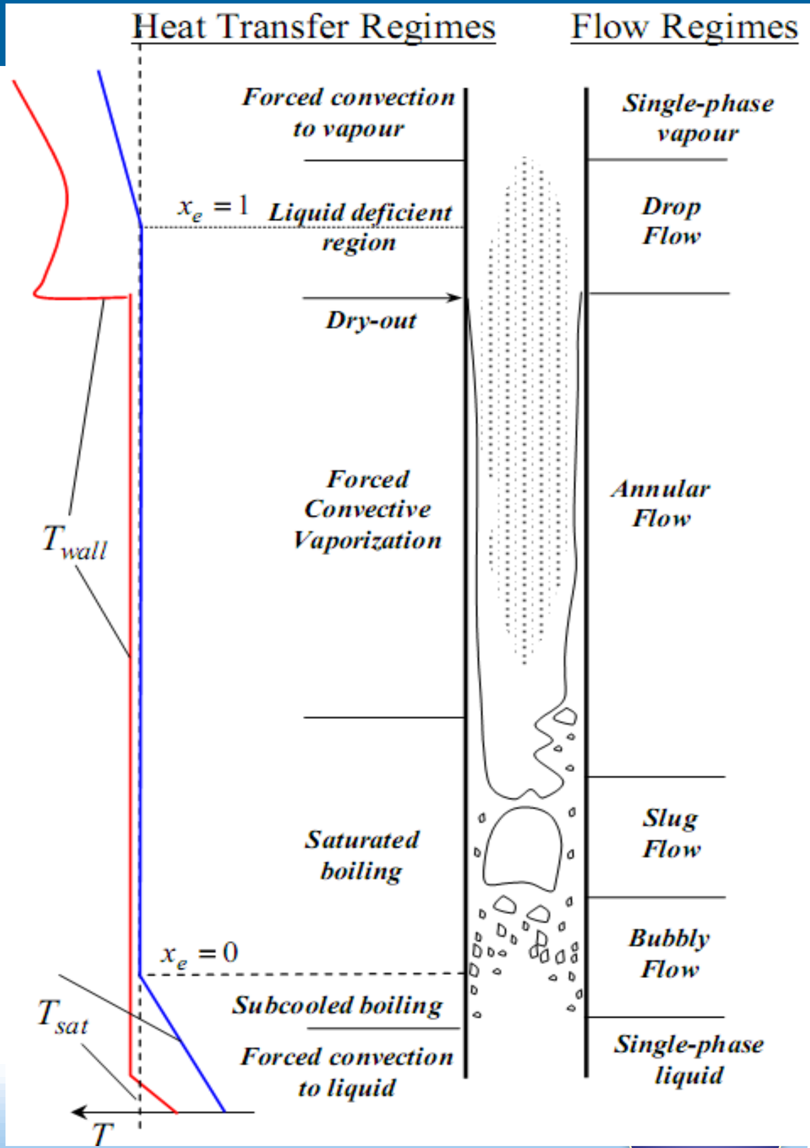
- **Boiling stages (as superheating increases):**
  - Film boiling
    - ✓ Wall totally covered by a vapour film
    - ✓ Very poor heat transfer (governed by low thermal conductivity of vapour)
  - Transition boiling
    - ✓ Wall partly covered by vapour patches
    - ✓ Decrease in heat flux
  - Nucleate boiling
    - ✓ Starts with sufficient superheating
    - ✓ Enhanced by presence of impurities and micro-cavities in the wall
  - Single phase natural convection
    - ✓ Below minimum superheating required, heat transfer occurs by natural conventior without any phase change



- Several correlations exist in the literature to predict the heat transfer for each region of pool boiling. They are normally obtained by experiments and dimensional analysis.

Flow boiling

- Flow (or convective) boiling has the additional variables of the flow and the distribution of void fraction in the flow duct, which affect the heat transfer mechanisms, including the critical heat flux.
- Dry-out before the channel exit is one of the forms of thermal crisis (or CHF)
- In some 2Φ flow channel CHF may occur also in conditions with small void fraction



- Example: correlations for HTC for nucleate boiling

Kutateladze

$$\frac{hl_a}{k_l} = 7.0\times10^{-4}\, Pr_l^{0.35}\left(\frac{ql_a}{\rho_v L_{lv} v_l}\right)^{0.7}\left(\frac{pl_a}{\sigma}\right)^{0.7}$$

Rohsenow

l_a: Capillary Const.

$$\frac{hl_a}{k_l} = \frac{Pr_l^{-0.7}}{C_{sf}}\left(\frac{ql_a}{\rho_v L_{lv} v_l}\right)^{0.67}\left(\frac{\rho_v}{\rho_l}\right)^{0.67}$$

Jens-Lottes

$$\Delta T_s = 0.79 q^{0.25} \exp\left(-\frac{p}{6.2}\right)$$

ΔT_s: K, q: W/m^2, p: MPa

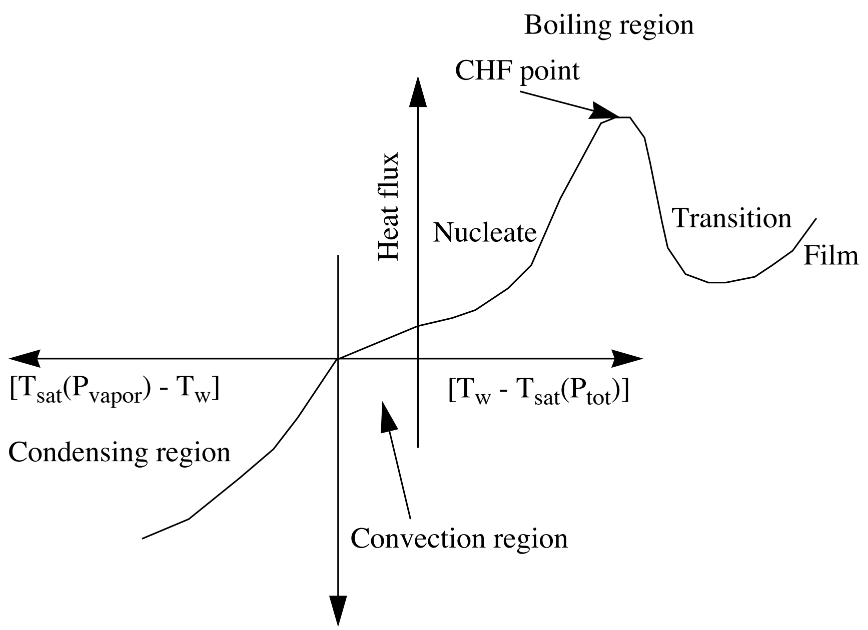
Wall heat transfer in RELAP

A boiling curve is used to govern the selection of the wall heat transfer correlations

$$Q'' = h_{wg}(T_w - T_{refg}) + h_{wf}(T_w - T_{reff})$$

h_{wg} = heat transfer coefficient to vapor (gas)
h_{wf}= heat transfer coefficient to liquid
T_w= wall temperature
T_{refg}= vapor/gas reference temperature
T_{reff}= liquid reference temperature

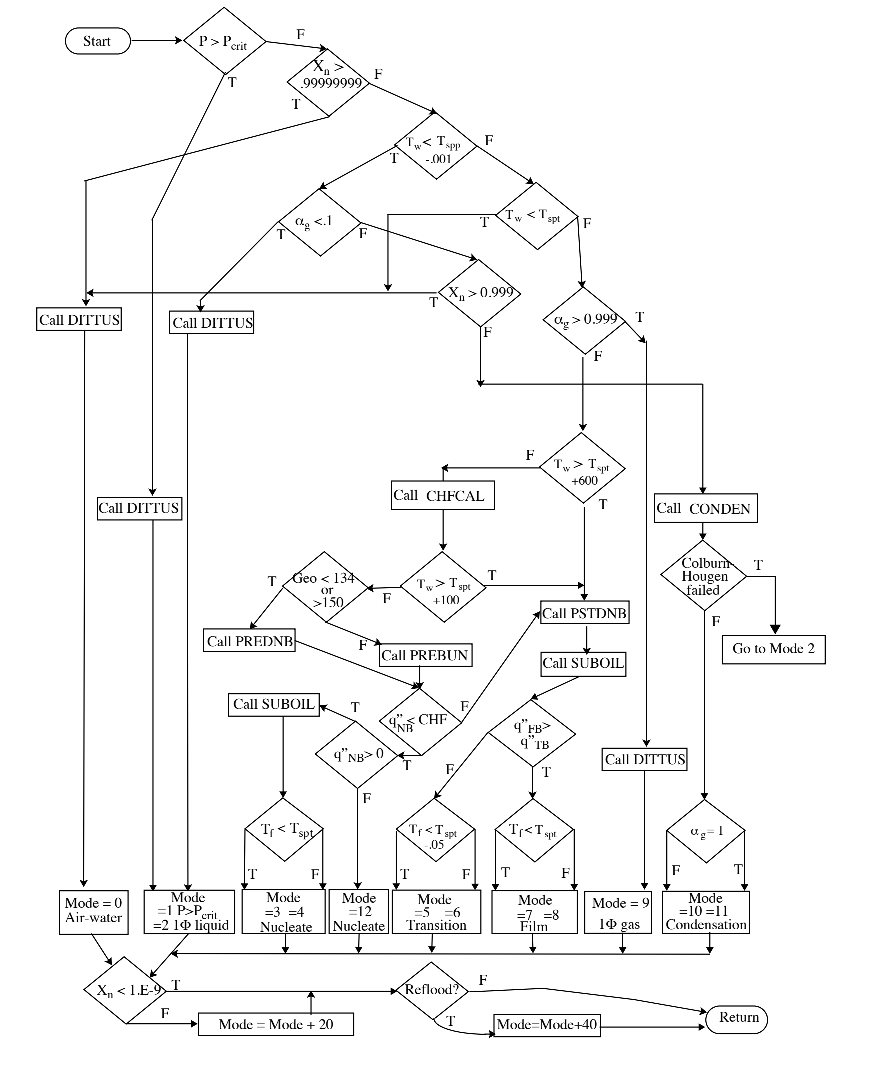
The reference temperatures can be the local vapor/gas or liquid temperature or the saturation temperature, depending on the heat transfer coefficient correlation being used.



Correlations used:

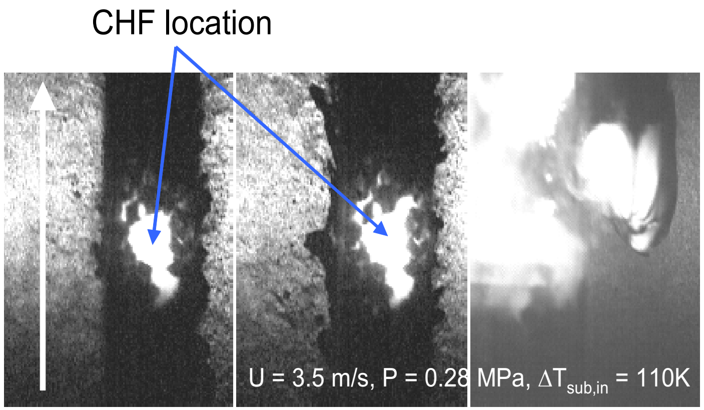
- Chen boiling correlation up to the critical heat flux point.
- Groeneveld, Cheng, and Doan table lookup method developed by is used for the prediction of the critical heat flux.
- When the wall superheat exceeds the critical value, the heat flux for both the transition boiling and the film boiling regimes are calculated and the maximum value is used.
- Chen-Sundaram-Ozkaynak correlation for transition boiling
- Modified Bromley correlation is used for film boiling.

Wall heat transfer flow chart in RELAP



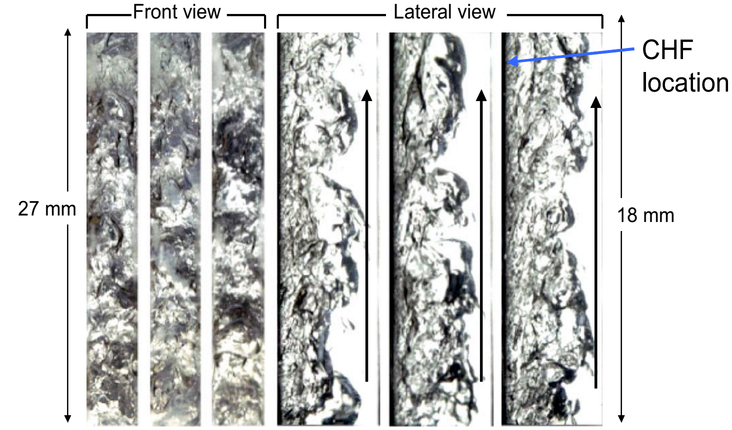
Two phase heat transfer
DNB

DNB visual experiments & flow regime map

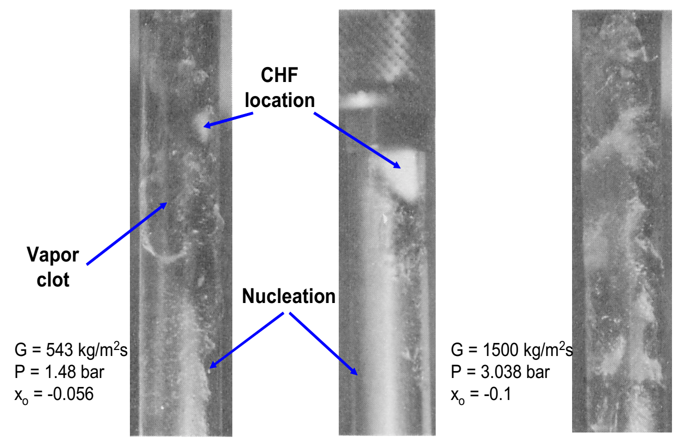


From Celata *et al., Rev. Gén. Therm. (1998)*

- **Three main types of flow regime at DNB:**
  - **Type 1: Bubbly flow**
  - **Type 2: Near-wall vapor clots**
  - **Type 3: Slug flow**



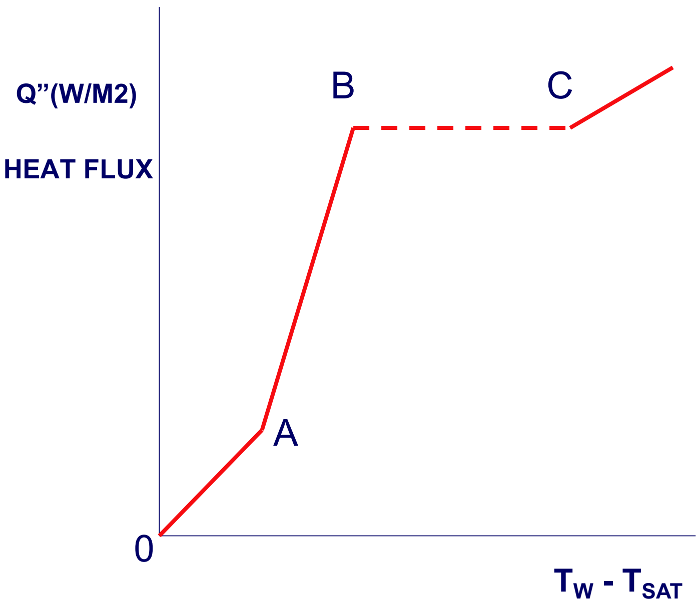
P = 7 bars, G = 2000 kg/m²s, x_o = -0.037 From Bang *et al., Int. J. Heat. Mass Transfer (2004)*



From Fiori and Bergles, 4th *Int. Heat Transfer Conf. (1970)*

Two phase heat transfer
Pool boiling

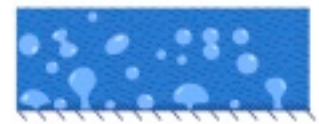
Consider simple experiment: water boils over a flat heated surface at atmospheric pressure:



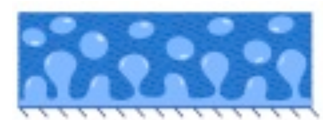
0 – A: In this region the heat from the wall is transferred by single-phase free convection

A: The first bubbles appear on the surface - onset of nucleate boiling

A – B: Bubbles are formed and grow at the wall, and detach from the wall under the effect of buoyancy – nucleate boiling



B – C: Vapor film on the heated surface - Departure from Nucleate Boiling (DNB), or Critical Heat Flux (CHF), or burnout, or boiling crisis - drastic reduction of the heat transfer coefficient because vapor is a poor conductor of heat and wall temperature increase



C + Film boiling

Images by MIT OpenCourseWare.

Two-phase heat transfer: Pool Boiling

- **Boiling stages (as superheating increases):**
  - Single phase natural convection
    - ✓ Below minimum superheating required, heat transfer occurs by natural convention, without any phase change
  - Nucleate boiling
    - ✓ Starts with sufficient superheating
    - ✓ Enhanced by presence of impurities and micro-cavities in the wall
  - Transition boiling
    - ✓ Wall partly covered by vapour patches
    - ✓ Decrease in heat flux
  - Film boiling
    - ✓ Wall totally covered by a vapour film
    - ✓ Very poor heat transfer (governed by low thermal conductivity of vapour)
- Several correlations exist in the literature to predict the heat transfer for each region of pool boiling. They are normally obtained by experiments and dimensional analysis.

Boiling Crisis (Dryout, DNB)

Definitions

- Boiling crisis: a film of vapor is formed, that coats the surface and, practically, impedes heat transfer
- Dryout: In flow boiling at higher velocities, thickness of annular liquid film on wall decreases until film disappears
- Critical heat flux: The CHF is the heat flux at which a boiling crisis occurs that causes an abrupt rise of the fuel rod surface temperature and subsequently might cause a failure of the cladding material
- Burn-out: it may be a consequence of dry-out, occurring when, degradation of heat transfer leads to high temperature of the heater, as in some power controlled situations
- Departure from nucleate boiling (DNB): In pool boiling or flow boiling at low velocities, increased vapor flow rate away from surface prevents liquid from reaching surface (Glossary of US-NRC "*The point at which the heat transfer from a fuel rod rapidly decreases due to the insulating effect of a steam blanket that forms on the rod surface when the temperature continues to increase*")
- Departure from nucleate boiling ratio (DNBR): The ratio of the heat flux needed to cause departure from nucleate boiling to the actual heat flux of a fuel rod

Evaluation of CHF

- Many different correlations for evaluating CHF are available
  - E.g. Groeneveld's "look-up tables"
- Groeneveld's "look-up tables" provide an extensive base of data for predicting CHF in several conditions
  - Groeneveld published in 1986 method to predict CHF based on experiments
  - CHF values measured in experiments (for 8mm tubes) collected, and written in table
  - CHF can be looked up depending on pressure, thermodynamic quality, and mass flux
  - Correction factors have to be applied to account for different geometry (bundle or not bundle), presence of grid spacers, global parameters like heated length, boiling length, horizontal or vertical flow

Radiation heat transfer (1/3)

- Radiant heat transfer involves the transfer of heat by electromagnetic radiation that arises due to the temperature of a body.
- Most energy of this type is in the infra-red region of the electromagnetic spectrum although some of it is in the visible region. The term thermal radiation is frequently used to distinguish this form of electromagnetic radiation from other forms, such as radio waves, x-rays, or gamma rays.
  - The transfer of heat from a fireplace across a room in the line of sight is an example of radiant heat transfer.
- Radiant heat transfer does not need a medium, such as air or metal, to take place. Any material that has a temperature above absolute zero gives off some radiant energy.
  - When a cloud covers the sun, both its heat and light diminish. This is one of the most familiar examples of heat transfer by thermal radiation.

Radiation heat transfer (2/3)

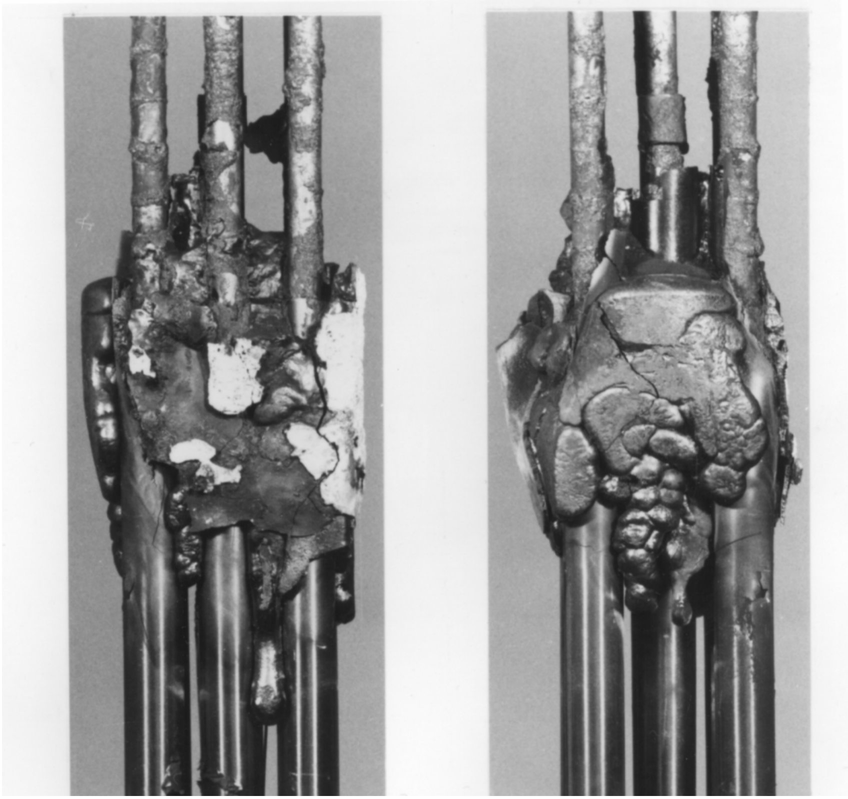
The expression for the radiated heat for a blackbody is given by STEFAN – BOLTZMANN:

$$E_n = \sigma T^4 \qquad \sigma = 5.67 \cdot 10^{-8} \left[m^2 K^4 \right]$$

- Radiation is a heat exchange is not relevant in the normal operation of the NPP
  - Relevant during accident conditions involving temperature increase of the active structures (fuel elements)
  - The radiation heat exchange is neglected by TH-SYS or is treated by a simplified model → more complex models are available in severe accident codes (e.g. RELAP5/SCDAP)
  - High temperature implies core uncovery (single STEAM phase)

Radiation heat transfer (3/3)

- Radiation heat transfer is important during severe accidents
- "Run-away" exothermic oxidation of the cladding at temperatures greater than ~1200C
- Control rod melting (Ag-In-Cd alloy) melting temperature ~ 800C due to radiation heat transfer from hot fuel rods



Summary

- Three heat transfer modes: conduction, convection and radiation
- Two-phase heat transfer mechanisms are of outstanding importance for the design and safety of a NPP
- Boiling processes are encountered in normal operation of both PWRs (steam generator) and BWRs (reactor core)
- …as well as in abnormal and accidental conditions
- Much higher heat transfer coefficients in 2Φ heat transfer than 1Φ (up to 10^4-10^5)
- Relationships between 2Φ flow regimes and heat transfer mechanisms; efficiency of transfer affected by topology of interface between phases

Outline

- Uncertainty
- Brief discussion of physical process during postulated accidents
- Fluid Flow – Basic Concepts
- Heat Transfer – Basic Concepts
- Constitutive relations and special models
  - Flow regimes
  - Heat transfer
- **Models and inputs**

How is the information on the design, initial and boundary conditions, material properties, and transients to be calculated, provided to the computer code?

Input models!

- Two principal building blocks:
  - **Hydrodynamic components (fluid volumes and junctions)**
  - **Heat structures (pipe walls, fuel rods, etc.)**
- For the building blocks information to be provided includes:
  - Geometric specifications (for example: volume, flow area, length, hydraulic diameter, orientation angles, elevation change, friction factors, loss coefficients, roughness,etc.)
  - Initial conditions (pressure, temperature, velocities, etc.)
  - Control flags (CCFL, horizontal stratification entrainment, choking, smooth/abrupt area change, homogeneous/ non-homogeneous, normal/crossflow), etc.
- Special models and components

Hydrodynamic components.

PRZ vessel is a cylindrical structure with elliptical bottom and head. In the nodalization scheme the volume of the PRZ vessel is split into 3 hydrodynamic components:

<u>Component 706:</u> **elliptical bottom**

- **type of the element: branch**
- **total volume: $V = 2.72\ m^3$**
- **flow area: $A = 3.88\ m^2$ (calculated by the code RELAP5/Mod3.2 from the expression A=V/L)**
- **length: L = 0.701 m**
- **hydraulic diameter: $d_h = 2.222$ m (calculated by code from the expression A = ? d_h^2/4)**
- **elevation: H = 0.701 m (H = L)**

Engineering handbook – examples

(2 of 2)

<u>Component 707:</u> cylindrical part

- type of the element: pipe, number of cells: 12
- flow area: $A_1 = 4.0\ m^2$ *; $A_2 = A_3 .... = A_{12} = 4.456\ m^2$
- lengths: $L_1 = 1.34$ m, $L_2 = L_3 = 0.85$ m, $L_4 = L_5 ..... = L_{10} = 0.5$ m, $L_{11} = L_{12} = 1.125$ m,
- total pipe length: L = ? $_{i=1-12}$ L_i = 8.79 m
- total volume: $V = 38.56\ m^3$ (calculated by the code summing the volumes of all cells)
- hydraulic diameter: d_h = 2.257 m for 1st cell, d_h = 2.382 m for cells 2-12 (calculated by the code for each cell from the expression A = ? $d_h^2/4$)
- total elevation: H = 8.79 m (H = L)

* Comment: flow area of the first cell is reduced due to presence of PRZ heaters

<u>Component 708:</u> elliptical head

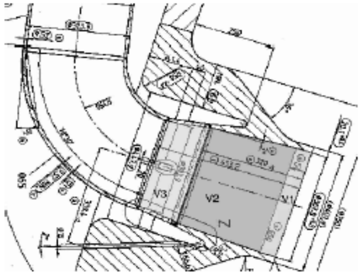
- type of the element: branch,
- total volume: $V = 2.72\ m^3$
- flow area: $A = 3.88\ m^2$ (calculated by the code from the expression A=V/L)
- length: L = 0.701 m
- hydraulic diameter: d_h = 2.222 m (calculated by the code from the expression A = ? $d_h^2/4$)

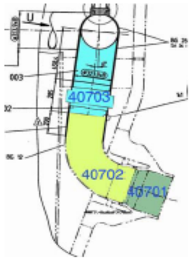
elevation: H = 0.701 m (H = L)

Preparation of an input model

RELAP5/MOD3 INPUT DATA DEVELOPMENT *rev. 0*	**Page:** 145
Parameter Type: BRANCH FW1RING **Description: Feedwater Nozzle, Inlet Line and Torus**	Card id: 4070101-4070107, 4070301-4070307, 4070601, 4070602, 4070701-4070704, 4070801, 4070802

Calculations, Comments and Figures:





FW nozzle

$V_{40701} = V_{nozzle} = V_1 + V_2 + V_3$
$L_{40701} = L_{nozzle} = 0.4532$

$r_1 = 0.3678/2 = 0.1839$
$h_1 = 0.05$
$V_1 = \cdot\pi * r_1^2 * h_1$
$V_1 = 5.31*10\text{-}3$

$R_2 = r_1;\ r_2 = r_1 - h_2*tg3° = 0.17$
$h_2 = 0.32 - 0.05 = 0.27$
formula /2/
$V_2 = 2.659*10\text{-}2$

$R_3 = r_2$; $r_3 = 0.3039/2 = 0.152$
$h_3 = 0.4532 - 0.32 = 0.1332$
formula /2/
$V_3 = 1.0858*10\text{-}2$

$\underline{V_{40701} = 0.0427}$ $\underline{L_{40701} = 0.453}$ $\underline{A_{40701} = V_{40701} / L_{40701} = 0.943}$

Hydraulic diameter: $\underline{D_{h40701} = 0.0}$ (default)

$\underline{\Delta e = L_{40701} * \sin(180° - 78.5° - 6°) = 0.136}$ /1/, /2/

FW line between nozzle and torus (walls thicker than torus)

$r_{line} = 0.3239/2 - 0.01 = 0.15195$ /1/

$\underline{A_{40702}} = r_{line}^2\ \pi = \underline{0.0725}$
$\underline{L_{40702}} = 0.35 * 78.5/180*\pi + 0.2 = 0.\underline{68}$ /1/, /2/

$\Delta e = 0.2 \cos 6° + 0.35 \sin 6° + 0.35 \cos(90 - 78.5° + °6)$ /1/, /2/
$\underline{\Delta e_{40702} = 0.569}$

Hydraulic diameter: $\underline{D_{h40702} = 0.0}$ (default)

FW line between nozzle and torus (wall thick as torus)

$r_{torus} = (d_o - \Delta)/2 = (0.324 - 2 \cdot 0.008)/2 = 0.308/2 = 0.154$ /1/
$A = r_{in}^2 \cdot \pi = \underline{0.0745 = A_{40703}}$

$\underline{L_{40703}} = 0.285 + 0.458 \underline{= 0.743}$ /1/
$\underline{\Delta e40703 =} L_{40703} * \cos 6° = \underline{0.739}$ /1/

Hydraulic diameter: $\underline{D_{h40703} = 0.0}$ (default)

References (Title, page number and revision):
/1/ dwg. NDM2E-00-112755
/2/ dwg. NDM2E-00-112735

Author:	**Date:**___/___/____	**NEK Proprietary**
Reviewer:	**Date:**___/___/____	

v407.doc

Reactor Vessel

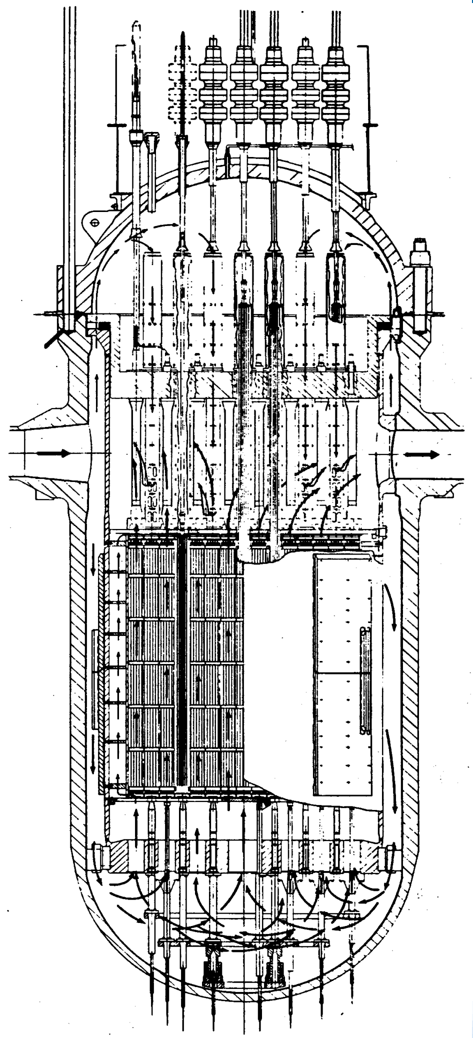
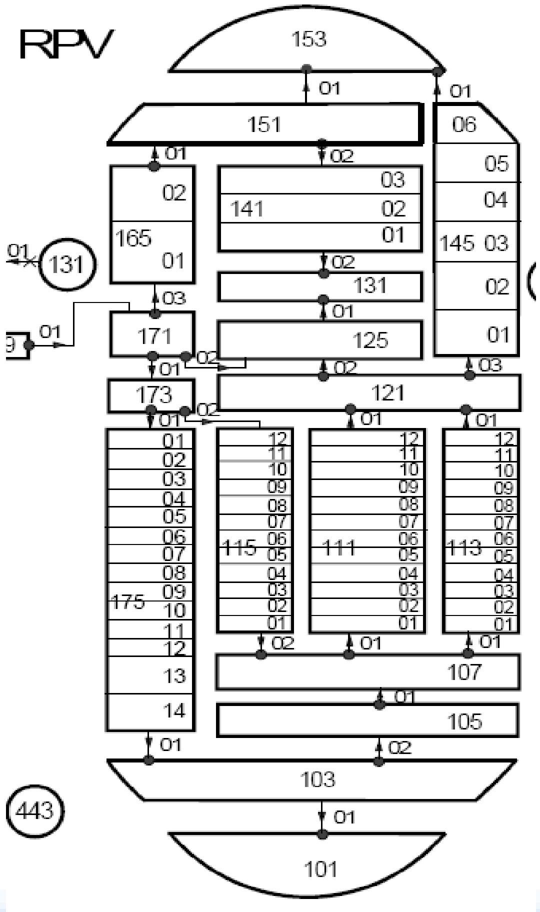
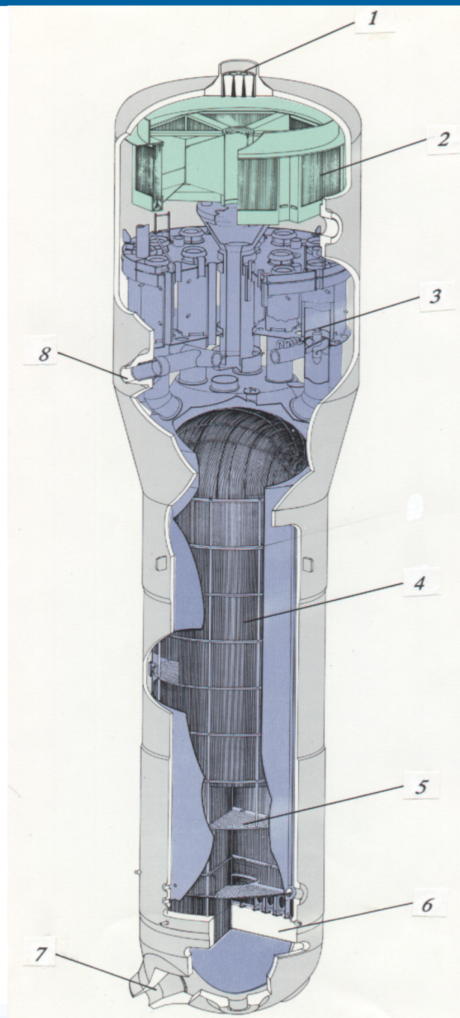


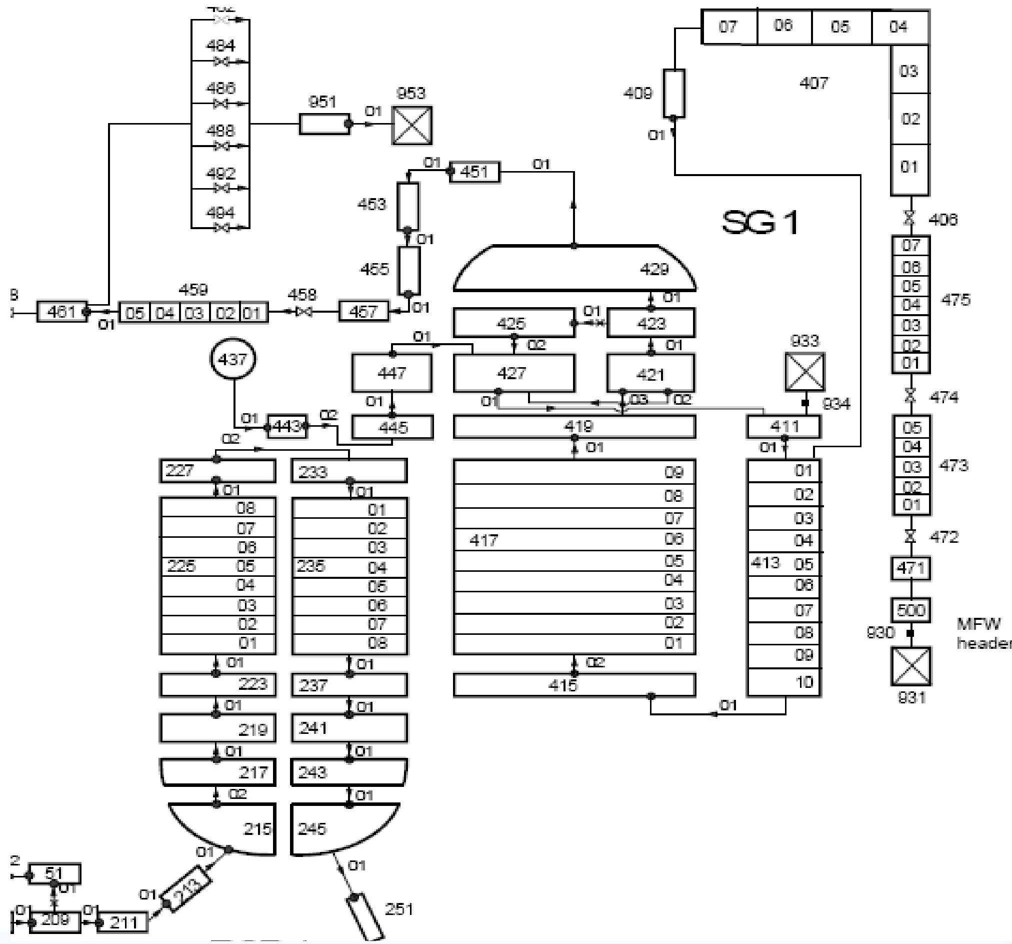
FIGURE II-1.2.2

II-1.2.14

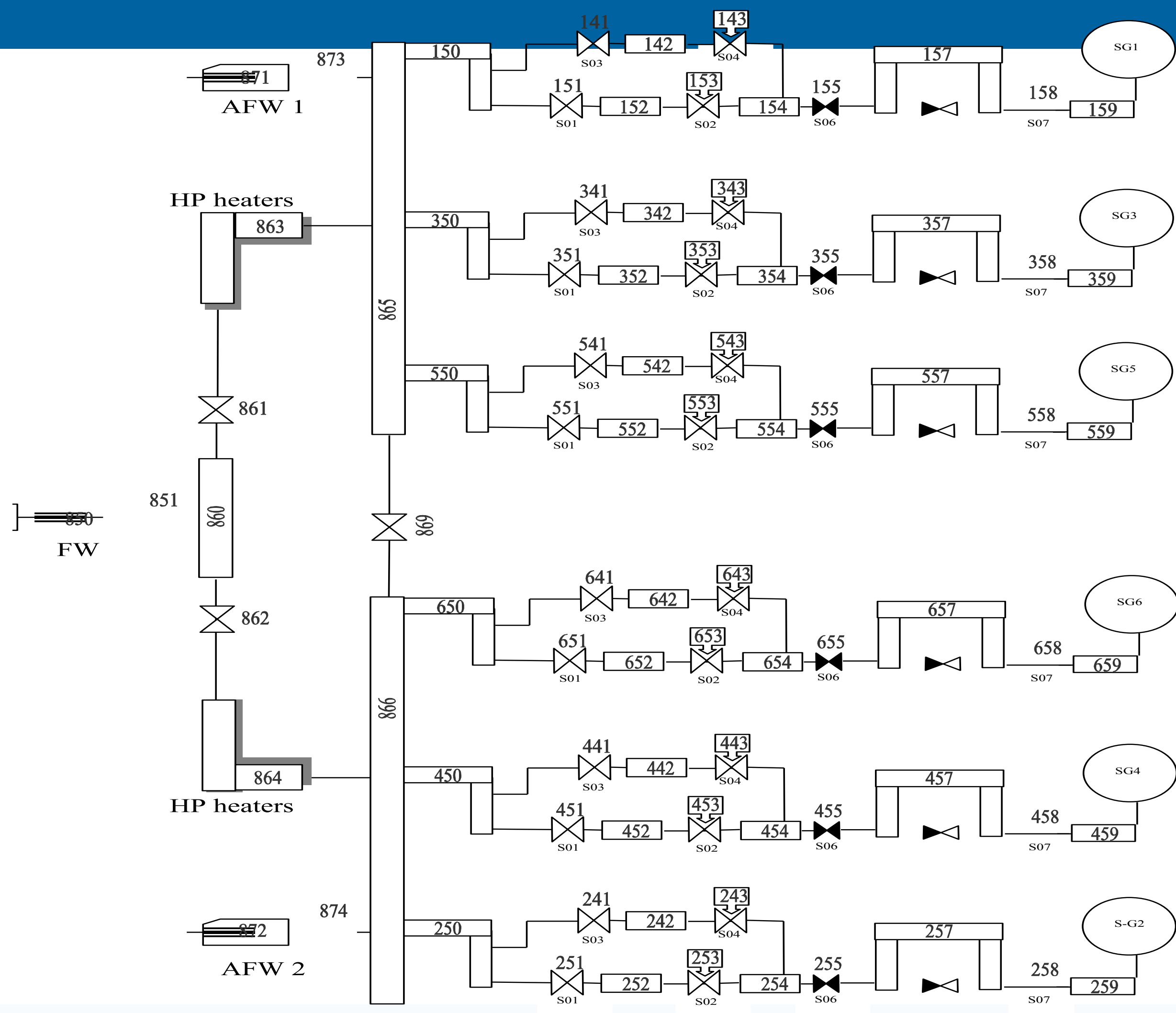


Steam Generator

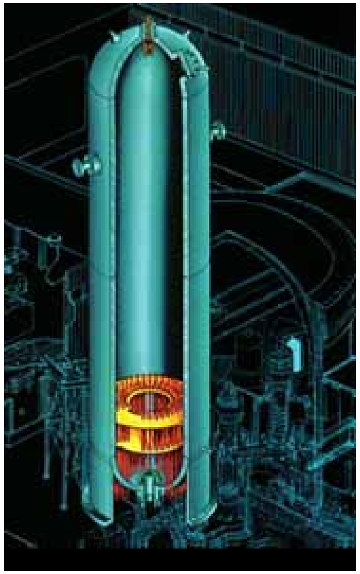


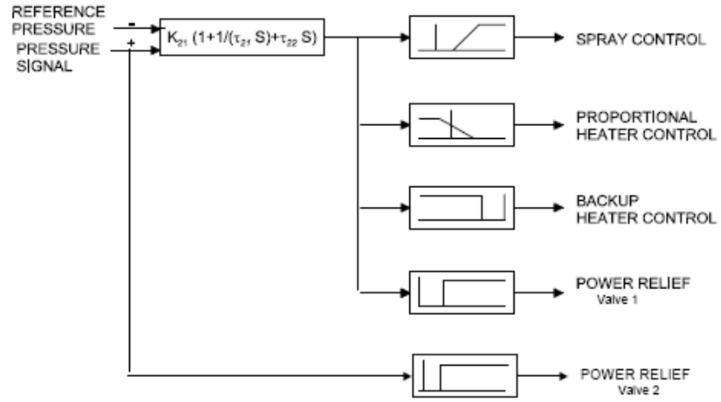


Feedwater system

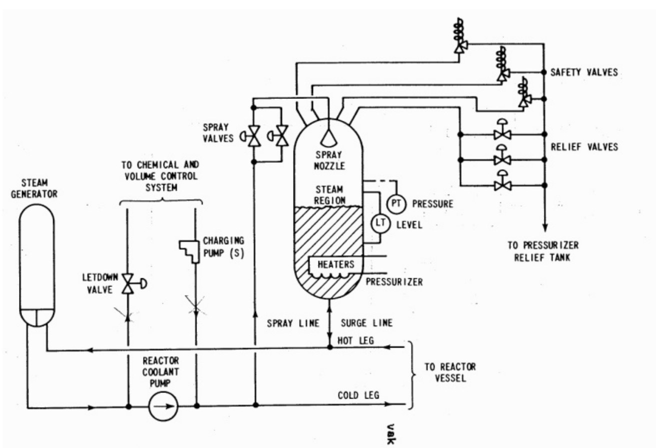


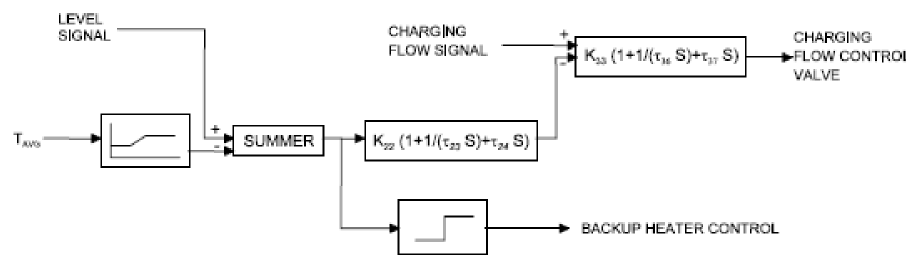
Pressure control





Pressurizer pressure control





Pressurizer level control

Example of an input deck

```
*  intact loop steam generator primary inlet plenum                  *
*****************************************************************
$          name        type
1060000    isgip       snglvol
$          flow area   length  volume  **   angle2  elevation  rough   De      v-flag
1060101    85.650      0.0     448.29  0.0  49.     3.958      1.e-4   6.029   00
$initial   control     pressure  temperature
1060200    3           2240.9    589.26
***************************************************************
$          name        type
1110000    isgop-ic    sngljun
$          from        to            flow area   f-loss   r-loss   j-flag
1110101    110010000   112000000     15.723      0.367    0.667    0000
$initial   control   f-flow          g-flow   I-flow
1110201    1         30464.55        0.0      0.0
****************************************************************
$          name   type
1570000    porv   valve
$          from          to            flow area   f-los   r-loss   j-flag
1570101    158000000     150000000     0.009375    0.0     0.0      0100
$initial   control   f-vel   g-vel   I-vel
1570201    0         0.0     0.0     0.0
$          valve type
1570300    trpvlv
$          valve trip
1570302    603
****************************************************************
```

Conclusion

Computer codes used in the safety analysis of systems provide only a simplified image of real physical processes and need to be applied with care and the calculation results interpreted and analyzed.

International Atomic Energy Agency

…Thank you for your attention

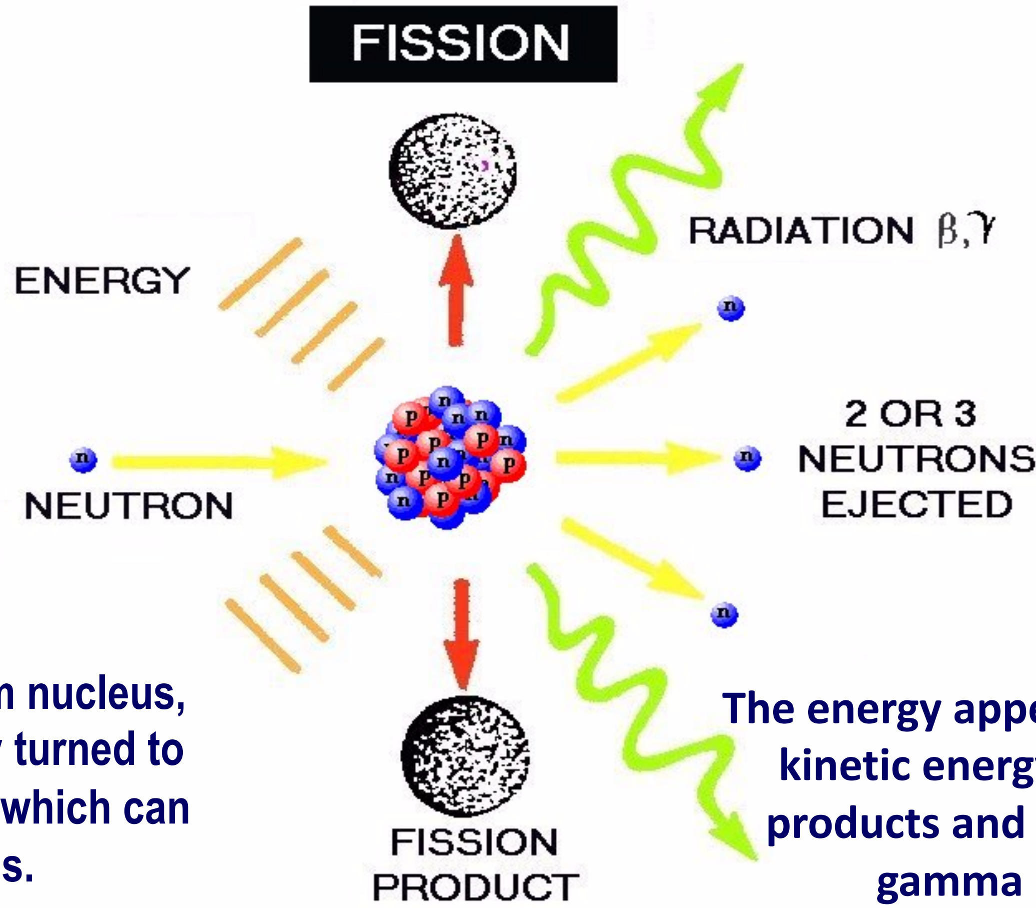
Outline

1. Overview of physics fundamentals
   - Fission, cross-section, moderation, reactivity, etc.

2. Implication for reactor design
   - Neutron diffusion
   - Fuel composition and burnup
   - Reactivity control
   - Reactivity coefficients
   - Xe-135

3. Assessment of reactor core design safety

Neutron-Induced Fission



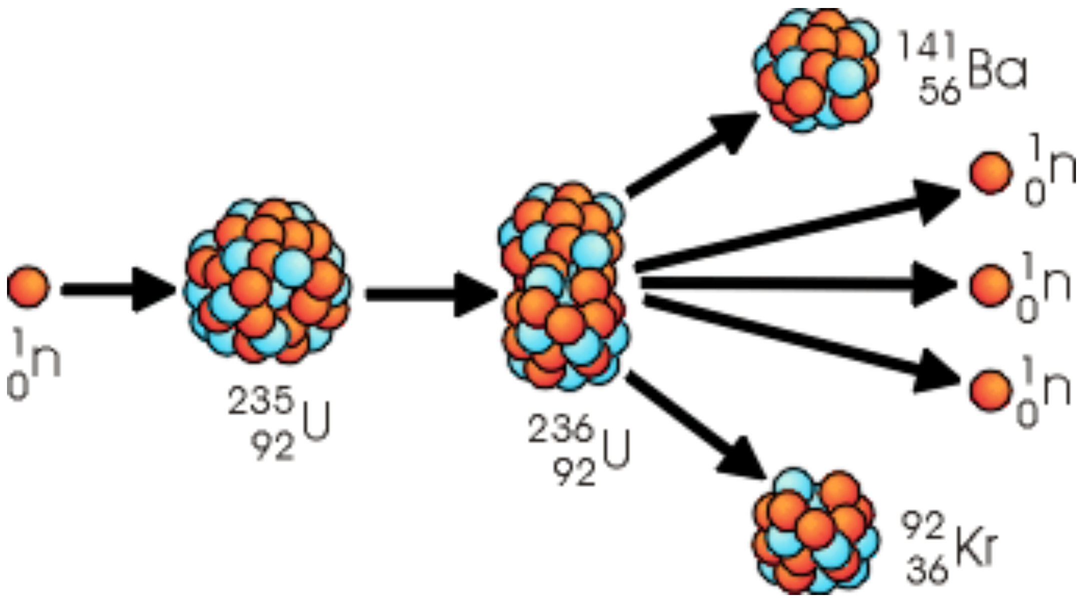
A neutron splits a uranium nucleus, releasing energy (quickly turned to heat) and more neutrons, which can repeat the process.

The energy appears mostly in the kinetic energy of the fission products and in the beta and gamma radiation.

Neutron – Nucleus Interaction

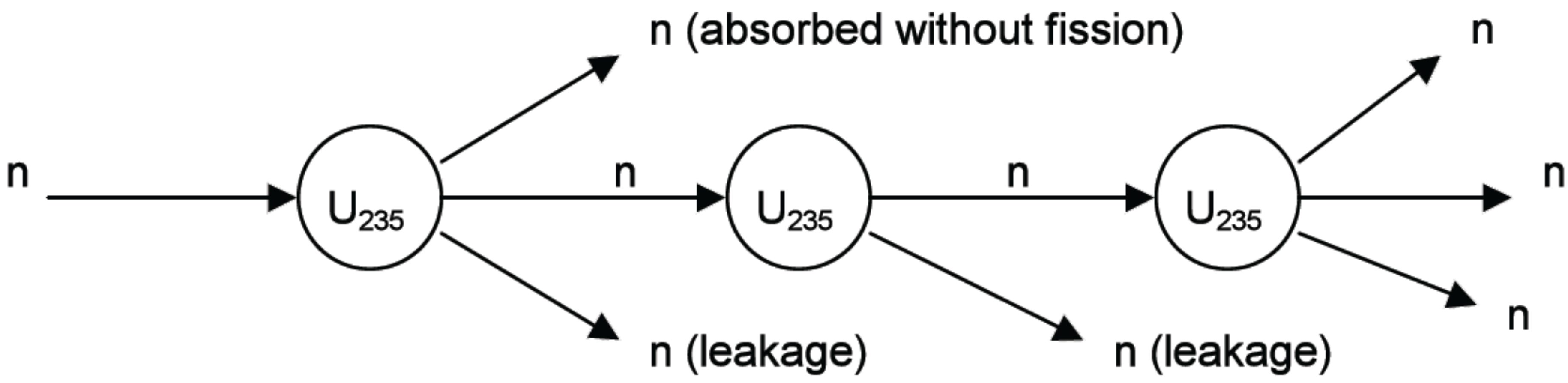
- A neutron may undergo several different reactions with a nucleus, including:
  - *Scattering* (elastic or inelastic): there is a transfer of energy between the neutron and the nucleus
  - *Absorption:* the neutron is absorbed into the nucleus and lost
  - ***Fission:* the neutron causes the nucleus to fission, *releasing additional neutrons and fission products***
- The likelihood of an interaction occurring is represented with a microscopic *cross section* (σ) [1 barn (b)== l0-28 m2]
  - Dependent on the *isotope* of the interacting material (and its temperature)
  - Dependent on the incident *neutron energy*

Induced Fission Reaction



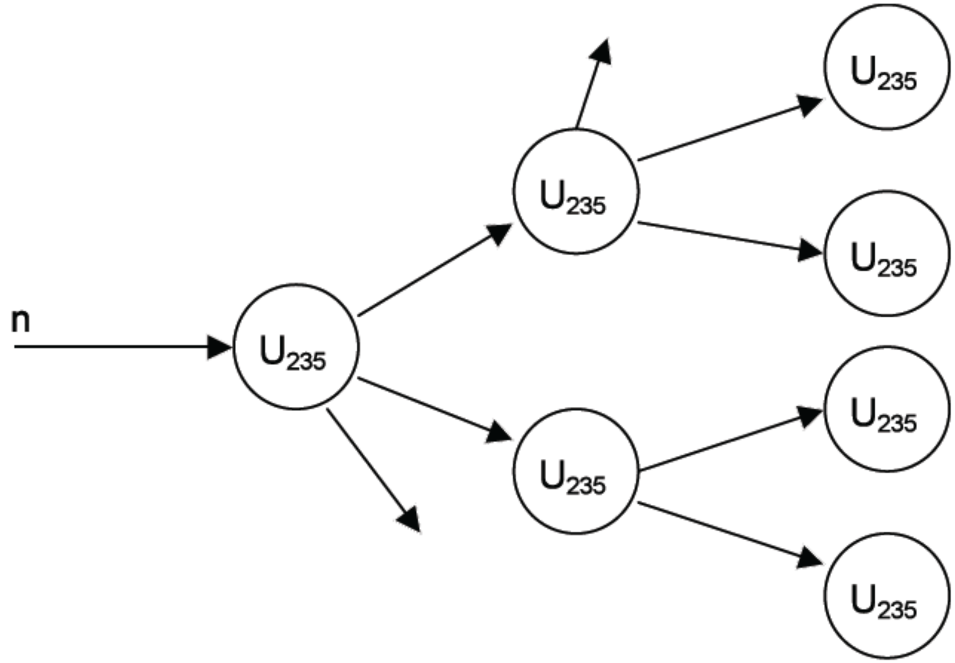
- Certain heavy nuclei can be induced to fission, as a result of one neutron capture.

Critical Chain Reaction



This reaction is termed a “critical” reaction because the number of fissions remains constant in each generation (multiplication factor k=1)

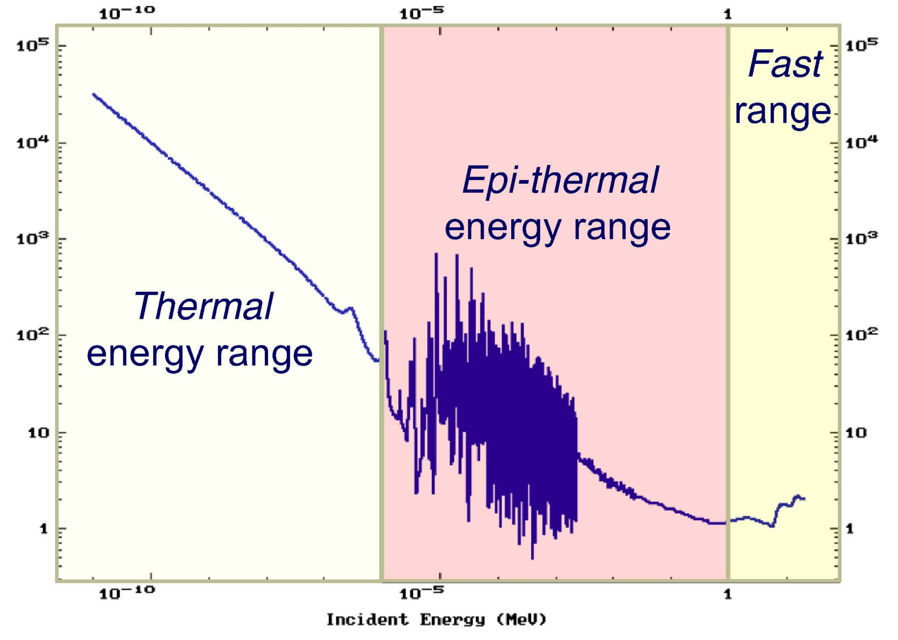
Supercritical Chain Reaction



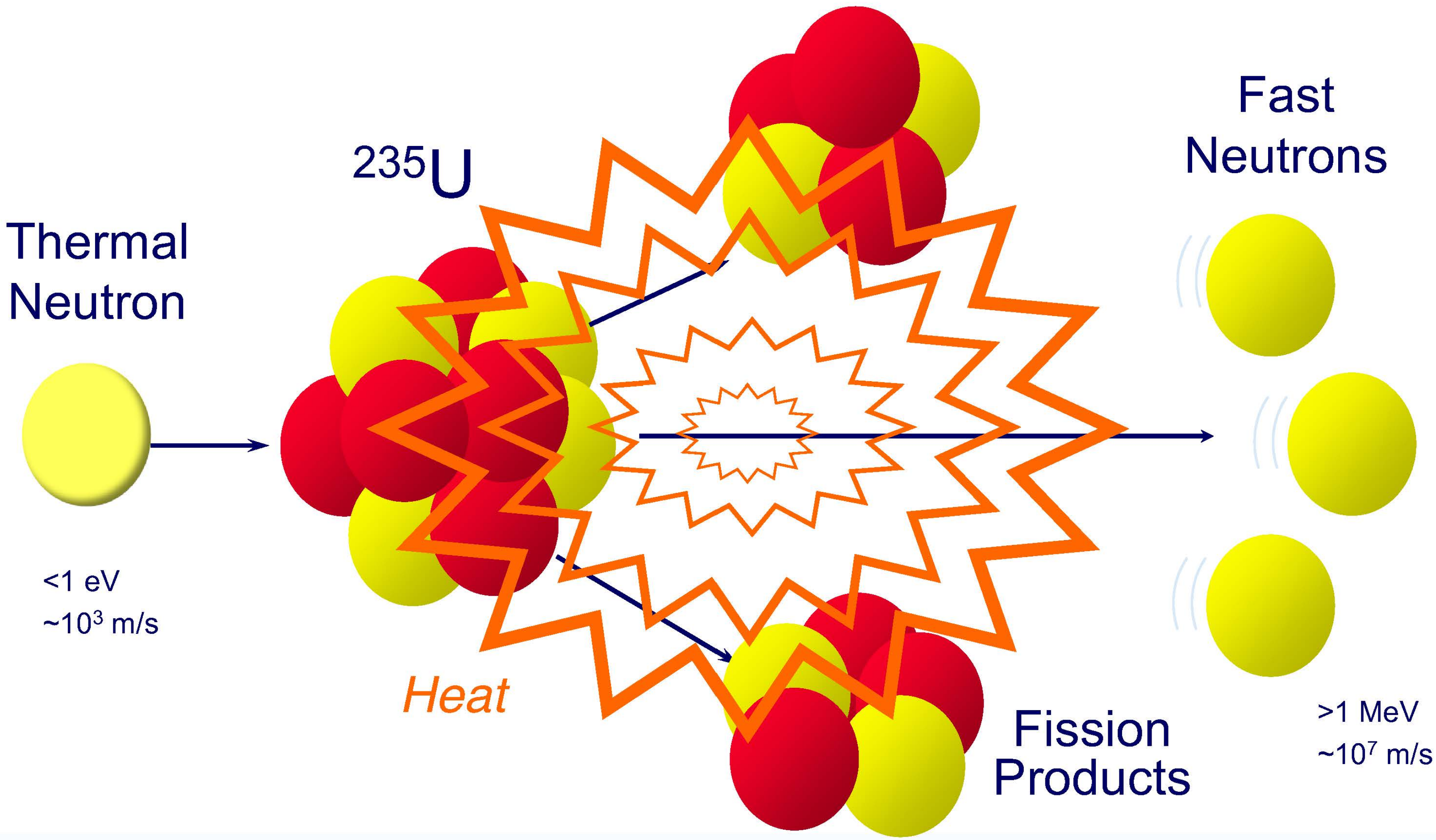
Supercritical chain reaction $k = 2$

^{235}U Cross Sections

- Neutron energies cover -10 orders of magnitude:
  - \- Fission spectrum
  - \- Delayed spectrum
  - \- Moderation
- Interaction cross sections may change by 5+ orders of magnitude over this range of energy.



Thermal Fission of ^{235}U

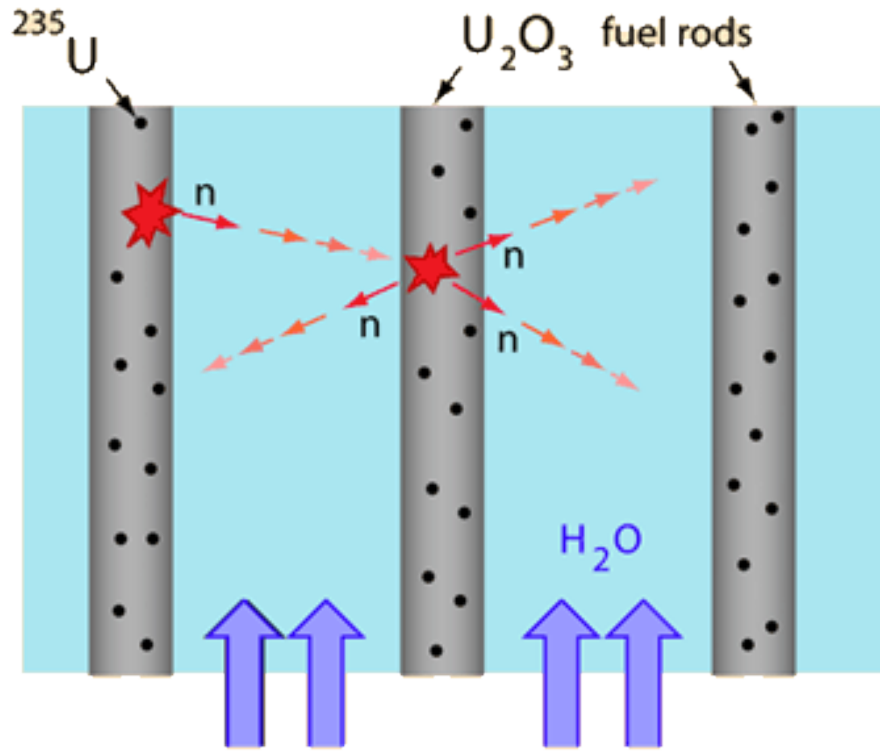


Neutron Moderation

- Most neutrons born from fission are in the fast range (high energy)
- **To sustain a fission chain reaction, the fast neutrons must be brought down to a lower energy (where $\sigma_{fission}$ is higher) via interaction with a *moderator***
  - *Thermal reactor*
- Neutrons transfer their "excess" energy to the moderator through series of scattering interactions / collisions
- Good moderators have:
  - Low absorption cross sections $\sigma_{absorption}$
  - Low atomic masses (to maximize dE in a single interaction)

Moderator

- In a thermal reactor, the fuel must be spaced out and additional material is added between the fuel elements to act as a “slowing down” medium and this is known as a moderator.
- A moderator consists of a material that contains a large proportion of light atoms.
  - **A hydrogen atom has a mass very close to that of a free neutron.**
  - **Each time a neutron collides with a hydrogen atom it can lose up to all of its kinetic energy, depending upon the angle of impact.**



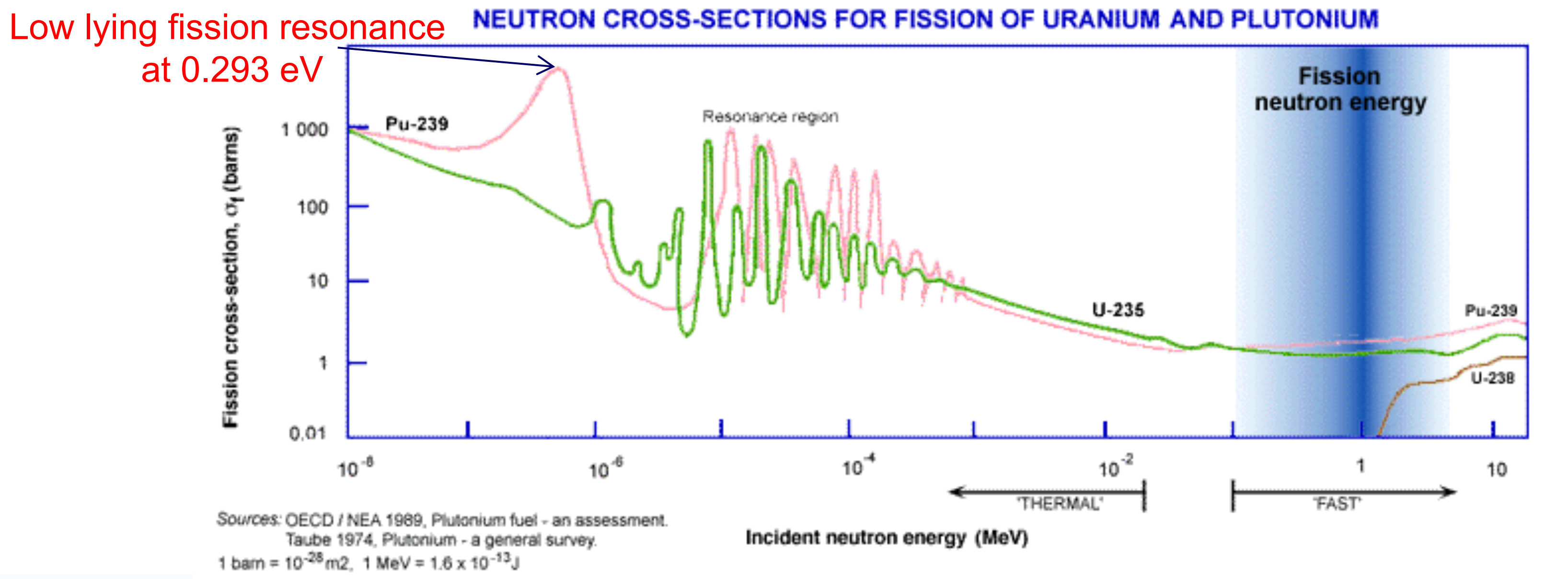
Water as coolant and moderator flows between fuel rods.

Neutron Moderation

- Most efficient moderator has light atoms:
  - H (light water), mass 1; excellent at slowing neutrons, but <u>absorbs</u> neutrons strongly! → Good for enriched fuel;
  - D (heavy water), mass 2; excellent moderator, low neutron absorption, high neutron economy → Good for natural U fuel.

Fission Resonances

- Not all resonances are non-productive capture resonances.
- For example, Pu-239 has an important low-lying **fission** resonance at ~0.3 eV, in which the fission cross section is greatly enhanced
- This plays an important role in several phenomena.



Multiplication Factor & Reactivity

- Reactor effective multiplication factor:

$$k_{eff} = \frac{Rate\, of\ neutron\ production}{Rate\, of\ neutron\, loss\,(by\, capture\, or\, leakage)}$$

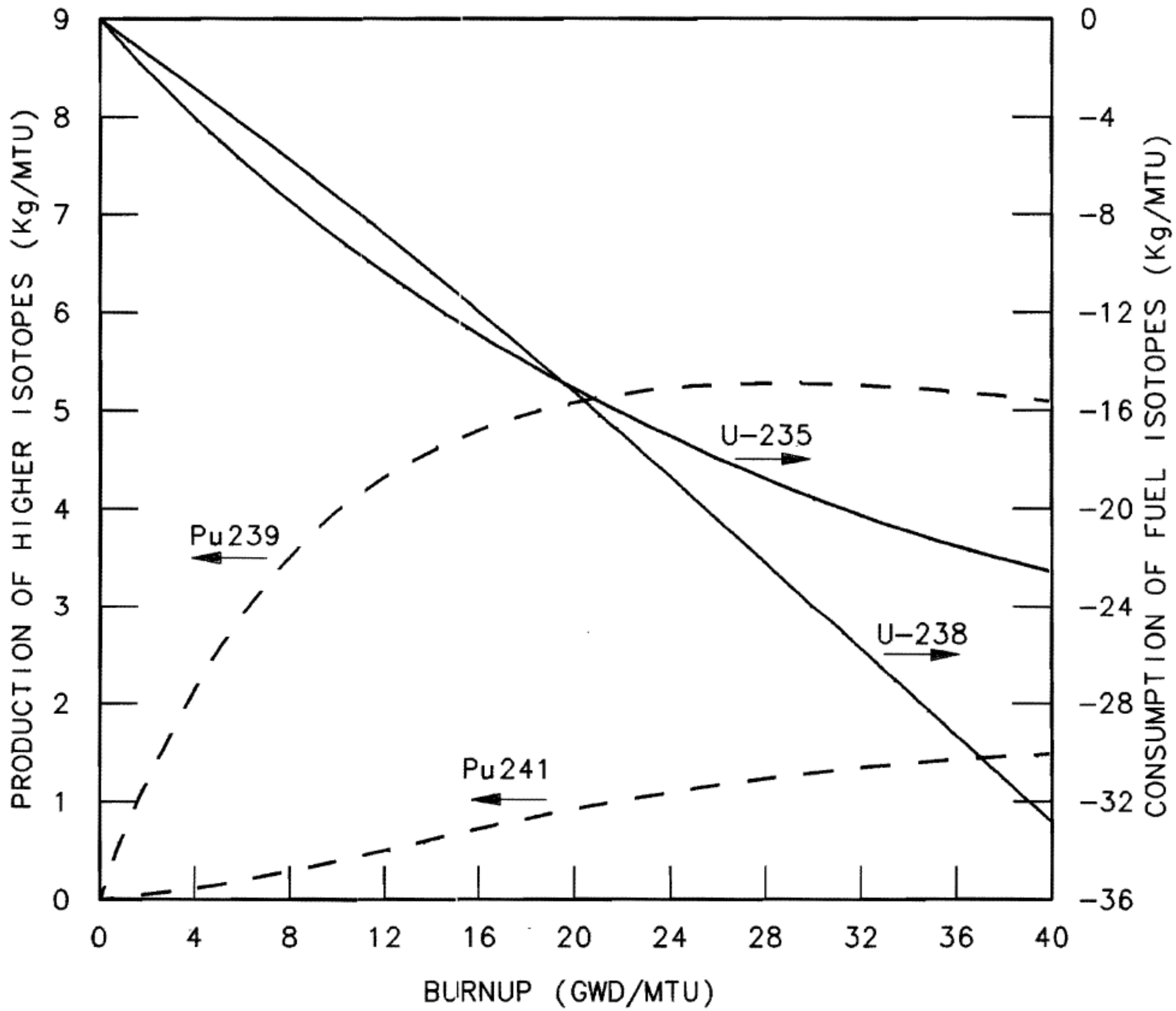
- k_{eff} < 1, = 1, > 1: subcritical, critical, supercritical
- Departures of k_{eff} from 1 measured in milli-k: 1 mk = 0.001
- Reactivity ρ also used, defined as

$$\rho = 1 - \frac{1}{k}$$

Fuel Composition & Burnup

- Fresh uranium fuel: initially 2 – 5 wt.% U-235.
- As fuel is irradiated in reactor, energy is generated.
- In fresh fuel, 95% of fissions occur in U-235, which depletes steadily.
- At discharge of fuel from the reactor, U-235 concentration ~0.8% (along with 0.4% U-236).
- Simultaneously, small fraction of U-238 is transformed into U-239 ($^{238}U + n \Rightarrow 239U$), then double beta decay leads to Pu-239.
- Pu-239 is fissile, participates in fission chain reaction as well: Pu-239 builds up in the fuel and is also burned "in situ".
- Formation of Pu-240 (absorber) and Pu-241 (fissile) by successive neutron absorption in Pu-239.
- For UO_2 fuel @ 55000 MWd/t in a PWR (NUREG/CR-7013),
  - Pu-239 concentration in the "heavy element" (i.e., as a fraction of the total U + Pu) is about 0.6 wt.%.
  - Total fissile material (U-235 + Pu-239) at discharge is ~1.4 wt.%, compared to initial fissile content of 4.5 wt.%.

Production & Consumption of Higher Isotopes

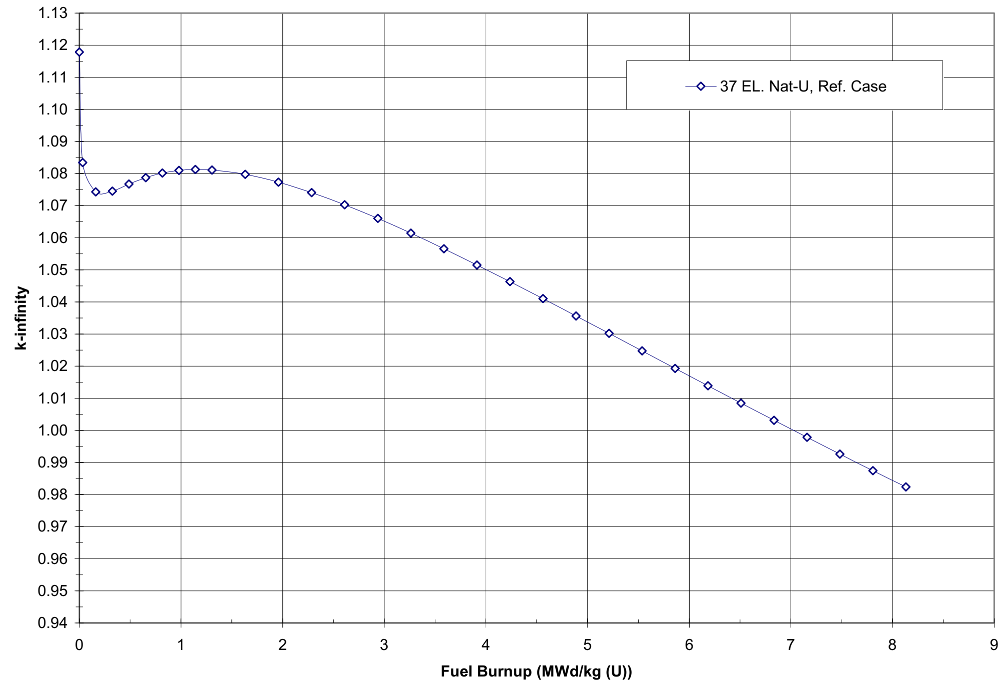


Multiplication Factor & Reactivity – Cont'd

- Infinite multiplication constant k_∞ also defined, for an idealized infinite lattice of identical unit cells (no interstitial reactivity devices, no leakage).

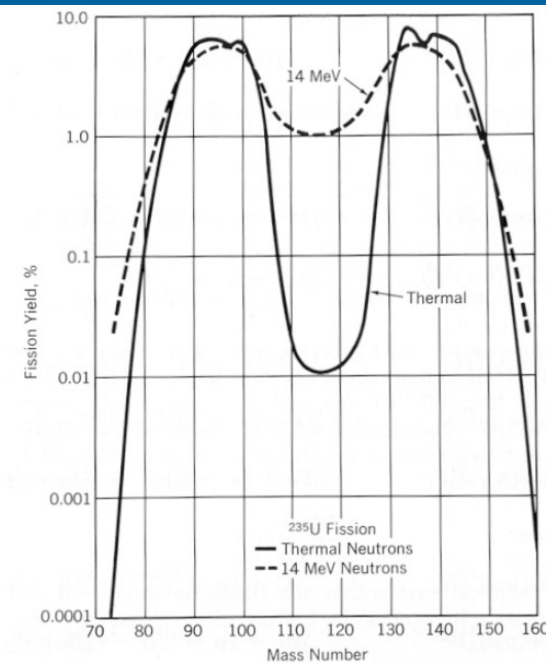
- No leakage $\Rightarrow$ for k_{eff} = 1, must have k_∞ >1.

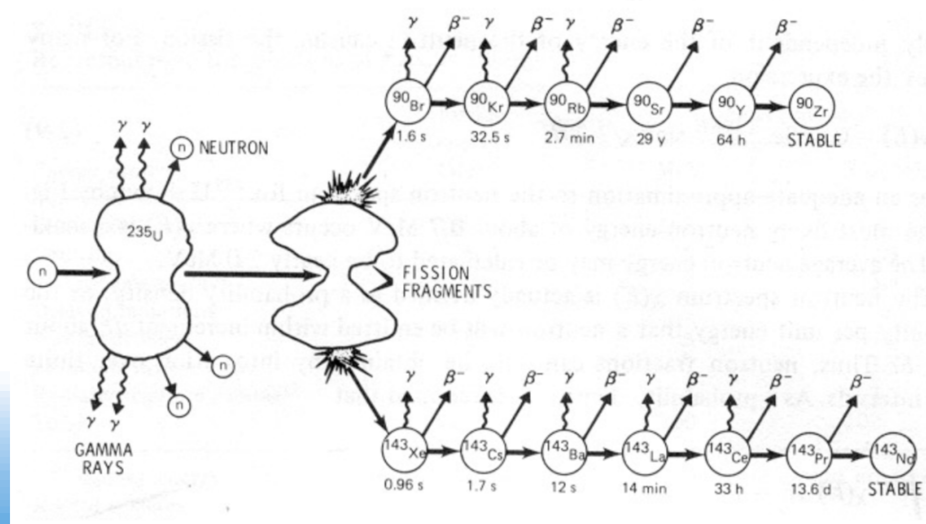
- Decreases with irradiation (depletion of the fissile material):



1.5 Fission Products

- Mass distribution; see Figure.
- May be gaseous (75%), solid (25%); migrate from fuel matrix → Impact of the fuel clad integrity, DNBR.
- FP decay; decay heat after reactor trip → one concern for accident scenarios.
- Sm, Xe: strong absorption of neutrons → impact on reactor control.





Implication for Reactor Design

- Choose fuels with high probability for fission
  - fast neutron energy
  - thermal neutron energy
- Select other materials with low probability for absorption
  - coolant
  - moderator
  - fuel cladding
  - core structural materials
- Select control materials with high probability for absorption
  - soluble poison (boron)
  - control rods (Ag-In-Cd, B_4C)
- Design geometry of the reactor to minimize leakage
  - add reflectors (scattering material) to keep neutrons in the reactor

Reactivity Control: Boron and BP Rods

- Excess reactivity; controlled by removable neutron absorbing material in the form of boron dissolved in the coolant and burnable absorber rods.
- As the boron concentration is increased, the moderator temperature coefficient becomes less negative → Concern: the use of boron alone would result in a positive moderator coefficient at BOL for the first cycle.
- To ensure the negative moderator temperature coefficient at power operating condition, burnable absorbers (BP) are used together in the first core to sufficiently reduce the soluble boron concentration.
- In addition to reactivity control, the BP rods are strategically located to provide a favourable radial power distribution.

Reactivity Coefficients

- **Reactivity change** may come from:
  - Fuel reloading
  - Saturated FP (Xe, Sm, …) transients
  - Sudden accidents or perturbations, which change one or more lattice parameters (e.g., fuel, coolant, or moderator temperature, coolant density, poison concentration, etc…).
- **Reactivity coefficient**
  - Defined as the derivative of the system reactivity with respect to the change in a lattice parameter; for example,
  - Fuel-temperature coefficient of reactivity = $\partial\rho / \partial T_f$
  - Moderator-density coefficient of reactivity = $\partial\rho / \partial M_d$
  - Coolant-density coefficient of reactivity = $\partial\rho / \partial C_d$
  - Power coefficient of reactivity = $\partial\rho / \partial P$
- **Significance**:
  - A positive value for a reactivity coefficient means that a positive change in that parameter will increase reactivity and tend to increase power;
  - A negative value for a reactivity coefficient means that a positive change in that parameter will decrease reactivity and tend to decrease power.

Reactivity Coefficients – Cont'd

- Important reactivity coefficients include the following but are not limited to:
  - Fuel-temperature reactivity coefficient, as fuel temperatures will change in any power maneuvers;
  - Coolant (moderator)-density reactivity coefficient, as coolant density will change with the amount of boiling, and, in safety analysis, coolant voiding (as a result of a Loss-of-Coolant Accident) is extremely important to analyze;
  - Power coefficient of reactivity, which combines effects from the above two coefficients (and perhaps others).

- Units
  - mk/C degree (or $degC^{-1}$) – for a temp coefficient
  - mk/(g/cm^3) – for a density coefficient
  - mk/%FP – for the power coefficient of reactivity coefficients

Fuel-Temperature reactivity Coefficient

- The fuel-temperature coefficient is governed by the effect of temperature on the neutron absorption by fuel;
- Neutron absorption in fuel is marked by the existence of resonances.
- Doppler broadening of resonance with fuel temperature: increase of absorption in resonances.

→ The fuel-temperature reactivity coefficient is negative.

→ In an accident where the power increases, a negative fuel-temperature reactivity coefficient provides a prompt negative feedback, which tends to bring power back down.

Effect of Pu-239

- Although the fuel-temperature reactivity coefficient is negative, the presence of Pu-239 in fuel makes it less negative.
- In plutonium-bearing fuel, the 0.3-eV Pu fission resonance gives a positive contribution to reactivity coefficient.
- At sufficiently high burnup, the coefficient will turn positive.

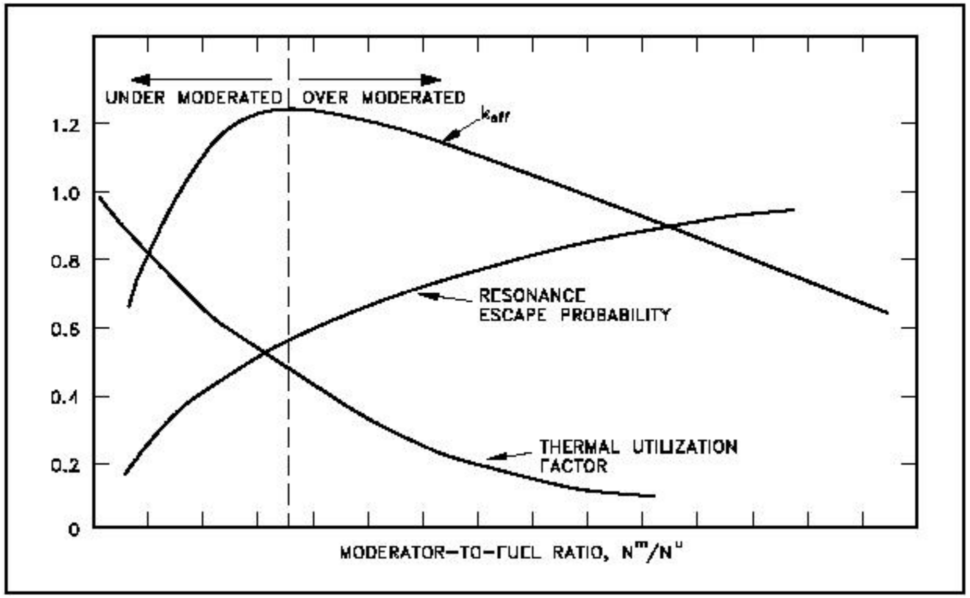
Reactivity Insertion on Shutdown

- With a negative fuel-temperature reactivity coefficient, the reduction in temperature when the reactor is shut down will result in a positive reactivity insertion.

- A reactivity device must be available to counter this positive reactivity on shutdown, to ensure core remains subcritical: e.g., the Mechanical Control Absorbers (MCAs), or moderator poison.

Coolant-Density Reactivity Coefficient

- In LWRs, where the coolant and the moderator are not separated, a reduction in coolant density is equivalent to a reduction in moderator density, which is a negative reactivity effect.
- Turning this around, an increase in coolant density is a positive reactivity effect in the LWRs.
- In LWR, coolant (moderator)-density reactivity coefficient becomes negative as temperature increases.



Power Coefficient of Reactivity

- An increase in power results in a prompt increase in fuel temperature, and may result in an increase in coolant boiling.

- Thus, the power coefficient of reactivity will in general be a combination of an increase in fuel temperature ($\Delta\rho < 0$) and a reduction in coolant density ($\Delta\rho < 0$ in LWR).

2.9 Xe-135: production & Loss

- Absorption cross-sections of many FPs are not important in short-term operation; Xe-135 has a cross-section of approx. 3,000,000 barns (over 4000 times that of U-235);
- Xe production (6.6% of all fissions)

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{99}_{38}Sr + ^{135}_{54}Xe + 2\,^{1}_{0}n + \gamma$$

$$^{135}_{53}\mathrm{I} \xrightarrow[T_{1/2} = 6.6\,\mathrm{hr}]{} ^{135}_{54}\mathrm{Xe} + \beta$$ (95% of total Xe production)

- Xe loss

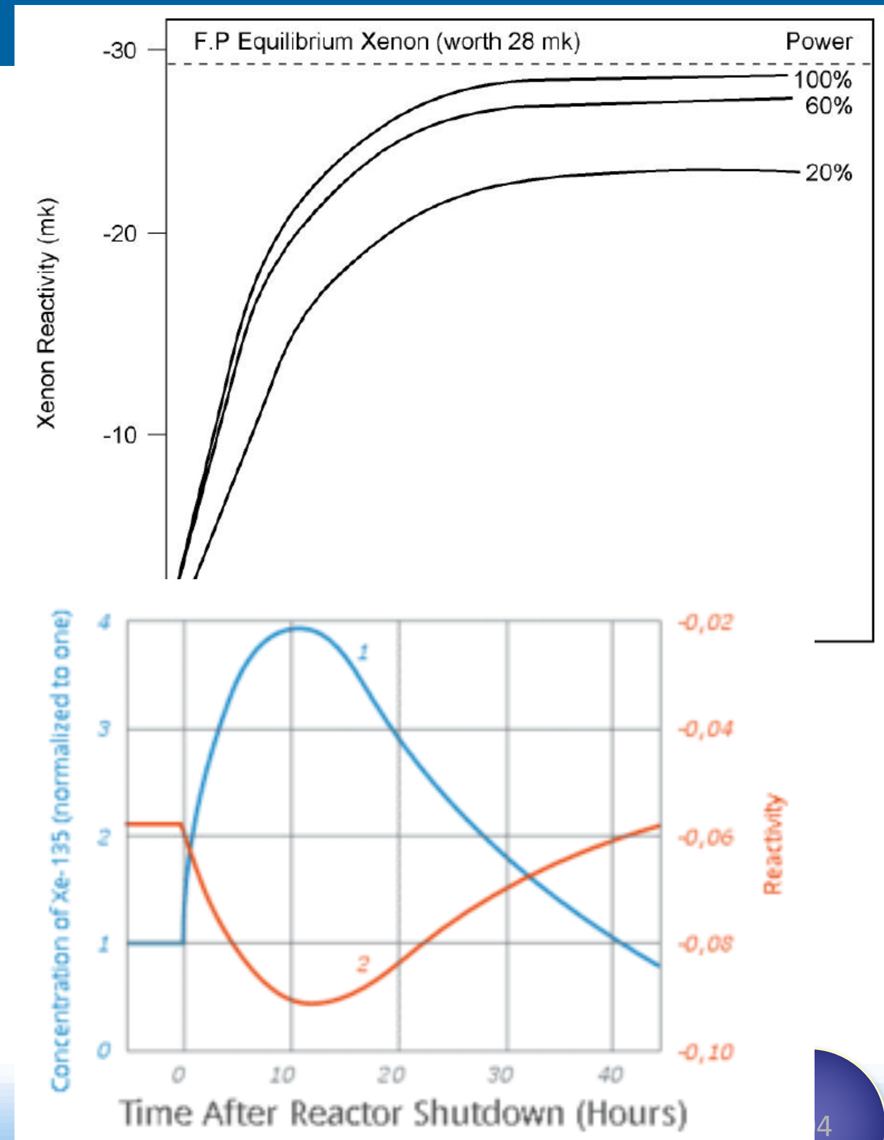
$$^{135}_{54}\mathrm{Xe} \xrightarrow[T_{1/2} = 9.1\,\mathrm{hr}]{} ^{135}_{55}\mathrm{Cs} + \beta$$

(90% of total Xe loss)

$$^{1}_{0}n + ^{135}_{54}Xe \rightarrow ^{136}_{54}Xe + \gamma$$

2.9.1 Equilibrium Xe Load

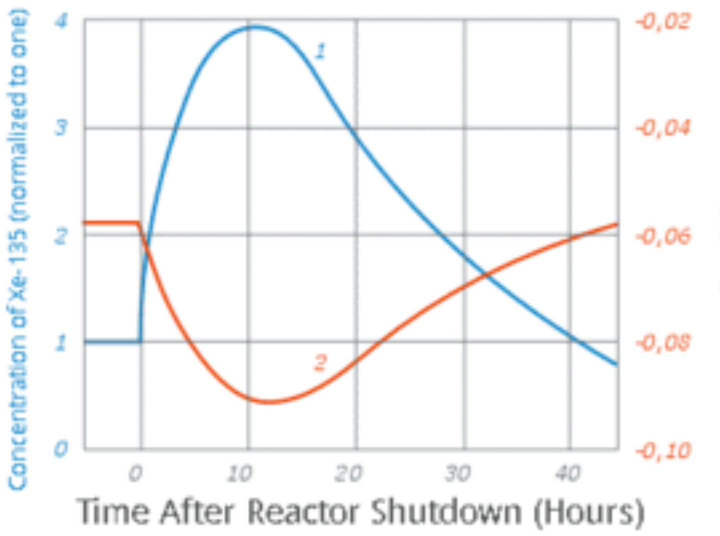
- No Xe in the fuel of a reactor that has been shut down for a long time (or has never been operated);
- Xe slowly build up to equilibrium after start-up; Xe load depends on the steady-state reactor power.
- The negative Xe reactivity is always present in normal steady operation, except during the first several hours after start-up.



Xe Transients

Immediately after a reactor trip:

- **Xe production**
  - From fission (5%) → stops immediately
  - From decay of Iodine (95%) → continues;
  - In short term, most production continues.
- **Xe loss**
  - By decay (10%) – continues
  - By neutron absorption – stops immediately;
  - In short term, most of removal stops.



To restart reactor shortly after shutdown:

- Positive reactivity must be supplied to "override" xenon growth, e.g. by withdrawal of adjuster rods within "xenon-override" time window → Impact on the integrity of the fuel cladding.

3. Assessment of Reactor Core Design Safety

Important Safety parameters	Acceptance criteria
Fuel exit (discharge) burnup	Sustainable chain reaction; Acceptable fuel design limits
Reactivity coefficients	Compensation for a rapid increase in reactivity due to a power change; Net negative value.
Control of power distribution	Acceptable fuel design limits
Maximum reactivity insertion rate	Acceptable fuel design limits; No damage to the reactor coolant pressure boundary
Shutdown margins	Reactor control
Stability (against power oscillation)	Acceptable fuel design limits