Broad topic	Lecture title
Basic principles of NPP	Introduction / Review of nuclear physics
	Interaction of neutrons with matter
	Nuclear fission
	Fundamentals of nuclear reactors
	LWR plants
Modeling the beast	The diffusion of neutrons - Part 1
	The diffusion of neutrons - Part 2
	Neutron moderation without absorption
	Neutron moderation with absorption
	Multigroup theory
	Element of lattice physics
	Neutron kinetics
	Depletion
Reactor Concepts Zoo	Advanced LWR technology
	Breeding and LFR
	AGR, HTGR
	Channels, MSR and thorium fuel
Review session	

THIS LESSON …

- Reactor Kinetics
- Kinetics without Delayed Neutrons
- Kinetics with Delayed Neutrons
- Point Kinetics Equations
- Inhour Equation
- Decay Heat
- Reactivity Variations
  - Reactivity Feedbacks
  - Reactivity Coefficients and Safety

- In general, one seeks to determine $\phi(\vec{r}, E, t)$
  - Time-dependent diffusion equation needs to be solved numerically

$$P(t) = \int_E dE \int_V n(\vec{r}, t)\, d\vec{r}$$

- For the global behaviour, a simplification can be made
  - "Point kinetics" equations for the total neutron population
  - Does not describe spatial effects in large complex systems, but very useful…

- Two cases may be considered for the time-dependent behaviour
  - Without delayed neutrons (hypothetical)
  - Real situation (with delayed neutrons)

- One particular case, can be considered analytically
  Step change in k_{eff}
  → Leads to Reactivity Equation (Inhour Equation)

- For the neutron population: $$\frac{\mathrm{d}P}{\mathrm{d}t} = \bar{\nu}F(t) - (A(t) + L(t))$$

- Using: $$k_{\text{eff}}(t) = \frac{\bar{\nu}F(t)}{A(t)+L(t)} \implies \frac{\mathrm{d}P}{\mathrm{d}t} = (k_{\text{eff}}(t) - 1)\cdot(A(t)+L(t))$$

Depends on cross sections, reactor size, …

- $$[A, L] \propto P \implies A(t) + L(t) = cst \cdot P(t) \simeq \frac{P(t)}{l}$$

Dimension of time

- Prompt Kinetics Equation $$\frac{\mathrm{d}P}{\mathrm{d}t} = \frac{k_{\text{eff}}(t) - 1}{l} P(t)$$

- For a constant k_{eff} :

$$P(t) = P(0)\exp\left(\frac{k_{\text{eff}} - 1}{l}t\right)$$

→ if k_{eff} >1, P↗ (supercritical system)
→ if k_{eff} <1, P↘ (subcritical system)

- For an hypothetical passive medium with same cross-sections but $k_{\text{eff}} = 0$ (e.g. $\nu = 0\ldots$), l is same and

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \frac{k_{\text{eff}}(t) - 1}{l} P(t) = -\frac{1}{l} P(t) \implies P(t) = P(0) \exp\left(-\frac{t}{l}\right)$$

- Result is analogous to the law of radioactive decay : $1/l$ is like λ , i.e. l is like T…

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- Thus, l is *neutron lifetime*
  Measure of time taken for "disappearance" of the n's (P ↘) , in face of absorption, leakage…

- Like k_{eff} , l may be calculated on the basis of different theories (diffusion, 1-group, multigroup, transport,…)
  → Consider particular case: bare homogeneous reactor, analysed via 1-group diffusion theory

- One has: $l = \dfrac{P(t)}{A(t)+L(t)}$ with $A(t) = \int_V \Sigma_a \phi(\vec{r},t)\mathrm{d}V = \Sigma_a v \int_V n(\boldsymbol{r},t)\mathrm{d}V = \Sigma_a v P(t)$

- Leakage ~ supplementary absorptions corresponding to: $\Sigma_a' \simeq DB^2$

- Thus, $L(t) = DB^2 vP(t) \implies A(t) + L(t) = (\Sigma_a + DB^2)vP(t)$

- i.e. $l = \dfrac{P(t)}{A(t)+L(t)} = \dfrac{1}{v(\Sigma_a + DB^2)} = \dfrac{1}{v\Sigma_a(1+B^2L^2)}$ (independent of P)

- For an infinite system: $l = \dfrac{1}{v\Sigma_a} = \dfrac{\lambda_a}{v} = t_d$ (thermal diff. time; slowing-down time negligible…)

- One may write: $l = \dfrac{1}{v\Sigma_{am}} \dfrac{\Sigma_{am}}{(\Sigma_a)_{tot}} = \dfrac{1}{v\Sigma_{am}}(1-f) = (t_d)_m\,(1-f)$

- For the reactor without delayed neutrons, $P(t) = P(0)\exp\left(\frac{k_{eff} - 1}{l}t\right)$

$$P(t) = P(0)\exp\left(\frac{t}{T}\right) \quad \text{with} \quad T = \frac{l}{k_{eff} - 1}$$

- t_d for different moderators:

H_2O	$2{,}1\cdot10^{-4}$ sec.	
D_2O	$1{,}4\cdot10^{-1}$ sec.	
Be	$3{,}9\cdot10^{-3}$ sec.	
Graphite	$1{,}7\cdot10^{-2}$ sec.	

thus typically: $l = (t_d)_m\,(1 - f) \simeq 10^{-2}$ to 10^{-4} s

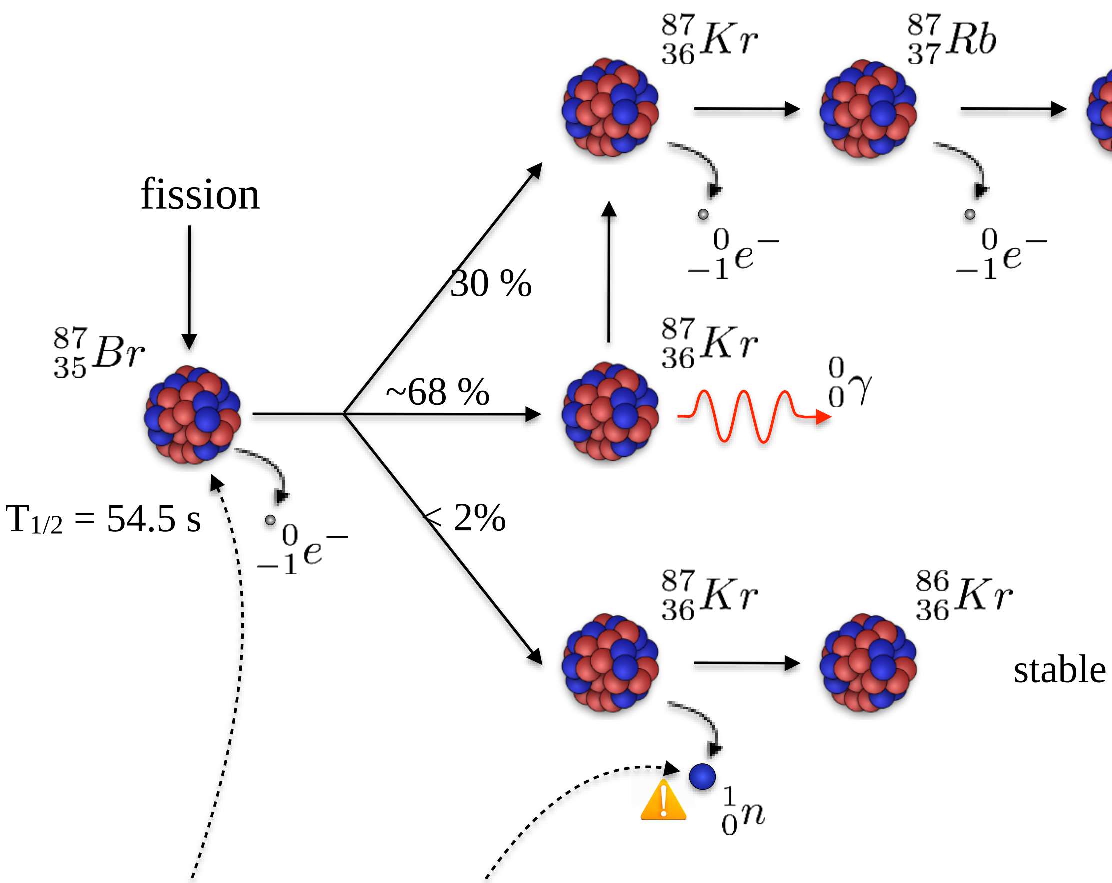
- If k_{eff}: 1.00000 ➞ 1.00500, $P(t) = P(0)\exp\left(\frac{k_{\text{eff}} - 1}{l}t\right) \simeq P(0)\exp\left(\frac{0.005}{10^{-3}}t\right)$

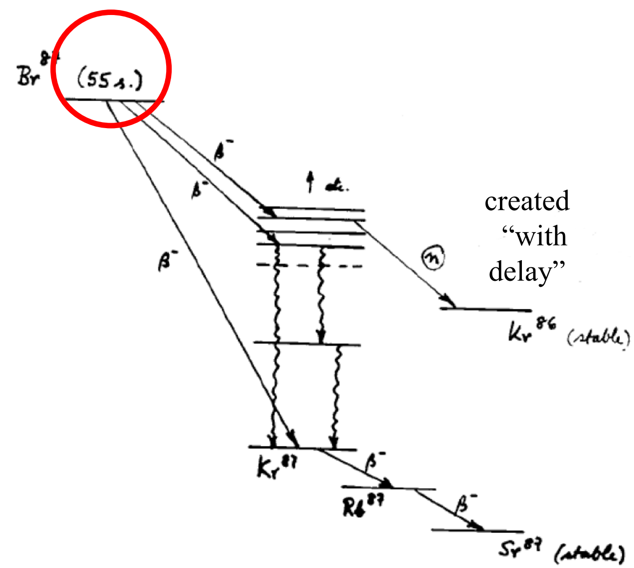
- Period T=1/5 s ➞ P↗ by e^5 = 148 is 1 s !!

- For a fast reactor, $l=10^{-6}$ to 10^{-7} s ➞ factor of 148 in < 1 ms !

Reactors would be practically impossible to control…

- Small fraction of the neutrons, not prompt (~ 0.6% for ^{235}U)
  Produced by decay of FP's, e.g.





- « Precursor » of « delayed neutron »
  ~ 6 groups of precursors
  $y_i, T_i \Rightarrow \beta_i, \lambda_i$ (i = 1,6)

- E_{avg} of delayed n's ~ 0.4MeV
- λ_i's relatively constant
- β_i's depend on nuclide, e.g.

  $\beta = \mathrm{Sum}(\beta_i) = 0.21\%$ for ^{239}Pu

  $= 0.26\%$ for ^{233}U
- β small, but very important for control of the chain reaction → *kinetic behaviour*
- Response of a reactor which becomes slightly supercritical, much slower

for ^{235}U:

Gp	Precursor	$T_{1/2}$ (s)	λ_i (1/s)	β_i (%)
1	^{87}Br, ^{142}Cs	55.7	0.012	0.022
2	^{137}I, ^{88}Br	22.7	0.031	0.142
3	^{138}I, ^{89}Br, …	6.2	0.11	0.127
4	^{139}I, Cs, …	2.3	0.30	0.257
5	^{140}I, Kr, …	0.61	1.14	0.075
6	Br, Rb, …	0.23	3.01	0.027

$\beta = \mathrm{Sum}(\beta_i)$
$= 0.65\ \%$

- Fraction β of n's in reactor are delayed, so that the neutron production rate $\neq \bar{\nu} F$
- It is, in fact: $$\underbrace{\bar{\nu} \cdot F \cdot (1-\beta)}_{\text{Prompt Sources}} + \underbrace{\sum_{i=1}^{6} \left[\underbrace{\lambda_i}_{\text{Decay constant}} \times \underbrace{C_i(t)}_{\text{Precursor density at time t}} \right]}_{\text{Delayed Sources}}$$
- Thus $$\frac{dP}{dt} = \bar{\nu} F(t)(1-\beta) - [A(t) + L(t)] + \sum_{i=1}^{6} \lambda_i C_i(t)$$
- As before, substituting

$$k_{\text{eff}}(t) = \frac{\bar{\nu} F(t)}{A(t) + L(t)} \qquad \ell = \frac{P(t)}{A(t) + L(t)} \qquad \Rightarrow \frac{dP}{dt} = \frac{(1-\beta) k_{\text{eff}}(t) - 1}{\ell} \times P(t) + \sum_{i=1}^{6} \lambda_i C_i(t)$$

- k_{eff}, l: reactor characteristics indep. of P, may be calculated (e.g. 1-gp. diff. theory…)

- Supplementary eqns. needed for Ci 's (precursor equations)

$$\frac{dC_i(t)}{dt} = \underbrace{\beta_i \bar{\nu} F(t)}_{\text{Precursor Production}} - \underbrace{\lambda_i C_i(t)}_{\text{Precursor Decay}} \Rightarrow \frac{dC_i(t)}{dt} + \lambda_i C_i(t) = \beta_i k_{eff}\left(A(t) + L(t)\right)$$

$$\frac{dC_i(t)}{dt} + \lambda_i C_i(t) = \beta_i \frac{k_{eff}}{l} P(t)$$

- With the definitions: $\frac{k_{\text{eff}} - 1}{k_{\text{eff}}} = \underbrace{\rho}_{\text{Reactivity}}, \quad \frac{\ell}{k_{\text{eff}}} = \underbrace{\Lambda}_{\text{Prompt Neutron Generation Time}}$

$$\Rightarrow \frac{dP}{dt} = \frac{\rho(t) - \beta}{\Lambda} P(t) + \sum_{i=1}^{6} \lambda_i C_i(t)$$

$$\frac{dC_i(t)}{dt} + \lambda_i C_i(t) = \frac{\beta_i}{\Lambda} P(t), \quad i = 1, \ldots 6$$

- complete system of 7 linear differential eqns. (***Point Kinetics Equations***)
  → Very important basis for studies of kinetics, reactor stability, nuclear safety, etc.

N.B.: ρ... deviation of k_{eff} from 1 (normally very small, but very wide range: $-\infty$ to 1)

- Stationary Case: $$0 = \frac{\rho - \beta}{\Lambda} P(0) + \sum_{i=1}^{6} \lambda_i C_i(0) \qquad (1)$$

$$\lambda_i C_i(0) = \frac{\beta_i}{\Lambda} P(0)$$

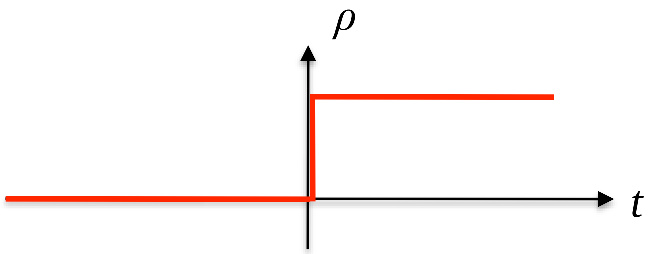
Substituting for $C_i(0)$ into eq. 1,

$$\Rightarrow \quad 0 = \frac{\rho - \beta}{\Lambda} P(0) + \sum_{i=1}^{6} \frac{\beta_i}{\Lambda} P(0) \quad \Rightarrow \rho = 0$$

$\Rightarrow$ Stationary states correspond to $\rho = 0$ ($k_{\mathrm{eff}} = 1$), and the delayed neutrons have no effect…

Step Change in Reactivity

- Important specific application of point kinetics equations
  → Illustrative, analytical solution possible



- Constant ρ (±) introduced at $t = 0$
  → E.g. quick movement of a control rod

- Point kinetics eqns.:

$$\frac{dP}{dt} = \frac{\rho(t) - \beta}{\Lambda} P(t) + \sum_i \lambda_i C_i(t) \quad (1)$$

$$\frac{dC_i}{dt} + \lambda_i C_i(t) = \frac{\beta_i}{\Lambda} P(t) \quad (2)$$

- For solution, one may apply method of Laplace transforms
  → Differential equations replaced by algebraic eqns.

- Laplace Transform: $L[F(t)] = \int_0^{+\infty} F(t) e^{-st} dt = \tilde{F}(s)$

- After certain manipulations, one "reconverts" to obtain solution of original eqn. (in time)

- Often needed information come directly from algebraic eqn. itself (e.g. via graphical soln.)

- N.B.: not necessary to compute transformations analytically:
  → One can use "tables" of Laplace transforms

$F(t)$	$\tilde{F}(s)$	$F(t)$	$\tilde{F}(s)$
$F'(t)$	$s\tilde{F}(s) - F(0)$	1	$1/s$
$F''(t)$	$s^2\tilde{F}(s) - sF(0) - F'(0)$	t	$1/s^2$
$\vdots$	$\vdots$	$t^{n-1}/(n-1)!$	$1/s^n$
$\int_0^t F(\tau)\,d\tau$	$\frac{1}{s}\cdot\tilde{F}(s)$	$\vdots$	$\vdots$
$-t\,f(t)$	$\tilde{F}'(s)$	e^{-at}	$1/(s+a)$
$\vdots$	$\vdots$	$t\,e^{-at}$	$1/(s+a)^2$
		$\vdots$	$\vdots$

- From (1) & (2) , taking the Laplace transform, it comes

$$s.\tilde{P}(s) - P(0) = \frac{\rho - \beta}{\Lambda}\tilde{P}(s) + \sum_i \lambda_i \tilde{C}_i(s)$$

$$s.\tilde{C}_i(s) - C_i(0) + \lambda_i \tilde{C}_i(s) = \frac{\beta_i}{\Lambda}\tilde{P}(s)$$

where $\tilde{P}(s), \tilde{C}_i(s)$ are the Laplace transforms of $P(t), C_i(t)$

- Eliminating $\tilde{C}_i(s)$,

$$\tilde{P}(s) = \Lambda \frac{P(0) + \sum_i \frac{\beta_i C_i(0)}{\lambda_i + s}}{\beta - \sum_i \frac{\beta_i \lambda_i}{\lambda_i + s} + \Lambda . s - \rho}$$

If the reactor was critical at t = 0, using the precursor balance:

$$\lambda_i C_i(0) = \frac{\beta_i}{\Lambda} P(0) \quad \Rightarrow \quad C_i(0) = \frac{\beta_i}{\lambda_i \Lambda} P(0)$$

Partial fraction decomposition

- Thus, $$\frac{\tilde{P}(s)}{P(0)} = \frac{\Lambda + \sum_i \frac{\beta_i}{\lambda_i + s}}{\beta - \sum_i \frac{\beta_i \lambda_i}{\lambda_i + s} + \Lambda.s - \rho} = \sum_{j=1}^{7} \frac{B_j}{s - w_j}$$

where ω_j are the roots of the denominator $$\beta - \sum_i \frac{\beta_i \lambda_i}{\lambda_i + s} + \Lambda.s - \rho$$

i.e. of $$\rho = \beta - \sum_i \frac{\beta_i \lambda_i}{\lambda_i + w} + \Lambda.w$$

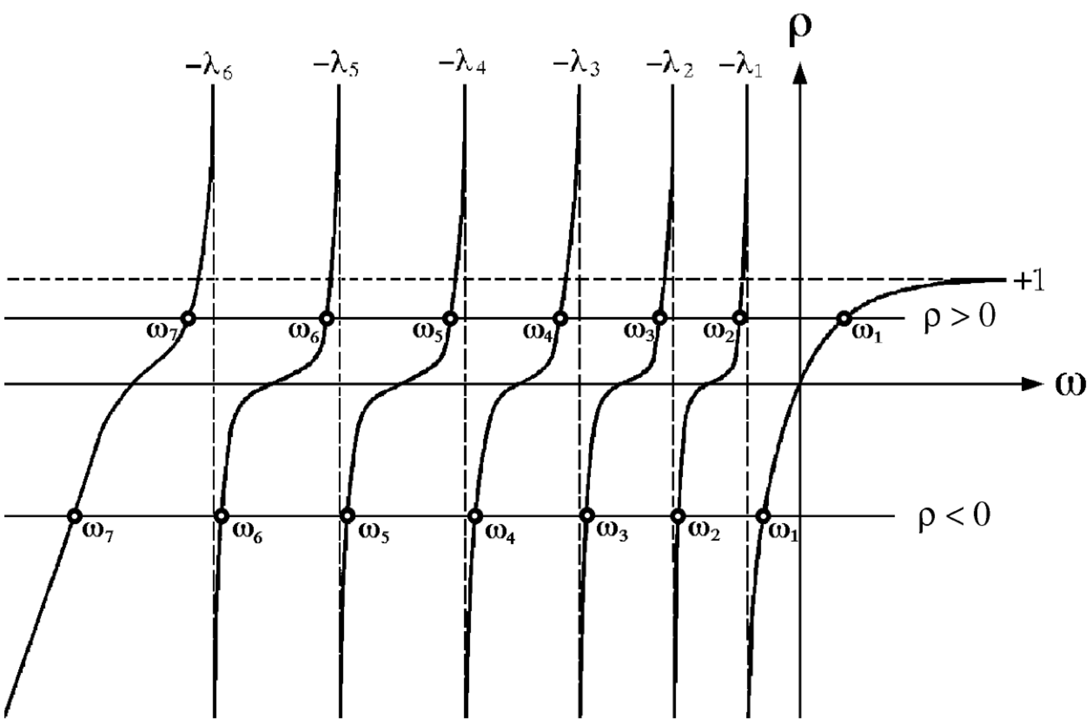
$$\boxed{\rho = \Lambda.w + \sum_i \frac{\beta_i w}{\lambda_i + w}}$$ *Reactivity Equation* ***(Inhour Equation)***

- The solution has the following form:

$$\boxed{\frac{P(t)}{P(0)} = \sum_{i=1}^{7} B_j \exp(\omega_j t)}$$ (from inversion of the Laplace-transform equation (1) above)

The Roots ω_j

- The solution is therefore: $P(t) = \sum_{i=1}^{7} B_j \exp(\omega_j t)$ ω_j solutions of $\rho = \Lambda\omega + \sum_i \frac{\beta_i \omega}{(\omega + \lambda_i)}$
- One may solve the equation (Reactivity Eqn.) graphically:



- R.H.S.… function of ω ,
  L.H.S.… ρ (±) , constant

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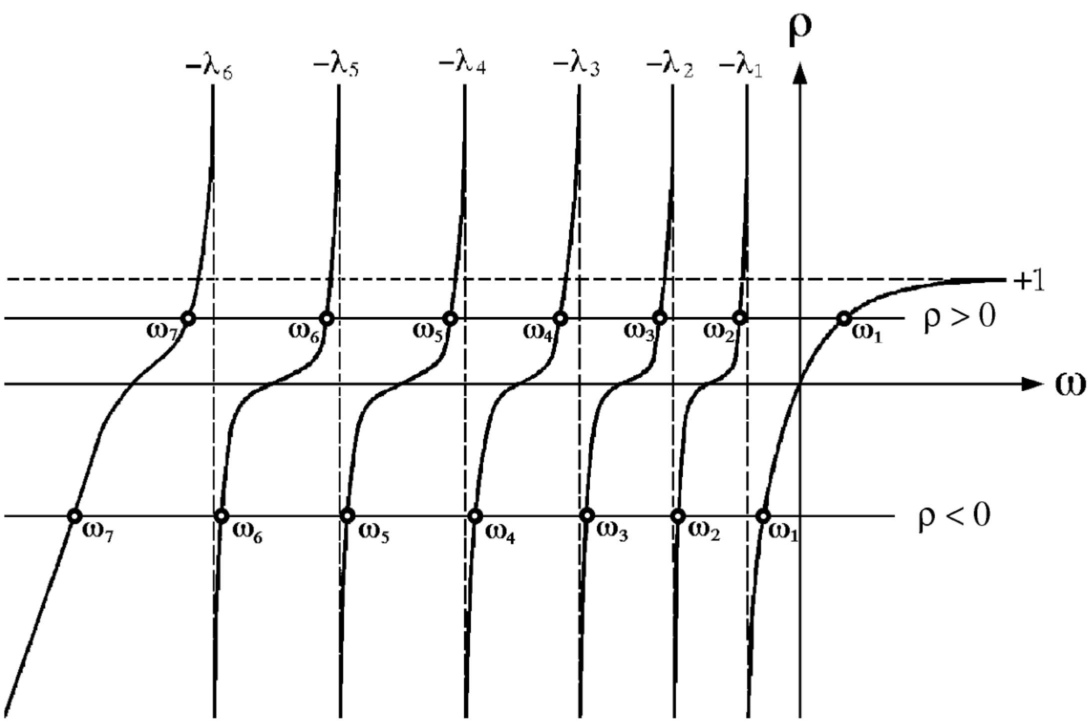


- R.H.S…. function of ω ,
  L.H.S…. ρ (±) , constant

- For positive ρ (supercritical reactor), one value of ω is positive, the others negative

- For negatice ρ (subcritical reactor), all 7 roots ω are negative

Stable Period … positive ρ

- For $\rho > 0$, after a certain time: $P(t) = B_1 \exp(\omega_1 t)$

  → All the other $\exp(\omega_j t)$ terms disappear (negative ω_i 's)

- Stable period: $T = \dfrac{1}{\omega_1}$

  → Time (in stable region) for P (or Φ) to increase by factor of e

- Solution ω_1 obtained graphically

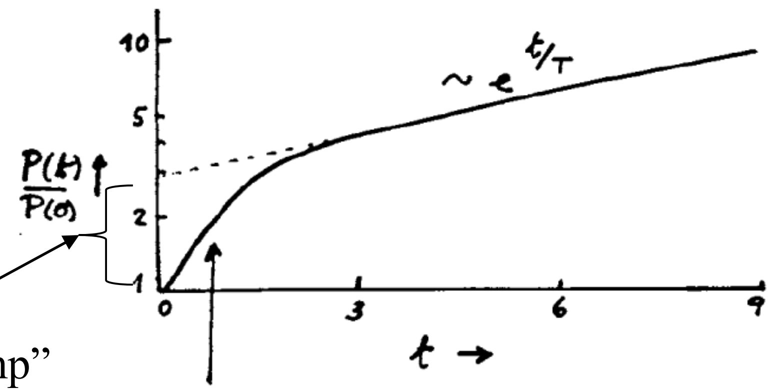
  → For a given set of kinetics parameters (Λ , β_i , λ_i), each $\rho \Leftrightarrow$ specific ω_1

  → E.g. with

  $\Lambda = 10^{-3}$ sec.; $\beta_i, \lambda_i \Rightarrow U^{235}$

  $\rho = 3 \cdot 10^{-3} \Rightarrow \omega_1 = 0{,}127 \text{ sec}^{-1} \Rightarrow T = 7{,}9 \text{ sec}.$

“prompt jump”



transitory region:
negative terms which vanish rapidly

“prompt jump”: $\dfrac{P(t)}{P(0)} = \dfrac{\beta}{\beta - \rho}$

Stable Period … positive ρ

- Without delayed n's, one had: $P(t) = P(0)\exp\left[\frac{k_{\text{eff}}-1}{l}t\right] \cong P(0)\exp\left[\frac{\rho}{\Lambda}t\right] = \exp\left[\frac{3\cdot 10^{-3}}{10^{-3}}t\right]$

  i.e $T = \frac{\Lambda}{\rho} = \frac{10^{-3}}{3\cdot 10^{-3}} = 0{,}33\,\text{sec} \Rightarrow$ a factor of ~ 24 on period (for this example)

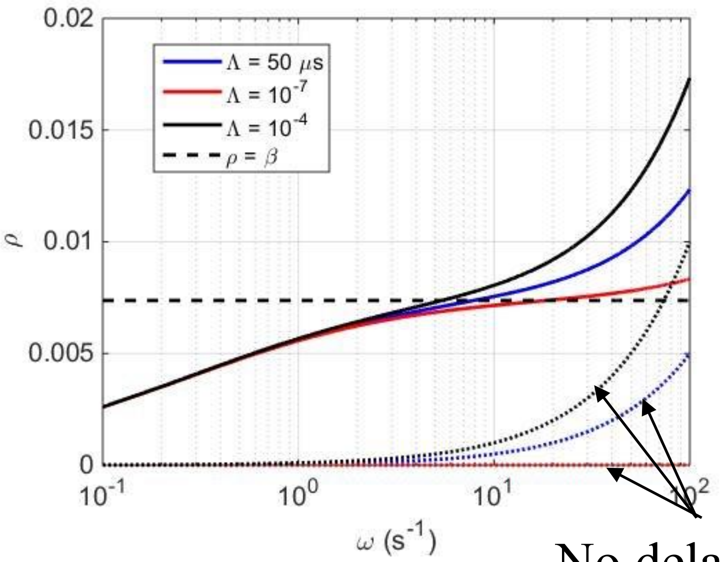
  → Delayed n's render the reactor controllable

- For "[235]U systems" (β_i , λ_i):

- For $\rho < \beta/2$, no dependence on Λ

- In absence of delayed n's ($\beta = 0$),

$$\omega = \frac{\rho}{\Lambda}$$



No delayed n's

→ For small ρ's, differences with/without delayed n's, very large
→ For $\rho \sim \beta$, differences decrease strongly (role of Λ becomes much more important)

Delayed, Prompt Criticality

- Normally, reactor is "delayed critical": $\text{Production} = (1-\beta)k_{\text{eff}} + \sum_{i=1}^{6} \lambda_i C_i$

- If $\rho = \beta$, reactor is critical only with prompt n's (T becomes very short)

- For $\rho >> \beta$, delayed neutrons no longer important
  ➞ ρ - vs - ω curves become asymptotic to $\rho = \Lambda.\omega + \beta$

$$\rho = \Lambda\omega + \sum_i \frac{\beta_i \omega}{(\omega + \lambda_i)} \approx \Lambda\omega + \beta \quad \text{for } \lambda_i << \omega$$

- Extremely important that all reactivity insertions are significantly less than $+\beta$
  ➞ Withdrawal of a control rod
  ➞ Effects of temperature, voidage (e.g. due to boiling of a liquid moderator)

- $\rho = \beta$ important enough limit to provide a special unit for reactivity, the *dollar*
  ➞ $\rho = 0.65\%$ (^{235}U system) $\Rightarrow$ 1 dollar (100 cents)

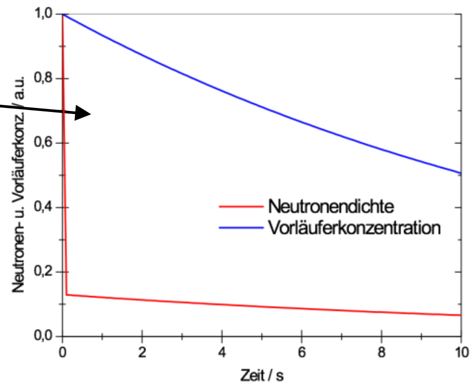
- $\Delta\rho$ usually small: 0.65% or 0.2% not really convenient
  0.65% = 650 **pcm** "per cent mille" (*one-thousandth of a percent*) is prefered for the reactivity

- For systems with ^{239}Pu, ^{233}U, reactivity insertions have to be smaller
  → It is $\frac{\rho}{\beta}$ which matters, i.e. the value of ρ in \$ or ¢ …

- Fast reactors (with ^{239}Pu as primary fuel material), more sensitive because of their lower value of β, not because of their very small Λ
  → However, ρ_{abs} values are also generally lower in fast reactors (cross sections ↘)

Stable period … negative ρ

- For a "prompt drop"



Flux immediately after drop:

$$\frac{P(t)}{P(0)} = \frac{\beta}{\beta - \rho}$$

- For the stable period, one needs to consider the roots of the Reactivity Equation
  → All the ω values are negative with $|\omega_7| > |\omega_6| > |\omega_5| > \ldots > |\omega_1|$
  → The stable region is where only term $-\omega 1$ remains and the flux is:

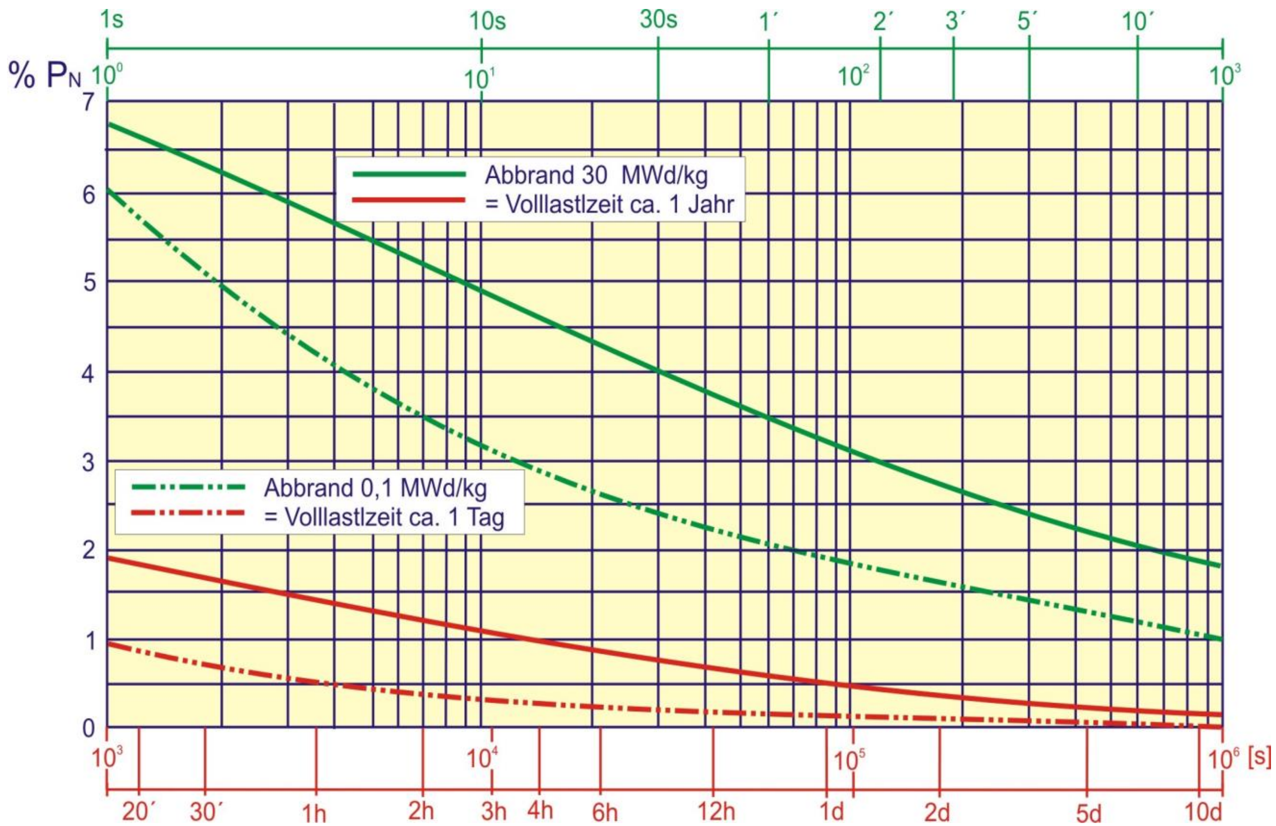
$$\Phi(t) = \Phi_1 \exp(-t/T) \quad \text{with } T = \frac{1}{|\omega_1|}$$

- For negative ρ with $|\rho| >> \beta$, $\omega_1 \rightarrow \lambda_1$ (decay const. of 1st gp.) $\quad T = \frac{1}{\lambda_1} \cong 80\,\text{sec.}$

→ Thus, a reactor cannot be shut down more quickly than with a negative period of ~ 80s
→ The "neutronic" power is determined by the prompt jump and T (80s)
→ After a certain time, thermal power ~ fission-product "decay power" (residual heat)

Decay Heat (Way-Wigner): $P_N = 6{,}22\ \% \cdot \left(t^{-0{,}2} - (t_0 + t)^{-0{,}2}\right) \overset{t_0 \to \infty}{=} 6{,}22\ \% \cdot t^{-0{,}2}$

- Directly after Scram 6,4 % of full power level
- after one minute half thereof (~ 3,2 %)
- after one hour half thereof (~ 1,6 %)
- after one day half thereof (~ 0,8 %)



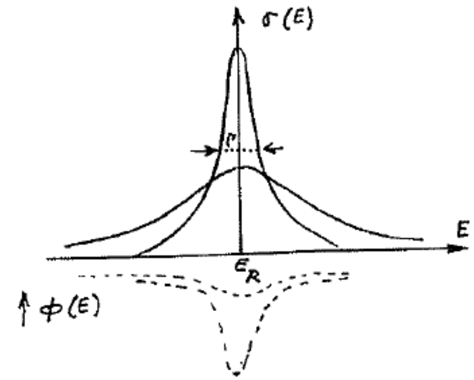
Reactivity Variations

- Normally, ρ change not sudden, e.g. could be ~ linear ramp in reactivity: $\rho(t) = K.t$
  → Point kinetics equations need to be solved numerically
- Change in power changes thermal balance, affects temperatures, hence σ's and ρ
  → Feedback effects: have to be negative (act as "brakes")… safety studies involve coupling of thermal-hydraulics, neutron kinetics…

- Various "time constants" involved (e.g. time for power change to affect temperature,…)
  - Values quite different for different types of "feedbacks"
- Short-term causes for ρ-variation
  - Fuel temperature (*Doppler effect*), < 1 sec (effect ~ prompt → most important…)
  - Moderator temperature, secs - mins
  - Voiding of liquid moderator/coolant, secs (boiling, bubble formation, effect on density…)
- Medium-term causes
  - Principal effect: Fission product Xe^{135} in a thermal reactor, hours - days
- Long-term effects
  - Fuel composition changes with irradiation (burnup), days - months
  - Largest effect in power reactors ("burning" of fissile, Pu-production, accumulation of FPs,…)

- When $T_F \uparrow$, U^{238} resonances broadened due to increased thermal agitation of nuclei
  - ➢ Area under resonance constant, but flux is less depressed

    $\Rightarrow$ Effective resonance integral, $I_{eff} \uparrow$
  - ➢ In $k_\infty = \eta\, f\, p\, \varepsilon, \quad p \downarrow$



$$p(E,T) = exp\left(-\underbrace{\int \frac{\overline{\sigma}_{A,\gamma}(E,T)}{N_A \overline{\sigma}_{A,\gamma}(E,T) + N_H \sigma_{s,H}} \frac{dE}{E}}_{I_{eff}}\right)$$

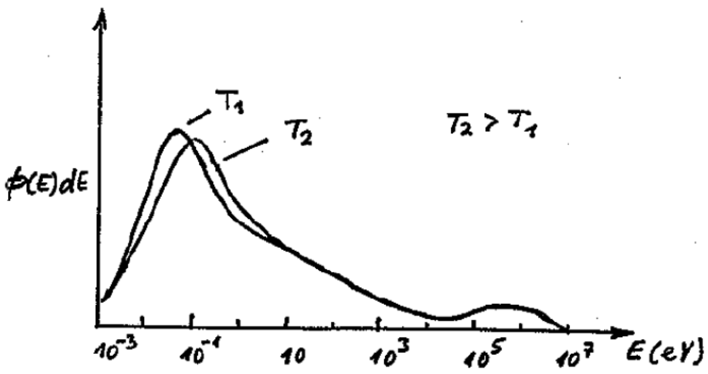
$$I_{eff}(T) \cong I_{eff}(300\ K) \cdot \left[1 + C \cdot \left(\sqrt{T} - \sqrt{300}\right)\right]$$

- Fuel Temperature Coefficient of Reactivity (*Doppler Coeff.*)

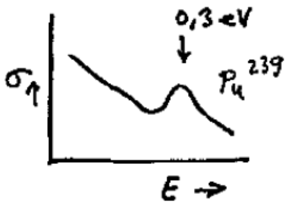
$$\Rightarrow \alpha_T = \frac{\partial \rho}{\partial T_F} = \frac{1}{k^2}\frac{\partial k}{\partial T_F} \cong \frac{1}{k}\frac{\partial k}{\partial T_F} = \frac{1}{\eta}\frac{\partial \eta}{\partial T_F} + \frac{1}{f}\frac{\partial f}{\partial T_F} + \frac{1}{p}\frac{\partial p}{\partial T_F} + \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial T_F}$$

$$\Rightarrow \alpha_T \cong \frac{1}{p}\frac{dp}{dT_F} = -\frac{C}{2\sqrt{T_F}} \ln\left[\frac{1}{p(300\ K)}\right]$$

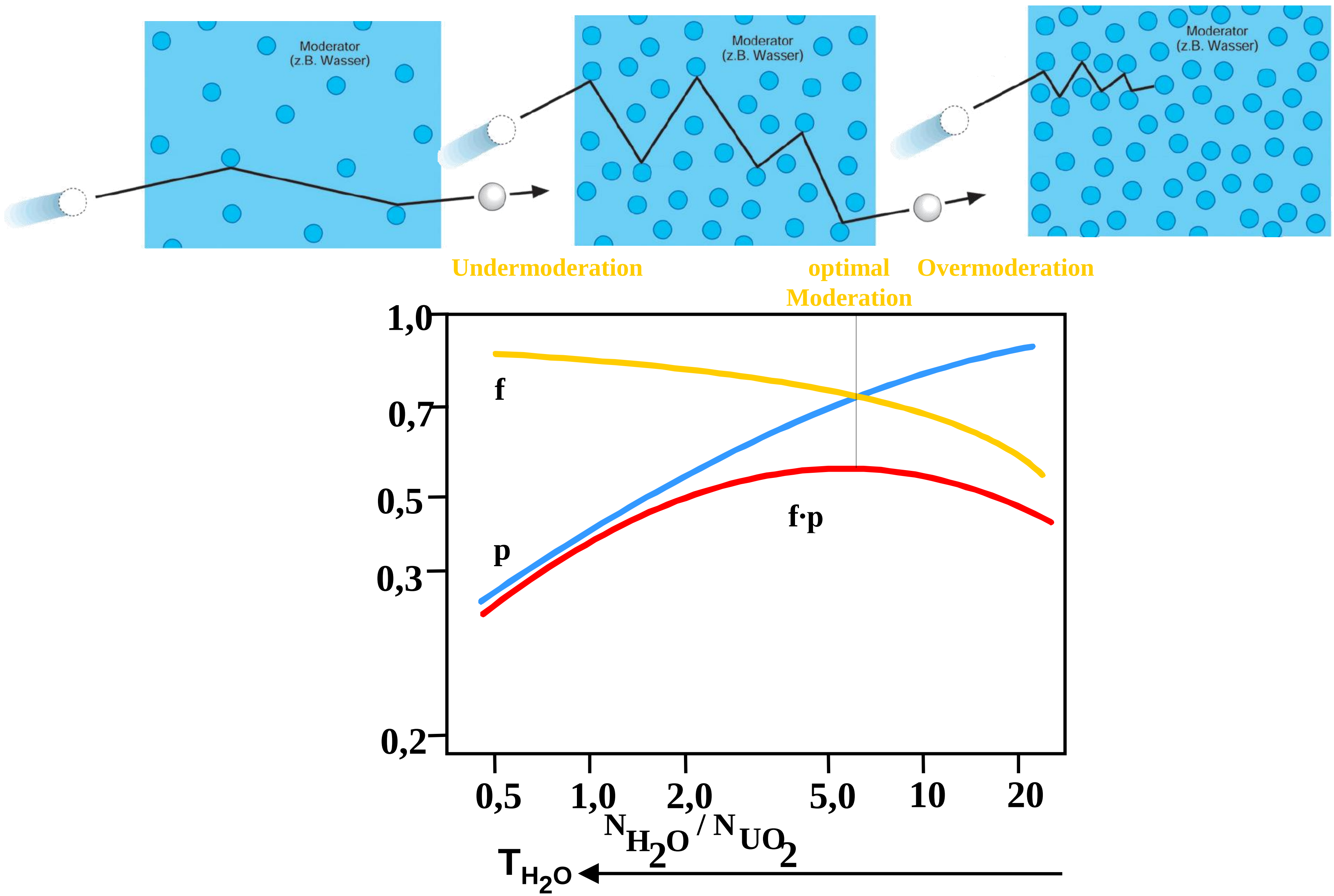
$$\alpha_m = \frac{\partial \rho}{\partial T_m} \cong \frac{1}{k_{eff}} \frac{\partial k_{eff}}{\partial T_m}$$



- Neutron spectrum effects
  - Maxwellian part shifted to right when $T_m \uparrow$
  - σ_{th}'s ~ 1/v (i.e. $1/\sqrt{E}$), but not exactly…
  - For $\eta = \bar{\nu}\frac{\Sigma_f}{\Sigma_a}$, individual changes of Σ_f, Σ_a important
  - For U_{nat}, $\eta \downarrow$ when $T_m \uparrow$
  - In presence of Pu , this changes (Pu^{239} resonance at 0.3 eV, positive effect)
    - ✓ Partly compensating effect from Pu^{240} (large capture resonance at 1ev)

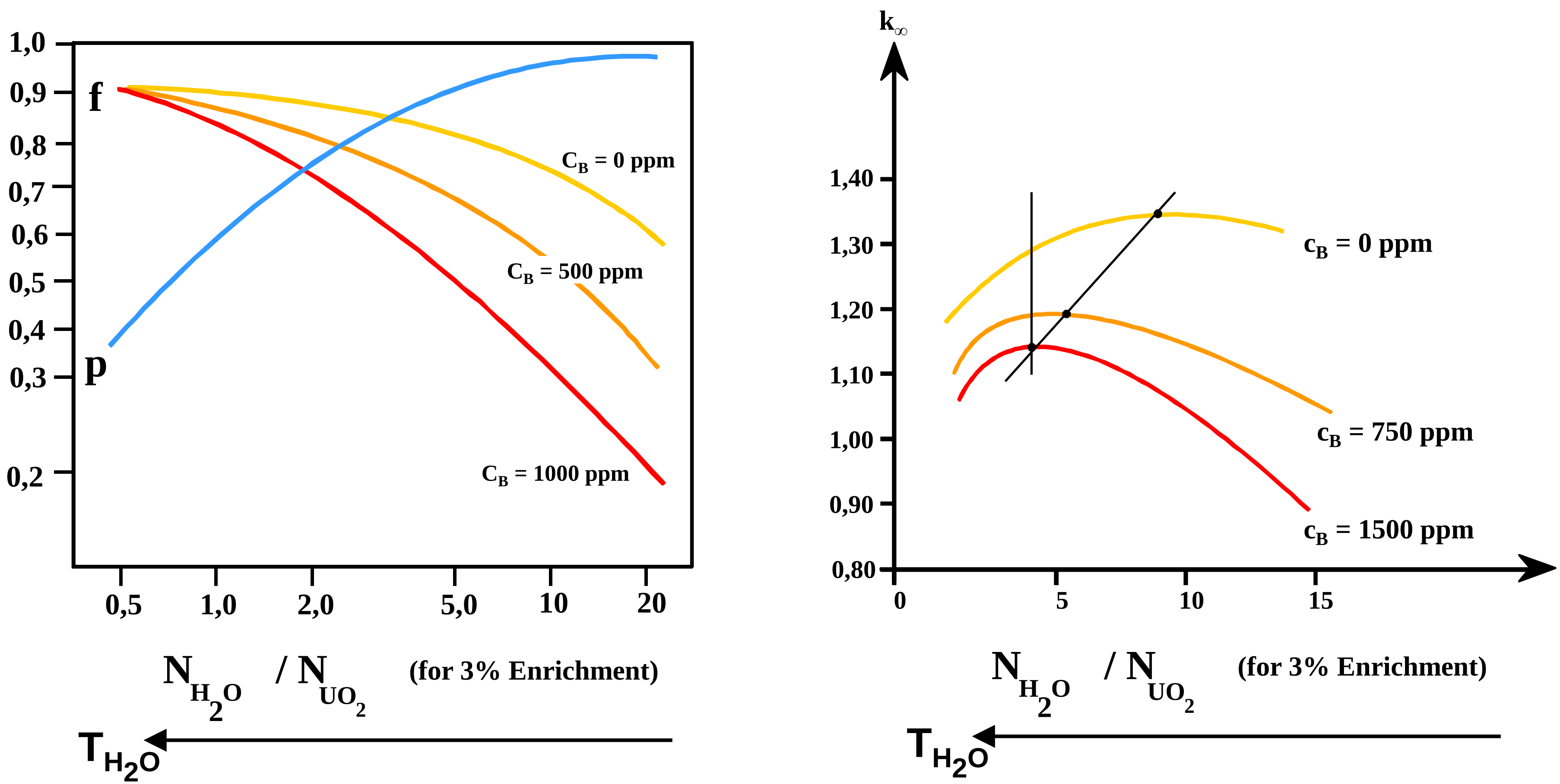


- Spectrum effect most important for solid moderator, e.g. graphite
- For a liquid moderator (coolant), density variation much more important effect



Moderator
(z.B. Wasser)
Moderator
(z.B. Wasser)
Moderator
(z.B. Wasser)
Undermoderation
optimal
Moderation
Overmoderation
1,0
0,7
0,5
0,3
0,2
f
p
f·p
0,5
1,0
2,0
5,0
10
20
N_{H_2O} / N_{UO_2}
T_{H_2O}

Moderator (Coolant) Temperature Coefficient, α_M



VOID COEFFICIENT, α_V

- $$\alpha_V = \frac{\partial\rho}{\partial V} \cong \frac{1}{k_{eff}} \frac{\partial k_{eff}}{\partial V}$$ (v : volumetric fraction of steam…)
  - Very important to have negative α_v for liquid moderator/coolant (Chernobyl…!)
  - Boiling implies a strong reduction of density
    - ✓ As for α_m , thermal reactor needs to be undermoderated

COMMENTS

- For the short-term effects, one may write: $\Delta\rho \cong \alpha_F \Delta T_F + \alpha_M \Delta T_M + \alpha_V \Delta V + ...$
  - ➢ However, this does not give the true "dynamic" behaviour
    - ✓ No consideration of the time constants

- One needs proper time-dependent "modelling" of the power reactor (including the secondary cooling system), with "coupling" betn. neutronics, thermal-hydraulics
  - ➢ Safety studies:
    - ✓ Numerical simulation and analysis of hypothetical accident situations

- In general, if all the α's are negative, reactor "inherently" safe from viewpoint of uncontrolled reactivity insertion

- Calculation of α's generally very delicate
  - ➢ Compensation of individual effects, e.g. sodium α_v , or α_m in HTR (graphite)
  - ➢ Necessary to carry out "checks" on power reactor before start-up

- Reactivity Equation (constant reactivities)
- Roots of Reactivity Equation
  → Stable Reactor Period
- Delayed, prompt criticality
  → Dollar
- "Prompt jump" (small positive, all negative ρ's)
- Negative reactivities
- Internal reactivity variations
  - Reactivity feedbacks (fuel temperature, moderator temperature, coolant voidage, etc.)
  - Importance for "inherent" safety