DASAR FISIKA REAKTOR

Haryo Seno

Pelatihan Operator dan Supervisor Reaktor Non Daya 2025

17 Februari – 12 Maret 2025

Direktorat Pengembangan Kompetensi BRIN - 2025

BIODATA

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Kompetensi : Radiation Safety, Nuclear Safety, RWM, RPO
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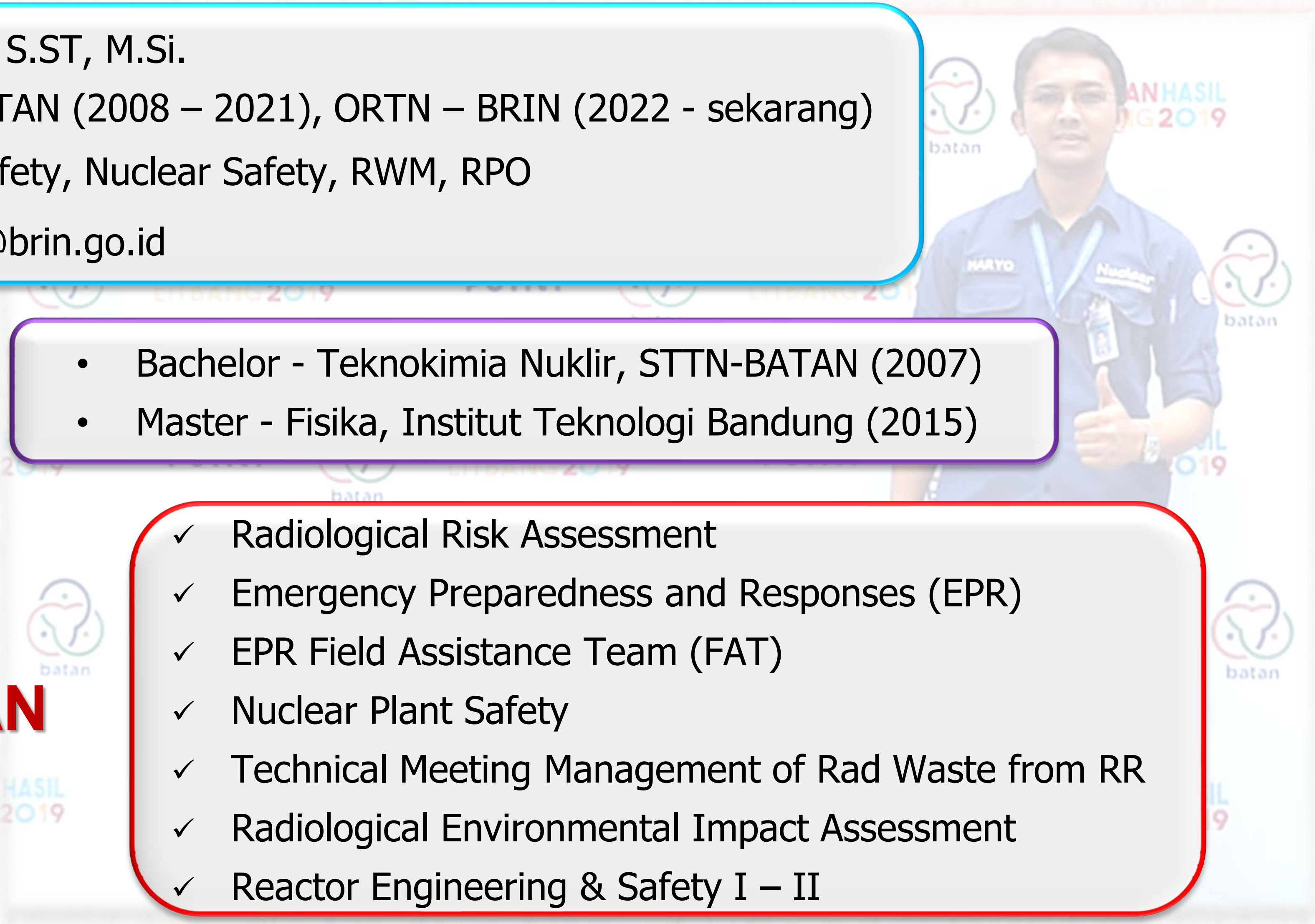


PENDIDIKAN

- Bachelor - Teknokimia Nuklir, STTN-BATAN (2007)
- Master - Fisika, Institut Teknologi Bandung (2015)

PELATIHAN

- ✓ Radiological Risk Assessment
- ✓ Emergency Preparedness and Responses (EPR)
- ✓ EPR Field Assistance Team (FAT)
- ✓ Nuclear Plant Safety
- ✓ Technical Meeting Management of Rad Waste from RR
- ✓ Radiological Environmental Impact Assessment
- ✓ Reactor Engineering & Safety I – II

1 PENDAHULUAN

LATAR BELAKANG

Pengetahuan dasar gejala fisika di reaktor nuklir

Prinsip terjadinya reaksi nuklir di reaktor riset

Perlunya operator dan supervisor memahami penerapan prinsip fisika reaktor untuk pengoperasian reaktor

MANFAAT

Operator dan supervisor memiliki kompetensi dasar dalam hal fenomena fisika yang terjadi di reaktor

Operator dan supervisor dapat mengoperasikan reaktor dengan baik, aman dan selamat

TUJUAN PEMBELAJARAN

Kompetensi Dasar

Mampu menjelaskan teori dasar reaksi nuklir yang terjadi di teras reaktor.

Indikator Keberhasilan

1. Mampu memahami persamaan dasar fisika nuklir dan reaksi nuklir.
2. Mampu menjelaskan tentang atom, struktur atom, radioaktivitas, interaksi atom dengan materi, faktor multiplikasi, reaktivitas, perioda, hubungan perioda dengan daya reaktor, koefisien reaktivitas, *neutron poison*, dinamika reaktor.
3. Mampu memahami mekanisme pengendalian reaksi nuklir di reaktor.

POKOK BAHASAN

- PENDAHULUAN
- DASAR FISIKA INTI
- INTERAKSI NEUTRON
- KINETIKA REAKTOR
- DINAMIKA REAKTOR

2 DASAR FISIKA INTI

Atom & Unsur (1)

- **Elements** are basic components of matter
  - 118 elements are currently known, 92 elements naturally occurring
  - Elements have specific names and symbols, e.g.:

    H – Hydrogen

    He – Helium

    Li – Lithium

    O – Oxygen

    U – Uranium

    …
- Basic constituents of element are **atoms:**
  - Atom is the smallest particle of an element, having its chemical properties
  - Atoms of different elements have different chemical properties

Source: IAEA International Atomic Energy Agency

Atom & Unsur (2)

- Different elements bond together to make a compound
- Basic constituents of a compound are molecules:
  - A molecule is the smallest particle of a compound, having its chemical properties
- Atoms combine into molecules in chemical reactions:

Hydrogen + Oxygen → Water	($2H_2 + O_2 \rightarrow 2H_2O$)
Sodium + Chlorine → Sodium chloride (salt)	($2Na + Cl_2 \rightarrow 2NaCl$)
Uranium + Oxygen → Uranium dioxide	($U + O_2 \rightarrow UO_2$)

Source: IAEA International Atomic Energy Agency

Atom & Unsur (3)

- Atoms are very small and very light

- A mass unit used in atomic physics and chemistry:

  1 **atomic mass unit** = 1 **amu** = 1 **u**

- Definition:

  1 u = 1/12 of mass of $^{12}C = 1.66 \cdot 10^{-27}$ kg

Source: IAEA International Atomic Energy Agency

Atom & Unsur (4)

- A_r is the ratio of atom mass and amu:

  atom mass = $A_r \times$ amu

- The value of A_r can be found e.g. in periodic system
  - Examples:

Hydrogen (H):	$A_r(H) = 1.0079$	≈ 1
Lithium (Li):	$A_r(Li) = 6.941$	≈ 6.9
Boron (B):	$A_r(B) = 10.81$	≈ 10.8
Carbon (C):	$A_r(C) = 12.011$	≈ 12
Oxygen (O):	$A_r(O) = 15.9994$	≈ 16
Iron (Fe):	$A_r(Fe) = 55.847$	≈ 55.8
Uranium (U):	$A_r(U) = 238.029$	≈ 238

Source: IAEA International Atomic Energy Agency

Atom & Unsur (5)

- M_r is the ratio of molecular mass and amu:

  mass of molecule = $M_r \times$ amu

  - M_r is calculated as the **sum** of relative atomic masses of atoms in the molecule:

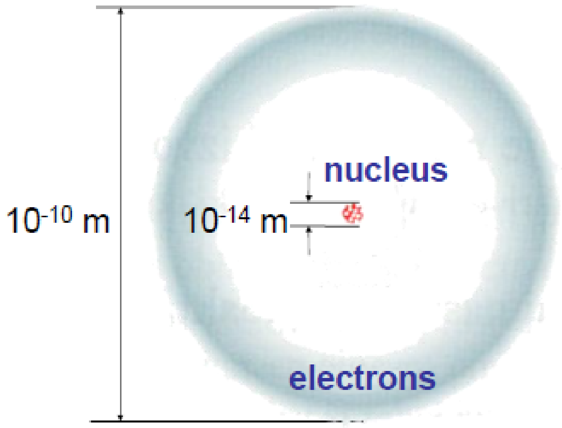
    $M_r(H_2O) = 2 \times 1 + 16 = 18$

  - Exercises:
    1. Calculate $M_r(H_3BO_3)$!
    2. Calculate $M_r(C_3H_5OH)$!
    3. How many molecules are there in one kg of water?

Source: IAEA International Atomic Energy Agency

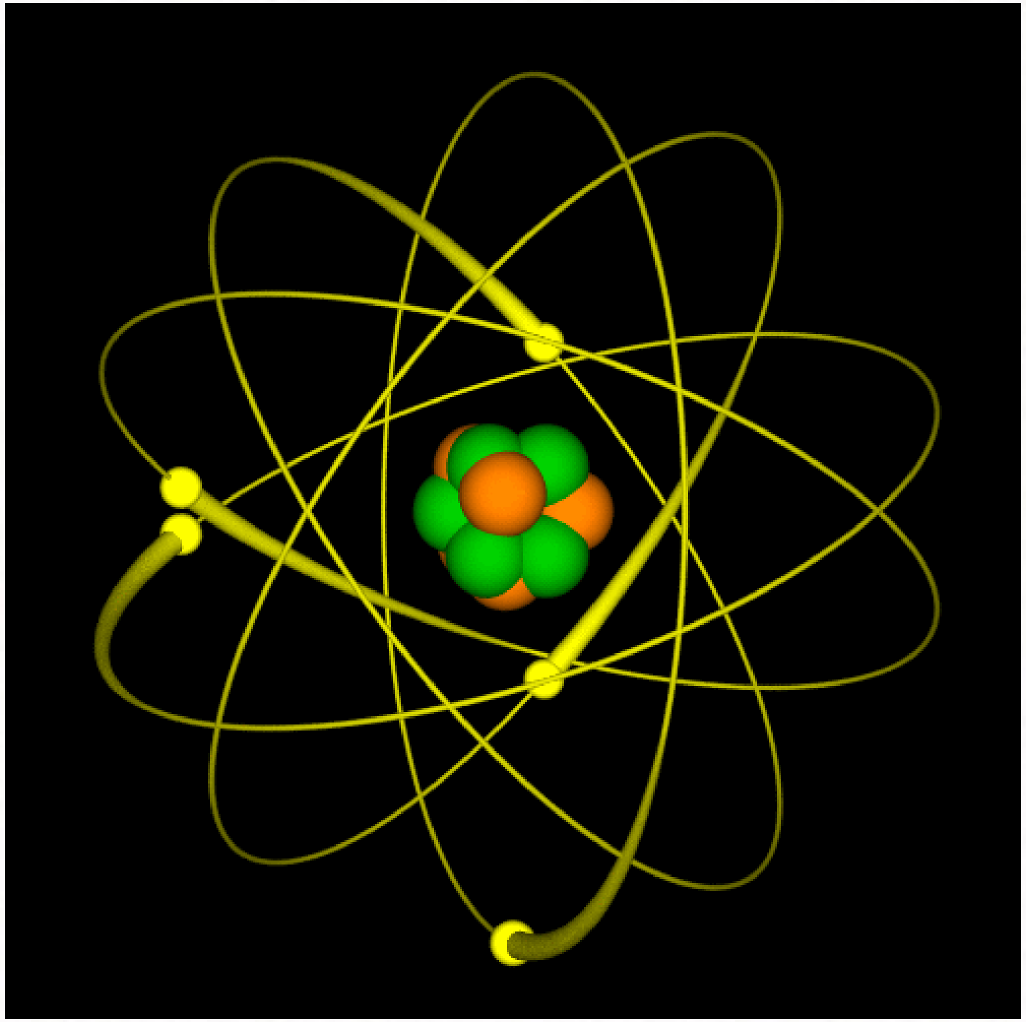
Dimensi Atom

- **Atom**: the smallest particle of an element, having it chemical and physical properties
- Atom is composed of:
  - **Nucleus**, which has **positive electrical charge**
  - **Negatively charged electrons**, which form sort of cloud around the nucleus – **the electron envelope**
- Size of atom ~ 10^{-10} m
- Diameter of atom : nucleus ~ 10000 : 1
- Mass of nucleus > 99,95% of atom mass



Source: IAEA International Atomic Energy Agency

Struktur Atom



Elektron (9,11 x 10^{-31} kg)
Proton (1,673 x 10^{-27} kg)
Neutron (1,675 x 10^{-27} kg)
Ø Nucleon = 10^{-12} cm
Ø Atom = 10^{-8} cm

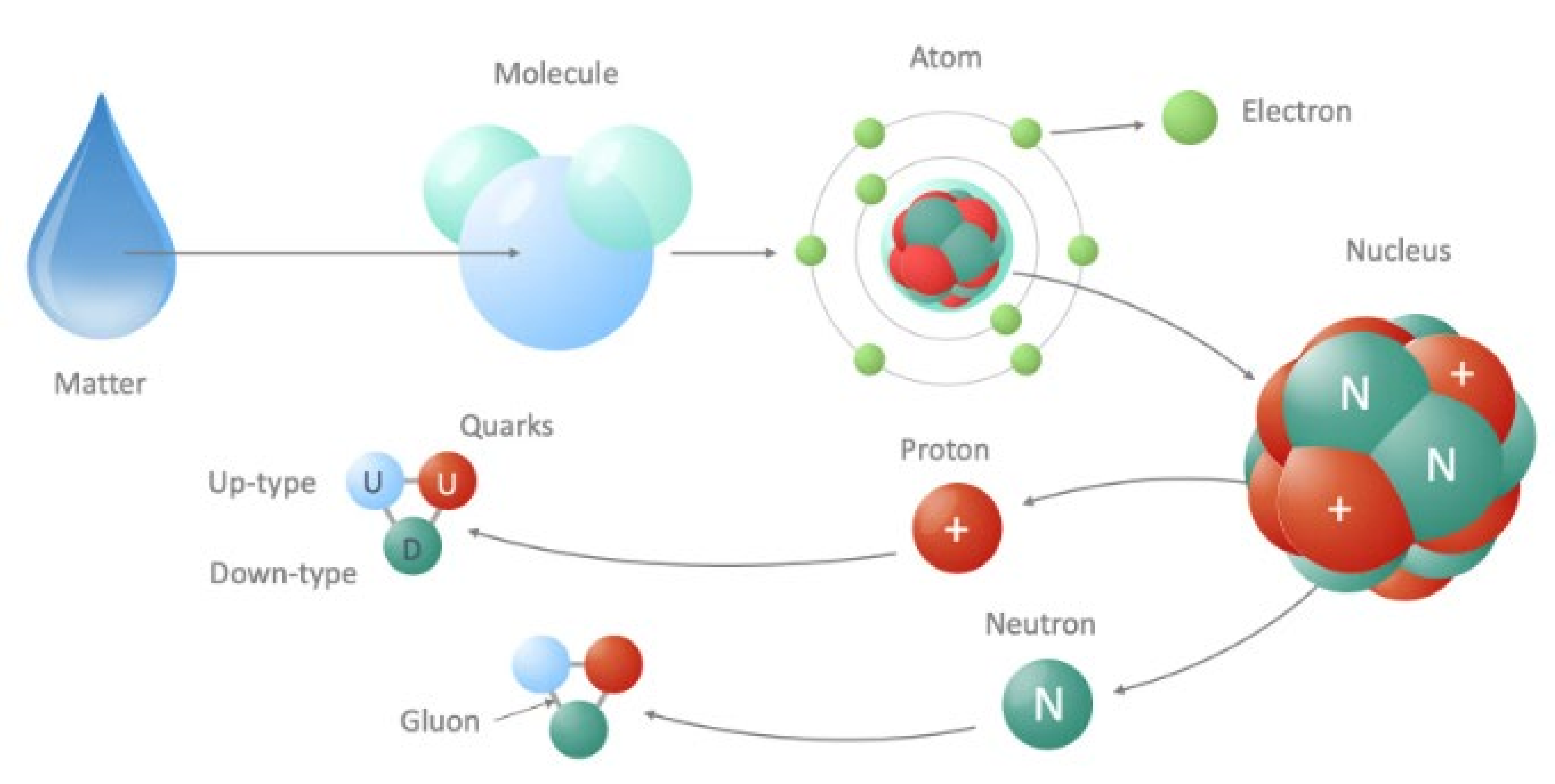
$${}_{Z}X^{A}$$

X : Lambang atom

A : Nomor massa (jumlah proton + jumlah neutron)

Z : Nomor atom (jumlah proton)

Materi dan Penyusunnya



Elektron

- **Electrons**: light particles with negative electric charge
  - $e_{electron} = -1.6 \cdot 10^{-19}$ As $= -1.6 \cdot 10^{-19}$ C $\equiv -e_0$
  - $m_{electron} = 9.1 \cdot 10^{-31}$ kg $\approx 1/1820$ u

- Electrons move in the **electron cloud**.
  - Electron cloud determines the outer boundary of atom and the chemical, electrical and mechanical properties of an element.

- Electrons are bound to positively charged nucleus with **electrical force**.

Source: IAEA International Atomic Energy Agency

Nomor Atom

- **Z – atomic number**
  - equal to number of electrons in neutral atom
  - equal to consecutive number of element in the periodic table
  - **all atoms of a specific element have the same number of electrons**

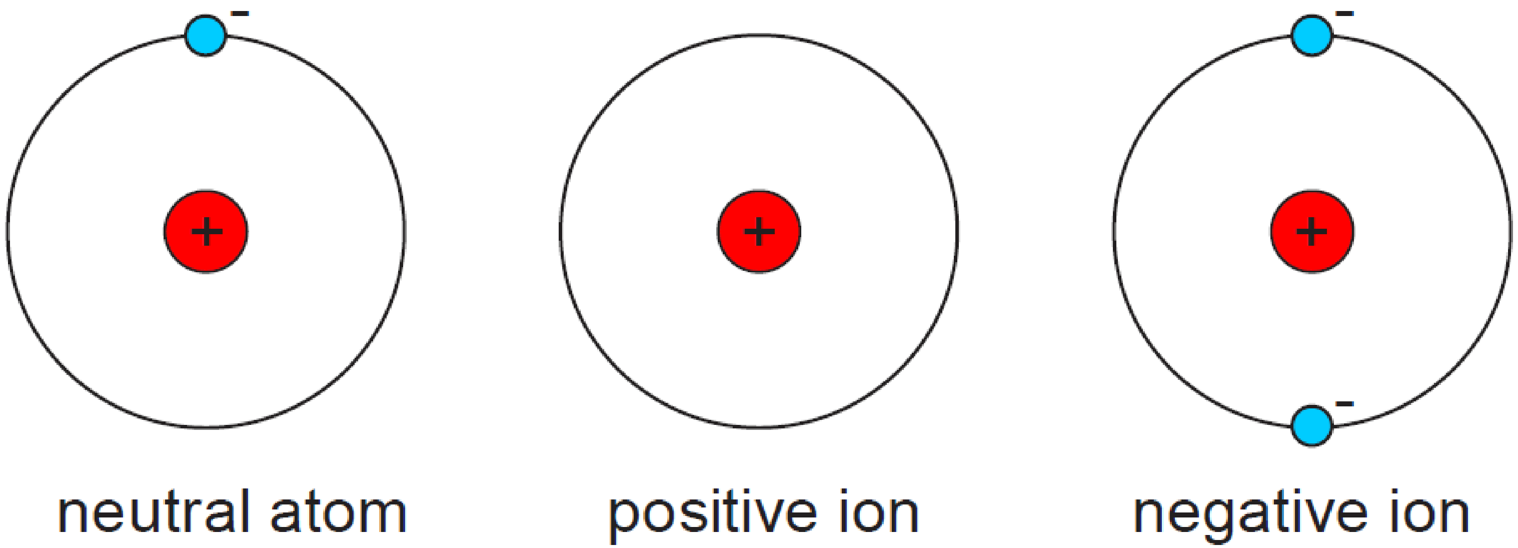
- As a rule, atom is **electrically neutral**

  ⇒ negative charge of electrons = positive charge of nucleus
  - charge of electrons in the atom = **- *Z* · e_0**
  - charge of nucleus in the atom = ***Z* · e_0**

Source: IAEA International Atomic Energy Agency

Ion

- Atom becomes:
  - a **positive ion**, if it loses electrons (positive charge of nucleus prevails)
  - a **negative ion**, if it gains electrons (negative charge of electrons prevails)



Source: IAEA International Atomic Energy Agency

Energi Elektron

- Free electrons, when moving, have positive (kinetic) energy
- Free electrons at rest have zero energy
- Electron which is bound in atom must be supplied with energy to become free electron

⇒ Energy of bound electron is negative

- **Binding energy** is always negative; the lower (more negative) the binding energy, the stronger electron is bound

Source: IAEA International Atomic Energy Agency

Elektron Volt (eV)

- Atoms are very small and light $\Rightarrow$ energies of particles within atom are very small

- The unit for energy on atomic scale is **electronvolt (eV)**:
  - Energy of a particle with elementary charge (e_0), accelerated with voltage of 1 V

    $1\ \text{eV} = 1.6 \cdot 10^{-19}\ \text{As} \cdot 1\ \text{V} = 1.6 \cdot 10^{-19}\ \text{J}$

    $1\ \text{keV} = 10^{3}\ \text{eV} \quad (= 1.6 \cdot 10^{-16}\ \text{J})$

    $1\ \text{MeV} = 10^{6}\ \text{eV} \quad (= 1.6 \cdot 10^{-13}\ \text{J})$

- Binding energies of electrons in atom: ~ eV - ~ keV

Source: IAEA International Atomic Energy Agency

Proton : Nomor Atom

- Protons are nucleons with positive elementary charge ($+ e_0$)

- Neutral atom:

  the number of negative charge carriers (electrons)
  = the number of positive charge carriers (protons)

- Atomic number is also the number of protons in nucleus
  - Nuclei of atoms of same element have equal number of protons
  - Nuclei of atoms of different elements have different number of protons

Source: IAEA International Atomic Energy Agency

Neutron : Massa Atom

- Neutrons are nucleons without electrical charge
- Mass number A is the number of all nucleons in nucleus
- The number of neutrons N is given by

$$N = A - Z$$

- **Nuclei of the same element can have different number of neutrons**

Source: IAEA International Atomic Energy Agency

Nuklida

= Atom with a nucleus containing
- A given number of protons *and*
- A given number of neutrons

$$^{A}_{Z}X_{N}$$

- Nuclide is defined with:
  - Number of protons = atomic number *Z*
  - Number of neutrons = neutron number *N*
  - Number of all nucleons = mass number *A*
  - The element that nuclide belongs to = chemical symbol X

- Nuclide fully defined already with the element and mass number ^{A}X
  - examples: $^{1}_{1}H_{0},\ ^{2}_{1}H_{1},\ ^{60}_{27}Co_{33},\ ^{238}_{92}U_{146} \rightarrow\ ^{1}H,\ ^{2}H,\ ^{60}Co,\ ^{238}U$

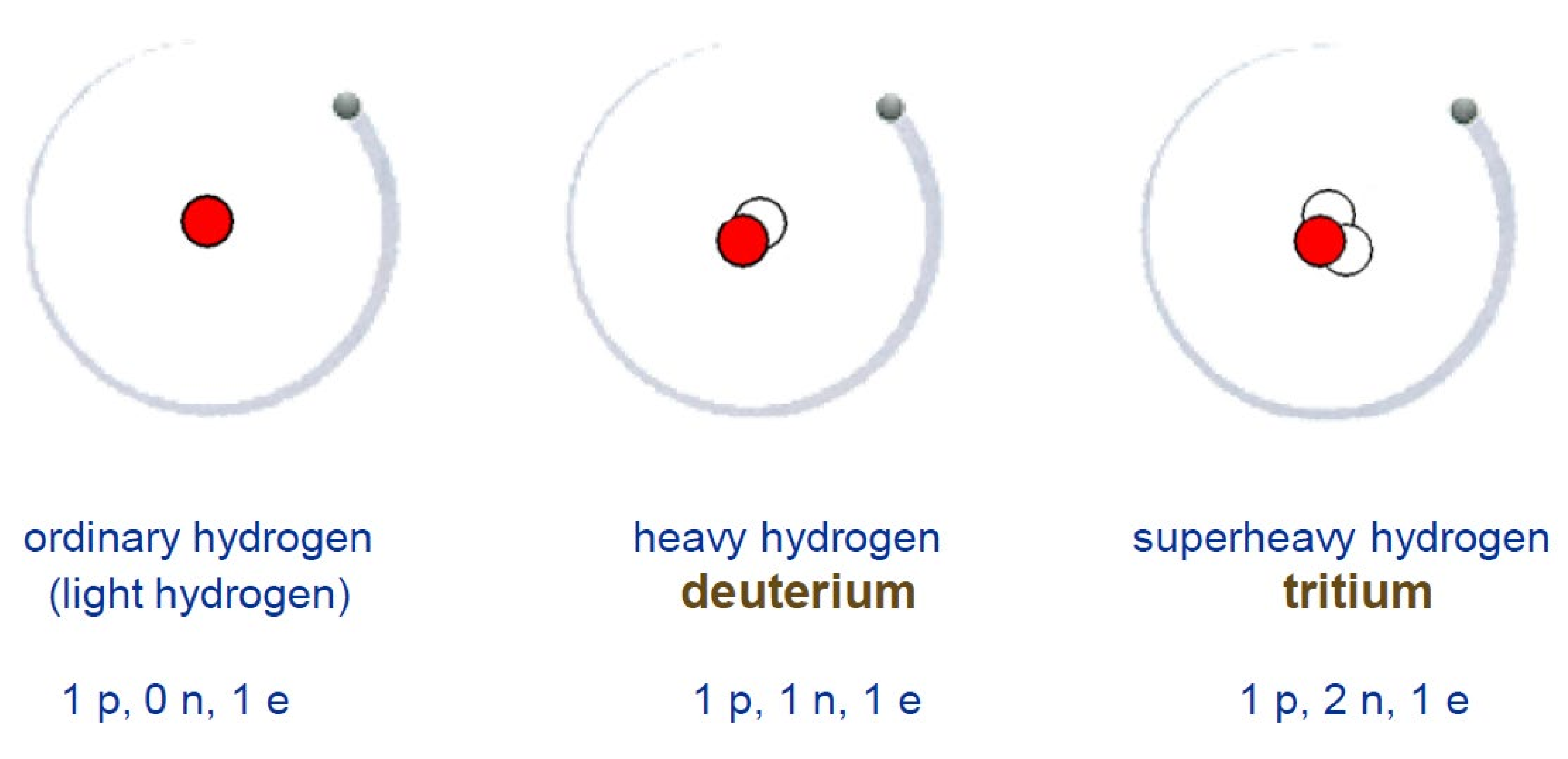
Source: IAEA International Atomic Energy Agency

Isotop

- Atoms of the same element can differ in weight:
  - Equal number of protons (and electrons)
  - Equal chemical properties
  - Their nuclei have different masses
  - The difference in masses originates from different number of neutrons
- Atoms of a given element with different number of neutrons are called **isotopes**
- (isotopes are nuclides, belonging to the same element)

Source: IAEA International Atomic Energy Agency

Isotop Hidrogen (contoh)



Source: IAEA International Atomic Energy Agency

Kelimpahan Isotop

- Everywhere on Earth, elements are composed from same isotopes in fixed relative proportions.
- These proportions are called **isotopic abundance** of an element.
- Examples:

Element	Isotopes and their relative proportions
Hydrogen	^{1}H – 99.985% ^{2}H – 0.015%
Boron	^{10}B – 19.8% ^{11}B – 80.2%
Aluminium	^{27}Al – 100%
Iron	^{54}Fe – 5.8% ^{56}Fe – 91.72% ^{57}Fe – 2.2% ^{58}Fe – 0.28%
Uranium	^{234}U – 0.0054% ^{235}U – 0.72% ^{238}U – 99.2746%

Source: IAEA International Atomic Energy Agency

Kurva Kestabilan

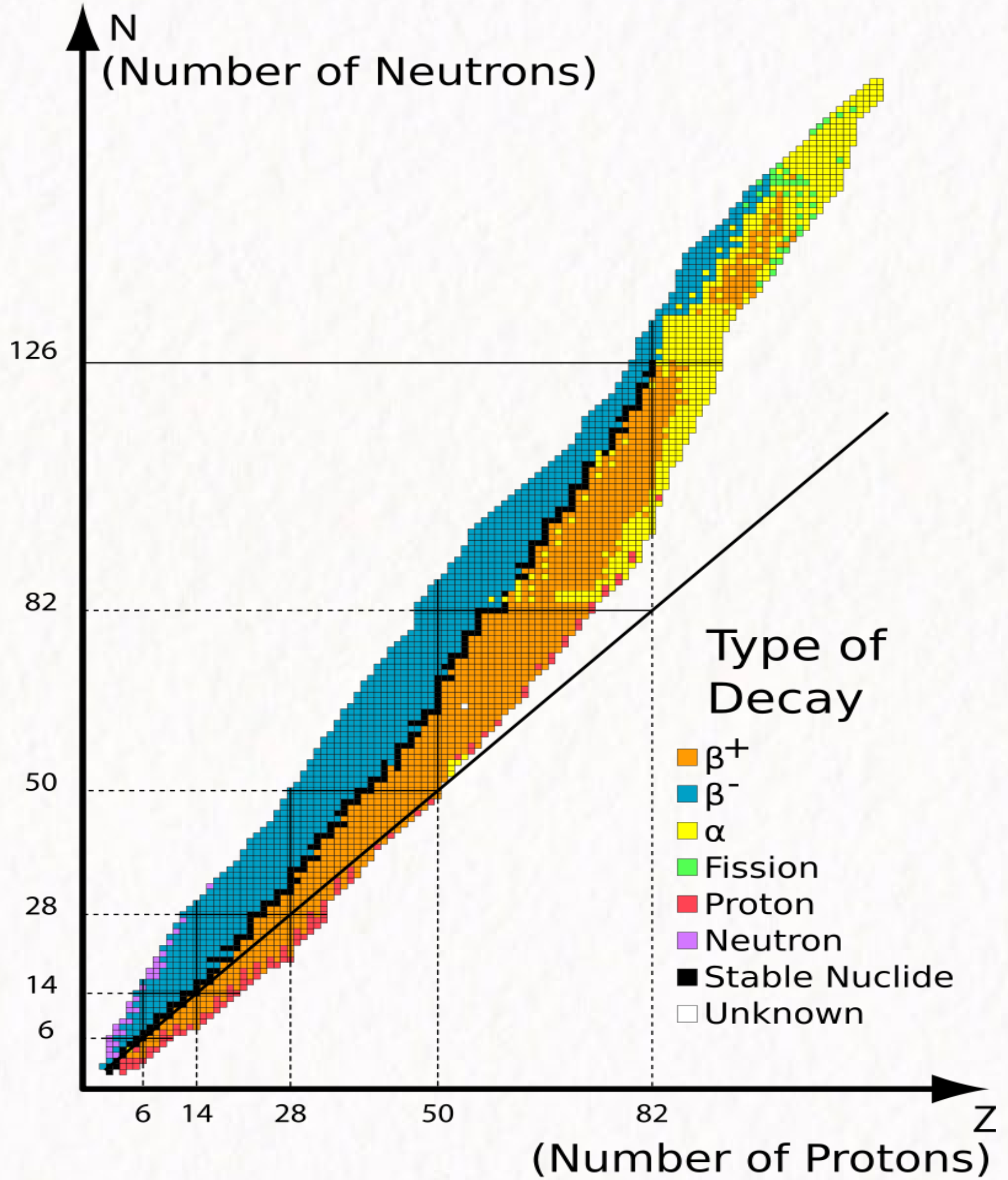
~ 3000 nuclides there are 237 stable nuclides

nuklida tidak stabil

(radionuklida)

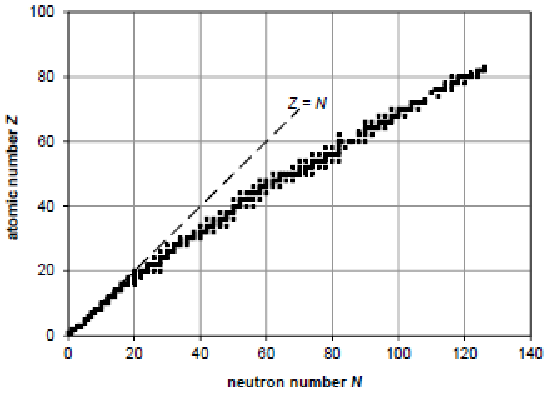
- Peluruhan alfa
- Peluruhan beta
- Peluruhan gamma
- Tangkapan elektron

nuklida stabil



Nuklida stabil & tidak stabil

- There are 81 elements with stable isotopes
  - All together 237 stable nuclides



- Outside the region of stability, the nuclei are unstable
  - By internal changes and particle emissions unstable nuclei are converted to stable nuclei
  - The process of internal changes → **radioactive decay**
  - Unstable nuclei → **radioactive nuclides or radionuclides**
  - Around 3000 radionuclides are known (~ 100 natural, others man-made)

Source: IAEA International Atomic Energy Agency

Peluruhan Radioaktif

- Decay of unstable atomic nuclei
  - The internal energy of nucleus is decreased
  - The energy difference is carried away by particles and/or EM radiation

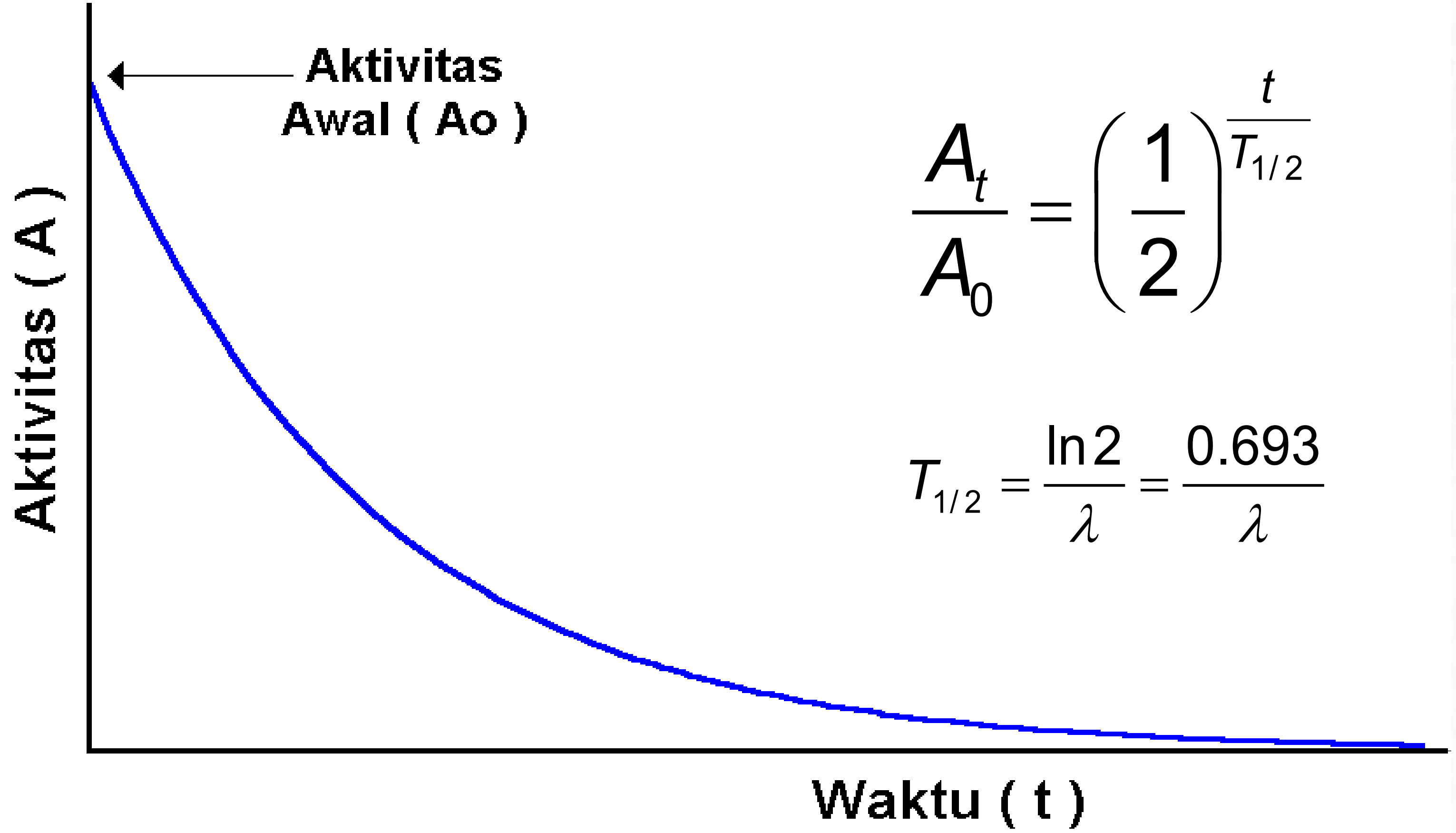
$\Rightarrow$ (radioactive) **radiation**

- Radioactive decay is a spontaneous process
  - The mode and the rate of decay cannot be influenced from the outside

- Often, an isotope of one element is converted to an isotope of another element

Source: IAEA International Atomic Energy Agency

Radioaktivitas



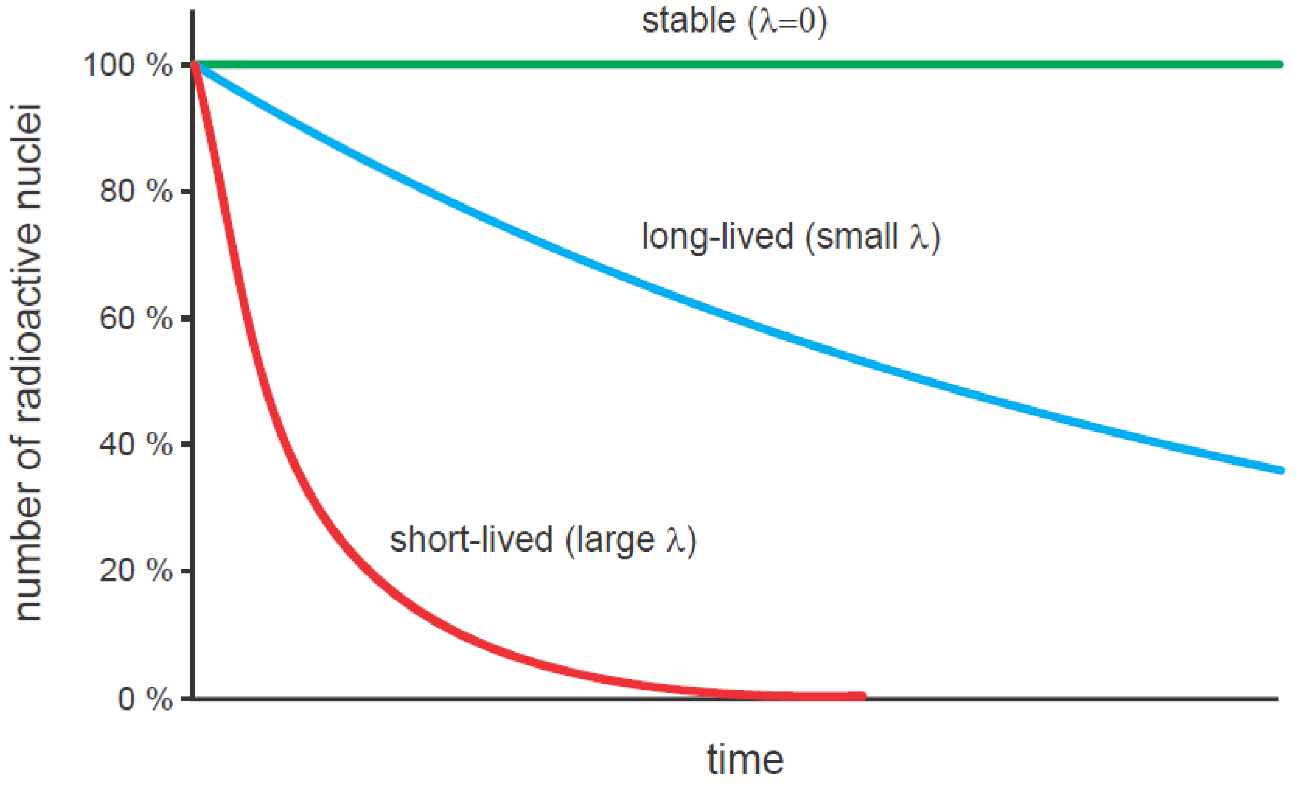
$$\frac{A_t}{A_0} = \left(\frac{1}{2}\right)^{\frac{t}{T_{1/2}}}$$

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

$$A_t = A_0 e^{-\lambda t}$$

Nuklida – T½ - λ

- Long-lived nuclides: large $t_{1/2}$, small λ
- Short-lived nuclides: small $t_{1/2}$, large λ



Source: IAEA International Atomic Energy Agency

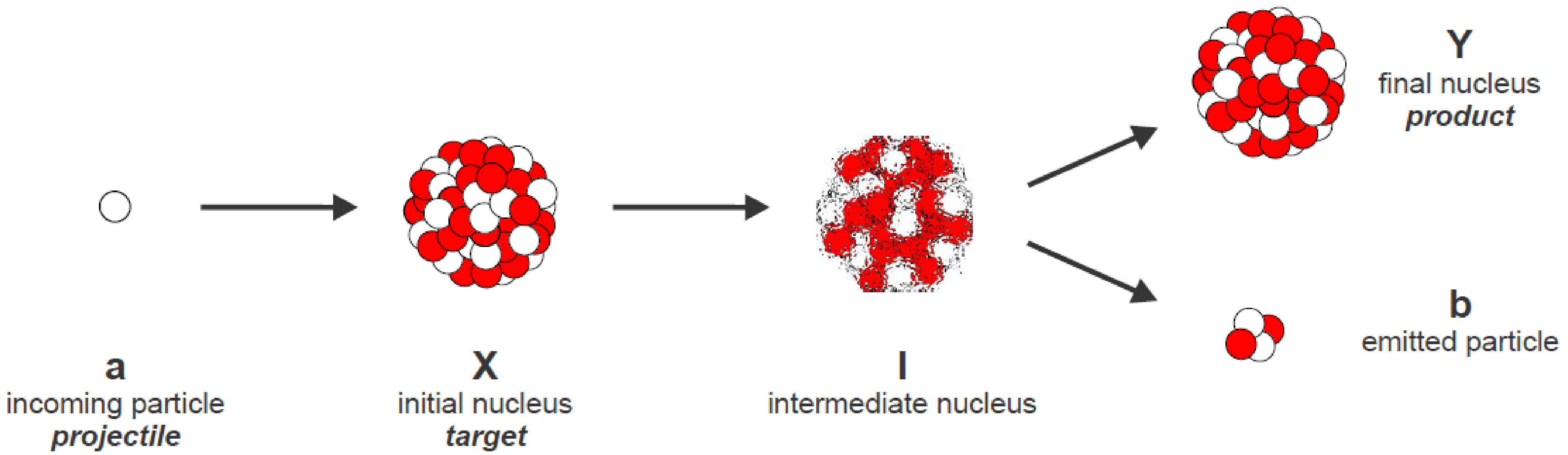
3 INTERAKSI NEUTRON

Interaksi Neutron → Inti Atom

- Serapan (*absorbtion*) :
  - Fisi atau pembelahan {n,f}
  - Tangkapan {n,γ}
  - Emisi partikel bermuatan {n,p}, {n,α}, {n,2n}
- Hamburan (*scattering*) :
  - Hamburan elastik {n,n}
  - Hamburan inelastik {n,n'}atau {n,n'γ}

Source: IAEA International Atomic Energy Agency

Reaksi Nuklir



$$a + X \rightarrow I \rightarrow Y + b$$

- short notation for nuclear reaction:

$$X\,(a,\,b)\,Y$$

Source: IAEA International Atomic Energy Agency

Reaksi Serapan (*Absorbtion*)

Penangkapan neutron (neutron capture) (n,γ)

$${}^{23}_{11}Na + {}^{1}_{0}n \rightarrow {}^{24}_{11}Na^{*} + \gamma$$

atau $${}^{23}Na(n,\gamma)\,{}^{24}Na$$

$${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U^{*} \rightarrow {}^{239}_{92}U + \gamma$$

atau $${}^{238}U(n,\gamma)\,{}^{239}U$$

Pemancaran partikel α (emission of α-particle) (n,α)

$${}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{4}_{2}He + {}^{3}_{1}H$$

atau $${}^{6}_{3}Li\,(n,\alpha)\,{}^{3}_{1}H$$

$${}^{3}_{2}He + {}^{1}_{0}n \rightarrow {}^{1}_{1}H + {}^{3}_{1}H$$

atau $${}^{3}_{2}He(n,p)\,{}^{3}_{1}H$$

Pemancaran proton (Proton emission) (n,p)

$${}^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{14}_{6}C + {}^{1}_{1}H$$

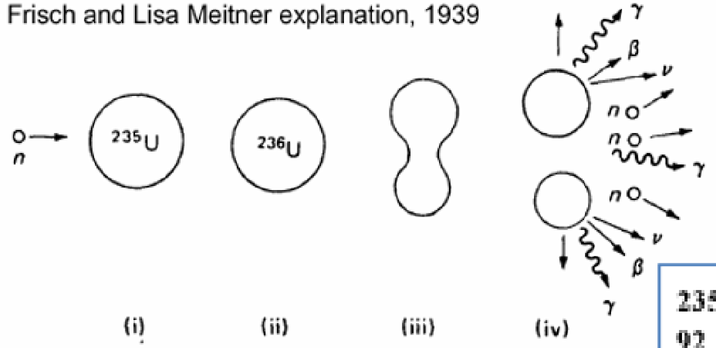
$${}^{31}_{15}P + {}^{1}_{0}n \rightarrow {}^{31}_{14}Si + {}^{1}_{1}H$$

Reaksi multiplikasi (multiplication reaction) (n,2n)

$${}^{63}_{29}Cu\,(n,2n)\,{}^{62}_{29}Cu$$

$${}^{65}_{29}Cu\,(n,2n)\,{}^{64}_{29}Cu$$

Otto Hahn and Fritz Strassman, 1938 - Berlin
Otto Frisch and Lisa Meitner explanation, 1939



Empat langkah reaksi fisi

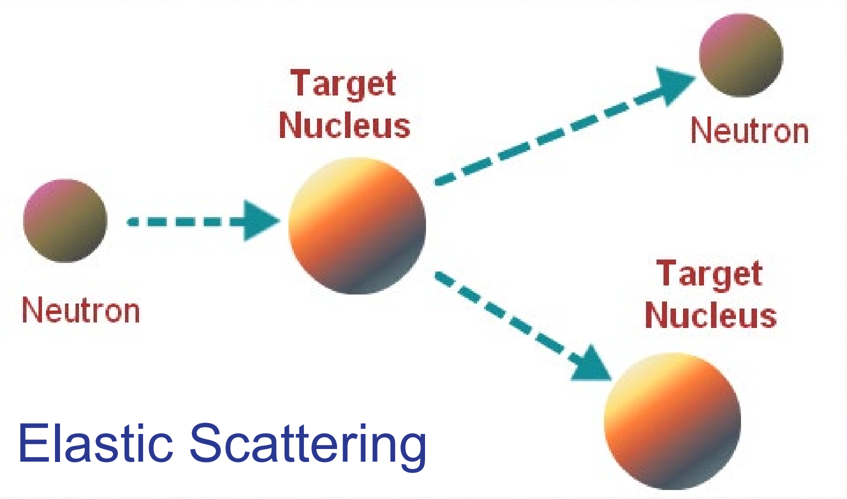
Reaksi Fisi

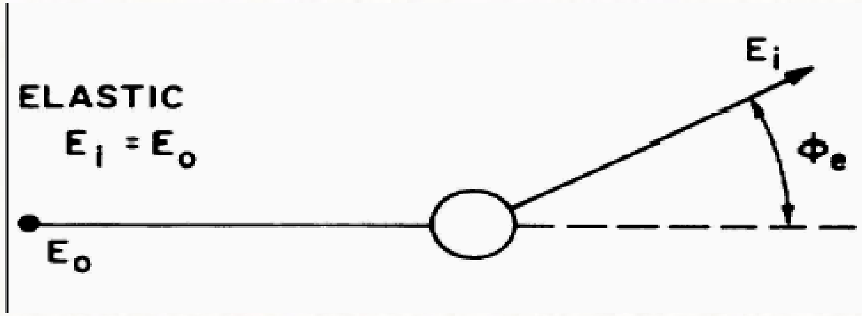
$${}^{235}_{92}U + n \rightarrow \left({}^{235}_{92}U\right)^{*} \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3\,{}^{1}_{0}n$$

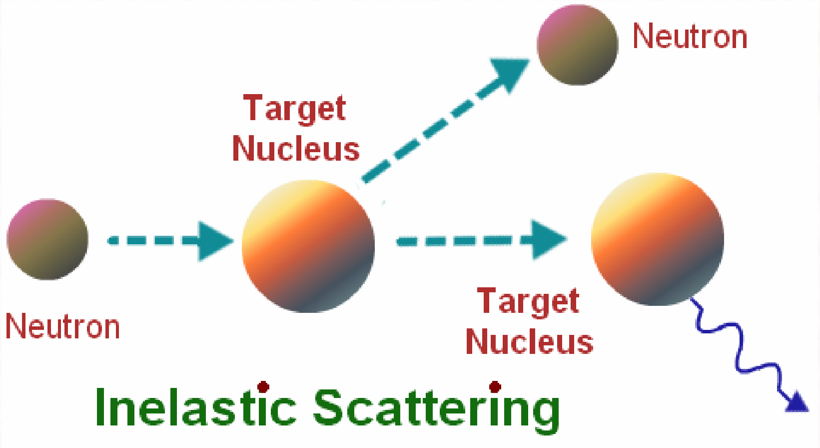
$${}^{235}_{92}U + n \rightarrow \left({}^{235}_{92}U\right)^{*} \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2\,{}^{1}_{0}n$$

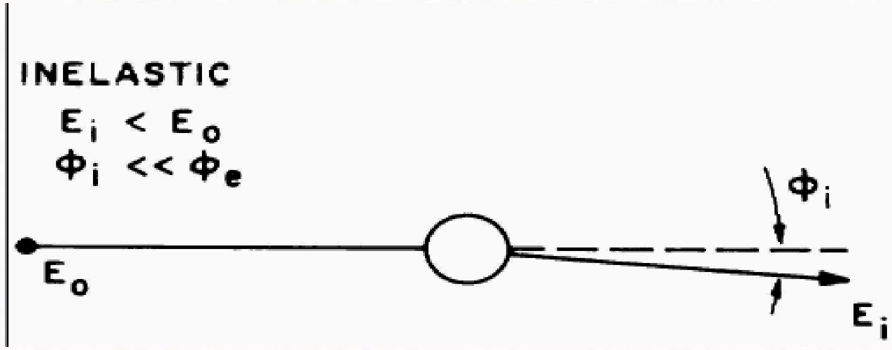
resume

Reaksi Hamburan (*Scattering*)







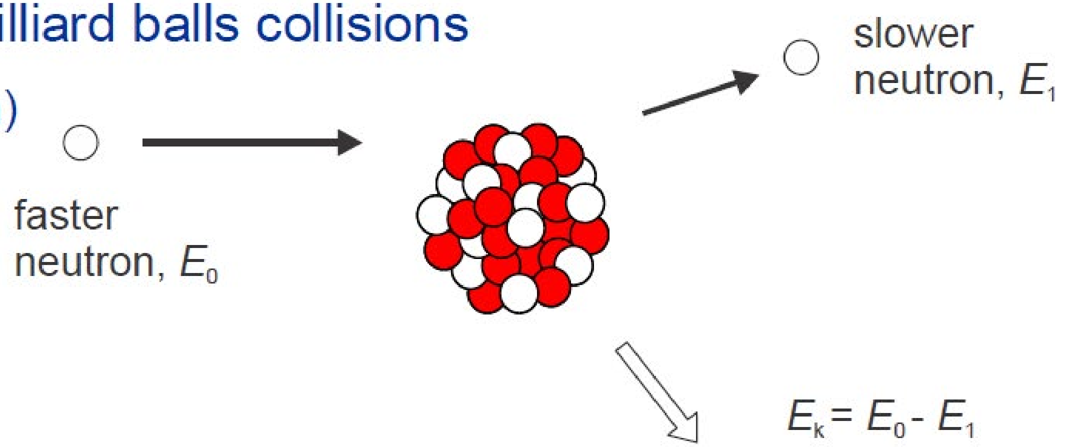


Hamburan Neutron

- neutrons collide with nuclei and bounce off them
- “products” of reaction (scattering) neutron and initial nucleus
- nucleus gains kinetic energy with the collision
- the kinetic energy of the neutron is decreased

  ⇒ the neutron is slowed down → neutrons change from *fast* neutrons into *slow* or **thermal neutrons**
- can be compared with billiard balls collisions

  n + X → X + n   or   (n, n)



Source:

IAEA International Atomic Energy Agency

Tampang Lintang Reaksi (1)

- **cross section** σ ~ effective cross sectional area of a nucleus "seen" by a beam of particles
- **a measure for probability of a reaction on nucleus**
- cross section unit: 1 barn = 1 b = 10^{-24} cm^2
- cross section values change markedly from one nucleus to another, and also relative to neutron energy

number of nuclear reactions = $\sigma \Phi n t$

Source: IAEA International Atomic Energy Agency

Tampang Lintang Reaksi (2)

❖ **Makroskopis (Σ)**

- probabilitas reaksi tersebut terjadi per satuan perjalanan neutron
- satuan = cm^{-1}

$$\Sigma = N\sigma$$

N = rapat atom nuklida ($atom/cm^3$)

❖ **Mikroskopis (σ)**

- probabilitas reaksi tersebut terjadi antara sebuah neutron dan sebuah inti
- satuan → barn atau cm^2

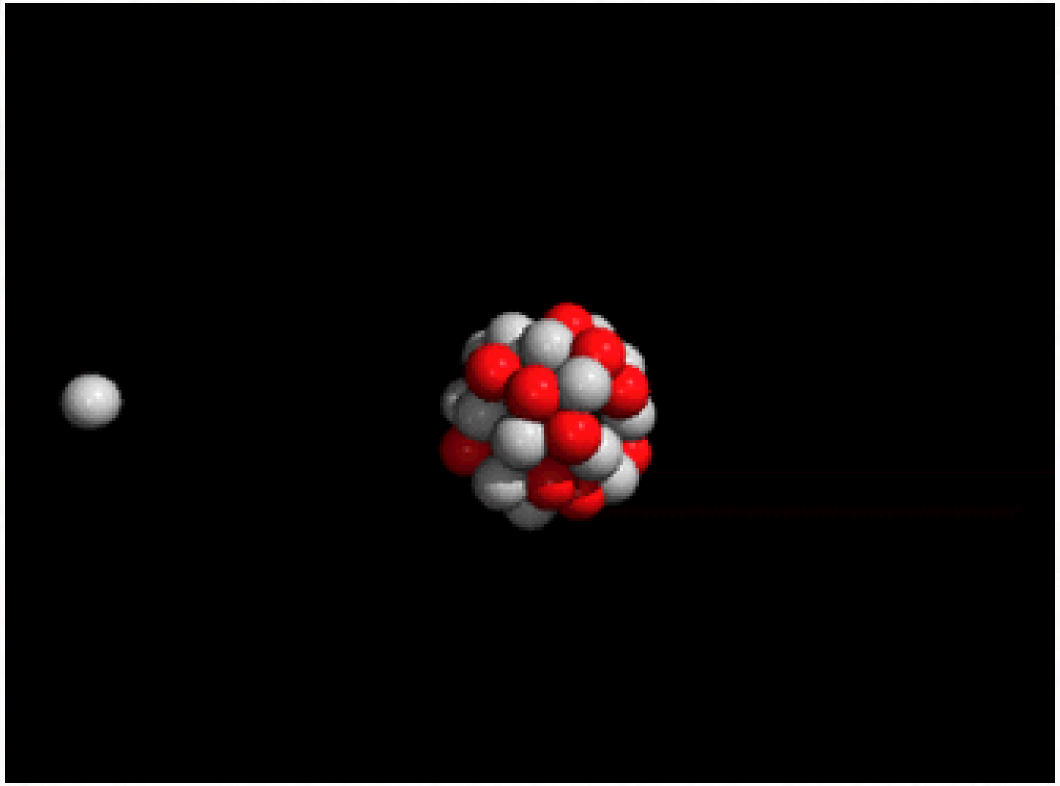
1 barn = 10^{-24} cm^2

$$\sigma_t = \sigma_s + \sigma_a$$

dengan $\sigma_s = \sigma_{se} + \sigma_{si}$

$$\sigma_a = \sigma_c + \sigma_f$$

Reaksi Pembelahan Inti



$$_{0}n^{1} + _{92}U^{235} \text{--------->} X_1 + X_2 + (2\text{-}3)n + E$$

n : neutron, berasal dari sumber neutron

$$Be^{9} + {}_{2}\alpha^{4} \text{-------->} C^{12} + {}_{0}n^{1}$$

U : Uranium, berasal dari batuan mineral uranium

X_1 , X_2 : inti hasil pembelahan (Sm^{149}, Xe^{135}, Cs^{137}, Mo^{99}, Ba^{141}, Kr^{92})

E : energi panas (200 MeV)

Bahan *Fissile* & *Fertile*

Fissile material: nuklida-nuklida yang bisa bereaksi fisi oleh neutron yang mempunyai segala macam energi (energi cepat dan energi termal)

- **U-235** di dalam uranium alam
- **Pu-239** dihasilkan dari U-238 (tangkapan neutron di dalam reaktor nuklir)
  - n + U-238 → U-239 (β decay) → **Pu-239**
- **Pu-241** dihasilkan dari Pu-240, dengan tangkapan neutron
  - n + Pu-239 → Pu-240, n + Pu-240 → **Pu-241**
- **U-233** dihasilkan dari Th-232, dengan tangkapan neutron
  - n + Th-232 → Th-233 (β decay) → Pa-233 (β decay) → **U-233**

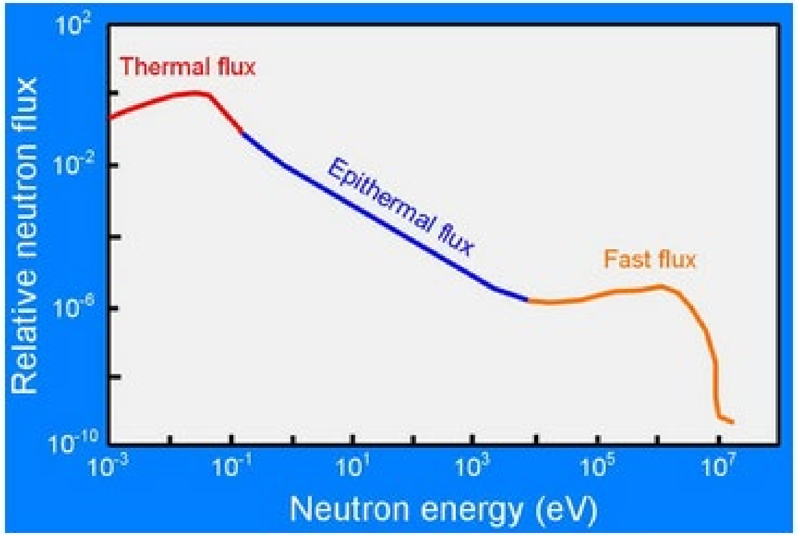
Fertile material: nuklida-nuklida yang tidak dapat bereaksi fisi, namun dapat berubah (bertransmutasi) menjadi bahan fisil dengan iradiasi di dalam reaktor

- **U-238**, **Th-232** , **Pu-240**

Klasifikasi Neutron

Untuk tujuan fisika reaktor (khususnya reaktor termal), klasifikasi neutron dibagi menjadi 3 rentang energi:

- **Thermal neutrons** (0.025 eV – 1 eV).
- **Resonance neutrons** (1 eV – 1 keV).
- **Fast neutrons** (1 keV – 10 MeV).



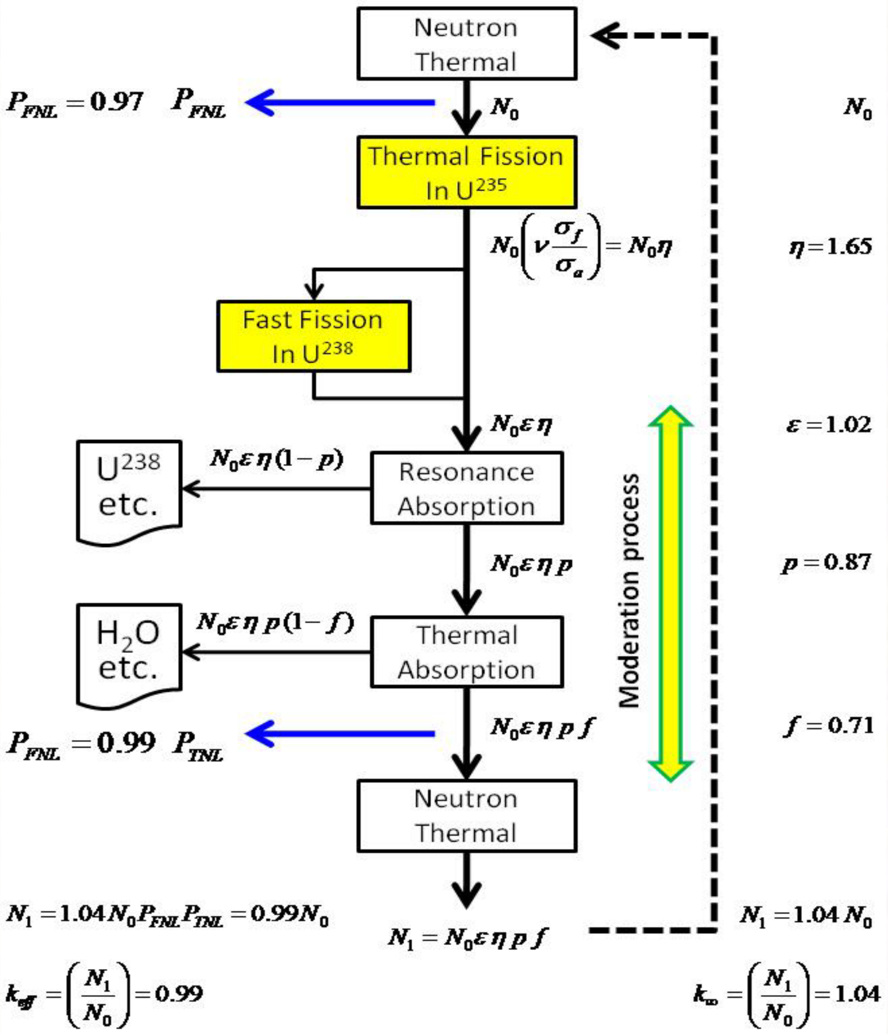
Source: serc.carleton.edu

Neutron Tunda (*delayed neutron*)

c	Waktu paro (detik)	Fraksi
1	55,7	0,00021
2	22,7	0,00142
3	6,2	0,00127
4	2,3	0,00257
5	0,61	0,00075
6	0,23	0,00027
Total		0,0065

4 KINETIKA REAKTOR

Siklus dan Keseimbangan Neutron



η : jumlah neutron fisi yang dipancarkan per neutron termal yang diserap oleh bahan bakar

ε (faktor fisi cepat): fisi yang disebabkan oleh neutron cepat yang berkontribusi pada reaksi berantai

p (probabilitas lepas resonansi): probabilitas menghindari penangkapan resonansi selama moderasi

f (faktor utilisasi termal): fraksi neutron termal diserap oleh bahan bakar

Faktor Multiplikasi

Four Factor Formula

$$k_\infty = \frac{N_1}{N_0} = \eta\, \varepsilon\, p\, f$$

k_∞ : faktor multiplikasi tak hingga (untuk reaktor sangat besar; asumsi konservatif)

k_{eff} : faktor multiplikasi tak hingga (untuk reaktor dengan ukuran aktual)

- $k_\infty < 1$ ($k_{eff} < 1$) → Subcritical condition
- $k_\infty = 1$ ($k_{eff} = 1$) → **Critical condition**
- $k_\infty > 1$ ($k_{eff} > 1$) → Supercritical condition

Six Factor Formula

$$k_{eff} = k_\infty\, P_{FNL}\, P_{TNL}$$

Reaktivitas

Ukuran **seberapa jauh** reaktor berada dari keadaan kritis

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

$\rho < 0 \rightarrow$ subkritis

$\rho = 0 \rightarrow$ kritis

$\rho > 0 \rightarrow$ superkritis

- ✓ Notasi reaktivitas $\rightarrow \rho$
- ✓ Satuan reaktivitas $\rightarrow \frac{\Delta k}{k}$, % $\frac{\Delta k}{k}$, pcm, dollar, cent
- ✓ Pengendalian reaktivitas $\rightarrow$ **batang kendali *(control rod)***
  - Batang kendali **turun** → reaktivitas menjadi **lebih negatif** (-)
  - Batang kendali **naik** → reaktivitas menjadi **lebih positif** (+)

Perioda

- ✓ Waktu yang dibutuhkan agar daya reaktor berubah dengan **faktor e**,

  e = 2.718
- ✓ Sebanding dengan waktu hidup neutron rata-rata
- ✓ Berbanding terbalik dengan perubahan nilai reaktivitas (Δk)
- ✓ Notasi perioda → T

$$T = \begin{pmatrix}\text{suku} \\ \text{serempak}\end{pmatrix} + \begin{pmatrix}\text{suku} \\ \text{tertunda}\end{pmatrix}$$

$$= \frac{\ell^*}{\rho} + \frac{\beta_{eff} - \rho}{\lambda_{eff}\,\rho + \dfrac{\partial \rho}{\partial t}}$$

ℓ^* = waktu generasi neutron serempak

β_{eff} = fraksi neutron tertunda efektif

ρ = reaktivitas

λ_{eff} = konstanta peluruhan neutron tertunda efektif

Hubungan Perioda & Daya Reaktor

$$T = \ell / (k_\infty - 1)$$

Misalnya: $k_\infty = 1.001$

✓ Hanya neutron serempak (tanpa neutron tunda) → $\ell = \ell_p = 10^{-4}$ sekon

T = 10^{-4}/(1.001–1) = 0.1 sekon

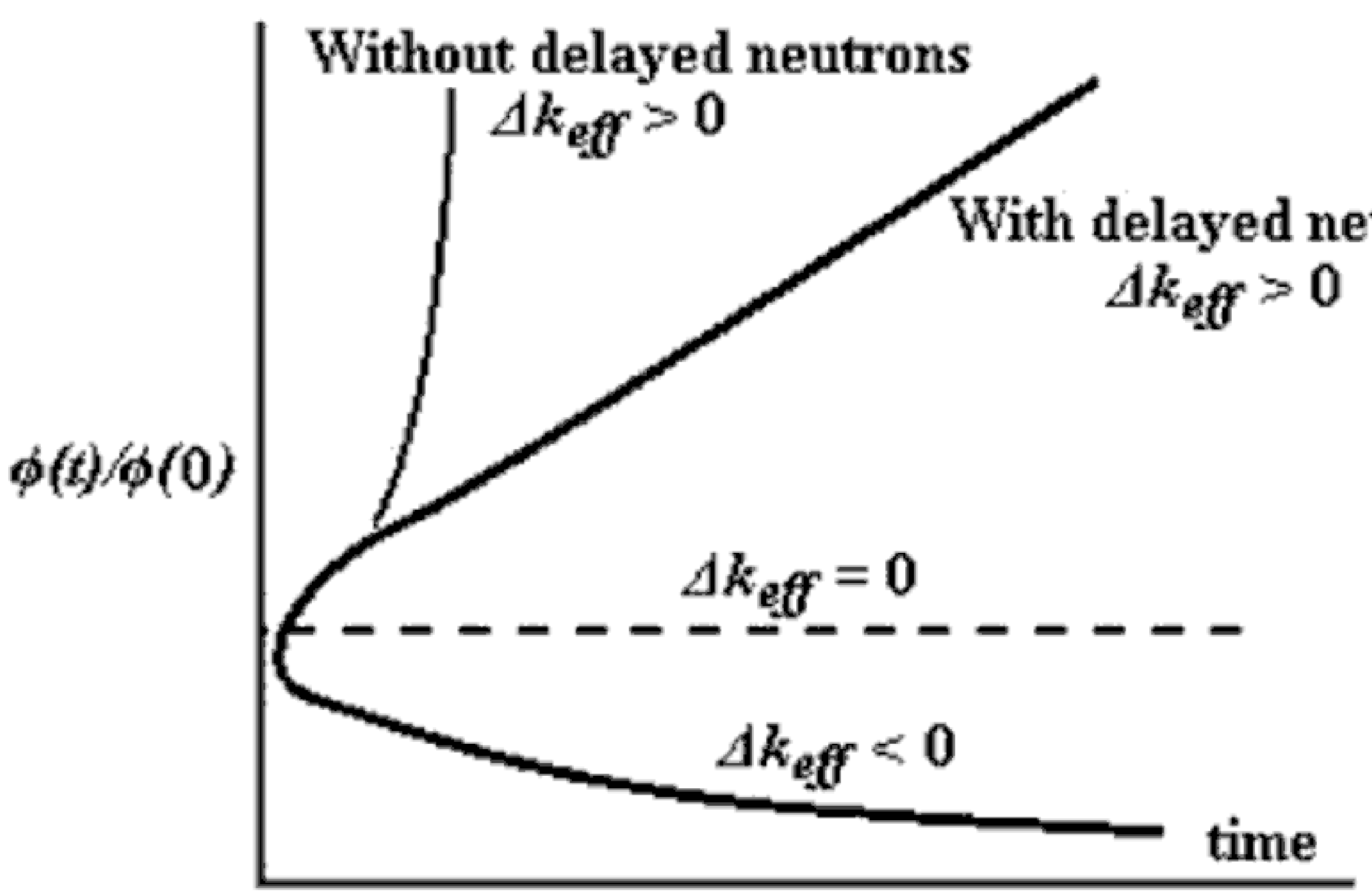
✓ **Dengan adanya neutron tunda** → $\ell = 0.1$ sekon

T = 0.1/(1.001–1) = 100 sekon

❖ Daya meningkat setelah t = 1 sekon → $P_t = P_0 e^{\frac{t}{T}}$

- Hanya neutron serempak → *P*(1) = *P*(0) 22003
- Dengan neutron tunda → *P*(1) = *P*(0) 1.01005

Skema Perubahan Daya Reaktor



Batang Kendali (1)

- ***Batang kendali pancung*** (*scram control*):

  batang kendali ini mampu memadamkan reaktor di seluruh kondisi operasi. Kemampuan masuknya batang kendali ini harus cepat dan harus beroperasi dengan tingkat keandalan yang sangat tinggi.

- ***Batang kendali pengatur*** (*regulating control*):

  batang kendali ini didesain untuk mengkompensasi perubahan reaktivitas yang kecil akibat perubahan temperatur dan perubahan tingkat daya.

- ***Batang kendali shim*** (*shim control*):

  batang kendali ini dideisain untuk menyediakan reaktivitas lebih yang diperlukan mengkompensasi perubahan fraksi bakar dan terbentuknya produk hasil belah, juga mengatur distribusi daya di teras agar fraksi bakar elemen bakar lebih merata.

→ Mekanisme *shutdown* darurat

→ Penyesuaian tingkat daya reaktor

Batang Kendali (2)

Nilai batang kendali ($\Delta\rho_i$)

- Nilai reaktivitas satu batang kendali.

Nilai padam (*shutdown margin*) ρ_{sm}

- Reaktivitas negatif teras pada saat seluruh batang kendali dimasukkan (fully inserted), untuk mencapai faktor perlipatan neutron teras minimum.

Nilai reaktivitas lebih (*excess reactivity*) ρ_{ex}

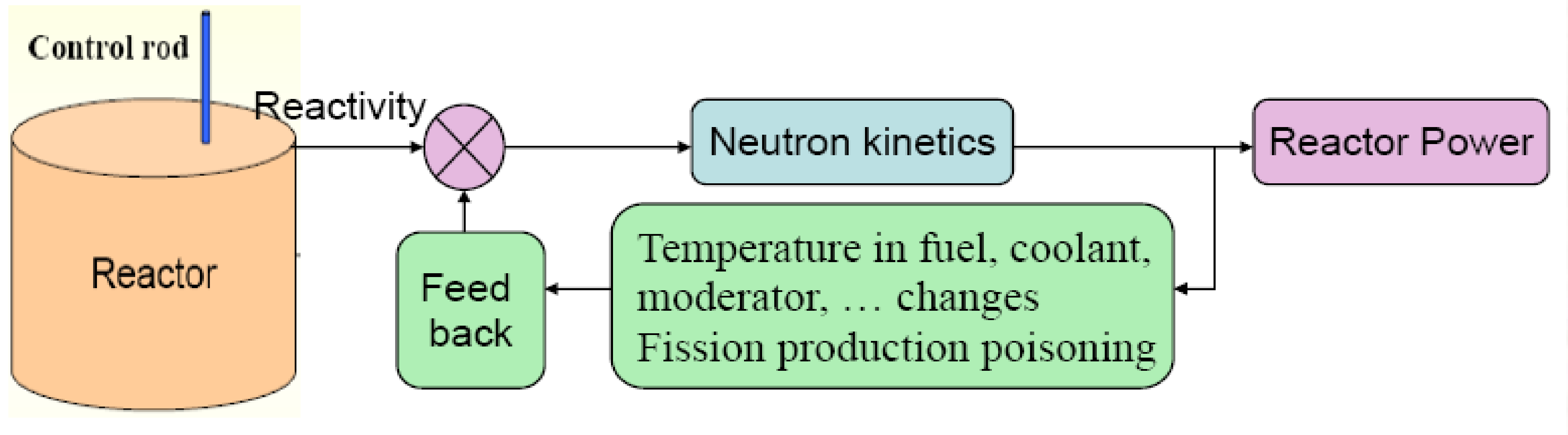
- Nilai kelebihan reaktivitas yang diperlukan untuk memungkinkan operasi reaktor pada daya nol.

Nilai elemen kendali total (nilai padam total) $\Delta\rho$

- Perbedaan antara nilai reaktivitas lebih dan nilai padam.

5 DINAMIKA REAKTOR

Skema "Umpan Balik" Reaktor



Koefisien Reaktivitas & Temperatur

$$\alpha_T = \frac{d\rho}{dT} = \left(\frac{\partial\rho}{\partial T}\right)_{\sigma} + \left(\frac{\partial\rho}{\partial T}\right)_{N} + \left(\frac{\partial\rho}{\partial T}\right)_{B^2}$$

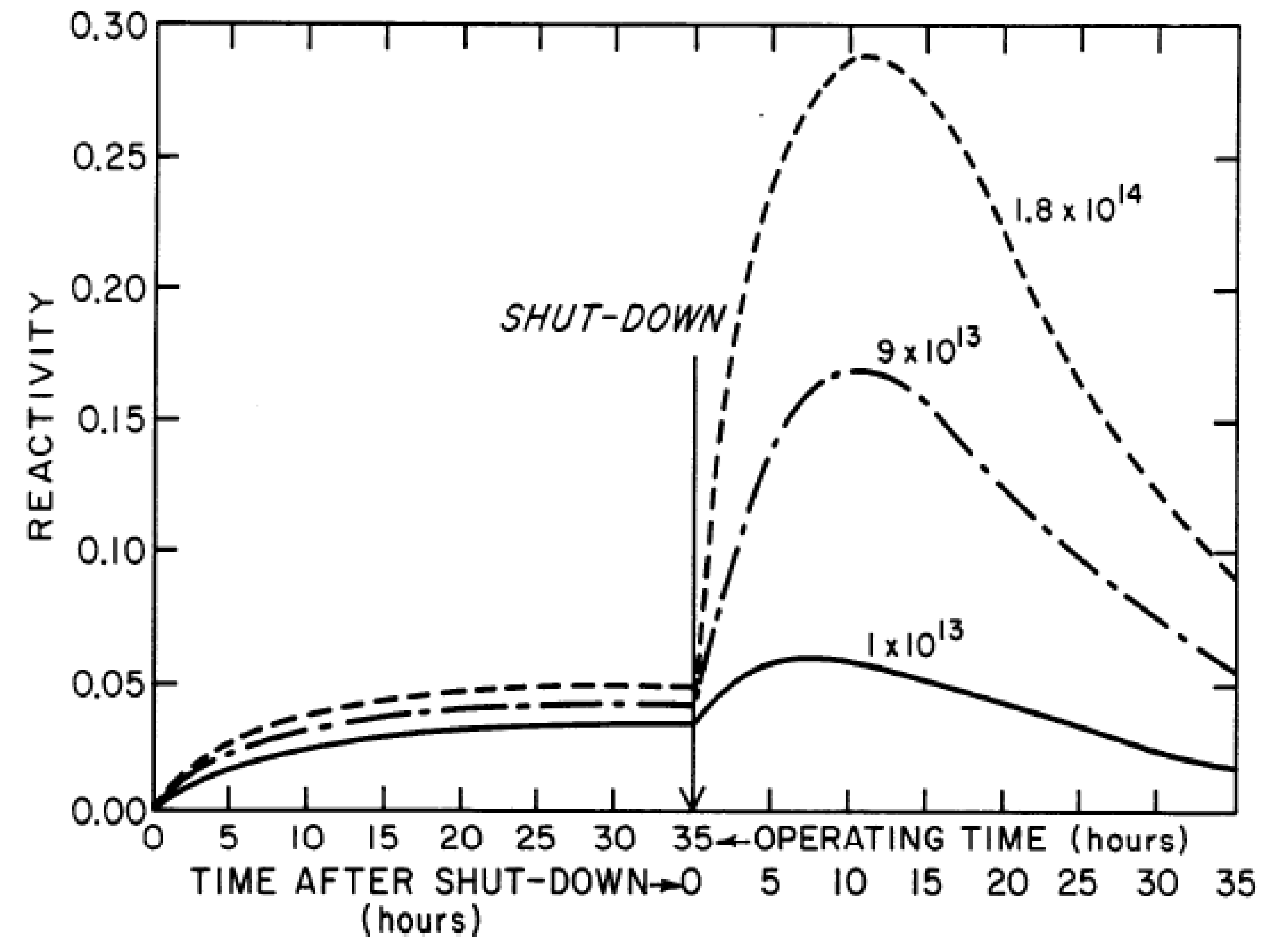
- ✓ Koefisien reaktivitas temperatur α harus negatif, agar operasi stabil.

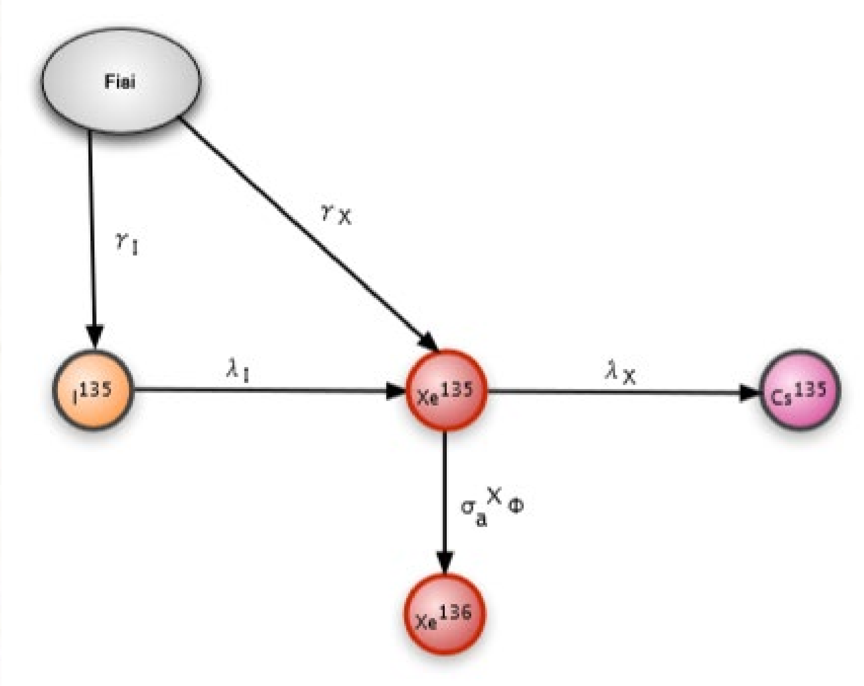
  α yang negatif berarti bahwa jika temperatur naik, reaktivitas turun, laju fisi turun, dan perpindahan panas turun, sehingga temperatur turun kembali ke nilai awalnya. Dalam hal ini dikatakan bahwa reaktor mengatur dirinya sendiri (***self regulating***).

- ✓ Sebaliknya jika α positif maka kenaikan temperatur akan menaikkan k_{eff}. Reaksi fisi yang terjadi akan meningkat dan temperatur akan naik lagi.

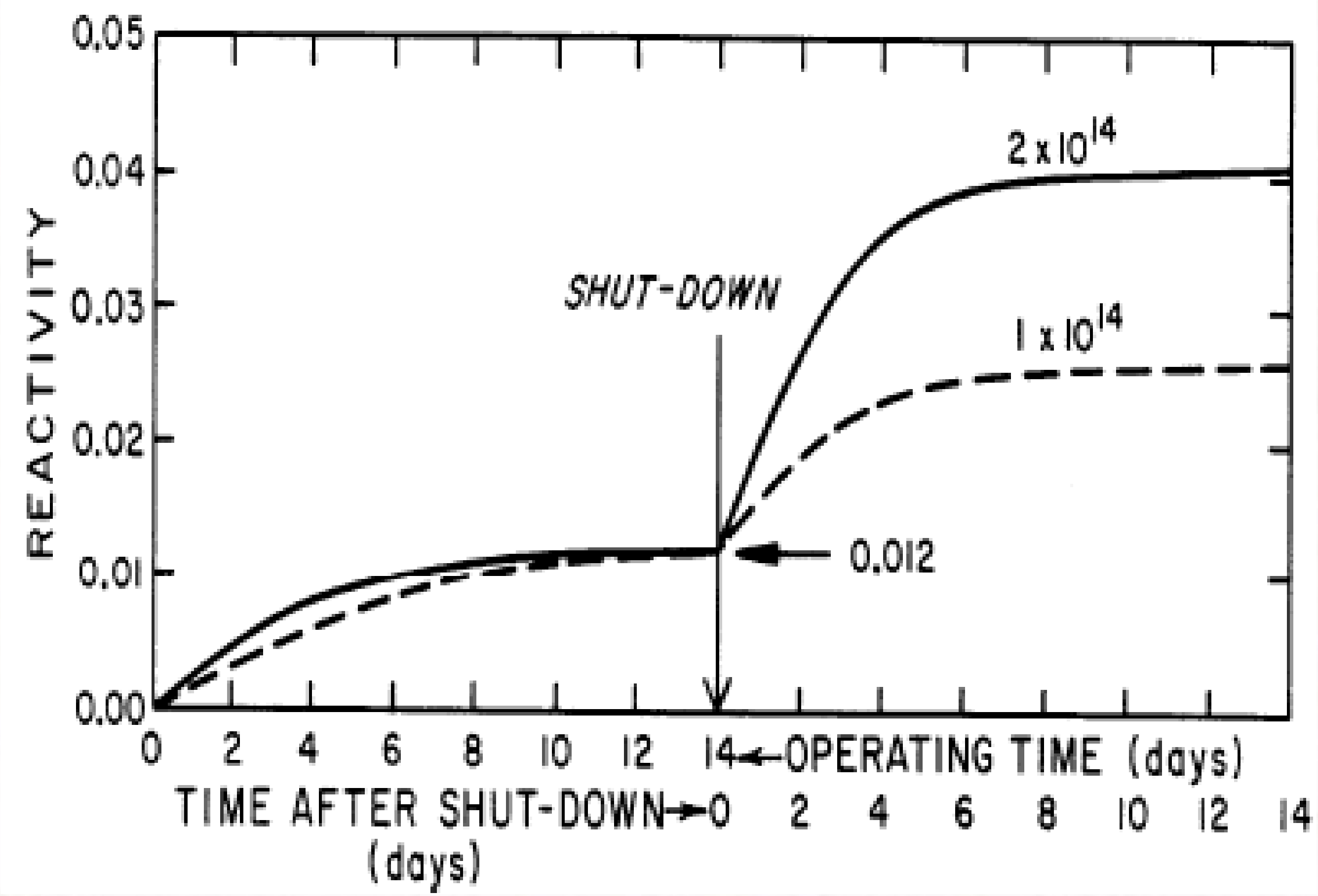
- ✓ Naiknya temperatur akan menambah nilai k_{eff}. Kenaikan nilai k_{eff} secara terus-menerus mengakibatkan reaktor menjadi sulit atau tidak dapat dikendalikan.

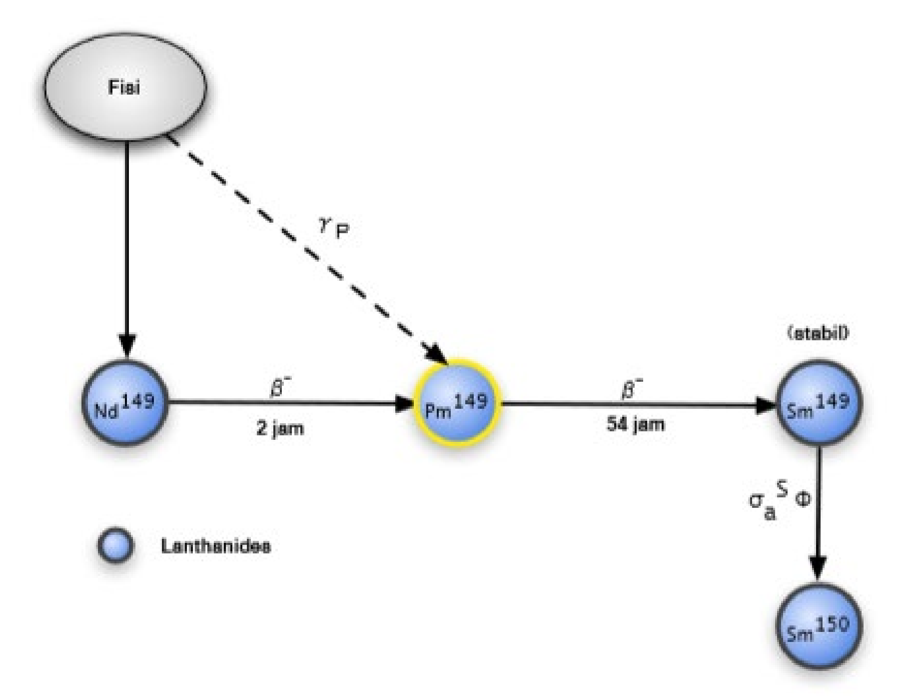
Peracunan Xenon (Xe^{135})





Peracunan Samarium (Sm^{149})





Terima Kasih

Atas Perhatian Anda

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