# Séminaire SCM Paris 16 mai 2024

# The Zoo of SMRs

**G.B. Bruna**

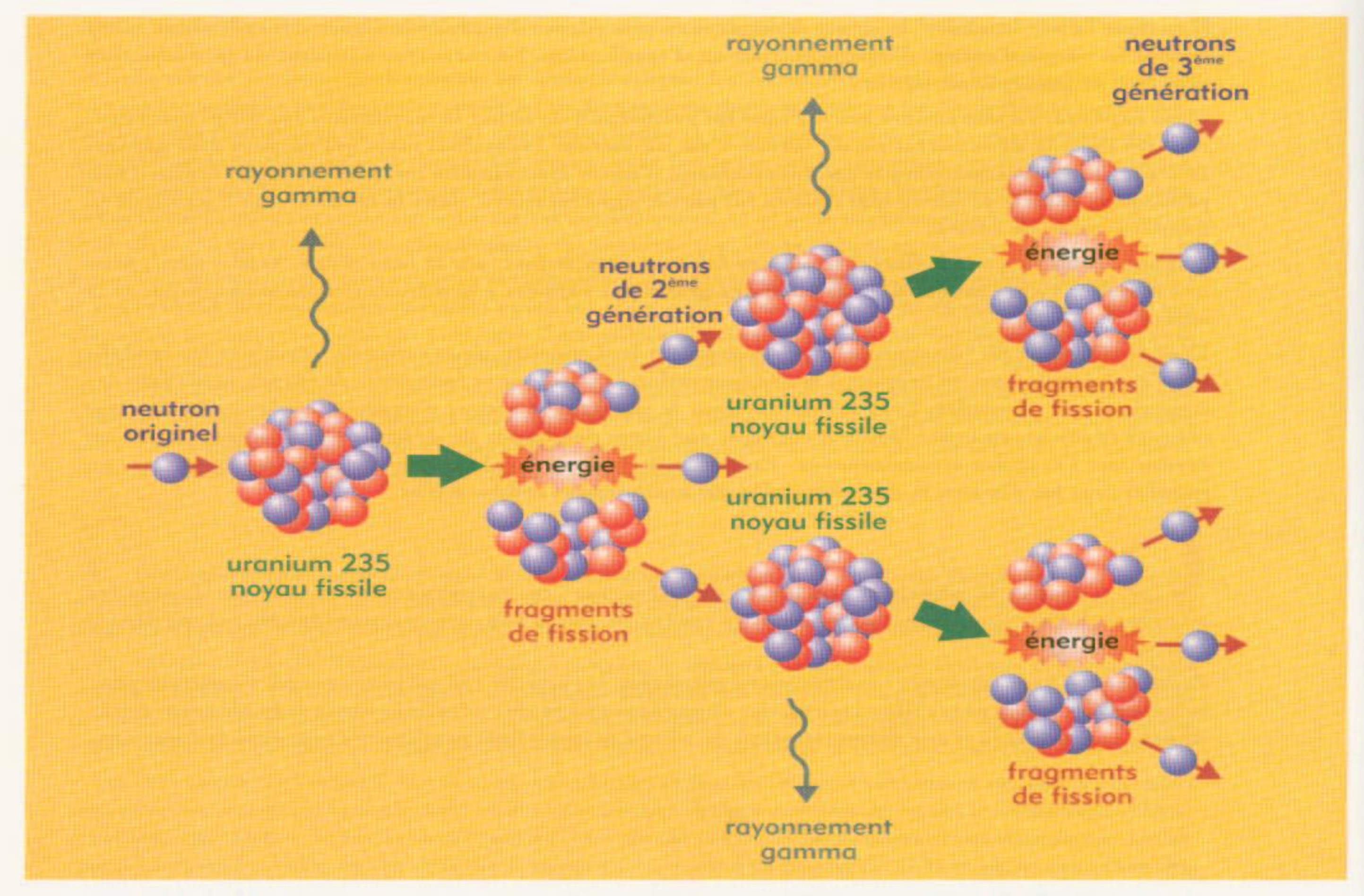
# Elements on Reactor Physics

## What neutrons in a Reactor System do ?

- Leak the system
- Interact with matter:
  - Generally, they are either scattered (either in an elastic or an inelastic way),
  - Or absorbed by the nuclei engendering, that way, a radioactive decay process,
  - But some specific heavy nuclei (called *fissiles* ) after a neutron capture can undergo a different process called Nuclear Fission
  - Nuclear Fission is most likely to occur either with high-energy neutrons (fast neutrons), or with neutrons in thermal equilibrium with the matter (thermal neutrons)

# Elements on Reactor Physics

- **The Nuclear Fission & the Chain Reaction**



# Elements on Reactor Physics

- The Nuclear Fission: Energy, but not only …

- A Nuclear Fission produces:

- About 200 Mev Energy (about 3*10-$^{11}$ Joule),

- In the average 2,5 secondary neutrons, that enables, under some specific circumstances, to establish and maintain the Chain Reaction,

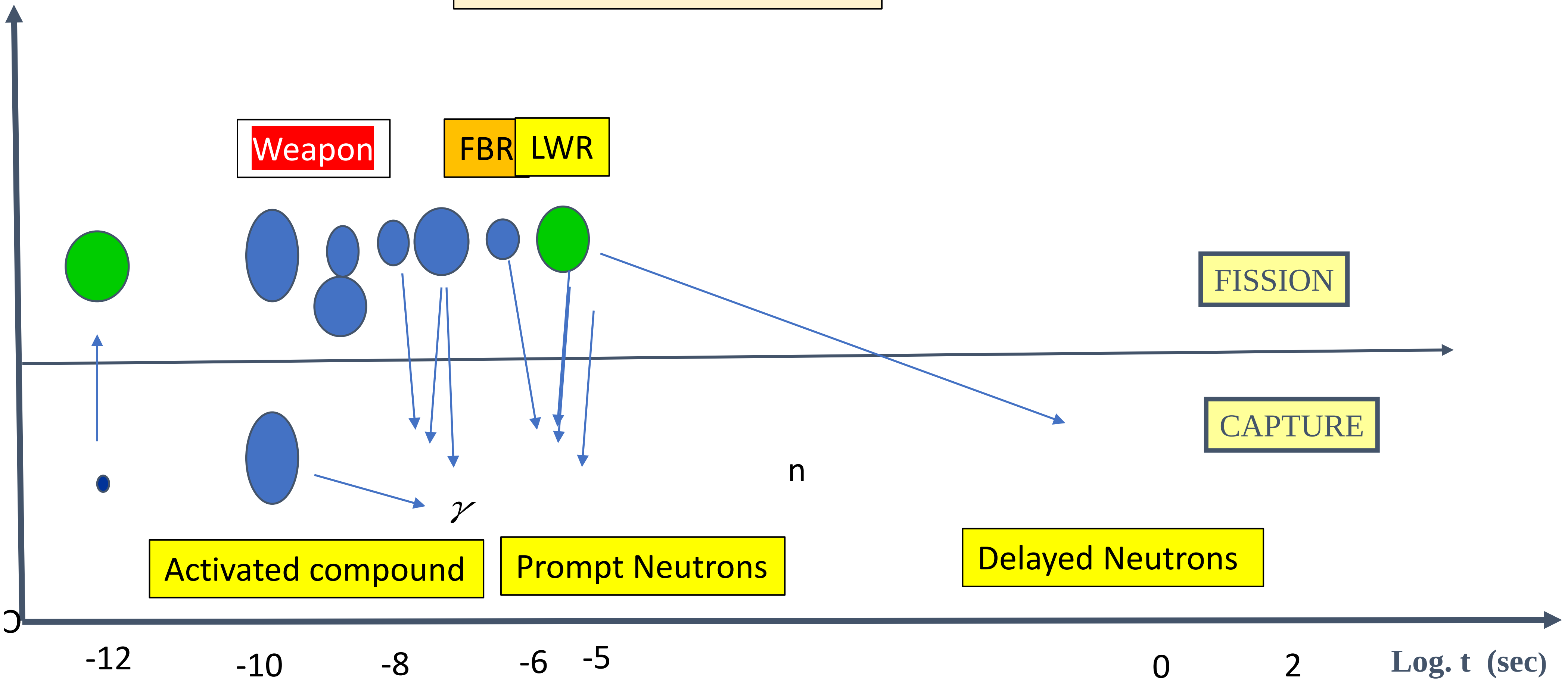
- 2 FP (Fission Products) (in an excited state - very radioactive -)

*(1 eV – electronvolt equals 1.6×10-$^{19}$ Joule)

# Elements of Reactor Physics

- **Event**

## The time scale



Weapon

FBR

LWR

FISSION

CAPTURE

n

$\gamma$

Activated compound

Prompt Neutrons

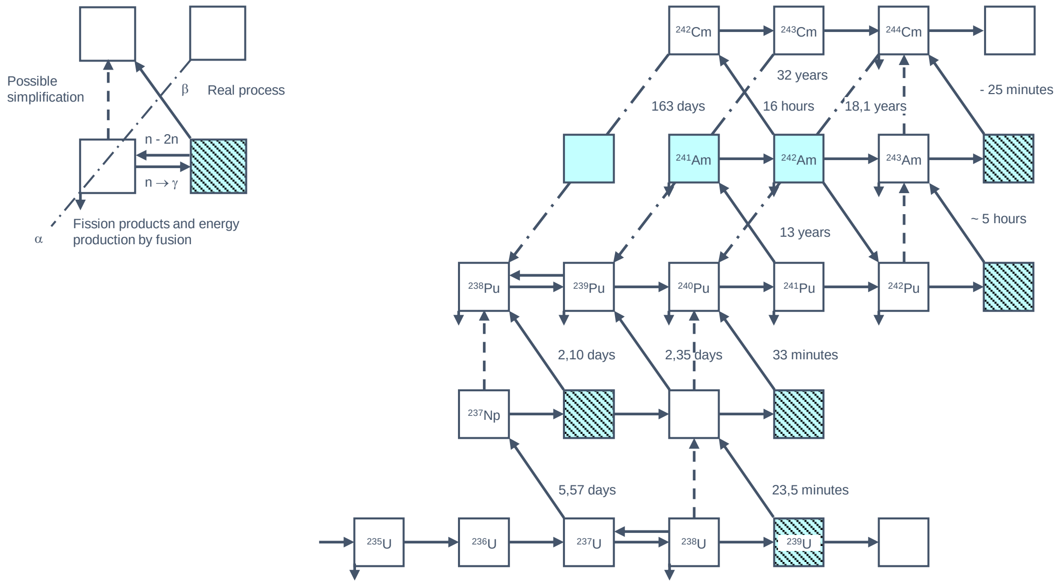
Delayed Neutrons

-12 -10 -8 -6 -5 0 2 **Log. t (sec)**

# Elements on Reactor Physics

- **Fuel Depletion – Conversion vs. Breeding**

  The Actinide Chain



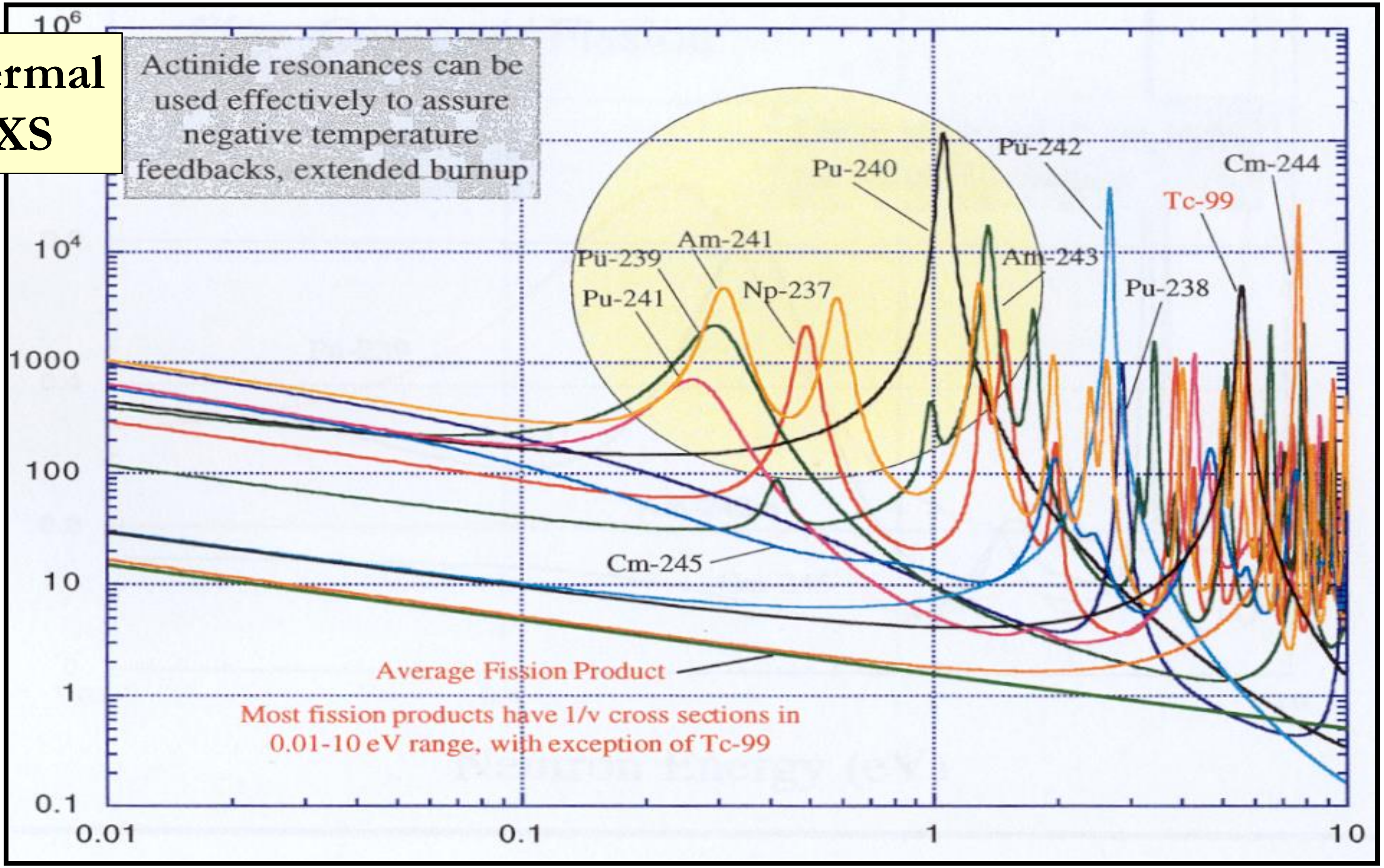
# Elements on Reactor Physics

## Interaction of neutrons with matter

- **The capacity of neutrons to interact with the matter depends on their energy and the reactor fuel, through the XS (Cross Sections).**
- **The XS are strongly dependent on the Isotopes.**
- **The XS are evaluated experimentally and tabulated in Data Files (ENDFB / JEFF …).**

# Elements on Reactor Physics

**Actinides Thermal Absorption XS**



Actinide resonances can be used effectively to assure negative temperature feedbacks, extended burnup

Average Fission Product

Most fission products have 1/v cross sections in 0.01-10 eV range, with exception of Tc-99

# Elements on Reactor Physics

**Total & Fission U235 XS**

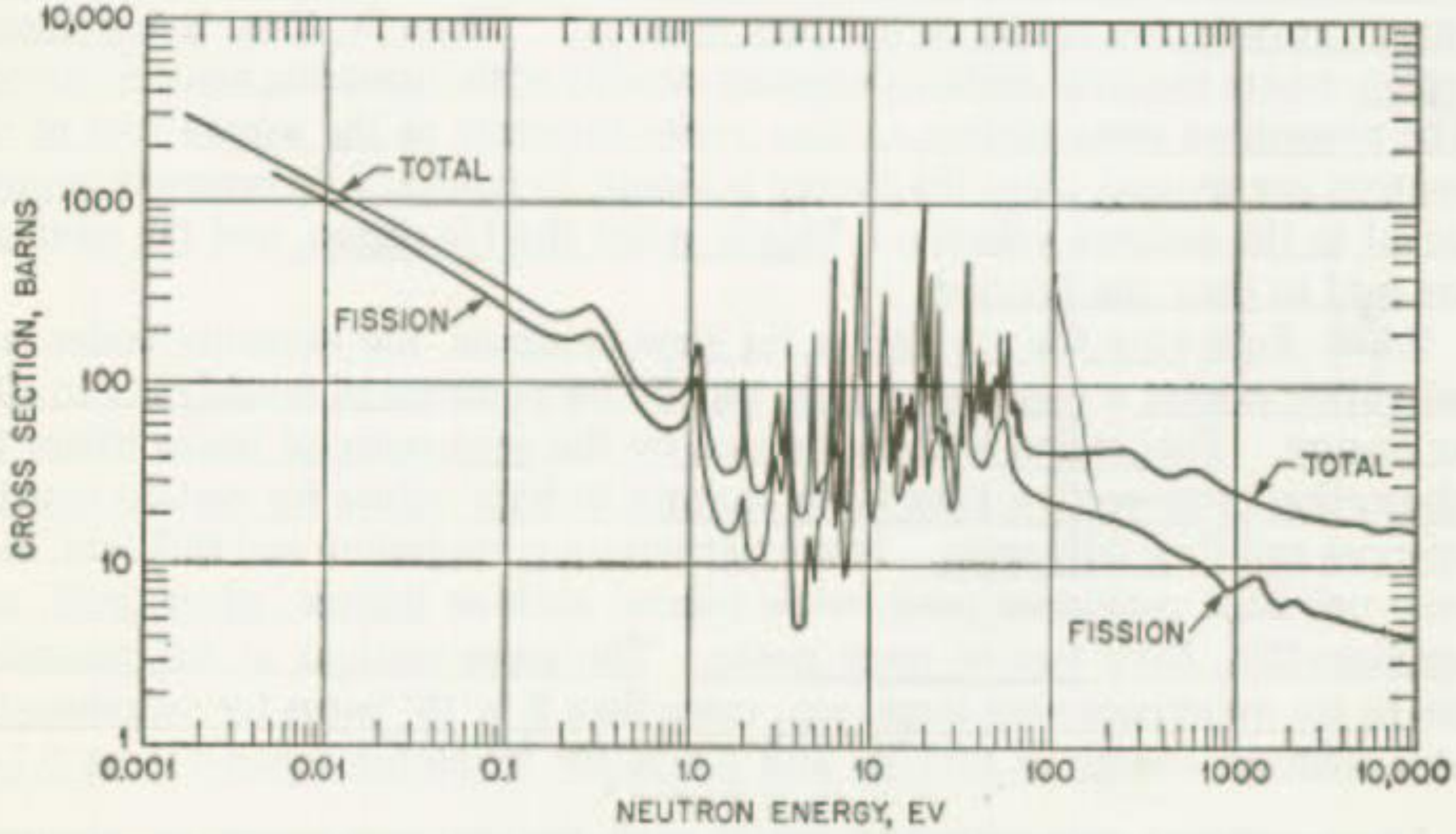


FIG. 2.19. Total and fission cross sections of uranium-235 as function of neutron energy

# Elements on Reactor Physics

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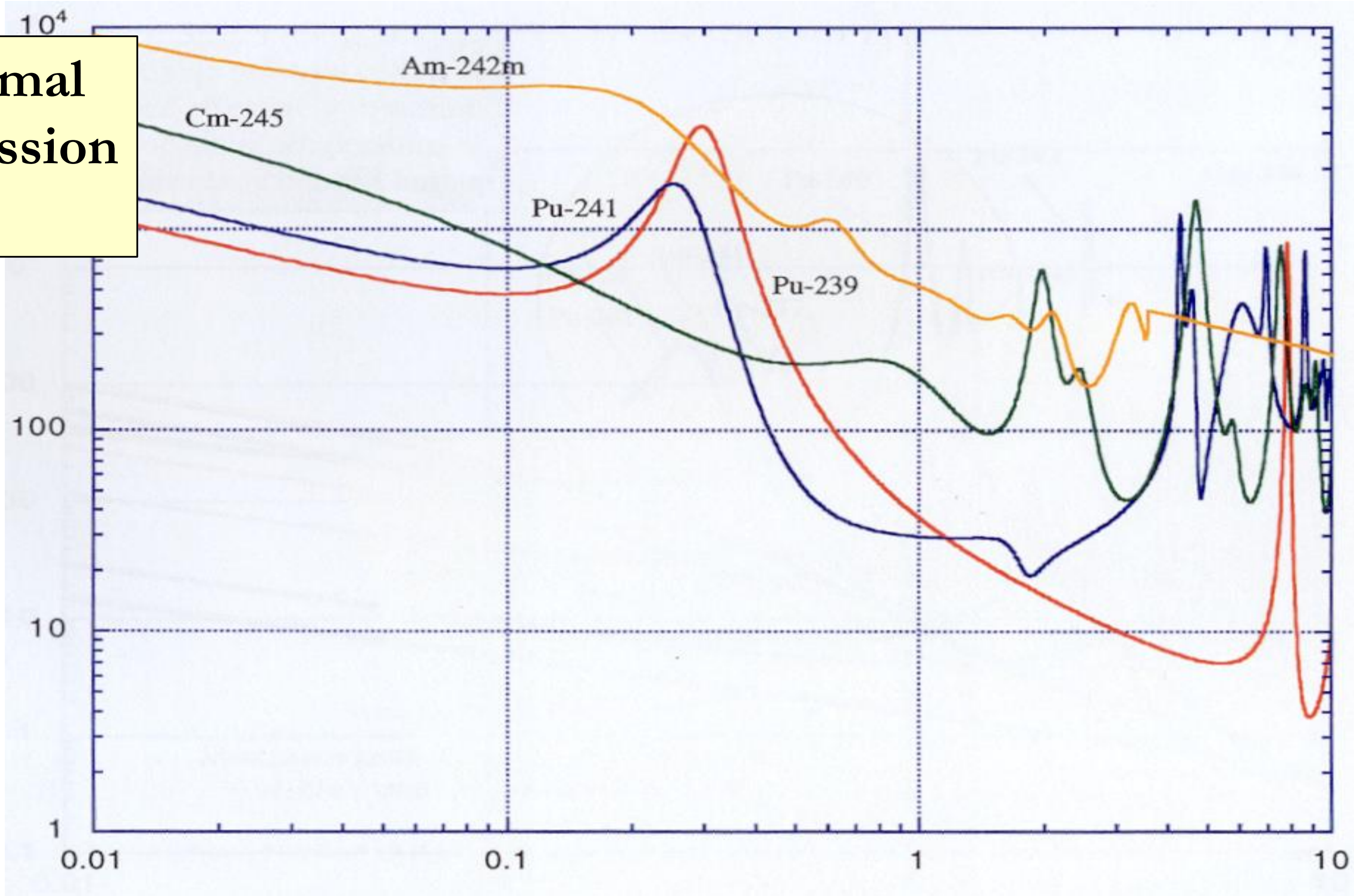
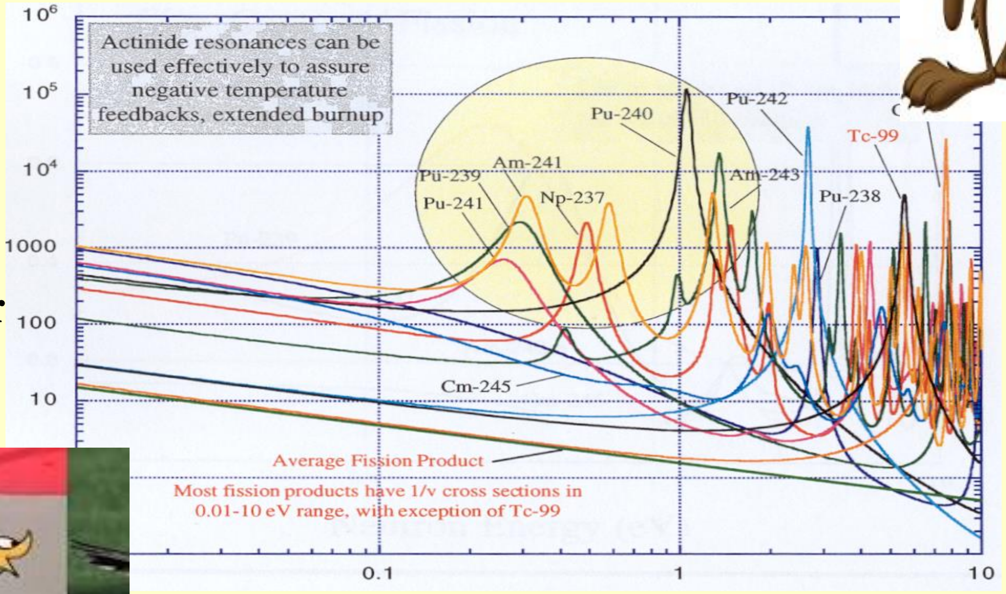
**Actinides Thermal & pi-thermal Fission XS**



# Elements of Reactor Physics

- **The Neutron Density**
- The Cross Sections
- The Fission
- The Slowing Down of Neutrons / the Moderator



Actinide resonances can be used effectively to assure negative temperature feedbacks, extended burnup

Most fission products have 1/v cross sections in 0.01-10 eV range, with exception of Tc-99

- **The Chain Reaction**

# Elements on Reactor Physics

## The Critical Mass & the Chain Reaction

- The capacity of a nuclear system to entertain the nuclear reaction depends on:
  - The fuel mass, the dimensions and shape: the Critical Mass
  - The secondary neutrons are born with a very high energy (about 200 Mev)
  - In the so-called Thermal Reactors, the neutron energy is reduced to support the fission likelihood:
    - The *moderator*
    - And the *slowing down* process

# Elements on Reactor Physics

- The neutrons within a Nuclear Reactor

- An extremely scarce commodity

  - Speed of neutrons in thermal equilibrium with the matter: 2200 m/sec,

  - Average speed of the neutrons in a Nuclear Reactor: about $10^{+6}$ m/sec,

  - Average neutron flux: $10^{+19}$n/m$^2$.sec

  - The average neutron density within a reactor core is in the range of $10^{+13}$n/m$^3$

# Elements on Reactor Physics

- **Neutron Balance Equation** of a multiplying system at time t:

$$H(t)\Phi(t)=S(t)$$

$$H(t)=\left[A(t)+\frac{F(t)}{k_{eff}(t)}\right]$$

$$S(t)=S_E(t)+\beta_{eff}\left[\Phi(t)-\Phi(t-\Delta t)\right]+\Theta\frac{1}{v}\frac{\delta\Phi}{\delta t}(t)$$

# Elements on Reactor Physics

- **The Reactor kinetics**
- The:
    - Migration Area
    - Prompt Neutron Lifetime
- **The Feed-back Effects**
    - The Doppler Effect
    - The Power and Temperature Effect
- Prompt and Delayed Neutrons
- The Prompt-criticality and the RIA [Reactivity Initiated Accidents]

# Elements on Reactor Physics

- **The Reactivity**

- **The Boltzmann Operator**
- **The Boltzmann Equation**
- **The Chain Reaction**

- The Reactivity Swing: the Burn-up,
- The *Bateman Equations* and the Build-up of the Fission Products and MA

# Elements of Reactor Physics

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## Other Accidents

Accidents initiated by

- Default of Cooling Capacity (**Default of Cooling Function**)
  - Loss of Ultimate Heat Sink
  - Loss of Electricity Supply
  - …
- Leg and Steam Line Breaks
- Default of Containment (Failures) (**Default of Containment Function**)
- **Human & Organizational Originated Accidents**
- **External Hazards**
- The DA, the other Postulated Occurrences
- The *DiD*
- The *Risk Informed Approach*

# The Zoo of SMRs

- **Innovation in the nuclear sector plays a critical role in reducing greenhouse gas emissions. This role contributes to increasing the public acceptance of nuclear power.**
- Even though the large Gen III/III+ reactors are being successfully deployed, demonstrating their reliability and safety, their development - which requires long and thorough preparation and considerable human effort, and challenge financial resources - remains a big deal. Also, their GW-scale capacity and large size may be an impediment for use in small grids or in locations to which transportation of the large components may be either difficult or impossible.
- In this context, **Small Modular Reactors (SMRs) could shape the future of nuclear industry, with the potential to provide energy without greenhouse gas emissions for a wide range of applications**, from grid-scale electricity through heat for industrial and domestic applications, the production of hydrogen to decarbonize industrial sectors and heavy transport, to provide access to nuclear power to countries with small grids and to remote communities.

# The Zoo of SMRs

- **The family of SMRs includes an exceptionally large diversity of concept designs;**
- **Each of them presents specific safety advantages with respect to conventional large power reactors;**
- **These advantages are tightly connected and depend on the physical features, design, and operation options of the system;**
- As typical examples, it is worth mentioning, e.g.:
  - **the exclusion of large breaks in LW-SMR (Light Water SMR),**
  - **the potential for higher thermal inertia** and the inherent safety features of the HT-SMR (High Temperature SMR),
  - **the exclusion of fuel fusion and the inherent safety** associated to the salt expansion of the MS-SMR (Molten Salt SMR), in both its versions, the fast and the thermal one.

# The Zoo of SMRs

- High inherent safety, favorable design and operational characteristics, compactness and modularity allowing for a high level of standardization, enhanced capacity to face external aggression and hazards, potential resistance to proliferation, reduced investment per unit : **all these features will allow SMRs to effectively contribute and positively solve the present-day challenges of nuclear power,** including its wider public acceptance and the acknowledgement of its key role on the path to net zero carbon emissions.
- However, **the SMRs promise must be evaluated with lucidity and rigor.** This is true for their safety demonstration, the importance of which cannot be overstated.
- Moreover, **global harmonization and coordination of licensing approaches is indispensable for SMRs large-scale deployment**.

# Where do the SMRs come from ?

- **The Main SMRs Families**

- **The first SMR ever**
- **The LWR SMRs**
- **The ADS SMRs**
- **The GIF's Family SMRs**
- **Others**

# The First SMR ever

- **The Nuclear Submarine**

# The first SMR ever

**The Nuclear engine vs. the Conventional one**

- The Process : Nuclear Fission vs. Combustion,
- The Fuel (U, Pu, MA vs. Wood, Crude, Coal…),
- The Comburent (The Neutrons vs. Oxygen)

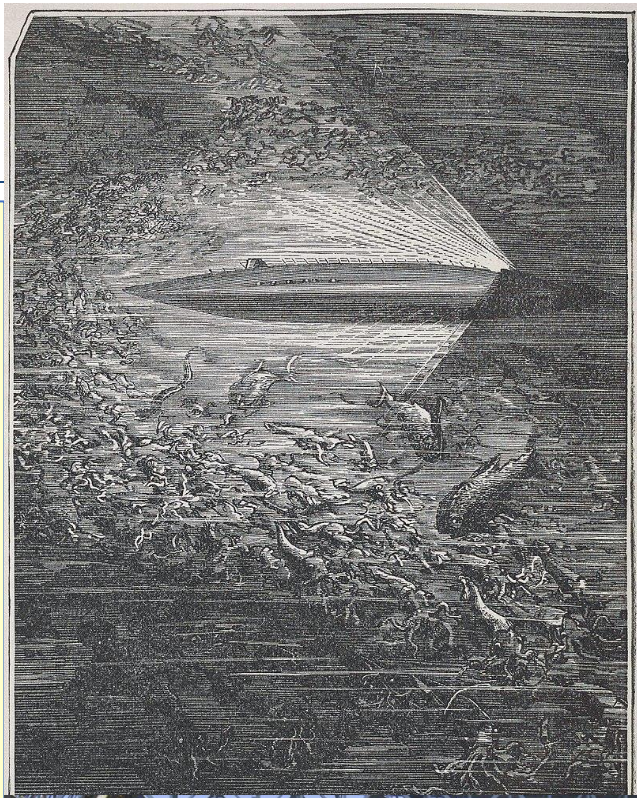
# The first SMR ever

Construction of the world's first nuclear-powered submarine was made possible by the successful development of a nuclear propulsion plant by a group of scientists and engineers in the United States at the Naval Reactors Branch of the Bureau of Ships and the Atomic Energy Commission.

**In July 1951**, the U.S. Congress authorized construction of the first nuclear-powered submarine, *Nautilus*, **a LWR (Light Water Reactor) concept**, under the leadership of Captain Hyman G. Rickover, USN (sharing a name with Captain Nemo's fictional submarine ***Nautilus*** in **Jules Verne's** ***Twenty Thousand Leagues Under the Sea***.

# The first SMR ever

- **The submarine**: **Jules Vernes's** *Twenty Thousand Leagues Under the Sea* and ***The Nautilus.***
  - The keel of the ***Nautilus*** designed by the US Admiral Rickover's Team was installed in June 1952, **the submarine got wet on January 21, 1954,** first ever nuclear nuclear-powered attack submarine.
  - On **February 4, 1957**, the *Nautilus* reached its **60 000th marine mile of continuous operation undersea** (i.e., 111 120 km) that is equivalent to the **20 000 nautical leagues** foreseen by the French Writer and on **August 3 1958**, at 11 h 15, it became the first ever boat to cruise under the North Pole.



# The first SMR ever

- The Soviet Union soon followed the United States in developing nuclear-powered submarines. Stimulated by the U.S. development of ***Nautilus***, Soviets began working on nuclear propulsion reactors in the early 1950s at the Institute of Physics and Power Engineering, in Obninsk, under Anatoliy P. Alexandrov.
- **In 1956**, the first Soviet propulsion reactor designed by his team began operational testing.
- Meanwhile, a design team worked on the vessel that would house the reactor.

# The first SMR ever

- The reactor was constructed by placing a pair of experimental VT-1 nuclear reactors that used a **liquid-metal coolant** (lead-bismuth eutectic) into the modified hull of a Project 627A vessel.
- After overcoming many obstacles, including steam generation problems, radiation leaks, and other difficulties, the first soviet nuclear submarine based on these combined efforts, **K-3 *Leninskiy Komsomol*** of the Project 627 *Kit* class, called a November-class submarine by NATO, entered service in the **Soviet Navy in 1958**.

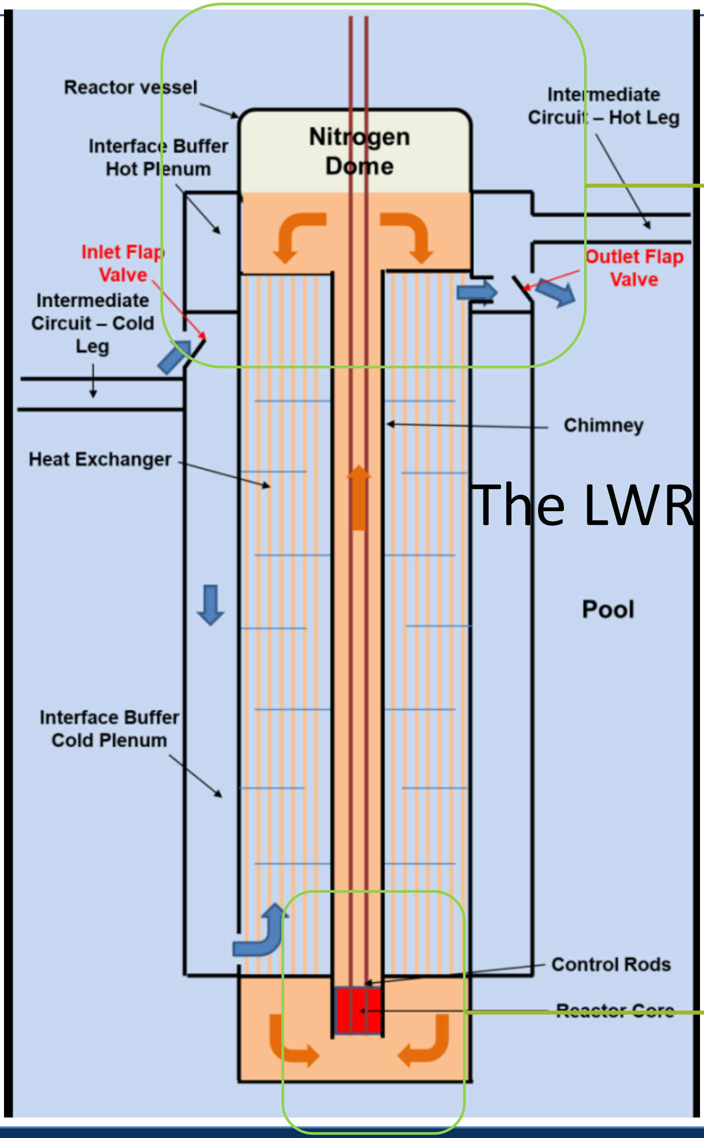
# The LWR SMRs

- **NEWARD**
- *« NUWARD™ est une centrale SMR de 340MWe comprenant deux réacteurs indépendants de 170MWe chacun, hébergés dans un bâtiment nucléaire unique permettant ainsi l'utilisation d'équipements mutualisés.*
- *NUWARD™ allie technologies éprouvées et innovation pour gagner en constructibilité, compétitivité opérationnelle et performance environnementale :*
- *Un réacteur à eau pressurisé de Génération III+* ***entièrement intégré****, satisfaisant aux normes de sûreté les plus élevées*
- *Un design centré sur* ***la standardisation, la construction modulaire et la simplicité*** *pour une production de masse en usine, flexible en phase de construction et d'exploitation, conforme aux standards de sûreté de l'Agence internationale de l'énergie atomique (IAEA) et de l'Association des autorités de sûreté nucléaire des pays d'Europe de l'Ouest (WENRA).*
- *Un design pensé pour favoriser* ***le suivi de charge*** *et* ***adapté aux usages non électrogènes***
- *Une solution* ***complémentaire aux énergies renouvelables*** *qui vise* ***le remplacement des centrales à charbon*** *autour de 300-400 MWe de puissance,* ***l'approvisionnement en électricité des communes isolées et des sites industriels énergivores****, ainsi que les réseaux aux capacités trop limitées pour les centrales électriques de forte puissance ».*
- **NUSCALE**

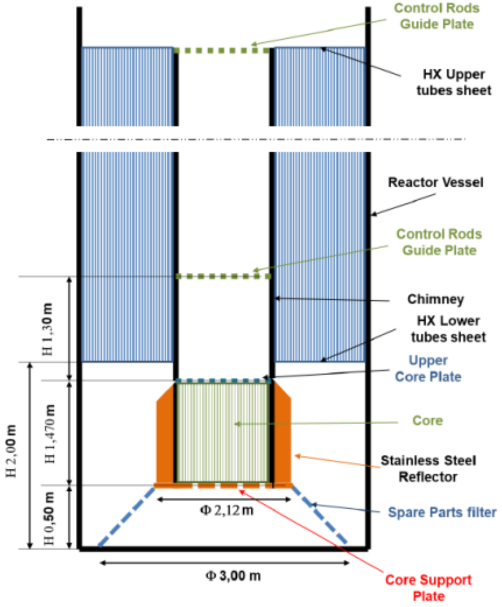
# The LWR SMRs

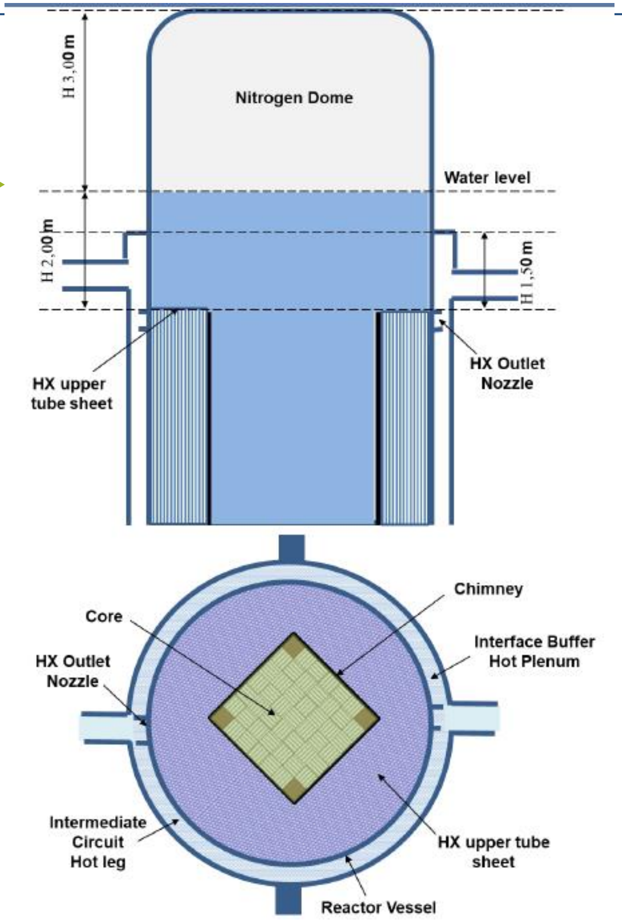
- **CALOGENA**
- *Réacteur SMR à eau d'une puissance de 30 MW thermiques, spécifiquement conçu pour décarboner le chauffage urbain.*
- *Son design simple et compact (le cœur mesure moins d'un mètre cube) permet aux systèmes et aux composants d'être assemblés en usine puis transportés vers son emplacement d'installation, ce qui rend sa construction plus courte et moins onéreuse que celle des grands réacteurs de puissance.*
- *La conception s'appuye sur des technologies maîtrisées et éprouvées depuis plusieurs dizaines d'années. Sa conception est dérivée des réacteurs de recherche de type piscine, en service dans le monde entier depuis des décennies.*
- *Le fonctionnement à basse pression (environ 5 bars, soit moins que la pression d'un chauffe-eau domestique) et basse température (autour de 100 °C), l'utilisation directe de la chaleur et le nombre très limité des systèmes auxiliaires rendent le concept intrinsèquement plus simple et plus sûr que tous les réacteurs actuellement en fonctionnement ou en projet*

# The LWR SMRs /CALOGENA



The LWR SMRs





# The ADS

- **The ADS : Accelerator Driven [Reactor] Systems**

- **GUNIEVRE**
- **MYRRA**

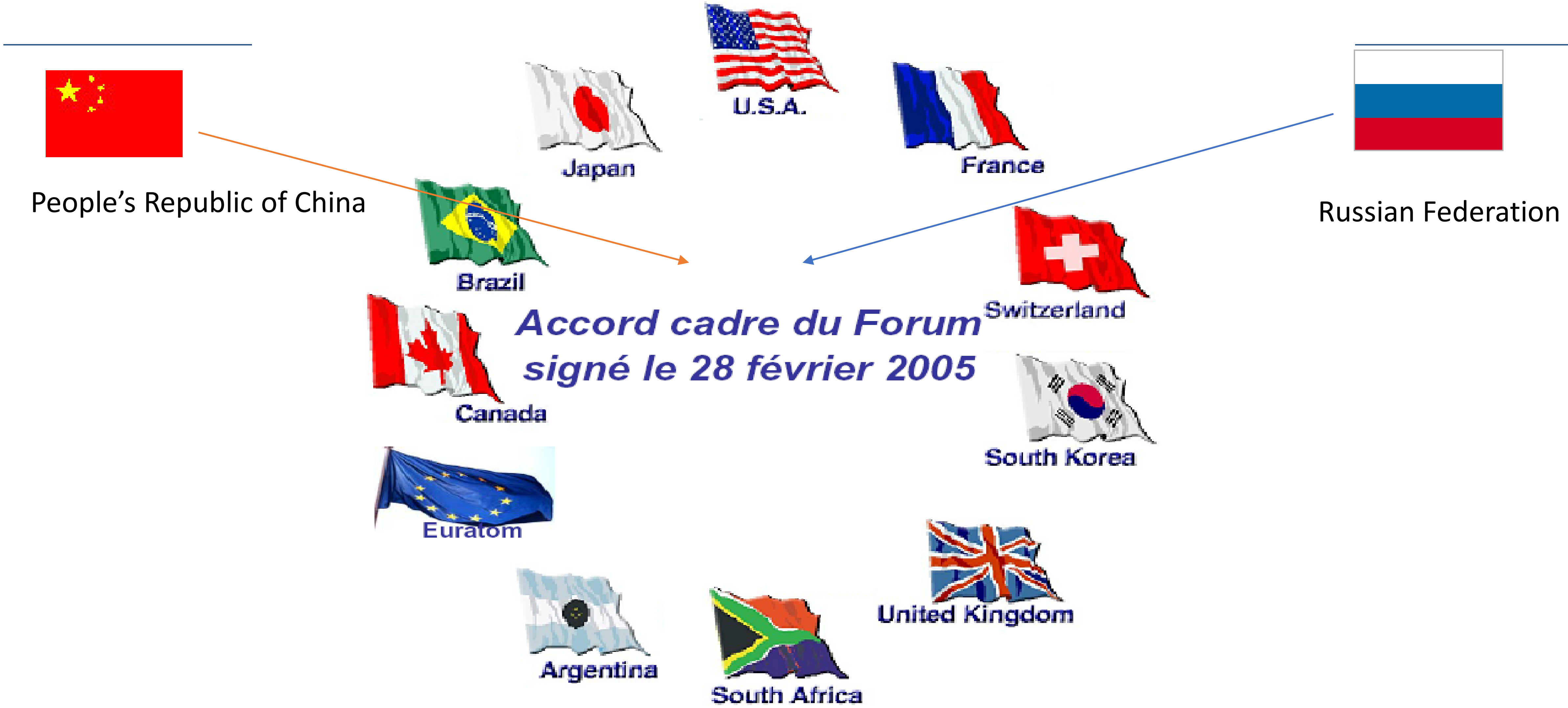
# The ADS-type SMRs

- **TRANSMUTEX**
- *« Le réacteur Transmutex, appelé « **TMX-START** » (Transmutex Subcritical Transmutation Accelerated Reactor with Thorium) est « sous-critique »: il n'y a pas de réaction en chaîne auto-entretenue. Si l'apport externe de neutrons cesse, la réaction s'arrête presque immédiatement: en 2ms selon Transmutex. On peut se demander comment un accident pourrait se produire dans ce contexte.*
- *Oui mais alors, d'où viennent les neutrons? C'est la partie ésotérique du projet: ils viennent d'un accélérateur de particules (un cyclotron de 800MeV – 5mA, de 40x60m, inspiré du projet MEGAPIE) ! Les protons approchant la vitesse de la lumière vont, en heurtant les cibles de métal placées à l'intérieur, produire des neutrons par « spallation ». Contrairement à ce qu'on peut croire, ce type d'équipement ne sont pas rares: il y aurait 30 000 accélérateurs de particules dans le monde, principalement à des fins médicales. En l'espèce, ce procédé est appelé « Accelerator Driven System » (ADS).*
- *Le **combustible** serait du thorium (fertile) qui se transformerait en uranium 233 (fissile) avant de fissionner. Les neutrons seraient « rapides » (et non lents ou thermiques), ce qui permet la transmutation et limiterait radicalement les déchets produits (de l'ordre de quelques kilos au lieu de tonnes) et d'une durée de vie plusieurs milliers de fois moindre. (source) Ils pourraient même transmuter et utiliser des atomes plus lourds, comme le plutonium, neptunium ou americium. Le caloporteur est un alliage de plomb-bismuth fondu. Le prix de l'énergie (LCOE) est estimé à moins de 70$/MWh* ».

# The GIF's family SMRs

- Lead  / Lead-Bismuth cooled (LFR) SMRs
- Sodium cooled (NFR) SMRs
- Molten Salt (MS) SMRs
- High temperature gaz cooled / Very high temperature gaz cooled (HTR – VHTR) SMRs
- Gaz cooled SMRs
- …

# THE GIF



People’s Republic of China

Russian Federation

# THE GIF

| | |
|---|---|
| *Economic competitiveness* | ➢ Competitiveness of the nuclear kWh cost, vs fossil energies |
| *Sustainability* | ➢ Increased reactor lifetime (over 60 years)<br>➢ Optimization of fissile material inventory<br>➢ Decrease of the waste volume and storage costs |
| *Safety* | ➢ Very low probability of severe damage of the core<br>➢ No need for off-site emergency plan for severe accidents |
| *Resistance to proliferation and to acts of malicious damage* | ➢ Fuel cycle minimizing the production of weapon-grade materials<br>➢ Efficient protection against internal and external hazards |

# THE GIF

## OBJECTIVES FOR THE GEN-IV SYSTEMS SUSTAINABILITY

- Optimization of the uranium resources and the fissile material inventory (closed fuel cycle)
- Decrease of the waste volume and storage costs
- Waste management taken into account in the design
- Multi-functionality (hydrogen, electricity, industrial heat)

# THE GIF

## OBJECTIVES FOR THE GEN-IV SYSTEMS SAFETY

- Reduction of fault rate of normal operation equipments
- Increased protection against external attacks and hazards (plane crash, malevolence, etc.)
- Very low probability of major core damage
  - Design features
  - Passive protection system

⇒ No need for off-site emergency plan for severe accidents

  - According to a defense in depth design approach including severe accidents in the design basis

# GEN – IV SYSTEMS

☐ HTR/VHTR

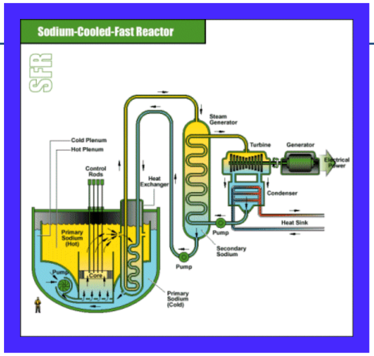
☐ SFR

☐ LFR

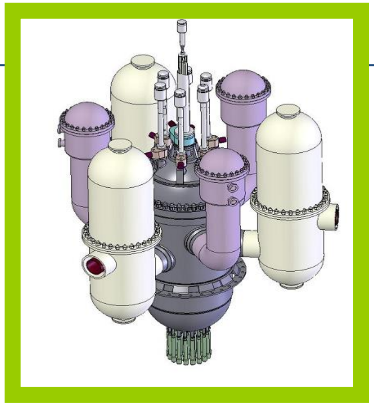
☐ GFR

☐ MSR

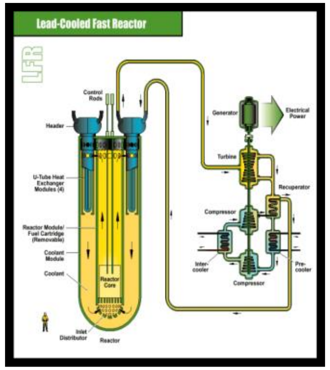
☐ SCWR



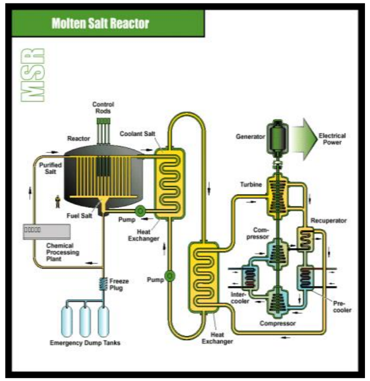
☐ SFR



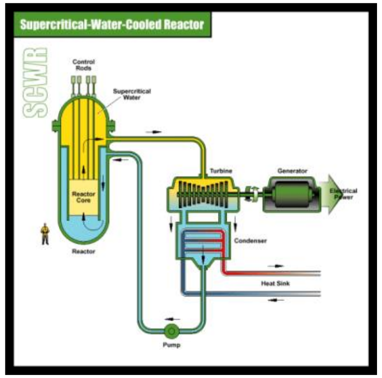
☐ GFR



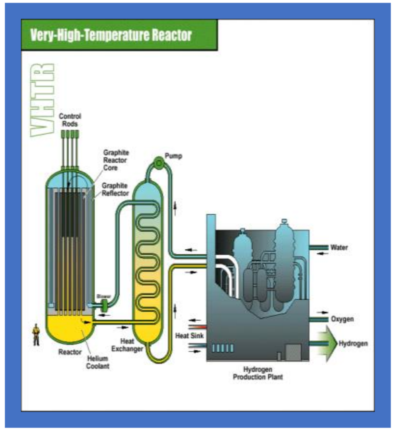
☐ LFR



☐ MSR



☐ SCWR



HTR/VHTR

# The GIF-family SMRs

- **LFR : Lead-Cooled Fast Reactor**
- **NEWCLEO**
- *« La technologie NEWCLEO contribue à répondre aux principaux défis de la filière nucléaire : sûreté, coûts et déchets. Elle a pour ambition de contribuer à accélérer la décarbonation de l'économie française dans une approche de souveraineté industrielle et énergétique, aux côtés de toute la filière nucléaire hexagonale. Le groupe s'est implanté en France avec la volonté de mettre en service en 2030 un réacteur de démonstration et d'irradiation de 30 MWe, ainsi qu'une unité pilote de combustibles innovants. Leur mise en service permettra de créer en France plus de 500 emplois directs qualifiés à l'horizon 2030, avec un investissement global allant jusqu'à 3 milliards d'euros sur la même période.*
- *Le plomb présente l'avantage d'une sécurité passive éliminant les risques de fuite (travail à pression atmosphérique, chimiquement inerte, propriétés de blindage, capacité thermique, etc.). Il permet aussi une protection physique intrinsèque du réacteur : en cas de nécessité, sa solidification, facile à atteindre (330°C), emprisonne le cœur dans un sarcophage inaccessible et intransportable.*
  - *Avec le multi-recyclage du combustible MOX NEWCLEO ambitionne de mettre en œuvre une solution globale contribuant à fermer le cycle du combustible ».*

# The GIF's-family SMRs

- **MSR : Molten Salt (Fast / Thermal) Reactor**
- **NAAREA**
- *« Le XAMR® de NAAREA combine trois innovations majeures ayant fait l'objet de nombreuses recherches dans la filière du nucléaire : les sels fondus, les neutrons rapides et les réacteurs modulaires SMR (Small Modular ReactorXAMR® de NAAREA combine trois innovations majeures ayant fait l'objet de nombreuses recherches dans la filière du nucléaire : les sels fondus, les neutrons rapides et les réacteurs modulaires SMR (Small Modular Reactor).*
- *NAAREA a opté pour le développement d'un réacteur nucléaire pour tirer parti de l'exceptionnelle densité énergétique de l'atome et de sa capacité à générer de l'énergie de manière pilotable ».*
-

# The GIF-family SMRs

- **HTR / VHTR : High Temperature Reactor**
- **JIMMY**

*« Les générateurs thermiques de Jimmy sont fondés sur des micro-réacteurs nucléaires à haute température (HTR) qui créent la chaleur désirée. Les générateurs thermiques de Jimmy sont fondés sur des micro-réacteurs nucléaires à haute température (HTR) qui créent la chaleur désirée. Ces réacteurs sont bien connus, très chauds et très sûrs »*

# The GIF’s Family SMRs

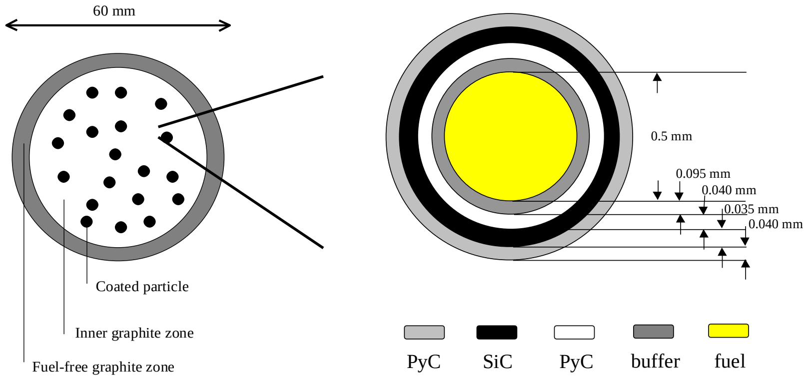
## The VHTR

The VHTR is seen as more efficient than conventional LWRs in operation in several aspects:

- **A higher thermodynamic efficiency** and a wider scope of applications, because of the very high temperature gas supply,
- **A different commercial approach**, to serve the market segment of medium-scale electricity production, as opposed to the traditional nuclear plants for large-scale production of electricity.
- **A minimized environmental impact** owing to the robustness of the fuel that retains fission products under both normal and accidental conditions,
- **A better resource utilisation** and a contribution to waste minimization through:
  - Its thermal efficiency,
  - Its quite high burn-up,
  - Its large capacity to transmute Actinides [both Plutonium and Minor Actinides].

# HTR DESIGNS : THE HTR / VHTR

## *The VHTR Fuel: A Multi Barrier System*



Graphite matrix

Outer PyC

SiC

Inner PyC

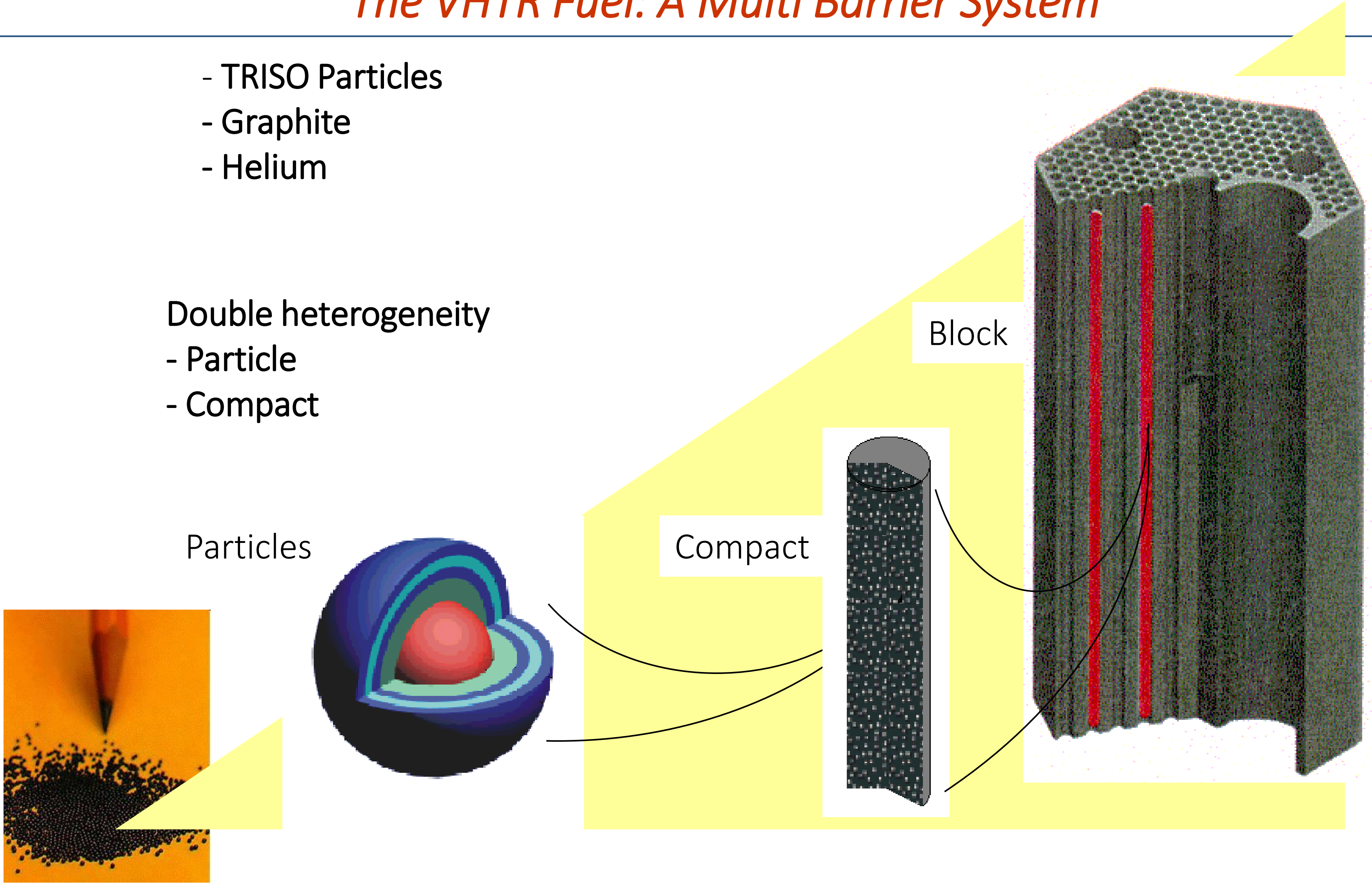
Kernel

# HTR DESIGNS : THE HTR / VHTR

## *The VHTR Fuel: A Multi Barrier System*

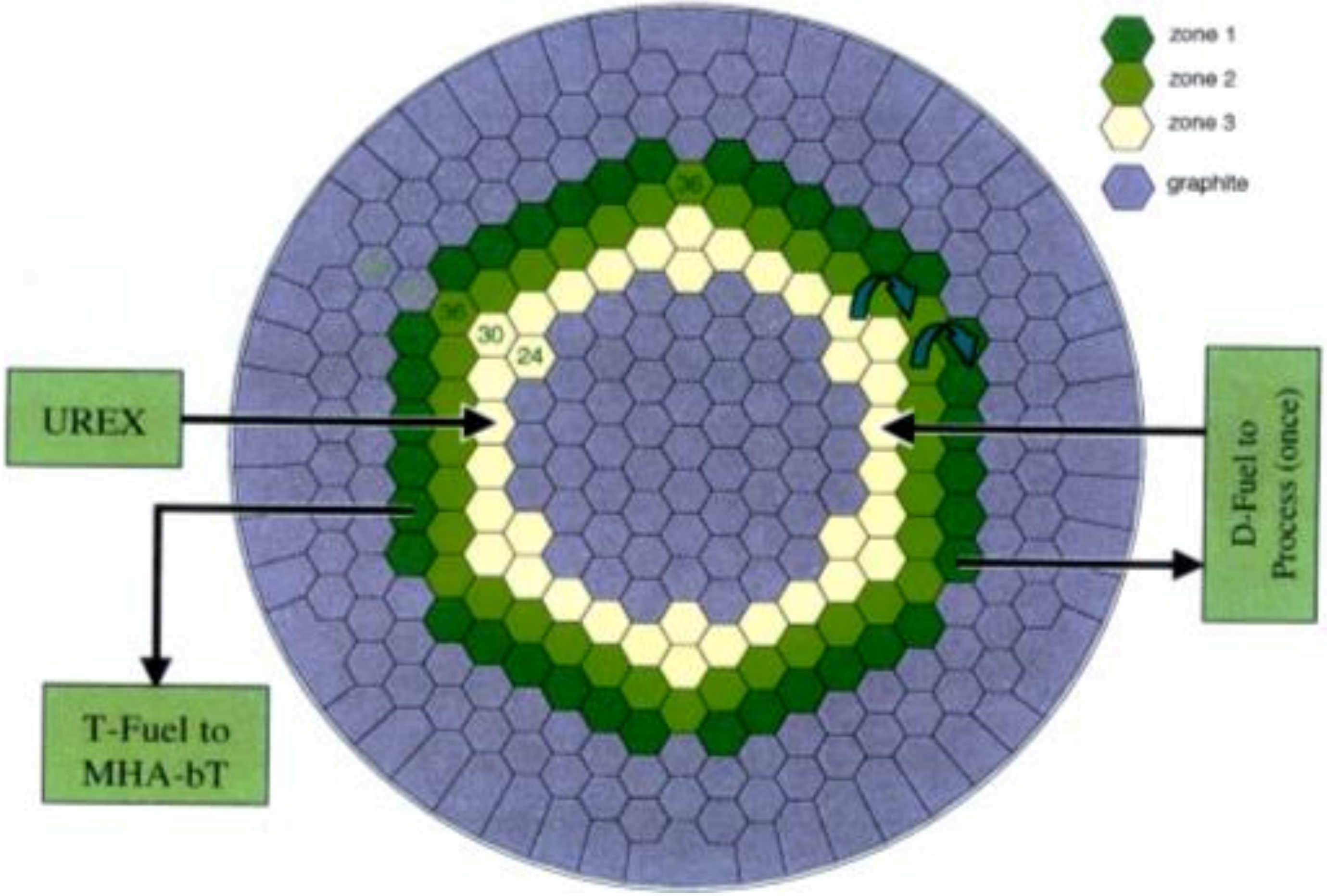
- TRISO Particles
- Graphite
- Helium

Double heterogeneity
- Particle
- Compact



# HTR DESIGNS : THE HTR / VHTR

## *The VHTR Core: A Very Heterogeneous System*



# HTR DESIGNS : THE HTR / VHTR

## ADVANTAGES HTR / VHTR

- Safety by design
- Fuel economy
- Resistant first barrier up to 1600°C
- Very low power density (few $MW/m^3$)
- Large inertia due to the important quantities of graphite; fuel temperature ~1600°C in case of non protected loss of active systems for the heat removal (passive evacuation of residual heat)
- Outstanding design and operation feedbacks (Peach Bottom, AVR, THTR, Fort Saint Vrain, etc.)
- Resistance to proliferation
- Fissile material high Incineration capacity
- Advanced maturity, but for limited reactor powers

## INCONVENIENTS AND/OR INCUMBENT DIFFICULTIES HTR / VHTR

- Fuel cycle open *(but some studies aiming at the closure of the cycle have been performed)* [*Deep burner GTMHR*]
- Weak efficiency of the coolant
- Quite high pressure
- High or very high temperatures for the structures (internal structures, etc.): materials to develop, specific risks ?
- Risk and consequences of big breaks on primary circuit (mechanical consequences, graphite oxidation or fire, etc. ?)
- In service inspection
- Risks for the reactor due to industrial linked process

# HT SMR FEATURES

Several HT SMR designs with different objectives exist,

The most of them are inspired to the HTR / VHTR,

All they share the same advantage and drawbacks of the industrial size reactor systems,

Significant differences hold among the designs: some of them reproduce the geometry of the conventional system, other ones do not and differ very much from,

The physical features and behavior depend on the design (coupling,  flux shape, power distribution …).

# The GIF’s Family SMRs

**The HT SMRs combine the well-known advantages of the SMRs**, (including high modularity, standardization, flexibility inspectability”, maintenance, possibility of remote operation and handling and the economic competitiveness), **with the already mentioned HTGR / VHTGR ones**, such as :

- **The inherent safety.**
  - **The HT SMRs are intrinsically safe by design,** due to their **very low power density** & their **very long prompt neutron lifetime**, which **excludes any prompt reactivity surge (RIA eliminated by design),**
  - **in case of major accidents, the core HT SMRs does not melt down,**
  - Because of the huge amount of moderator surrounding the core, **the residual heat dissipates passively into the environment**, whatever the scenario without external intervention and addition of complementary systems,
  - **The HT SMRs** do not need outside support to operate safely, including electricity supply.

# The GIF’s Family SMR

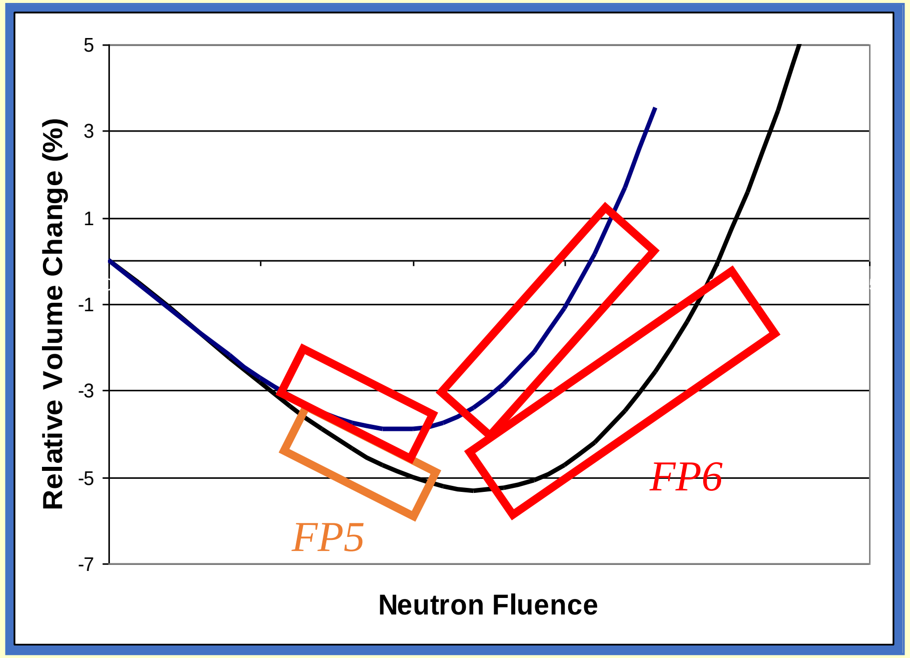
**The HT SMRs combine the well-known advantages of the SMRs**, (including high modularity, standardization, flexibility “inspectability”, easy maintenance, possibility of remote operation and handling and the economic competitiveness), **with the already mentioned HTGR / VHTGR ones,** such as :

- **The fuel**. The fuel margins of the HT SMR are so high that **the fission by-products retention is accomplished by the TRISO particles**, without any need for containment. The high-yield fissions products remain permanently inside the TRISO particles during and after the operation [nevertheless, they are not perfectly tight and allow leakage of some low yield fission products, such as Ag, during long term operation at very high temperature] ;
- **The coolant**. The HT SMR uses no water. Accordingly, there is no risk of spills to the environment during either normal and degraded operation and even accidents **Helium used in HT SMRs is an inert, radiologically transparent single-phase gas**, allowing no boiling or flashing. It does not react chemically with the fuel and the reactor components. Moreover, it is quite easy to measure the helium pressure in the reactor;
- **The waste.** The waste volume is quite low. Moreover, the HT MSRs combine the high resistance to nuclear proliferation and capacity to incinerate both Plutonium and Minor Actinides.

# The GIF's Family SMRs

Technical issues:

Need for e vessel irradiation tests
Need for Heat up experiment
Selection of IHX material for tests
Scope of graphite oxidation tests



- Vessel
  - Begin the 450°C Creep tests on pre-irradiated weld specimens
  - Address safety/ security issues for and work towards thermal mock up.
- High Temperature Materials
  - Materials for test programme (IHX & Control Rod)
- Graphite
  - Irradiation tests
  - Samples/ tests on oxidation & basis for modelling developments
  - Need for heat up experiment
- Codes & Standards
  - Enable web-based access to CMC data and planning for graphite and CMC guidelines. Recommendations for metallic developments.

# The GIF's Family SMRs

- **Identified needs for accurate investigation (1)**

- **Validation of computation chains:** Uncertainties
- **Severe Accidents**: the physical features of the HT SMR make it sensitive to air and water ingress from the external environment, which can initiate and feed-up severe accidents;
- **Tribology and corrosion** :For some concepts, the high temperature and / or the presence of salts in the coolant demand for extensive qualification of the materials resistance to corrosion. ***Key issues*** **: sliding components (hot gas duct seal, control rods,..) with VHTR operating conditions** ;
- **Cliff Edge Effect**: As it is the case for all SMRs, the multi units concept of the NPP increases the risk of propagation of incidents and accidents among the units;

# The GIF’s Family SMRs

## Identified needs for accurate investigation (2)

- **Underground operation**: The underground operation, if any, can turn out to be risky in case of flooding. Moreover, the system can be sensitive to extreme weather conditions and global warming;
- **Fuel**: The TRISO particles are not perfectly tight and allow leakage of some low yield fission products, such as Ag, during long term operation at very high temperature,
- **Remote operation**: The remote operation can be sensitive to cyber-attacks;
- **Operation & Industrial Experience** : The real size experience remains limited

# Thank-you for your attention

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