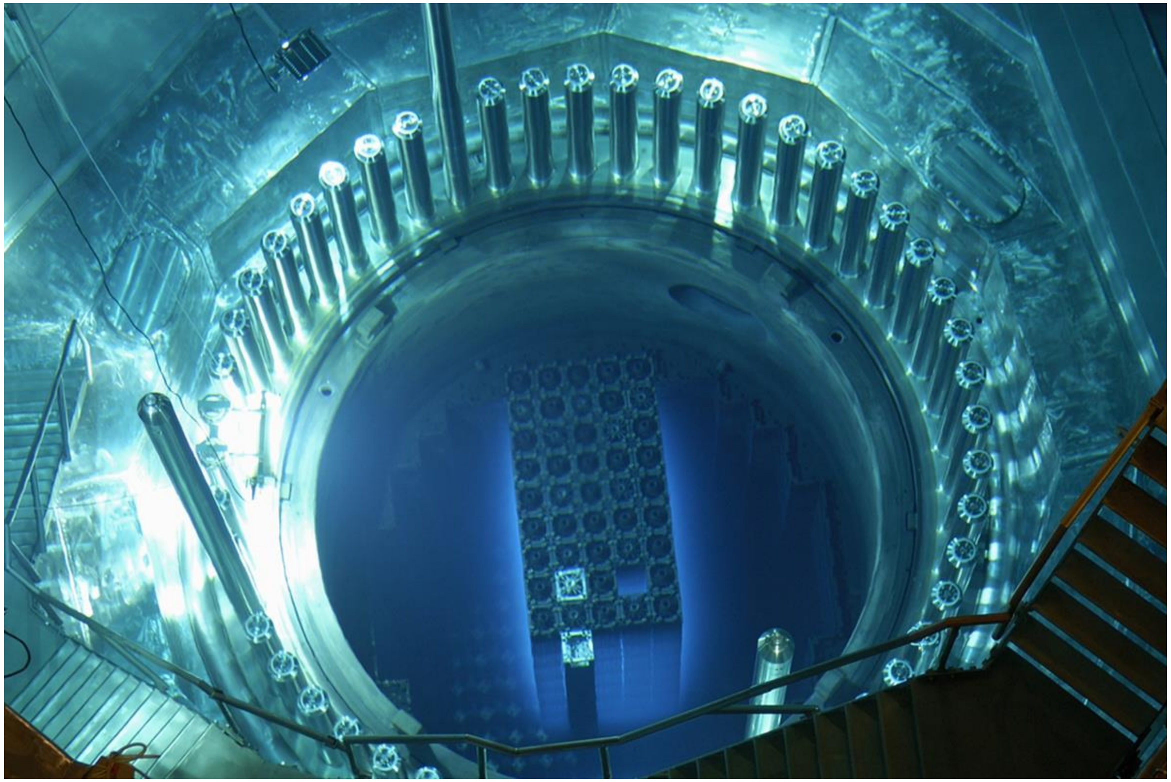
NUCLEAR REACTOR MODELLING:
DEVELOPING A 0D MODEL



Antoine LATERRE
Gauthier LIMPENS

14/10/2021

Context

➔ What is a nuclear reactor?

- It is a place where hundreds of different atoms can interact. There are millions of different reaction per seconds. The kinetic reactor behavior can be hard to predict.

➔ Learning the kinetic of a nuclear reactor through a simplified model:

- As part of MECA2600 classes, students have to analyze a reactor, simplify it and model the reactor kinetic behavior. This work is based on kinetic analysis for a 0D model of reactor.

Goals

➔ Create a model forecasting concentrations:

- Concentration of species (atoms and neutrons) in the reactor at any time
- Power produced by the reactor at each iteration
- Write a report (information will be provided):

➔ Understand reactor kinetics concepts (oral exam) :

- Prompt neutron/ delayed neutron
- fast neutron/thermal neutron
- Poisons (specific fission products)
- Control rods
- MOx use
- Oral exam during final exam (~15 minutes)

Input

➔ Geometry and neutronic data:

- Vessel characteristics (volume, geometry)
- neutronic data (cross sections, fission energy, delayed neutron fraction, half-life, fission yields…)

➔ Boundary conditions :

- m_X : initial atomic composition of the core (can be MOX)
- n_thermal initial : Source of neutrons (to start the reaction)
- t_final : end time of modelisation

➔ Target :

- Supply a constant power generation
- Play with the reactor to understand its behaviour

Your job:

➔ Simplify the reality through consistent hypothesis

- Key reactions
- Kinetics equations
- Power
- …

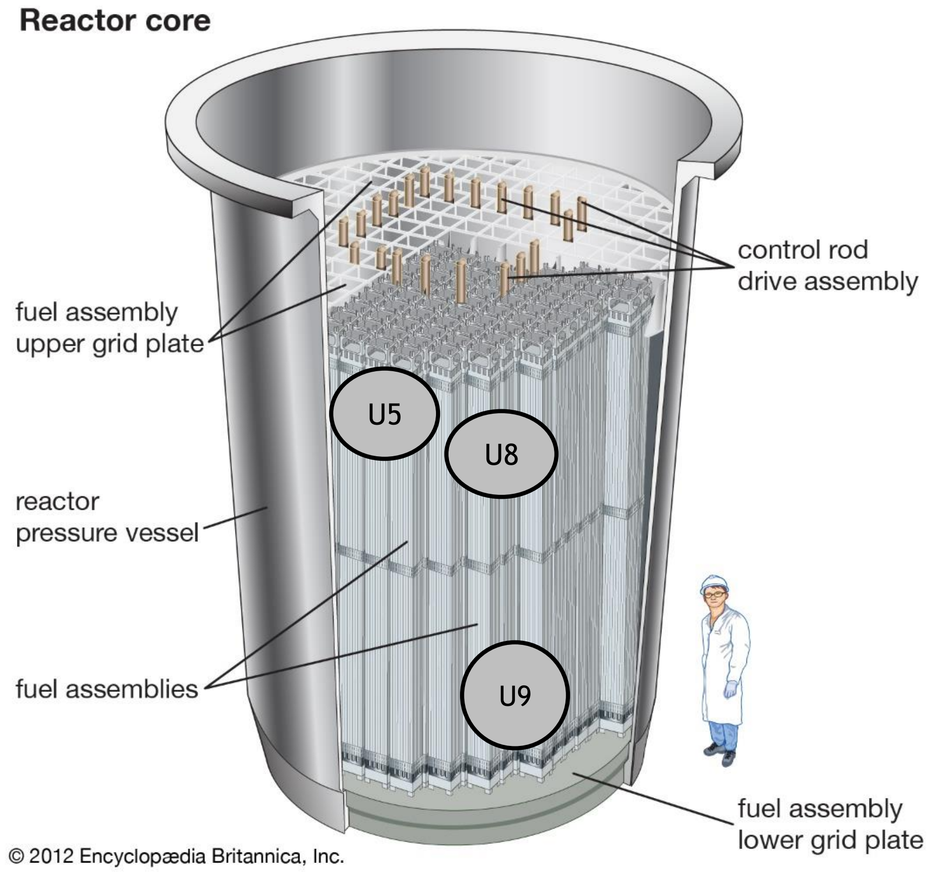
➔ Teaching staff is helping :

- Code structure (Python)
- Proposition of intermediate steps + feedback
- Example of results
- Time line

Help : Nuclear reactor overview

➔ What is considered:

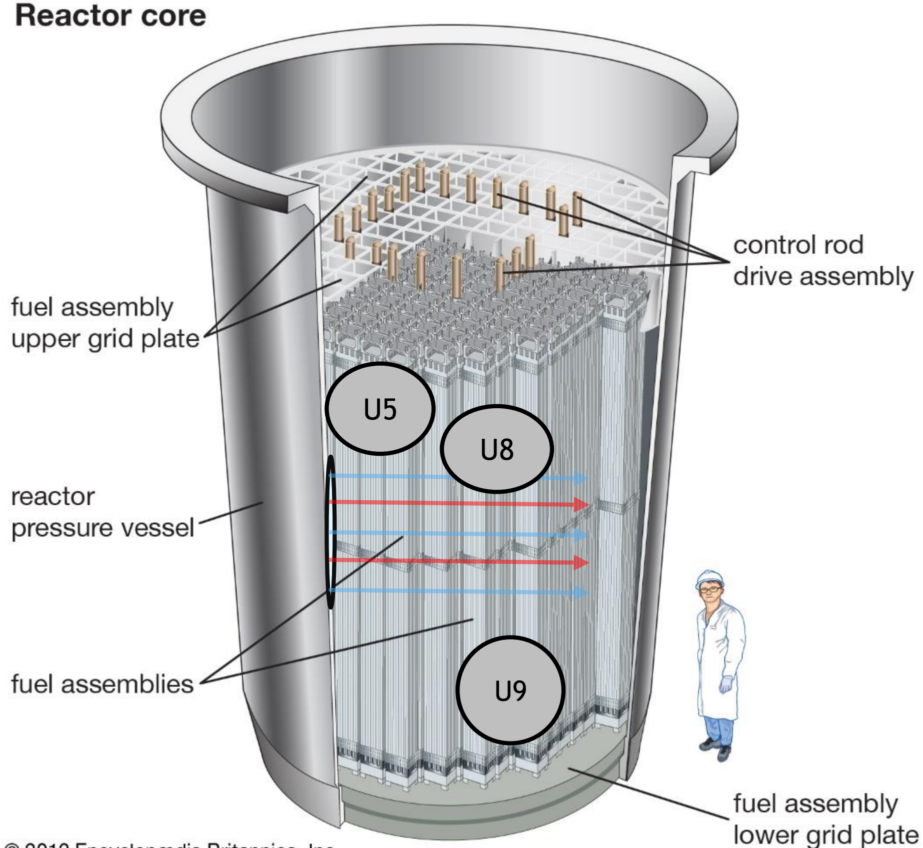
- Atoms inside:
  - Combustible
  - Neutrons
  - Some fission products



Help : Nuclear reactor overview

➔What is considered:

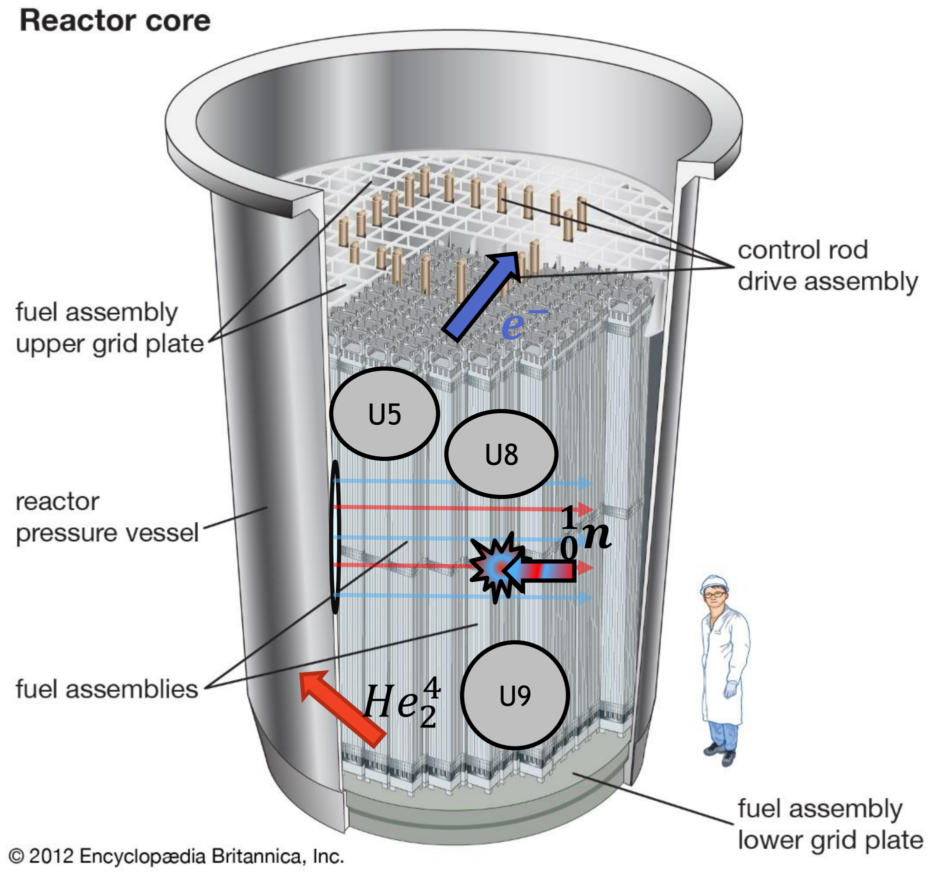
- Atoms inside:
  - Combustible
  - Neutrons
  - Some fission products
- Neutrons flow:



Help : Nuclear reactor overview

➔ What is considered:

- Atoms inside:
  - Combustible
  - Neutrons
  - Some fission products
- Neutrons flow:
- Major reactions
  - Fissions
  - Capture
  - Emissions



Help : Nuclear reactor overview

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- Atoms inside:
  - Combustible
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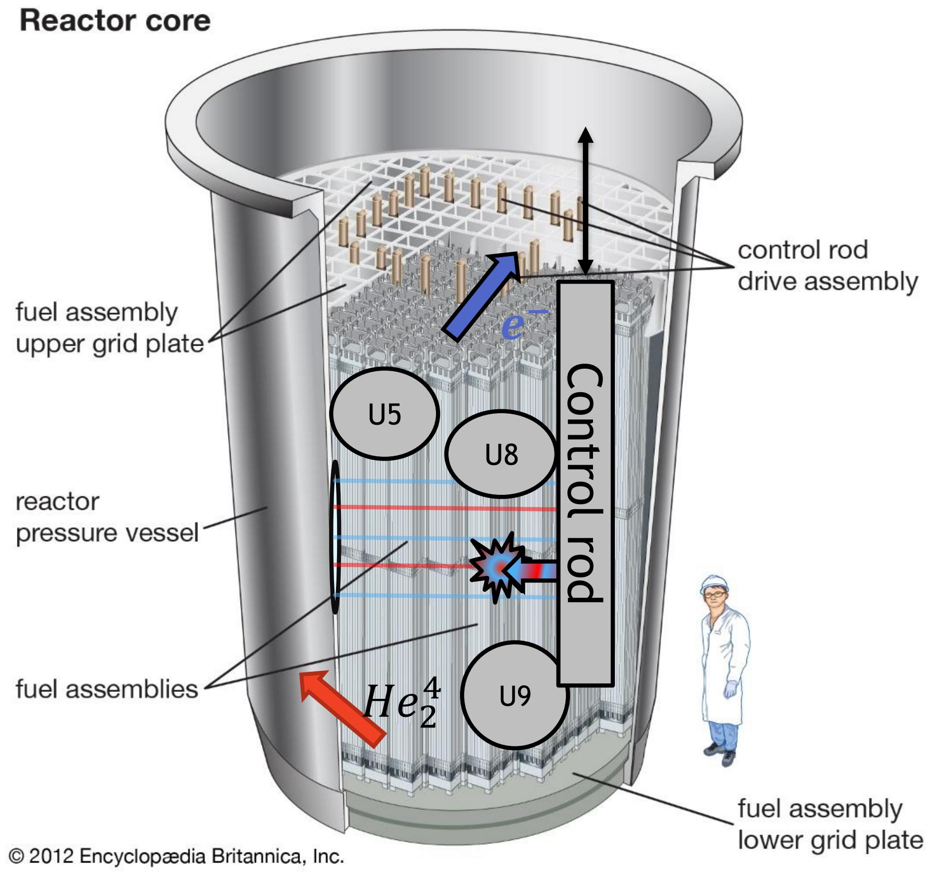
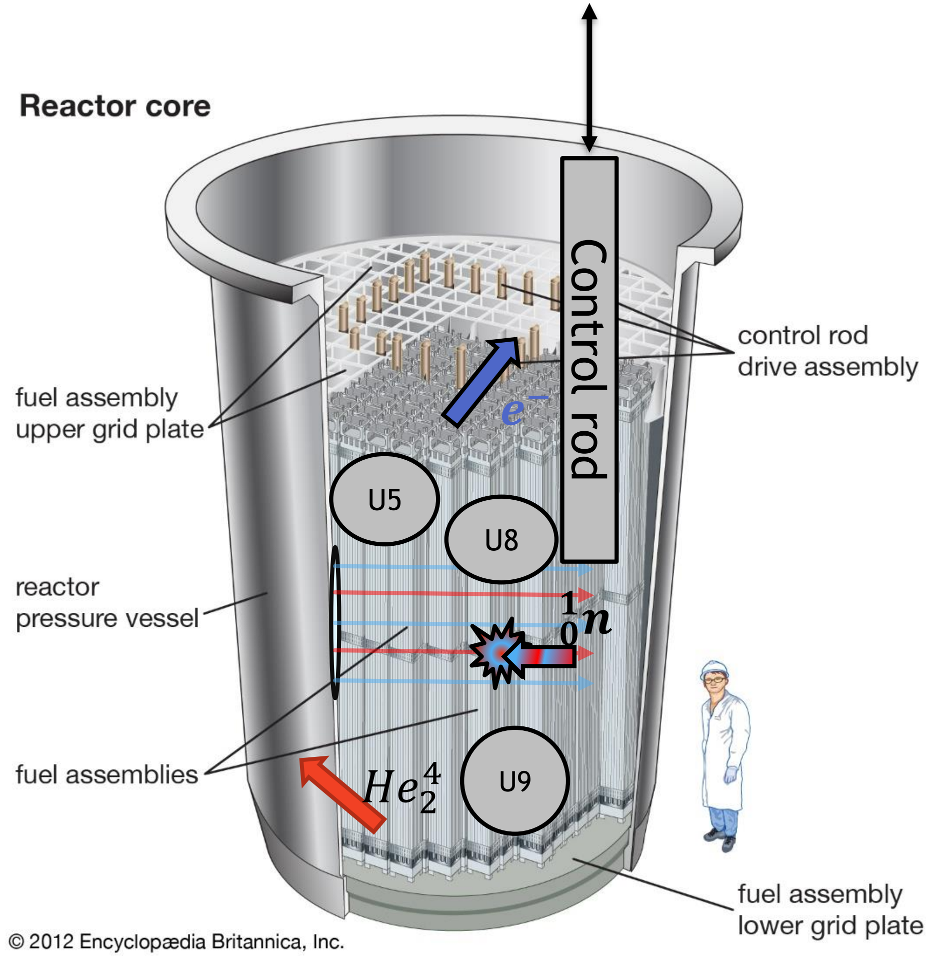
  - Emissions
- Control:
  - Control rods



Help : Nuclear reactor overview

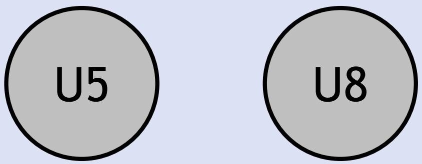
➔ What is considered:

- Atoms inside:
  - Combustible
  - Neutrons
  - Some fission products
- Neutrons flow:
- Major reactions
  - Fissions
  - Capture
  - Emissions
- Control:
  - Control rods (moving)



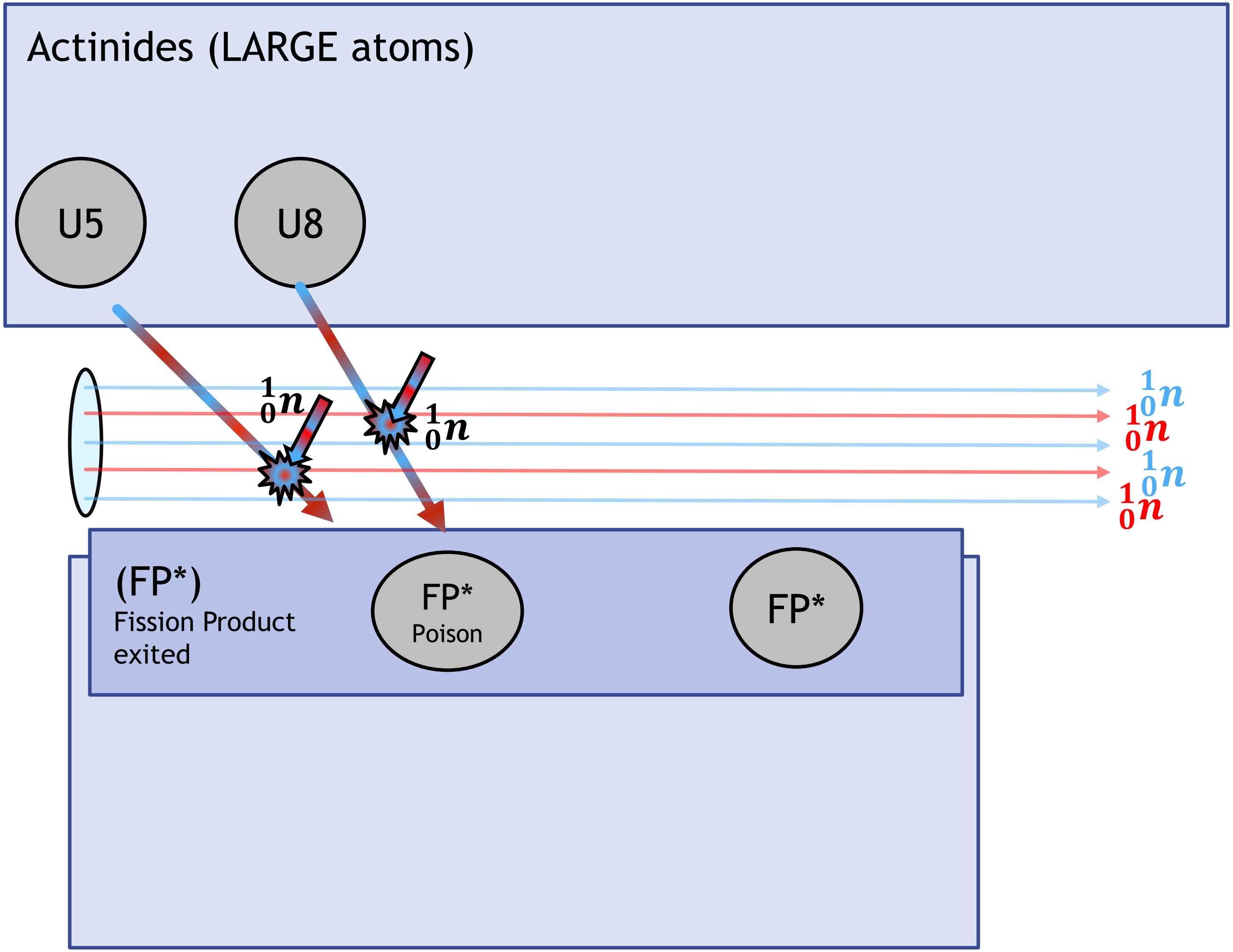
Help : Reaction considered

Actinides (LARGE atoms)



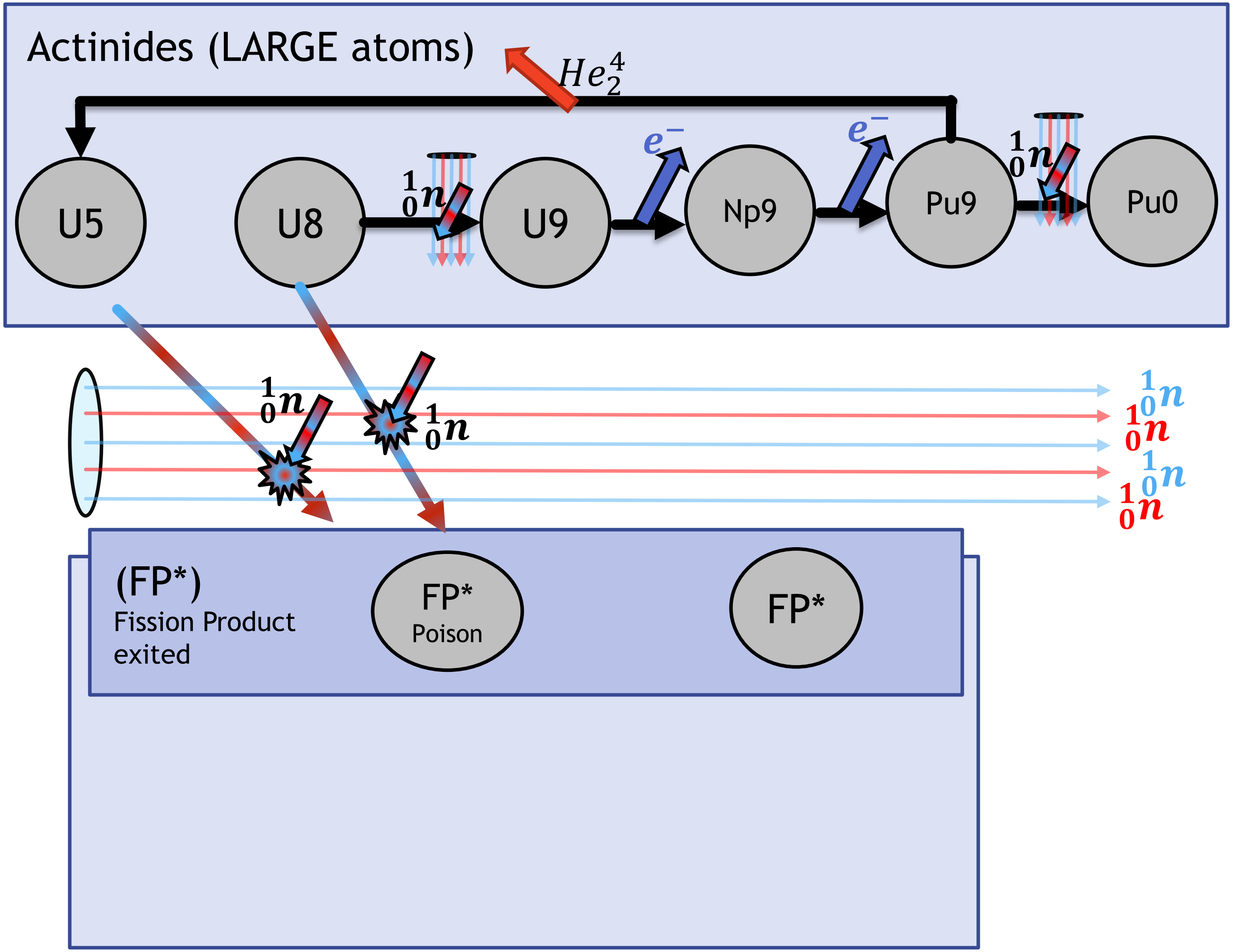
Legend	

Help : Reaction considered



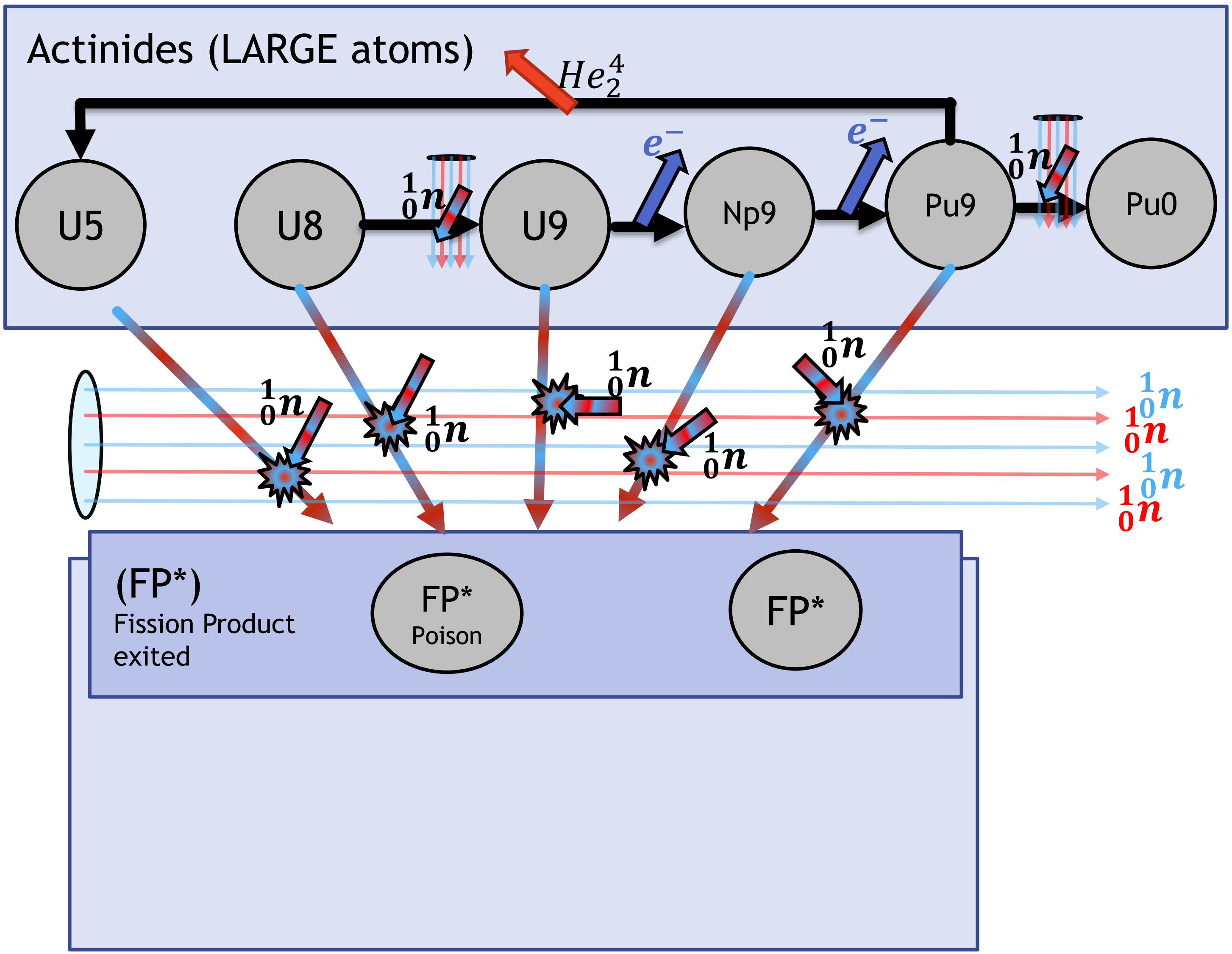
Legend	
	Neutron flux
^1_0n ^1_0n	Fast thermal neutron
^1_0n	Fast or thermal fission

Help : Reaction considered



Legend	
	Neutron flux
^1_0n ^1_0n	Fast thermal neutron
e^-	Beta - ray
^1_0n	Fast or thermal capture
^1_0n	Fast or thermal fission
He_2^4	Alpha ray

Help : Reaction considered



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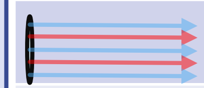	Neutron flux
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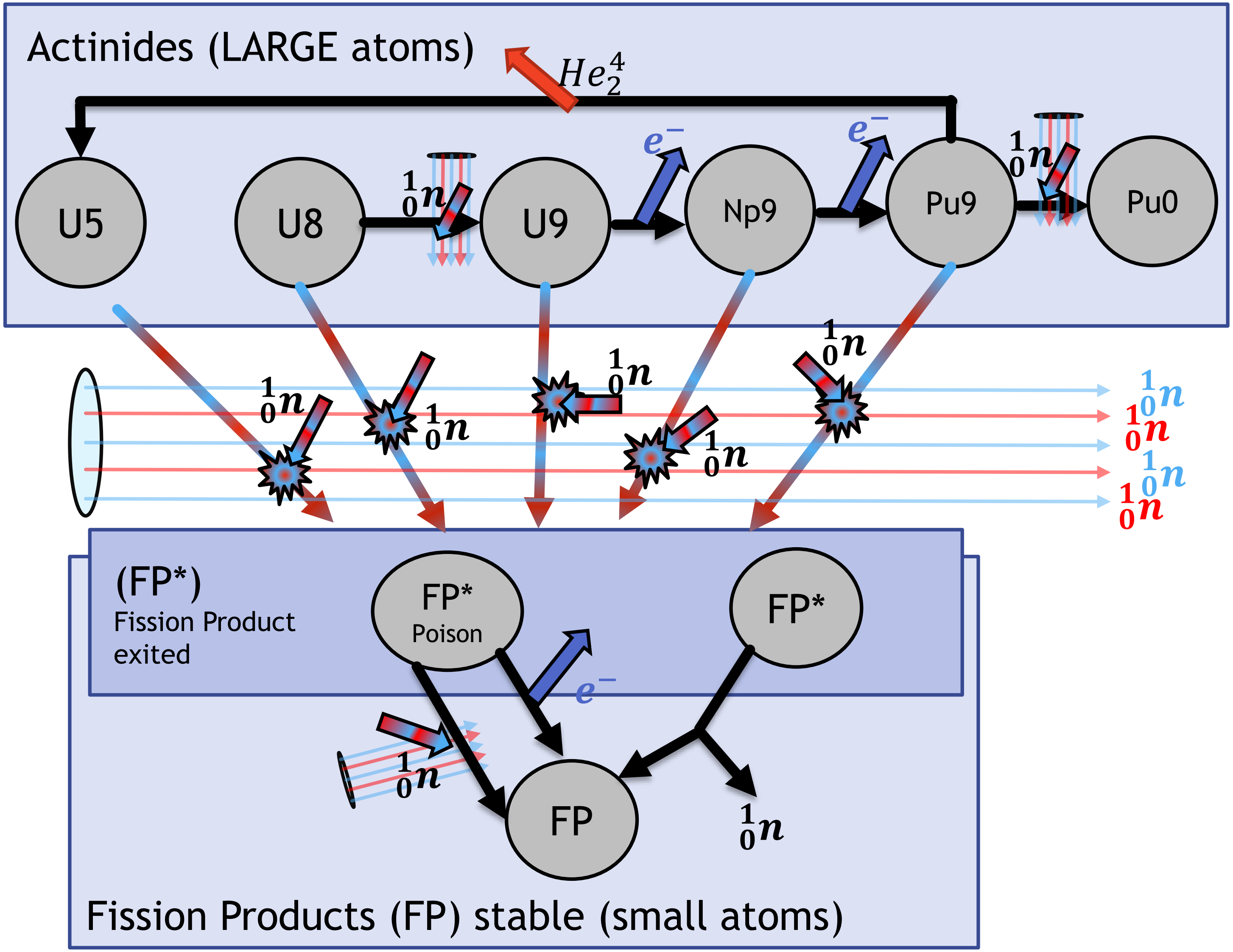

Legend	
	Neutron flux
${}_0^1n$ ${}_0^1n$	Fast thermal neutron
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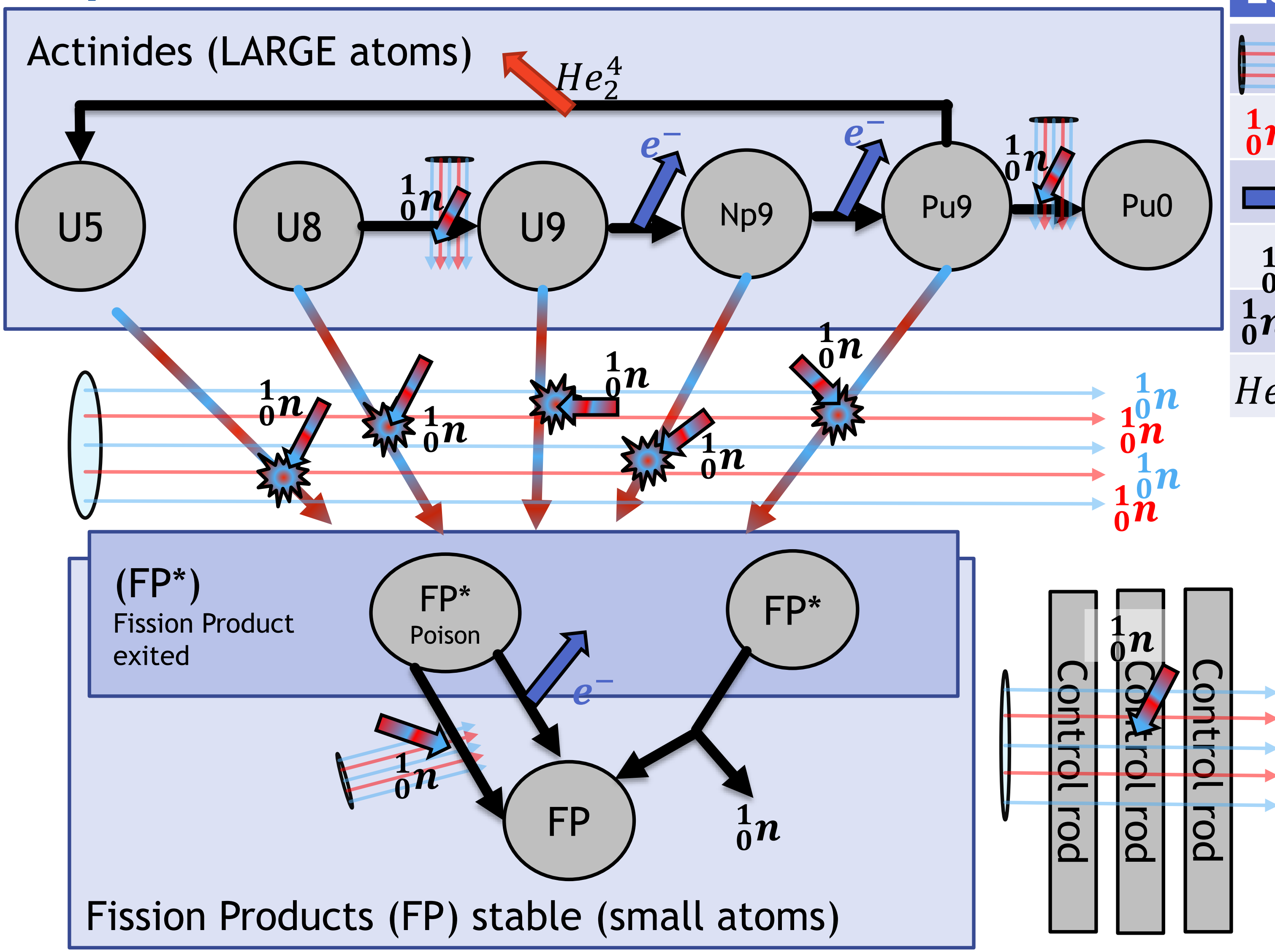

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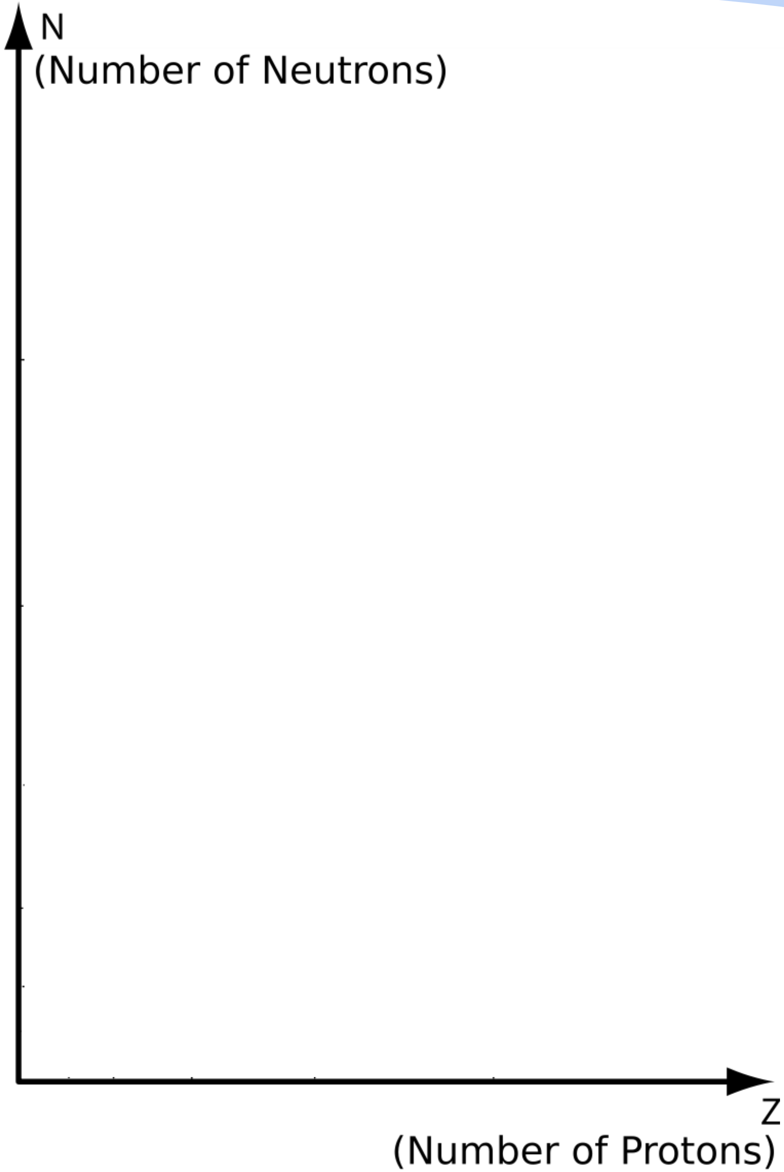
^1_0n	Fast or thermal fission
He_2^4	Alpha ray

	Assumption
1	Only these atoms
2	Only these reactions
3	No retarded neutrons from LARGE atoms
4	Infinite reactor (no leaks, or leaks included in Control rods)

What do you need?

→ Atoms caracteristics:

- Decay
- Cross sections
  - Fissions
  - Capture



Source : https://en.wikipedia.org/wiki/Stable_nuclide

UCLouvain
iMMC

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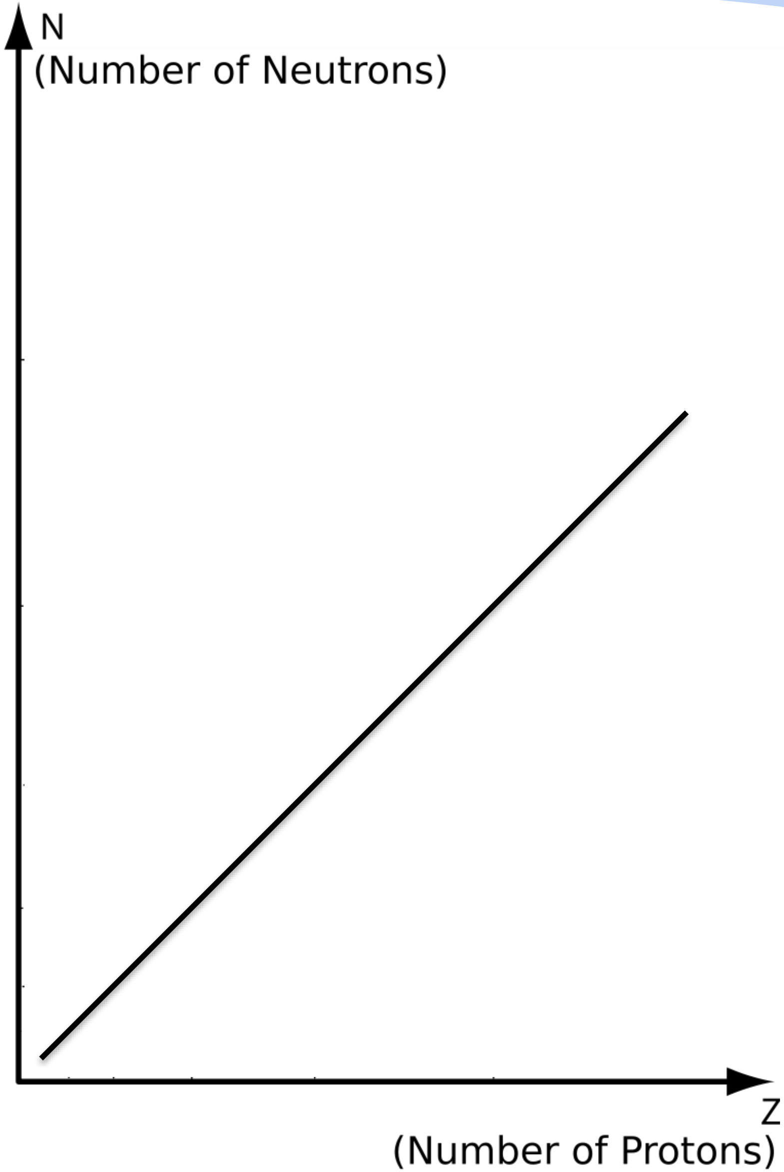

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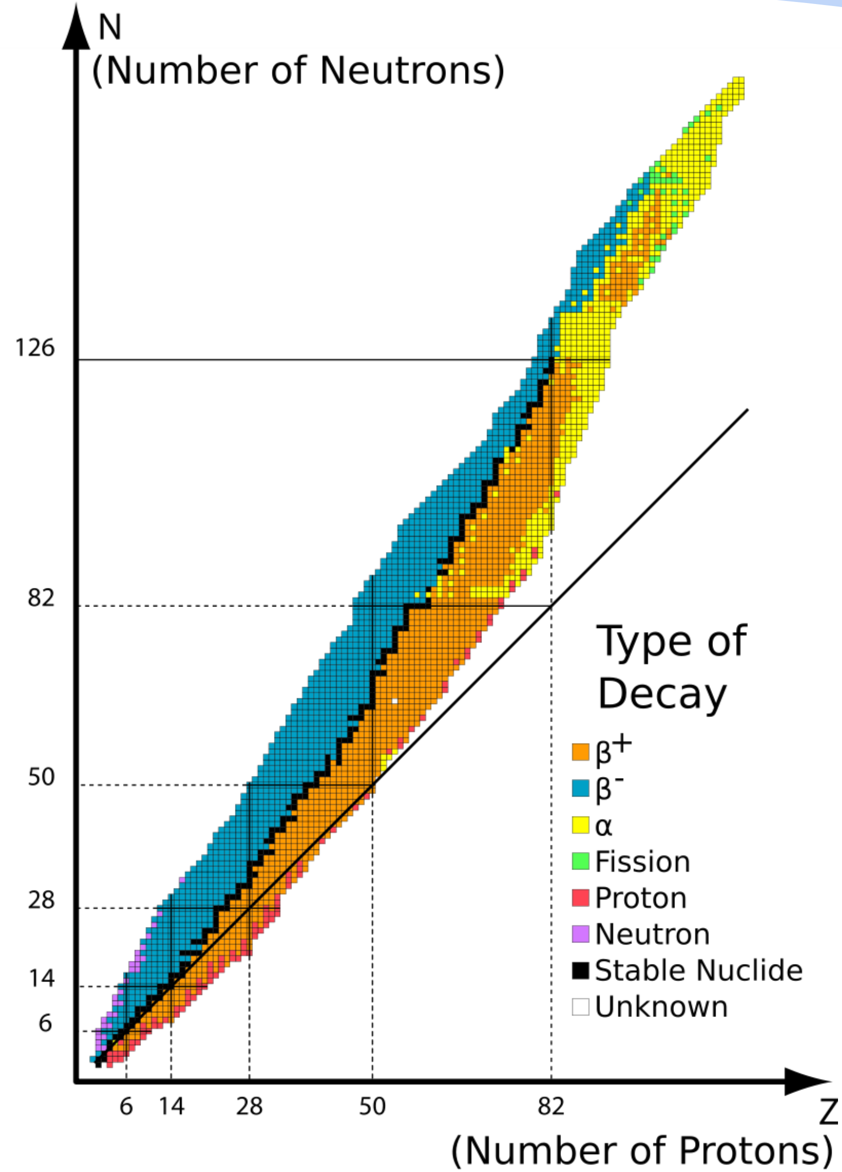

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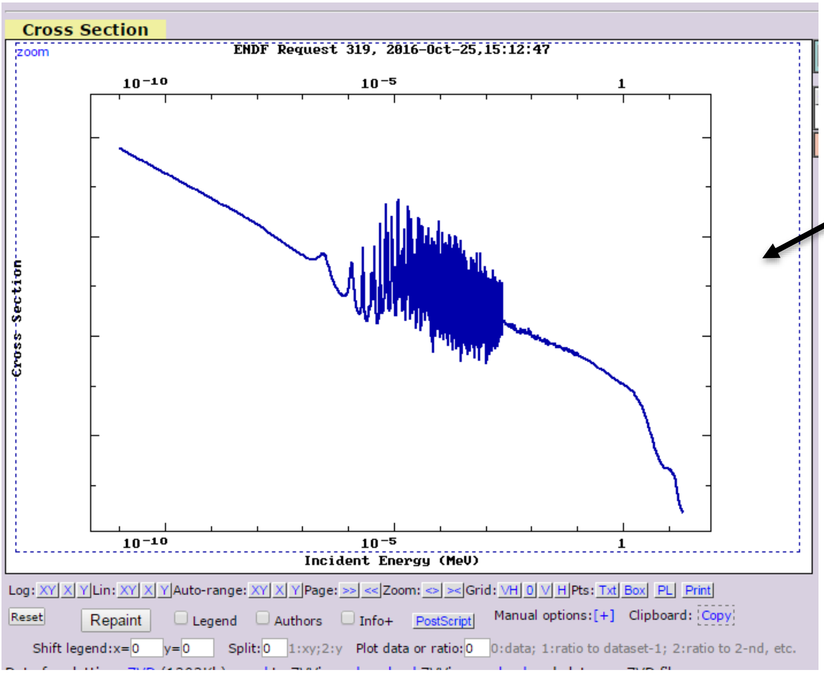
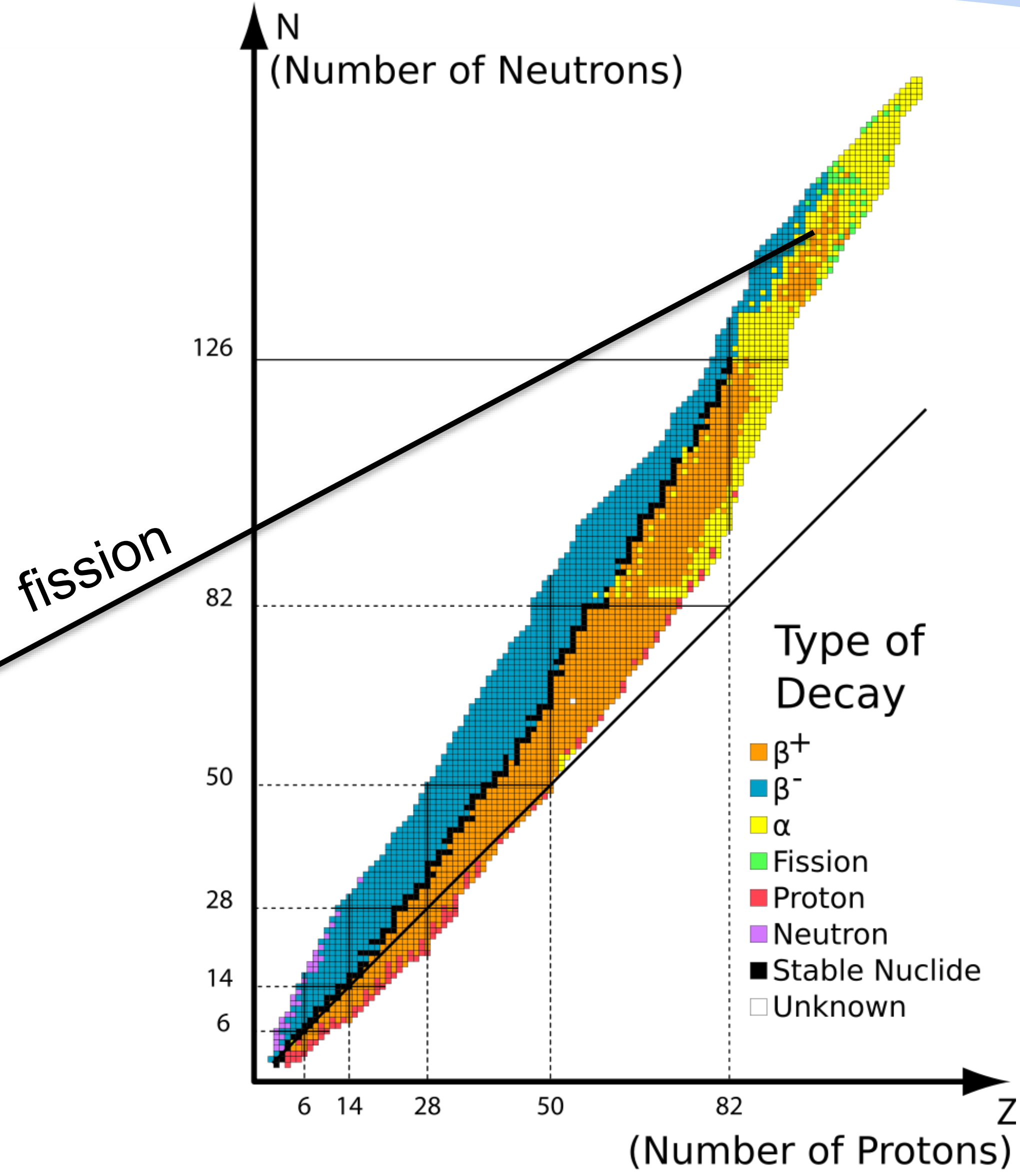


Source : https://www-nds.iaea.org/exfor/endf.htm



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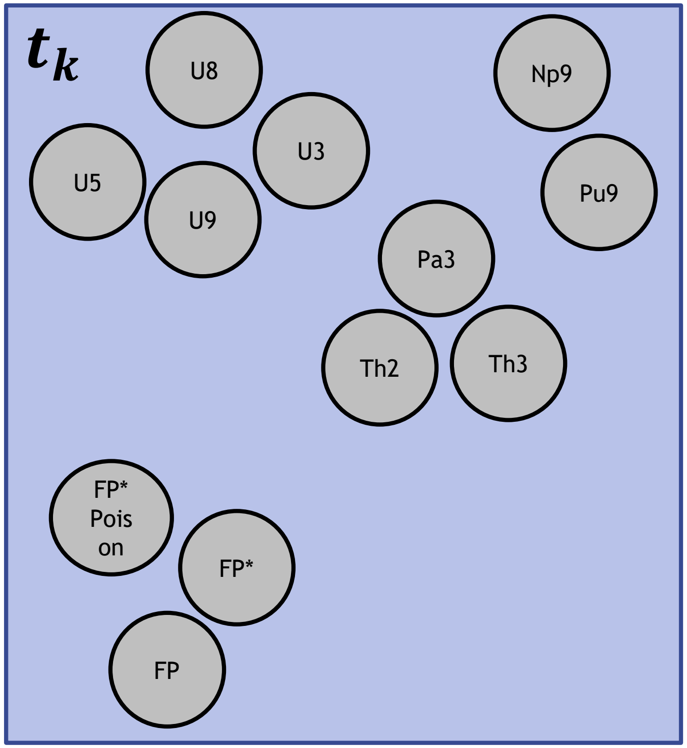
Help : Kinetic

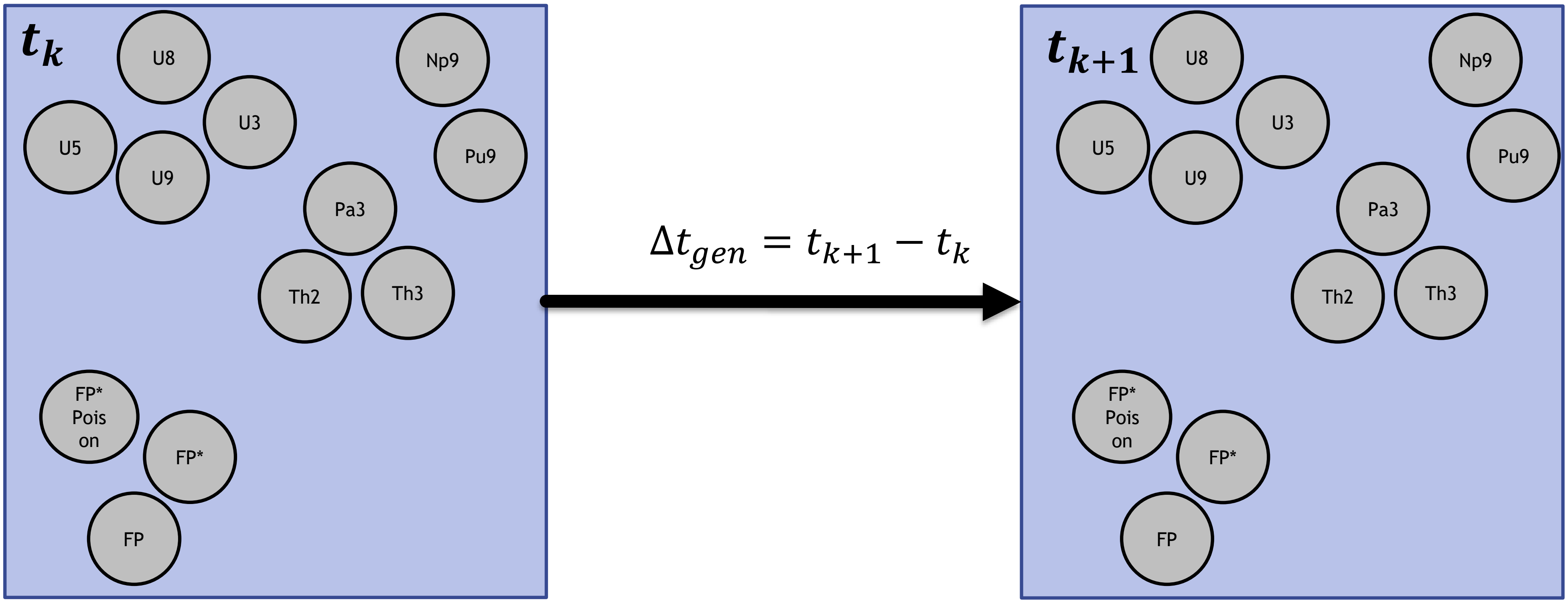
➔ **Reaction (given before)**



Help : Kinetic

➔ Reaction (given before)

- Time generation assumption : $\Delta t_{gen} = 10^{-4}[s]$



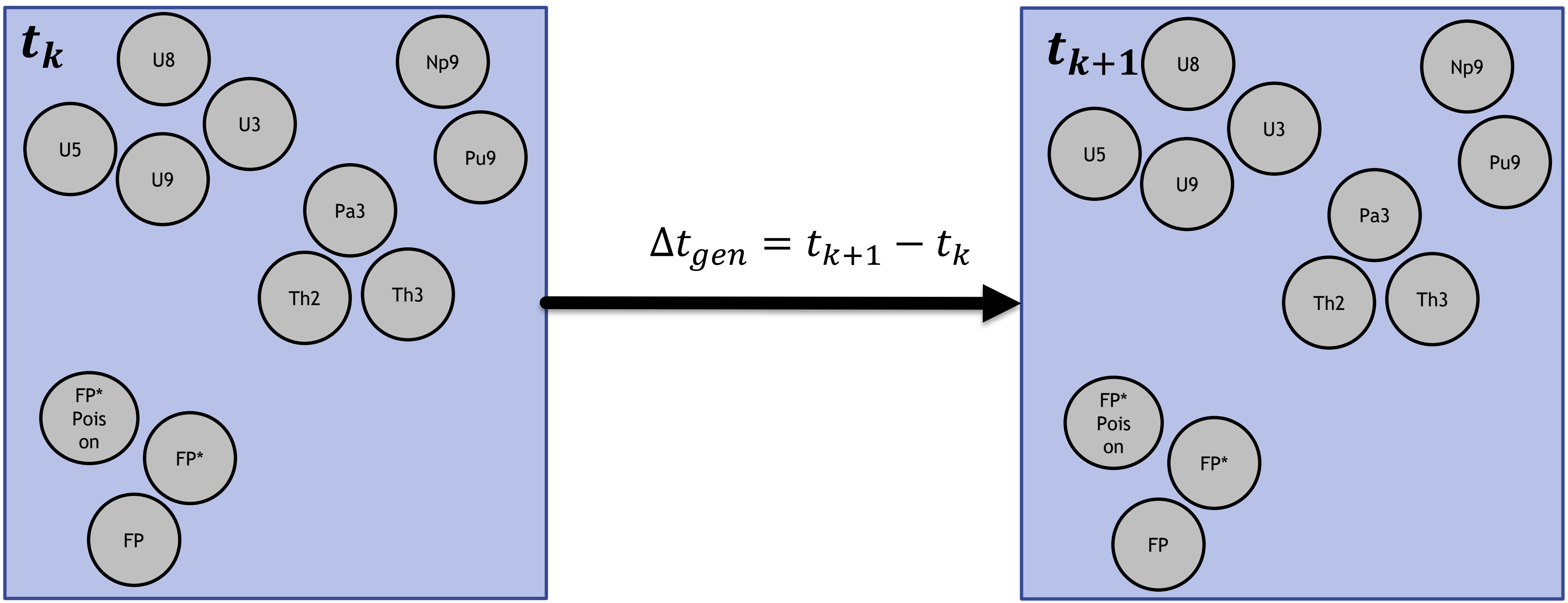
Help : Kinetic

➔ Reaction (given before)

- Time generation assumption : $\Delta t_{gen} = 10^{-4}[s]$

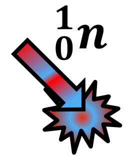
Assumption to give an intuitive understanding.

(normally you integrate the EDO with different time steps)

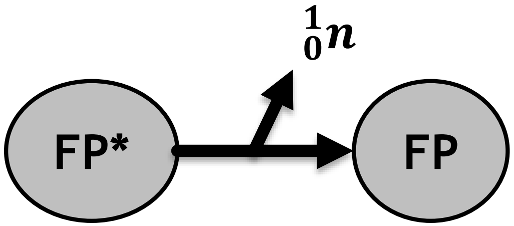


Help : Power

→ Assumption : 3 sources of energy :



- power released by fission : 200MeV
- power released by stabilization (FP*->FP +1n +E). E=5MeV
- power released by neutron fast to thermal



Help : Matlab structure

Main function

Reactor_model.py:

```
def Reactor_model (Percentage,t_final=10.0,n_th_init=10e15 ,n_fa_init=0.0 ,mTot=25,Poisson_pourc=0.0):
    # Authors: Gauthier Limpens, Antoine Metsue
    # REACTOR_MODEL modelise a nuclear reactor behavior in varying time.
    #      Based on the input arguments defining starting state (fuel,
    #      neutronic flows) and time of modelisation. The model computes and
    #      plots the evolutions of species in the reactor. Moreover, Power is
    #      estimated at each time. The reactor is targeting 3GW of power
    #      (similar to European PWR).
    #
    # INPUTS :
    # t_final   [s]      : time of the simulation. 1s of simulation takes around 2s of
    #                      modelisation = > small times (5 minutes max)
    # n_th_init [neutron]: number of thermal neutron at the first iteration (ex
    #                      10^10)
    # n_fa_init [neutron]: number of fast neutron at the first iteration (ex 0)
    # mTot      [kg]     : total number of kg of fuel at the initial state (ex
    #                      100kg). Unfortunately we can not do 25t : -  /
    # Percentage [%]     : structure containing the initial molar fractions of the following species:
    #                      Percentage.U235 : Percentage of U235  in fuel (ex : 3 )
    #                      Percentage.U238 : Percentage of U238  in fuel (ex : 97)
    #                      Percentage.Pu239 : Percentage of Pu239  in fuel (ex : 0 )
    #                      Percentage.Th232 : Percentage of Th232  in fuel (ex : 0 )
    # Pu9_pour  [%]      : Percentage of Pu239 in fuel (ex : 0 )
    # Poisson_pourc [%]  : Fraction of fission product which are poisons (ex : 5)
    #
    # OUPUTS :
    # Lambda_BC_thermal [] : Value of thermal control rod to reach criticity
    # Lambda_BC_fast    [] : Value of thermal control rod to reach criticity
    # U5_burning_rate   [] :
```

Auxiliary functions

Demi_vie.py: decay

```
def Demi_vie(X,Transfo):
    #FROM : http://wwwndc.jaea.go.jp/NuC/
    # Plus précisement : http://wwwndc.jaea.go.jp/CN14/index.html
    # Input
    #   [X] :
    #        Thorium      : 'Th232', 'Th233'
    #        Protactinium : 'Pa233'
    #        Uranium      : 'U233', ' 'U235' , 'U238' , 'U239'
    #        Neptunium    : 'Np239', 'Pu239'
    #        Xenon        : 'Xe135'
    #   [Transfo] : Alpha, BetaMinus or BetaPlus
    # Output
    #   [demi_vie] : half-life expressed in seconds
    #
    # WARNING : version 1.0_2016/10/20. Only BetaMinus has been implemented for
    # U239, Np239 and Xe135
    #
    # Comment : Poisons will be assimilated to have the same behavior than Xe135
```

molar Mass.py: molar masses

```
def molarMass(X):
    # M=molarMass(X) return the molar mass of element X
    #
    # INPUT:
    # [X]:
    #        Thorium: 'Th232', 'Th233'
    #        Protactinium: 'Pa233'
    #        Uranium: 'U233', 'U235' , 'U238' , 'U239'
    # Neptunium: 'Np239', 'Pu239'
    # Xenon: 'Xe135'
    # Neutron: 'n'
    #
    # OUTPUT:
    # M: Molar mass[kg / mol]
    # FROM: http: // wwwndc.jaea.go.jp / NuC /
```

Section efficace.py : cross section based on ENDF

```
def Section_efficace(X='Th232',Transfo='Fission',E_neutron=np.logspace(-5,6,10000).tolist(), display=False):
    # Section_efficace [barn]  Section efficace d'une transformation pour 1 composant
    #   [SIGMA] = Section_efficace(X,TRANSFO,E_neutron) donne la section
    #   efficace SIGMA de la transformation TRANSFO de l'element chimique X
    #   lorsque le neutron incident a une énergie de E_neutron
    #
    #   X : Espèce chimique.
    #       ATTENTION : ici on travail avec un nombre limité d'espèces
    #       chimiques
    #
    #   TRANSFO : seules les transformations ci dessous sont utilisées :
    #       Fission : Probabilité qu'un noyau absorbe un neutron et fissionne
    #       Capture : Probabilité qu'un noyau absorbe un neutron et fissionne
    #
    #   E_neutron : energie du neutron incident. Peut etre un vecteur
    #       ATTENTION : On suppose une energie comprise entre 1e-5 et 2e7 [eV]
    #
    #   Path : Adress of the data base
    #
    #   ETAPES : etapes intermédiaires pour construire la data base :
    #       1°) Construction d'une data base pour les elements Ux et Np9 et Pu9
    ... Ux peuvent soit fissioner soit capturer jusqu'à U9. Puis U9 à
    ...9 peuvent soit fissionner soit beta -. Pu peut juste fissioner

    ...S : fichier viennent de
    ...//www-nds.iaea.org/exfor/endf.htm
    ... la base ENDF qui a généralement été utilisé
```

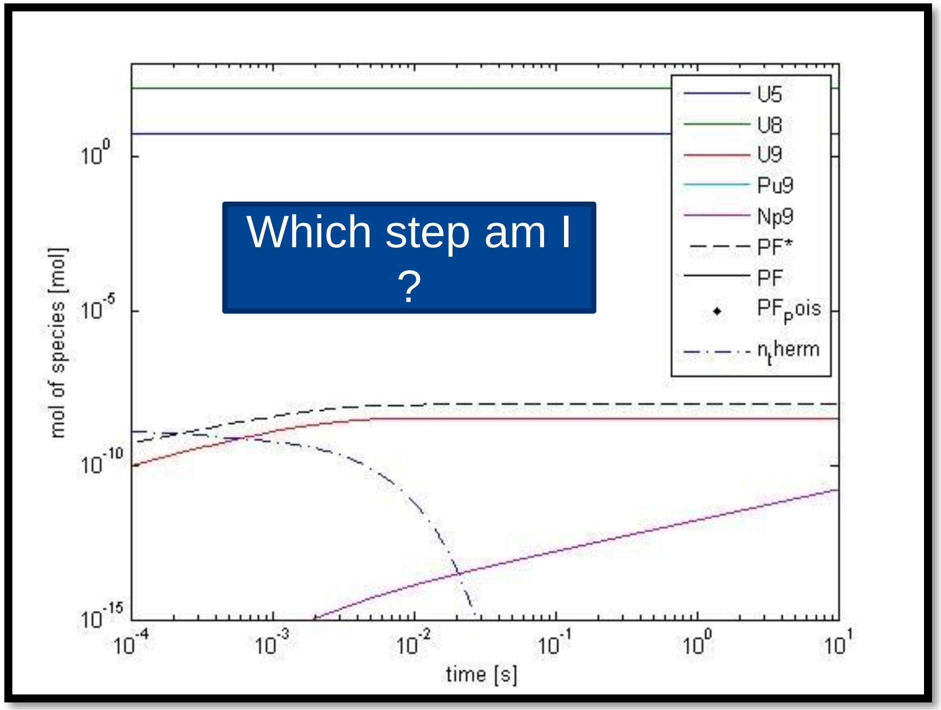
Help : intermediate steps

➔ Proposition of intermediate steps implementation

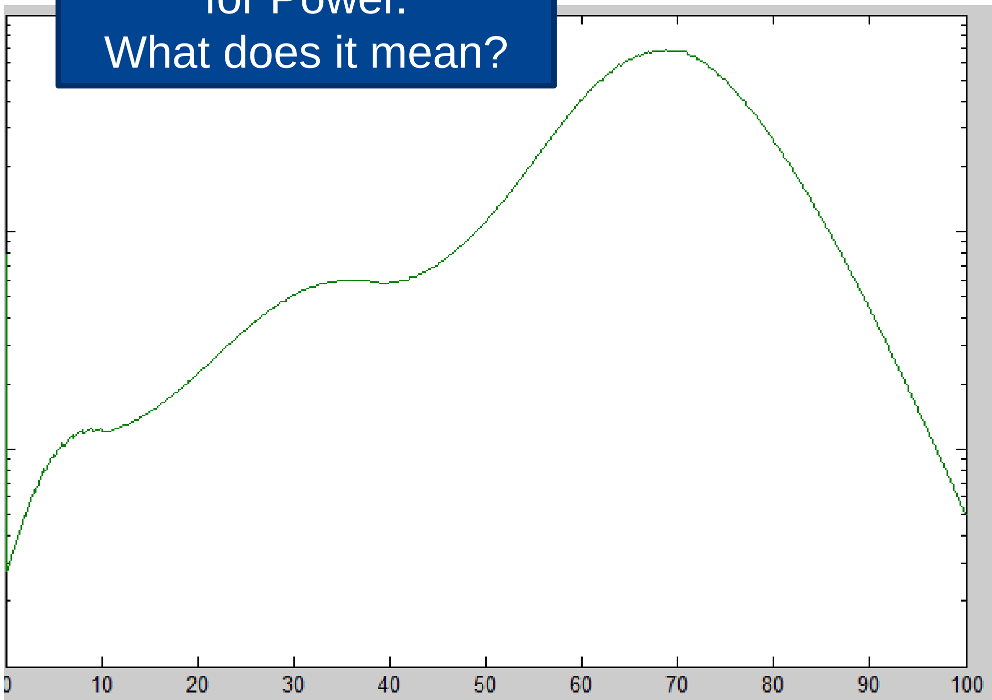
1. Create auxiliary functions (Molar mass, half life, cross sections)
2. Thermal reactions with constant neutron flow. No poison.
3. Add variable prompt neutron flow
4. Add variable delayed neutron flow
5. Add fast neutron which can slow down
6. Add fast reactions
7. Add control rod (at fixed value)
8. Add Poisons
9. Add control rod (variable value <-> Power)
10. Add Thorium cycles, is it relevant?
11. Improvement : how to significatively improve the project (remove assumption/ add content…)

Help : Illustrations

➔ What is this?



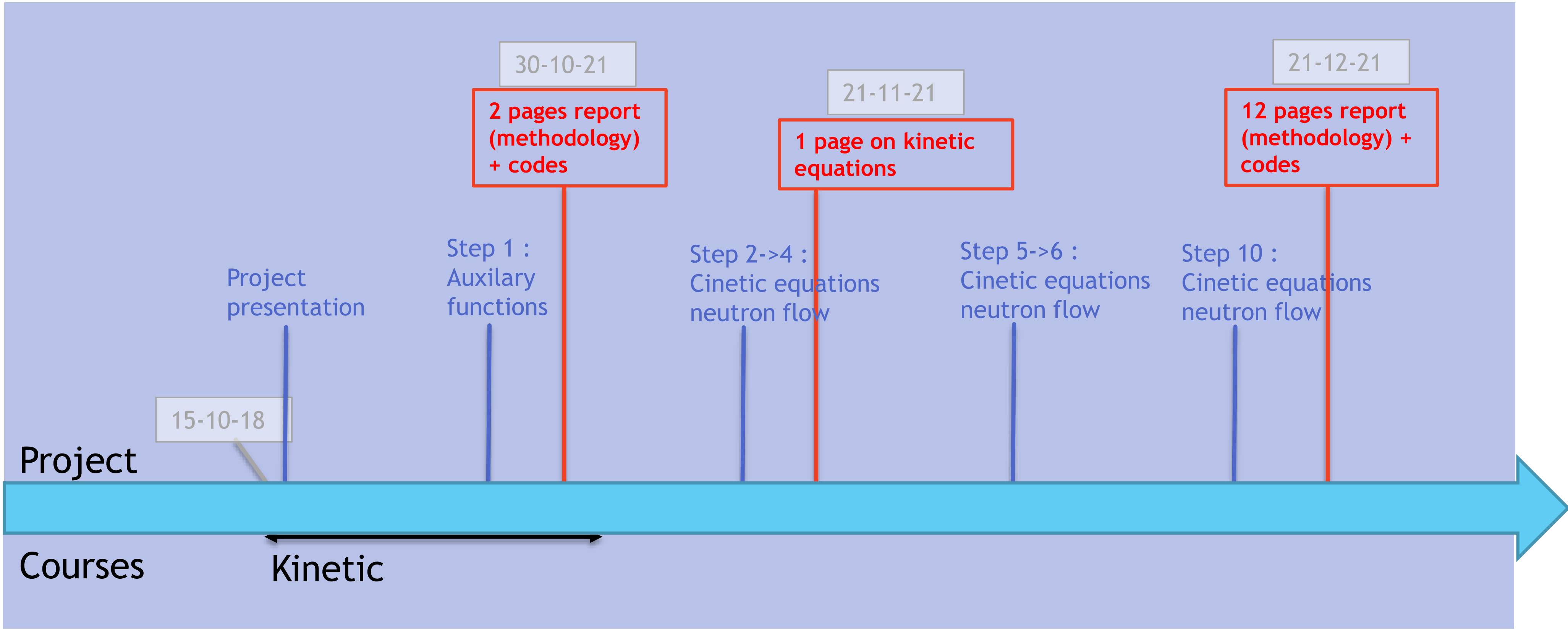
Example of final result for Power.
What does it mean?



Help : Time line

➔ Time line:

- For any question, ask an appointment (antoine.laterre@uclouvain.be & Gauthier.limpens@uclouvain.be)



Evaluation

➔ Evaluation (to be confirmed):

- Code : 20%
- Report : 50%
- Oral : 30%

➔ Report informations (10 pages) :

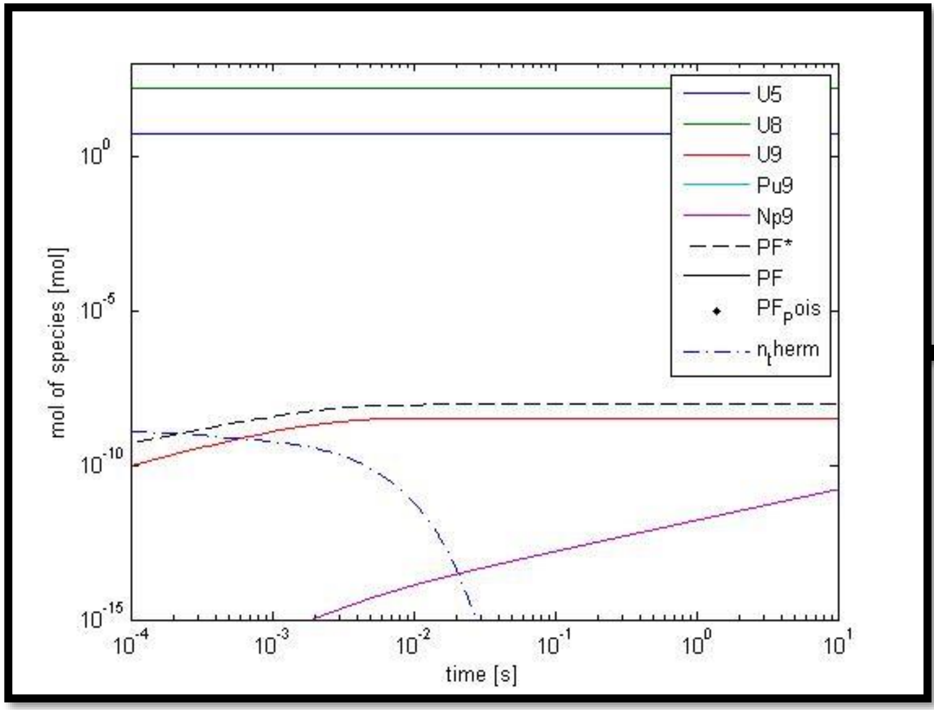
- 2 pages : Methodology how did you get cross sections, half-lifes and molar masses.
- 8-10 pages :
  - 3 pages : methodology :
    - 2 page additional work
    - 1 page equations
  - 4 pages : analyse of the results + parametric studies (behavior, exception…)
  - 1 page : Significative improvement + analysis (free topic)

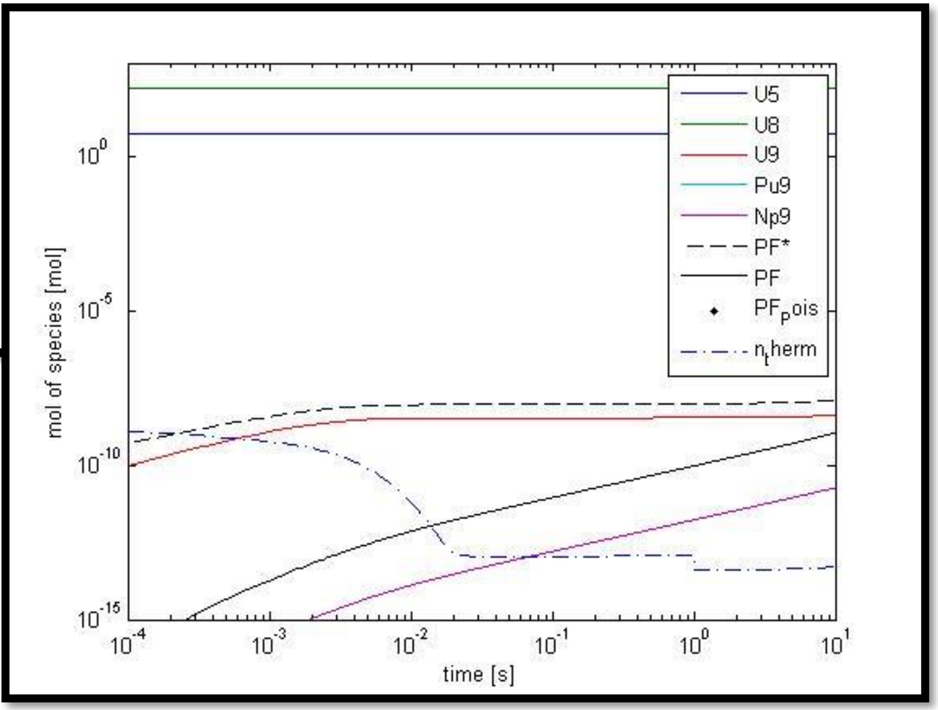
Help : Another illustration

➔ Example of results :

- Between with and without prompt neutrons :

$$\boxed{T_{\frac{1}{2}} = 1[s]: PF^* \rightarrow PF + {}^{1}_{0}n}$$





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i. Is a wrong simplification. However, it gives a correct intuitive approach of what happends in nuclear reactor with a short computational time.

Help : Input values (1/2)

→ Useful value for the set up :

- Assumptions. These assumptions are wrong but unavoidable to do this project.
  i. 1 n retarded per fission product (normally it is around 0.03%, without this value, the reactor is impossible to control)
  ii. Half life of 1s for an excited fission product. (Approximately right)
  iii. Core volume : 10m³ (approximately right for a nuclear reactor core)
  iv. Half time for fast neutron to become thermal : $5 \cdot 10^{-4}$[s] (approximately right)
  v. A Fission produces 2 Fission products (including poisons) and 2 neutrons.
  vi. Prompt neutrons can be taken at 1 MeV.

Due to the previous hypothesis, the critical mass must be changed. 25 kg works.

Reactor set up

1. Thermal reactions with constant neutron flow. No poison.
   1. Thermal/fast neutrons at (t=0) = 10^10 and 0 [n].
   2. mTot = 25 kg (instead of 25 tons) (3% U235 + 97% U238). A higher mass gives an uncontrollable reactor (critical mass is overtaken).
2. Add variable prompt neutron flow
   1. 1 fission gives 2 neutrons. Make a balance for neutrons
   2. Neutrons flow can be computed at t_k
3. Add variable delayed neutron flow
   1. PF* -> PF+ 1n (with half life 1[s]). We assume that the delayed neutron is a rapid neutron here.
      Make a balance on PF
4. Add fast neutron which can slow down :
   1. Neutrons from fission are fast neutrons with a half life : 5e-4 [s]

Reactor set up

5. Add fast reactions
6. Add control rod (at fixed value) (unavoidable to decrease the amount of neutrons in the reactor)
    1. Leaks can be implemented in the control rod term. The overall term can be represented by a variation such as : $\frac{d[n]}{dt} = \cdots - \lambda_{BC}[n]$, where λ_{BC} depends on the position of the rod and the vessel geometry.
    2. Values for $\lambda_{BC}^{r} \in [100; 2000]$ and $\lambda_{BC}^{th} \in [20;\ 100]$
7. Add Poisons
    1. 5% of PF* are poisons
    2. Dissociate PF* and PF*_poisons.
    3. Add poisons relations
8. Add control rod (variable value <-> Power)
    1. They can move by 5% per second.

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Studies

1. Basic analysis:
    a. How the species evolve over time?
    b. Which reactions are negligeable? (=> simplify the model)
    c. How does the control rods behave over time?

2. Advanced studies:
    a. What does the poisons impact the cycle? What happened after a short shut down?
    b. How many times can we re-use MOx?

3. Improvments

Studies (improvment)

➔ **Enjoy!!!**

- Ideas of extra studies :
  - Fast reactor
  - Tchernobyl accident
  - Realistic nuclear start
  - Step starts
  - Thorium cycle (identify the critical mass)
  - …