AREVA

Very High Temperature Reactor: Promising nuclear system specific reactor physics

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Proposed presentation items

- Why a HTR-VHTR program at AREVA/Framatome-ANP?
- Presentation of the AREVA HTR-VHTR concept:

  A-VHTR

- Specificity of the HTR reactor physics

What does market want now ?

- Producing large amounts of electricity at the lowest cost
- Taking avantage of the experience
- Consequence :
  - The market is now (and near future) for PWR or BWR
  - How long ? … until good reasons to change arise

Two types of reasons for changing

- **"Market PULL"**
- **New applications (markets) leading to new specifications**
  - **Cost reduction (investment, progressivity, M&O)**
  - **New site and grid concerns**
- **"Tech. PUSH"**
- **New constraints (or opportunities) from technological gaps producing clear (and substantial) avantages for the utilities**

Constraints on the fuel cycle

- Problem of uranium ressources (prices)
  - Only if there is a strong nuclear development in the near future
  - If not … go to 2050
- Constraints in the management of ultimate waste (optimal management of geological storage)
  - Rules about the destination of actinides
  - Cost of various solutions for final disposal (included in KWh cost)

Wonderful ! GENIV is good for both

- **Increase of natural uranium capabilities and optimization of the management of geological storage through actinide (auto) transmutation**

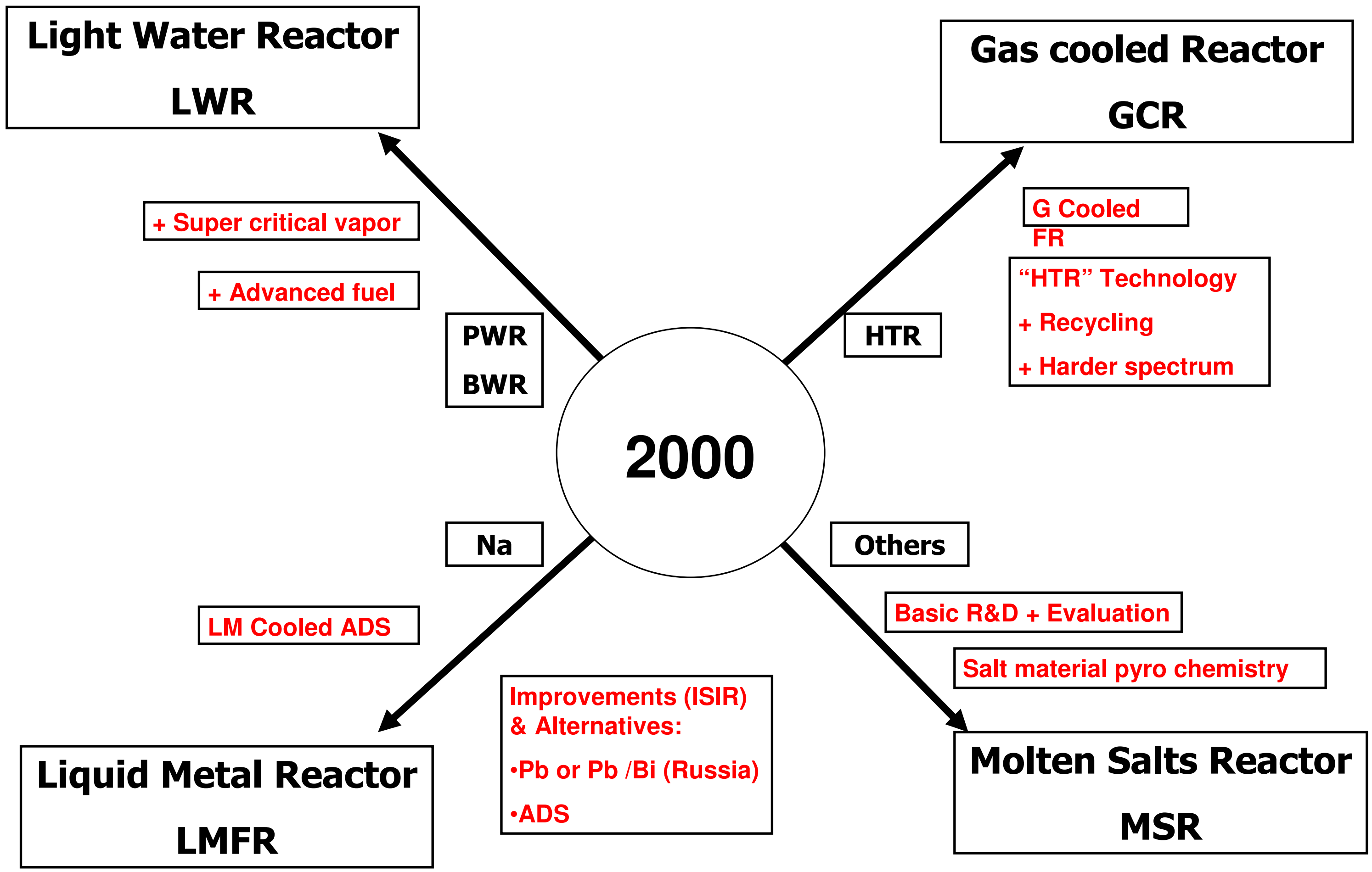
has a common elegant solution

through "fast" neutrons, close cycle plants

=> consensus of GEN IV analysis

when ? what kind of nuclear plant ?

Future nuclear systems: technological roadmap



Why HTR ?

- Small specific power, limited total power
- Large components (reactor vessel, heat exchangers, …)
- Qualification still underway (fuel, heat exchangers, …)
- Industrial viability, still to demonstrate
- Fully new safety approach or philosophy
- Costs and overall economy to prove

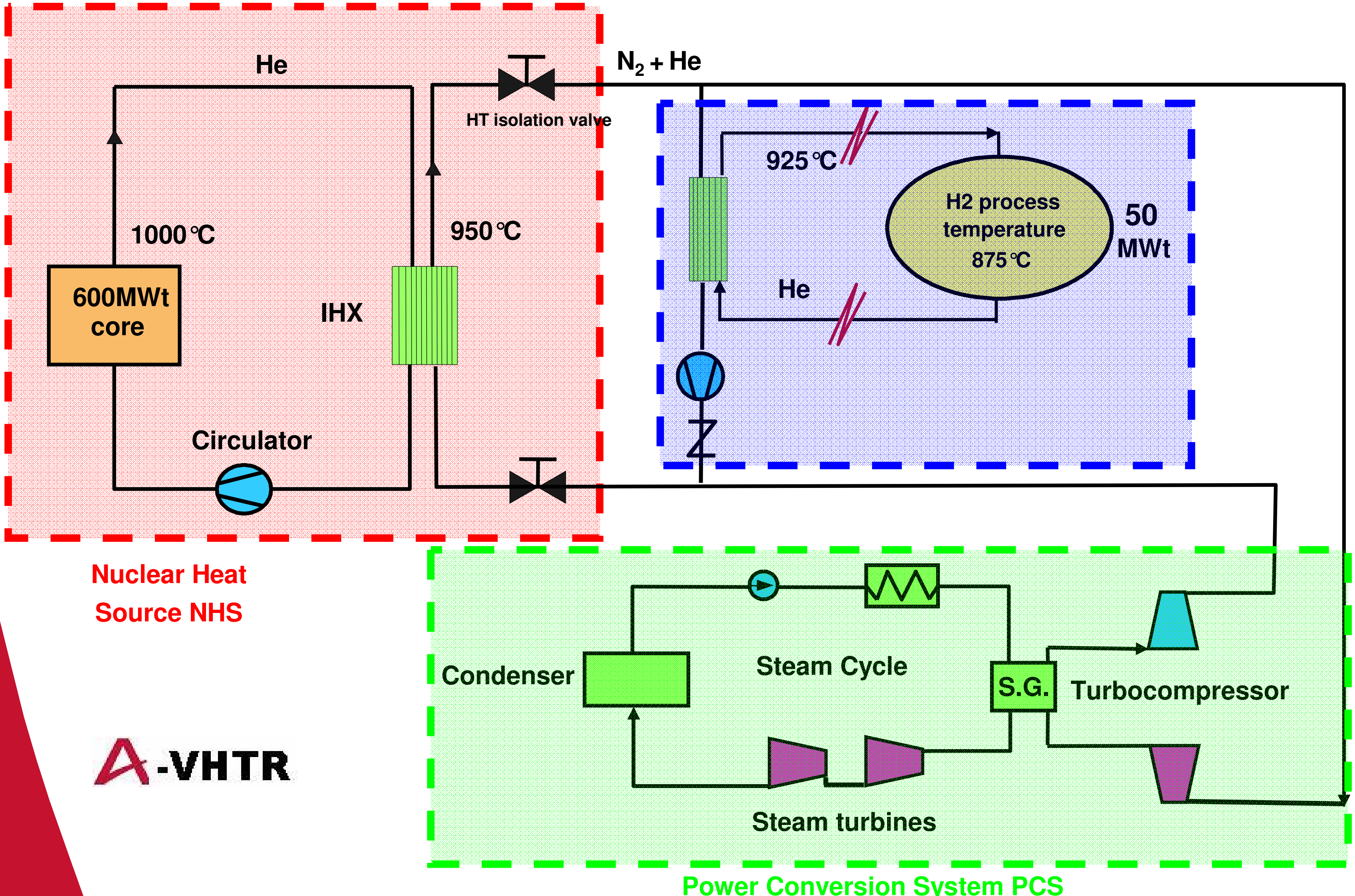
Main driving ideas for feature choices:

- Use existing proven technology as much as possible
- But take the challenge for key issues for the future
- Design a flexible nuclear heat source adaptable easily to different applications such as hydrogen production, electricity production, industrial heat or any combination thereof.
- Optimize the plant efficiency in the electricity production mode
- Minimize maintenance issues
- Take advantage of the safety specificity
- Make it economical

This leads to the following major choices:

- **Prismatic fuel concept for its low core pressure drop and flexibility in core management (zoning, burnable poisons, fuel types, etc..)**
- **Indirect cycle configuration for flexible heat source applications (pseudo direct cycle or closed CCGT cycle)**
- **A combined cycle electricity production design taking advantage of the gas cycle at high temperature and of the steam cycle at lower temperature for high efficiency**
  - **Based on existing CCGT technologies**
  - **Lower "cold" leg temperature**

NGNP Arrangement with Electricity and Hydrogen Cogeneration



A-HTR The AREVA concept

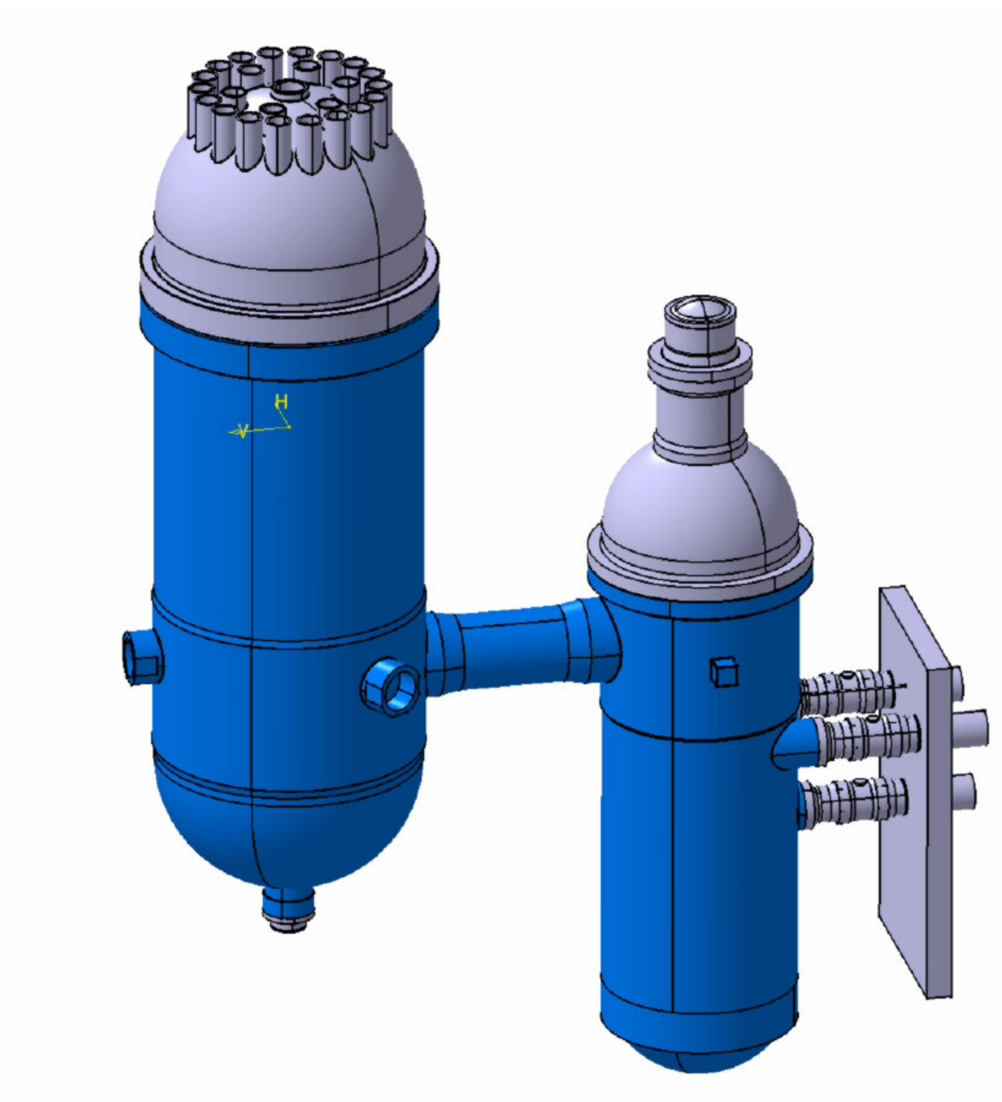
- **For electricity only production and a heat source limited to 850°C, the following has been established in common with CEA, EdF, MHI:**
  - **Net electric efficiency over 48%; higher than direct Brayton cycle**
  - **Components of the Power Conversion System readily feasible, erected in 2 years and easily maintained in a non contaminated environment**
  - **The vessel (PWR type material), blower and other components except the IHX are within present industrial capacities**
  - **The IHX must be developed. AREVA is pursuing different designs.**
- **For the very high temperature applications (over 950°C) such as hydrogen production, additional developments are needed, mainly concerning materials and their assemblies**

A-HTR

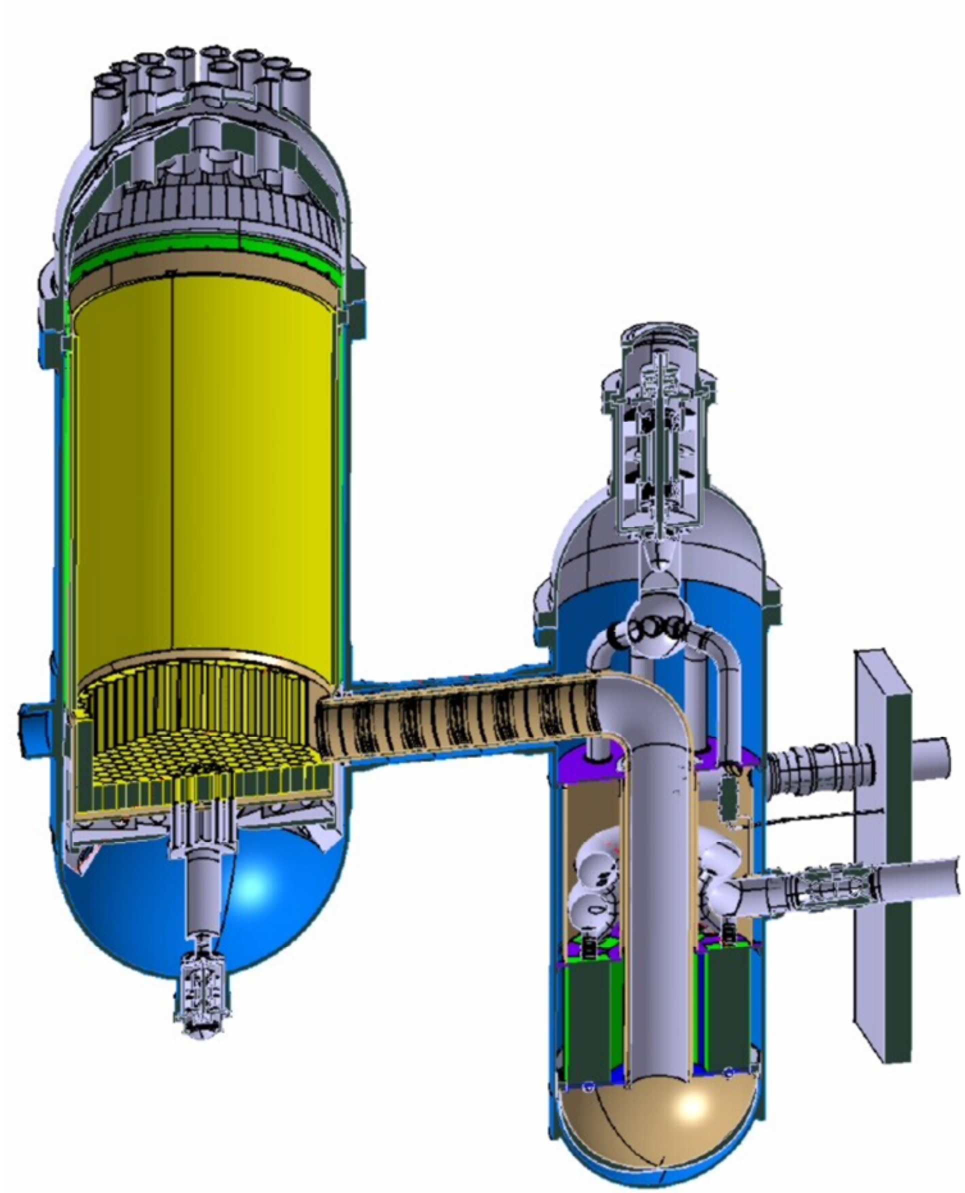
The AREVA concept

- A project organisation has been set up to achieve a full conceptual design of a VHTR
- A comprehensive R&D program is under way
- Further optimizations are under way:
  - Core design
  - Computer code coupling techniques permitting better design margin allocations
  - System options and configurations
  - Safety analysis
  - Component manufacturing processes based on Framatome experience as a manufacturer

Base options of the Framatome ANP design for NGNP



Indirect VHTR Supplies Energy to a Spectrum Of Applications



Fuel particle, compact and block

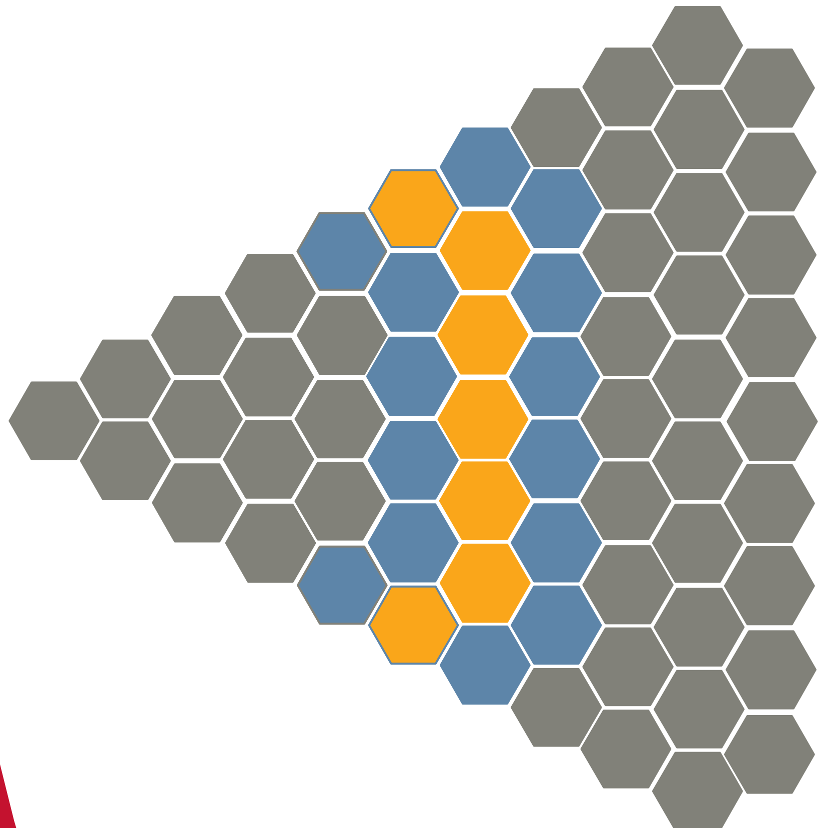
Coated Particule

Compact

Graphite Structure

Fuel assembly

Specificities of Annular Cores



- **Annular core design**

The major part of core is sensitive to the reflectors

Conditions in core zone highly depends of conditions in reflectors' zone

This has to be considered in calculation methods

Overview of Framatome ANP HTR Work

Internal FANP Activities

- **R&D**
  - **Calculation Tools & Methods**
  - **Fuel Design & Technology**
  - **Materials** *Vessel*
  - **Components** *IHX, Ducts, Valves*
  - **Helium Technology**
- **Safety Approach**
- **Reactor Engineering**
- **Fuel Plant Engineering**

Past Experience in Germany

- **AVR, THTR**
- **PNP, HTR-Modul Projects**
- **KVK Test Facility**

Collaborative R&D Activities

- Calculation Tools & Methods
- Fuel Technology
- Materials
- Helium Technology
- Test Facilities

Contracts with EC (FP)

- HTR-TN *Technical Network*
- HTR-E *Components*
- HTR-L *Licensing*
- HTR-F *Fuel*
- HTR-M *Materials*
- HTR-N *Neutronics*

Technology Supply

- HTR-10 China
- PBMR South Africa

EDF Collaboration

- PCS Optimization
- HTE Process
- O&M

DOE/Minatom GT-MHR Program

Support of Conceptual Design

Computational tools for:

- Deterministic safety analyses
- Probabilistic safety analyses
- Availability analyses
- Normal, incidental, accidental operation
- Radiation protection and shielding
- Decommissioning
- External hazards
- SSC design

Tools for deterministic safety analyses:

- Depressurization accidents
- Loss of primary forced circulation
- Loss of heat sink
- Reactivity insertion events
- Air ingress
- Water ingress
- Fuel and component handling faults

Phenomena needing to be predicted:

- Thermo "aerolic" analyses
  - Thermal mixing effects
  - Fluid – structure interaction
  - Acoustic effects
- Reactivity effects
  - Doppler, moderator effects
  - Xenon effect
  - Dilatation effects: axial and radial core dilatation, gaps, differential control rods dilatation
  - Reactivity effect resulting of water ingress
- Decay heat
- Evaluation on fuel consequences:
  - Variation of the failed fuel particle rate

Computational Tools

- Chemical consequences
  - Graphite/air reactions: gas production or disappearing, energy release
  - Graphite/water reactions
- Radionuclide releases in the primary circuit
  - Releases from the failed fuel particles
  - Releases from the intact particles
  - Releases of radionuclides not initially located in the fuel particles (e.g., activated elements)
  - Activation of the helium (e.g., tritium)
- Radionuclide releases from the primary circuit
- Environmental consequences

Tools have been selected for:

- Minimization of the number of used tools
- Qualification, development capabilities in pace with the safety analysis and the design activities
- Necessity of computer tools?: Simple conservative assumptions may be sufficient
- Need to analyze protected and unprotected transients
- Capability to analyze very high temperature case
- Common data base: e.g., helium, graphite, materials characteristics

SPECIFICITIES OF HTR REACTOR PHYSICS

Reactor Physic specificity in HTR

V/HTR system basic specificities / tools and models

- Graphite design
- Temperature, temperature range: material properties, nuclear data, thermal losses
- Heterogeneous fuel design (particles, compacts, blocks)
- Heterogeneous core design: high and thin annular core with inner and outer side reflectors, control rods in reflector
- Thermal coupling
- Very high fuel burnup (20% to 26% FIMA for U fuel)
- Core and internal structure design ⟶ gaps
- Gas coolant: leakages, component models (turbomachines, plate HX)
- Importance of inherent behaviour: convection, conduction, radiation; duration of the transients (many days)

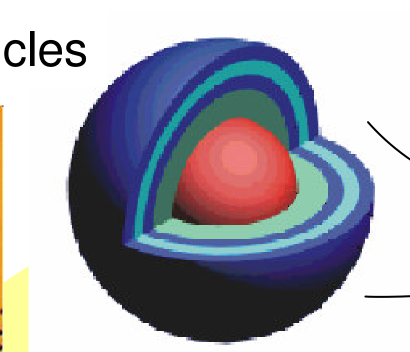
Reactor Physic specificity in HTR

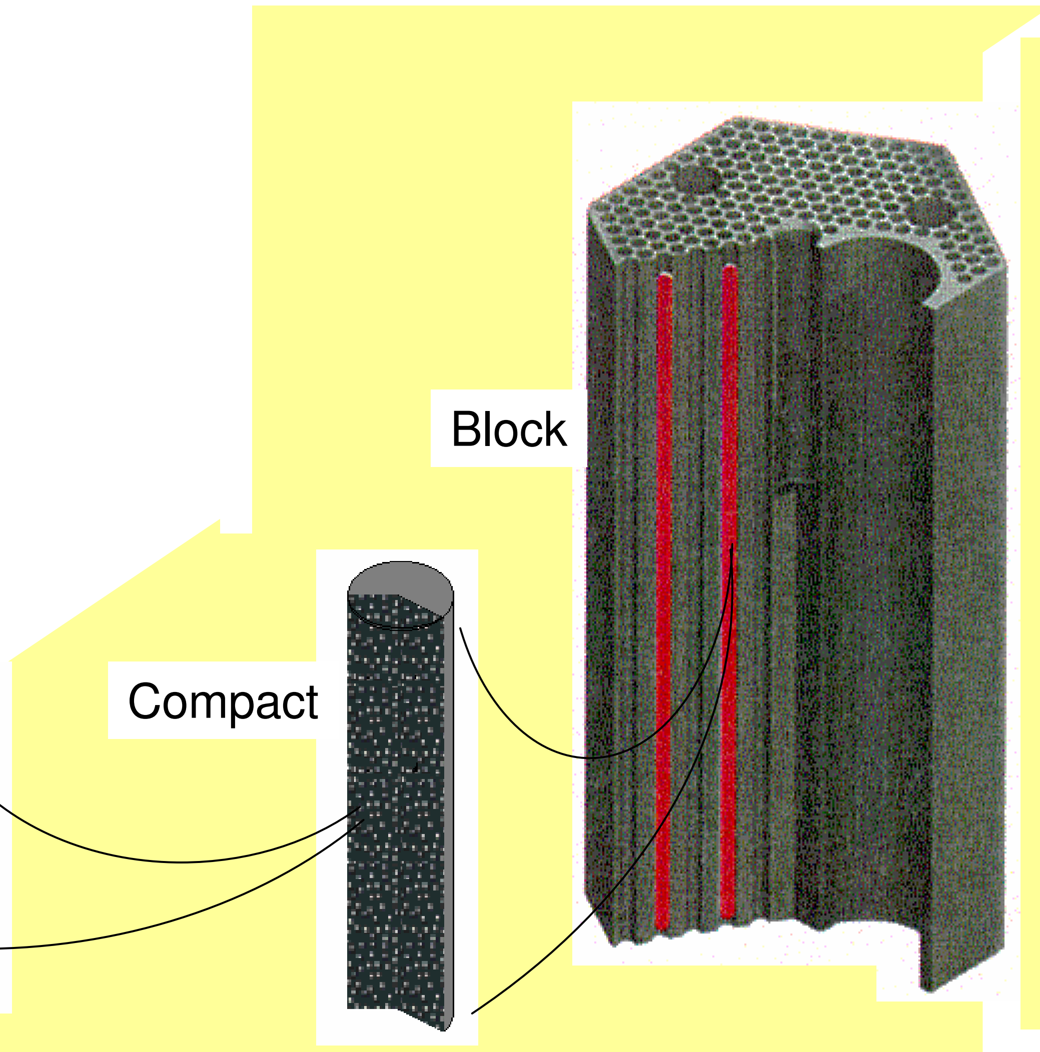
- **Needs for extension of the validation of the relevant codes**
  - Neutronic (spectrum, temperature range,…)
  - Core physics (reflector, size, power shifts,…)
  - Mock-up experiment
  - Thermo fluid of the thermo dynamic cycle (flow mixing, acoustic effects,…)
- **Needs for development of specific or adapatated codes and related validation**
  - Fuel (design, fabrication, irradiation, performance, PIE,…)
  - Radionuclides physico-chemical behaviour (in Graphite, He)
  - Transient analysis (regulated or not)
- **Safety authority "certification"**

A Specific Fuel Design

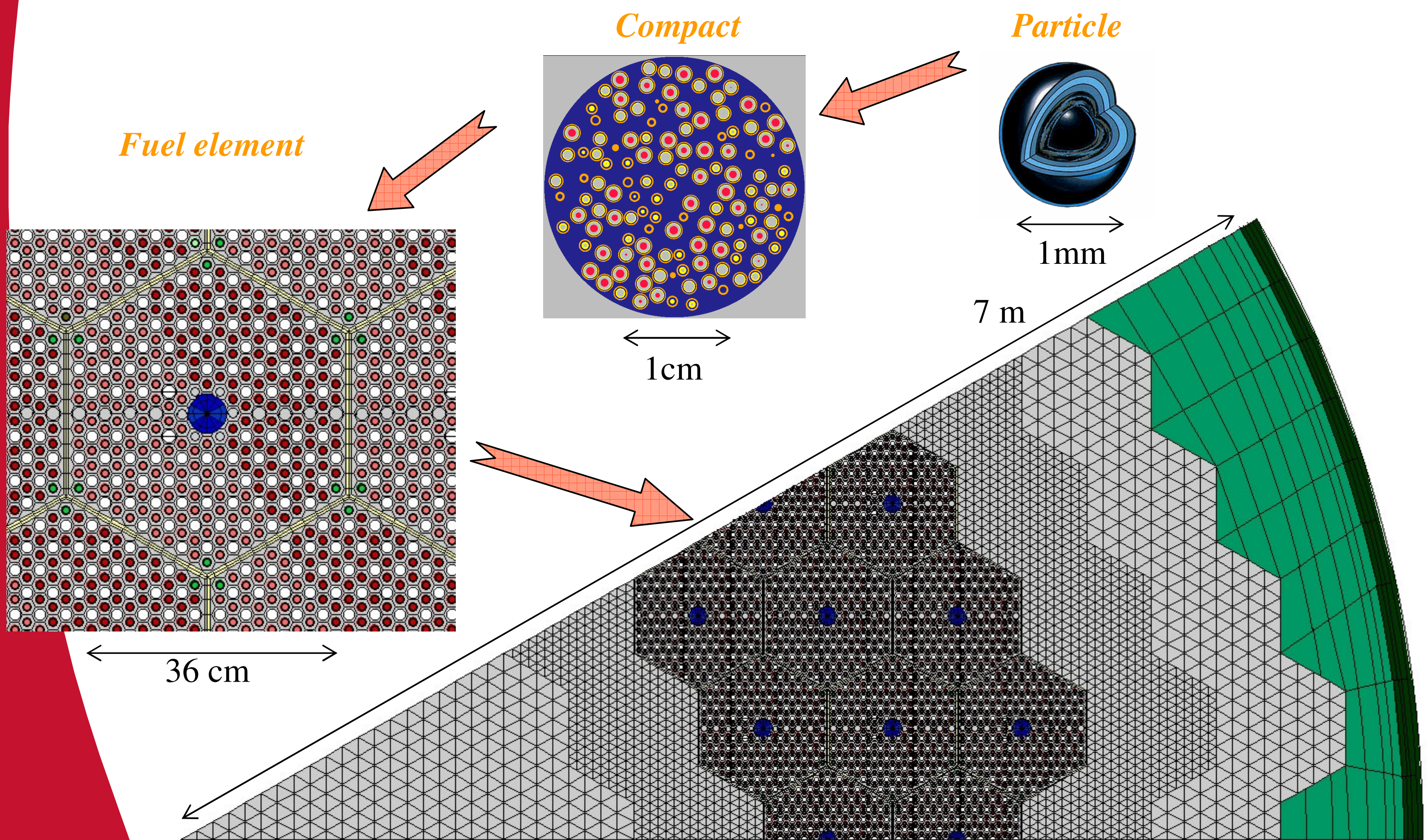
- TRISO Particles
- Graphite
- Helium

Double heterogeneity
- **Particle**
- **Compact**

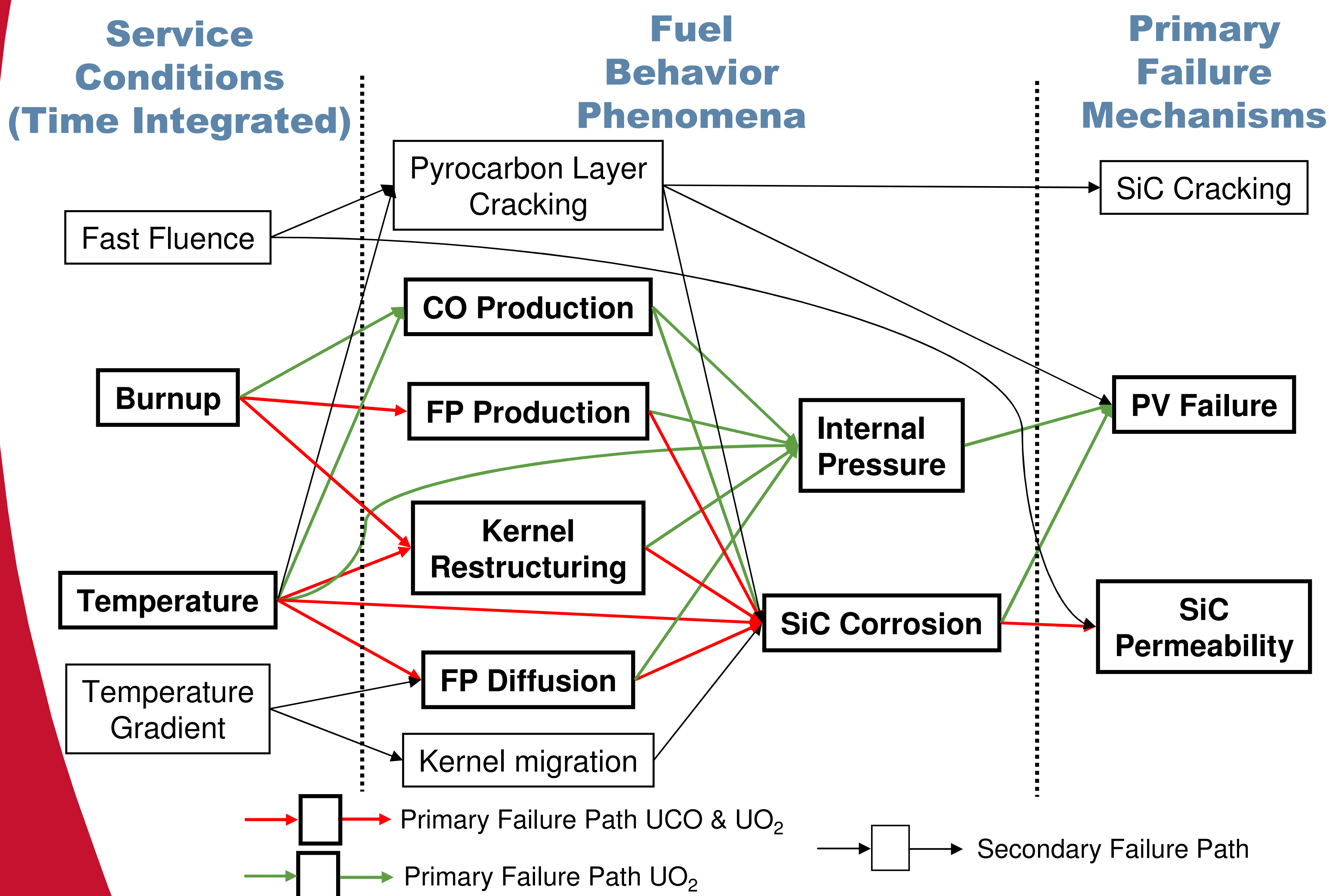




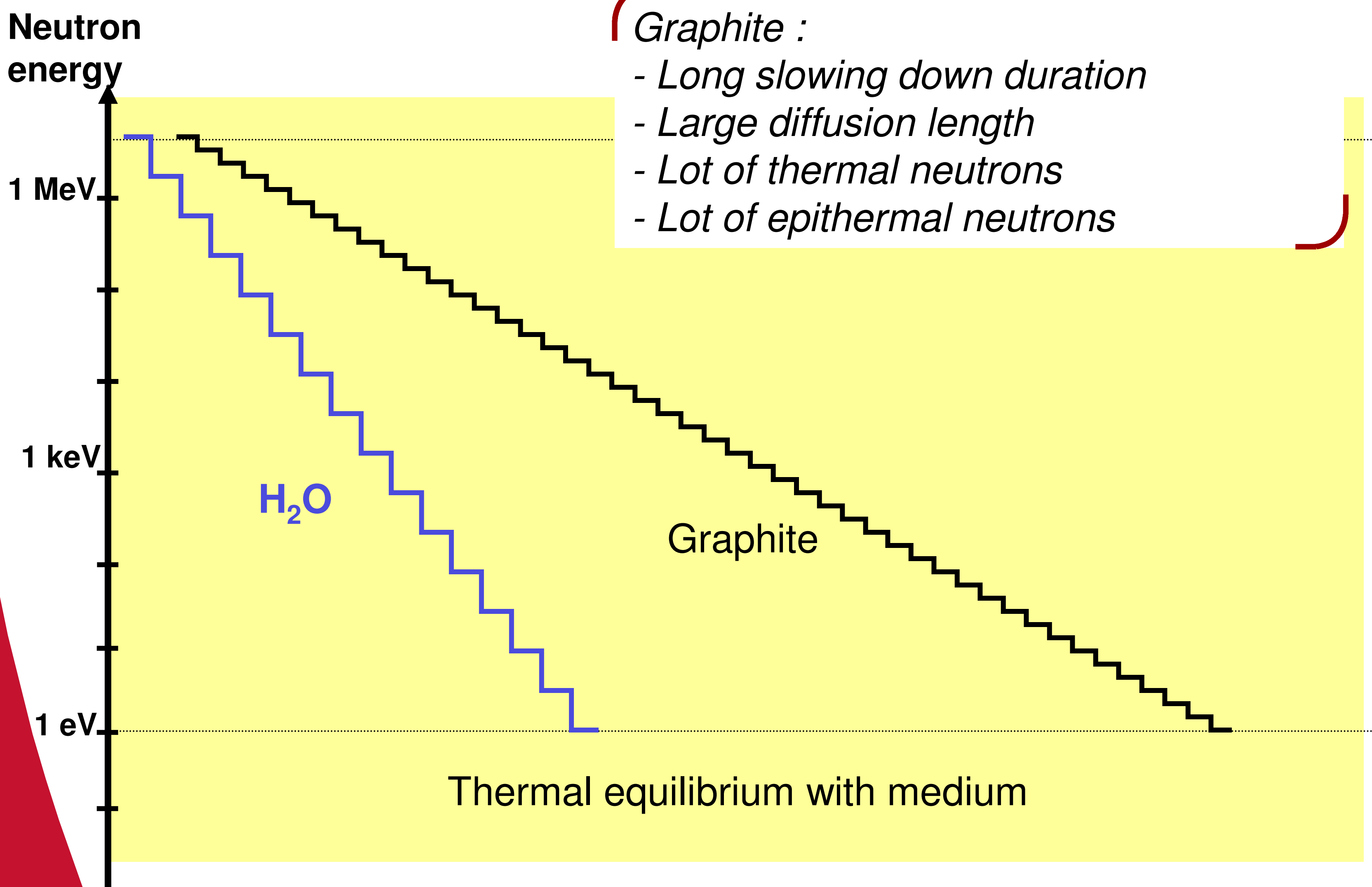
Reactor Physics: The core heterogeneities



Fuel behavior phenomena & failure mechanisms

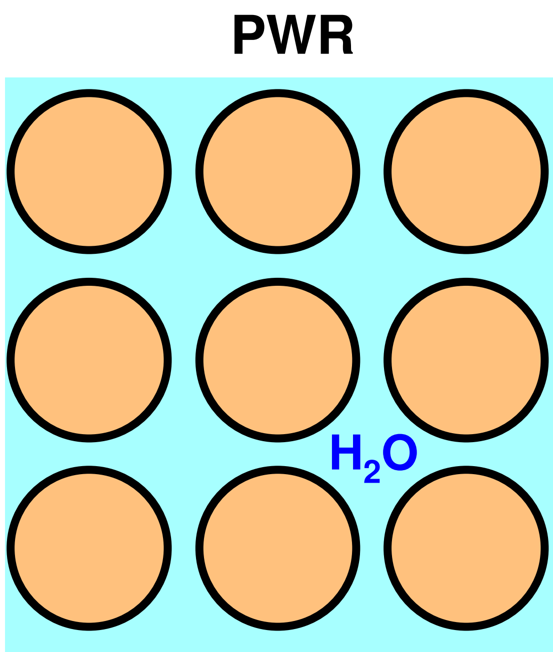


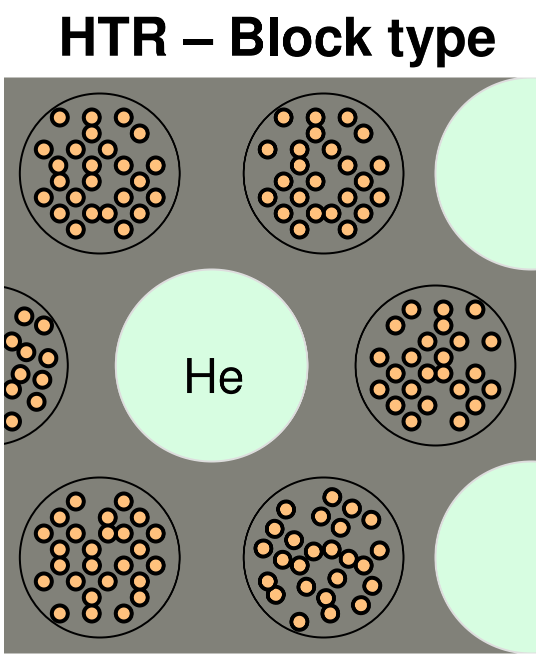
Moderation in Graphite



Graphite :
- Long slowing down duration
- Large diffusion length
- Lot of thermal neutrons
- Lot of epithermal neutrons

Diluted Fuel & Moderation by Graphite

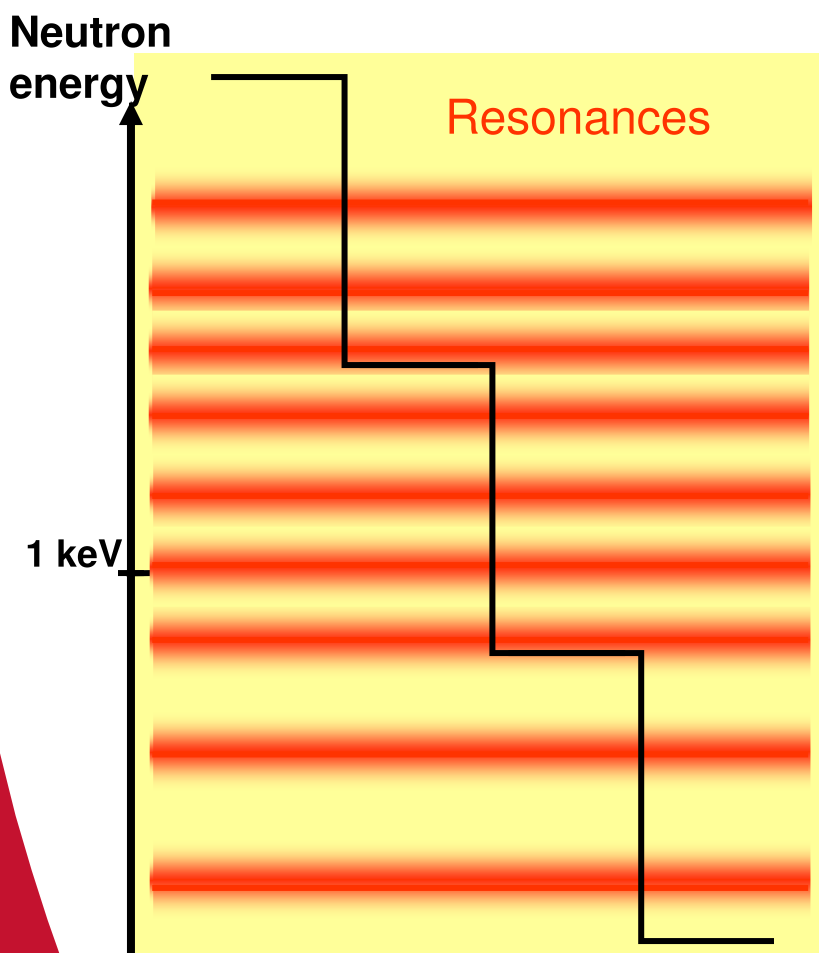




HTR : diluted fuel + long slowing down + low graphite absorption

- → **Important role of resonance absorption of fuel**
- → **Larger enrichments with regard to PWR**
- → **Importance of fuel particles' size**

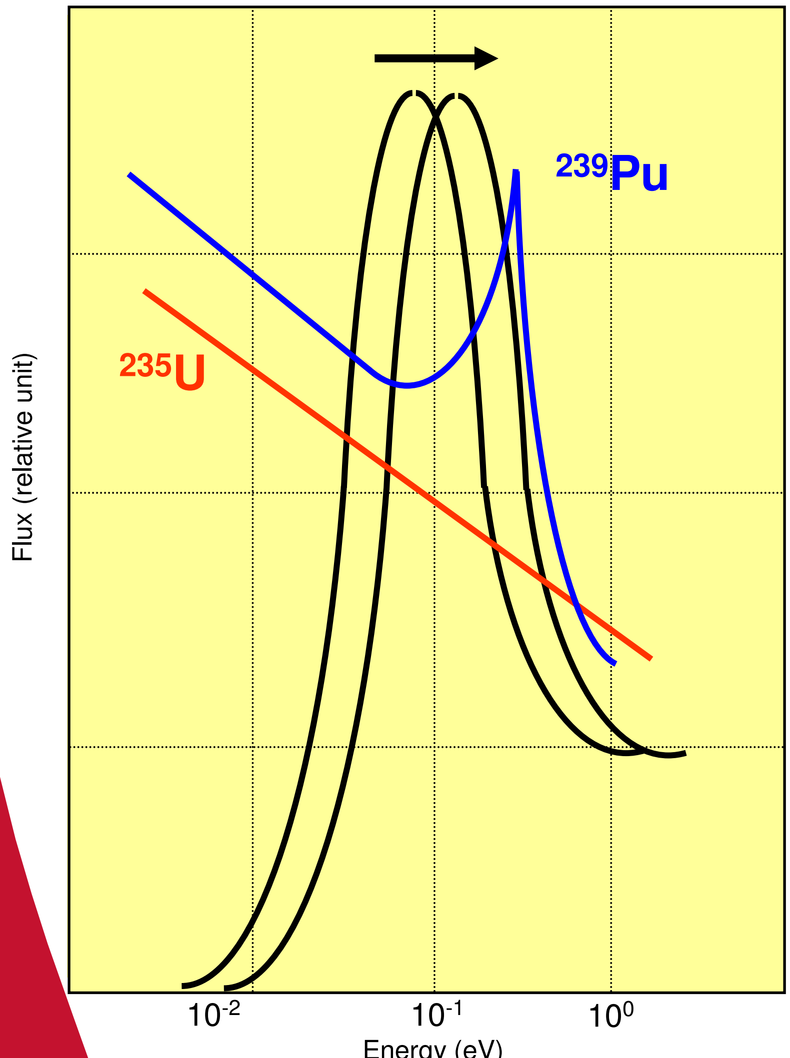
Effect of temperature : Doppler



T_{fuel} **increase :**

- **Broadening of absorption resonances of fuel nucleus**
- **Capture rate increase**
- **Very fast effect**
- **Negative reactivity effect**
- **Important in HTR**

Effect of temperature : Moderator



$T_{mod.}$ increase:

- **Decrease of medium density: small effect in solids**
- **Increase of thermal agitation of nucleus**

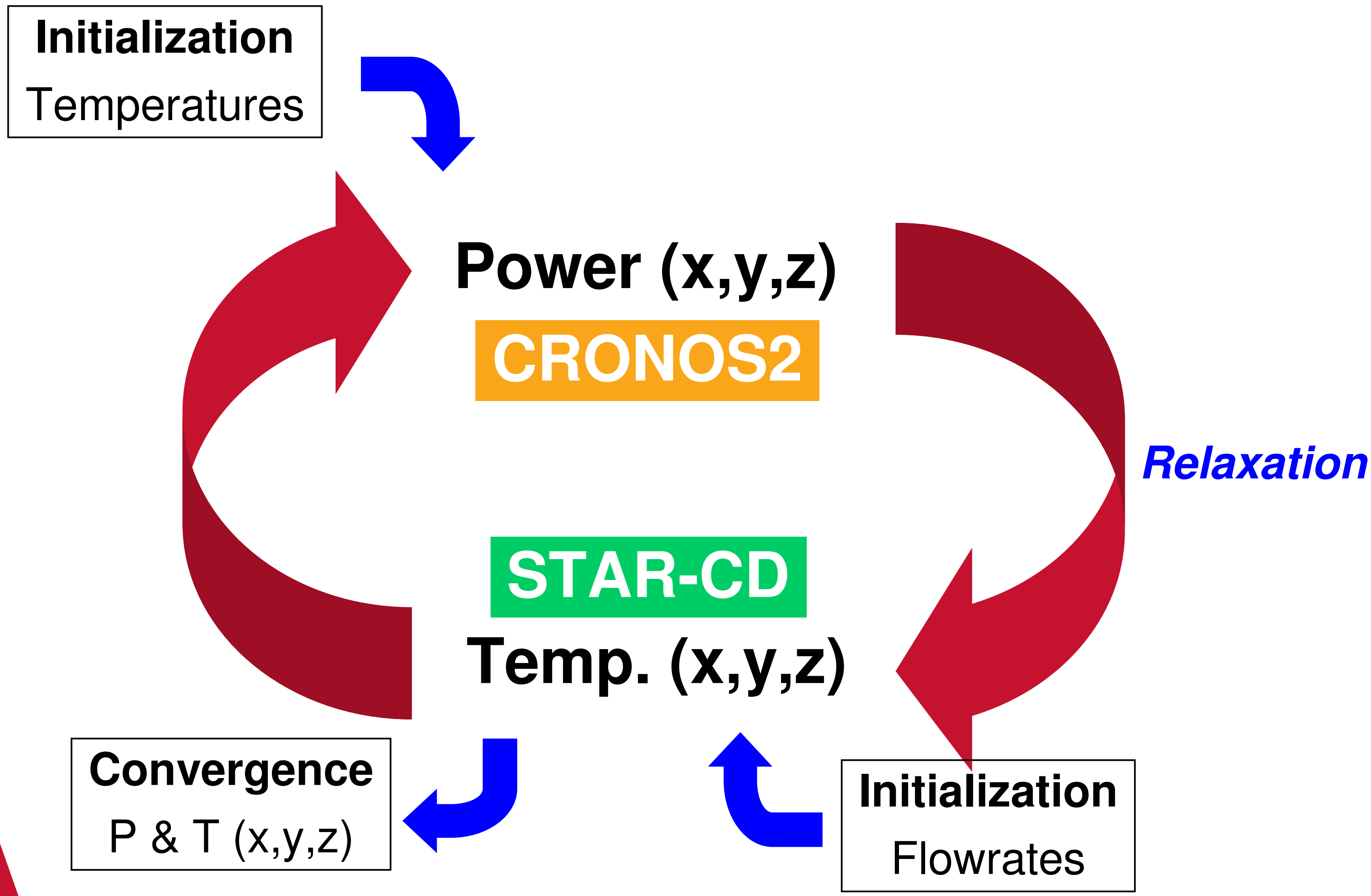
  Spectrum shifted toward high energies
- **Reactivity effect :**
  - Slow (graphite inertia)
  - Negative for uranium
  - Positive for plutonium

HTR COUPLED NEUTRONIC & THERMOHYDRAULIC CALCULATION CRONOS2 – STAR-CD MODEL

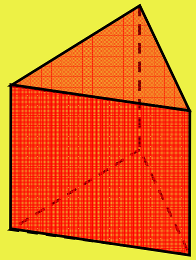
Necessity of N/Th coupling

- **Core power distribution is strongly dependent on both core and reflector temperatures**
- **The assessment of the neutronic characteristics of a HTR core requires the precise description of the core and reflector temperature fields**
- **This can be achieved by coupling neutronic and CFD codes**
  - **CRONOS2 : 3D neutronic core model (Xs supplied by APOLLO2)**
  - **STAR CD : 3D Computational Fluid Dynamic model of active core and reflectors**

CRONOS/STAR-CD Coupling Principle



CRONOS/STAR-CD Convergence Process



Neutronic cell:

Input

Cross sections functions of fuel and moderator average temperatures in the cell, Σi (Tf, Tm)

Output

Average power density in the cell, **p**

CRONOS

3D model

120°

Interface grid

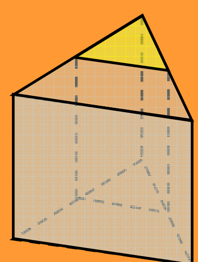
Tabulated **Tf** and **Tm** values for all cells

Interface grid

Tabulated **p** values for all cells (with relaxation option)

Post treatment

Processing of fuel and moderator average temperatures, **Tf** and **Tm**, on the basis of Ts, Tg and p



Thermalfluid dynamic cell:

Input

Average power density in the solid cell, p'

Output

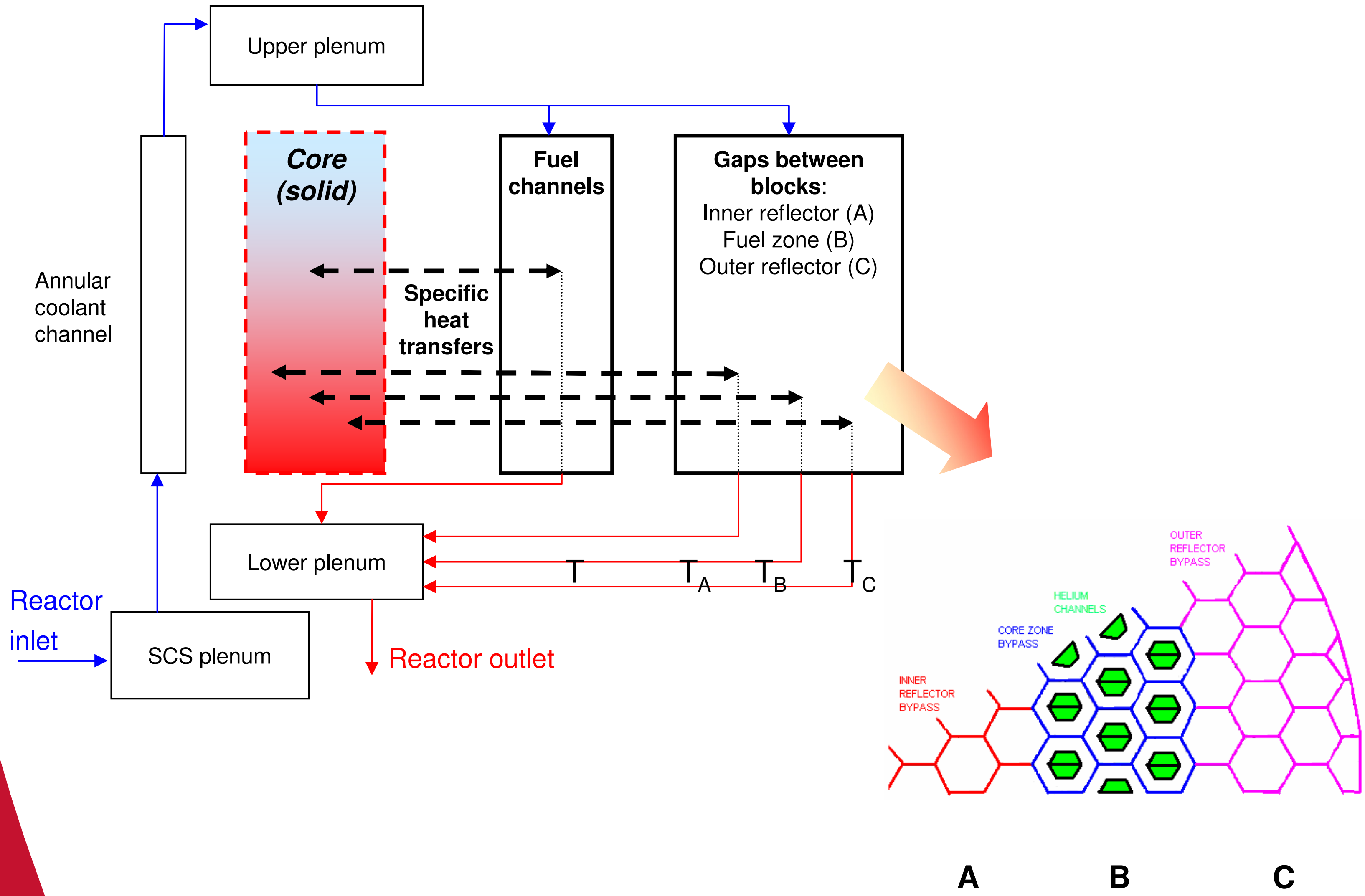
Average temperatures in gas and solid subcells (**Tg, Ts**)

STAR-CD

3D model

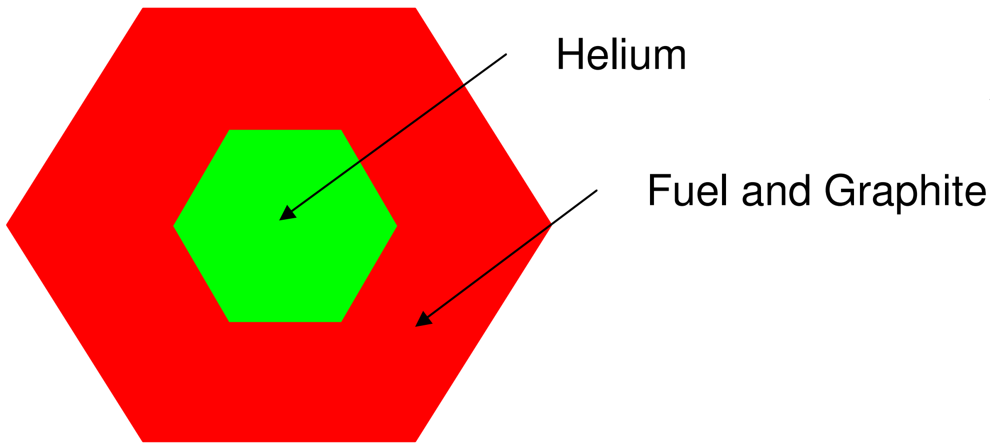
120°

Core Thermalhydraulics Model

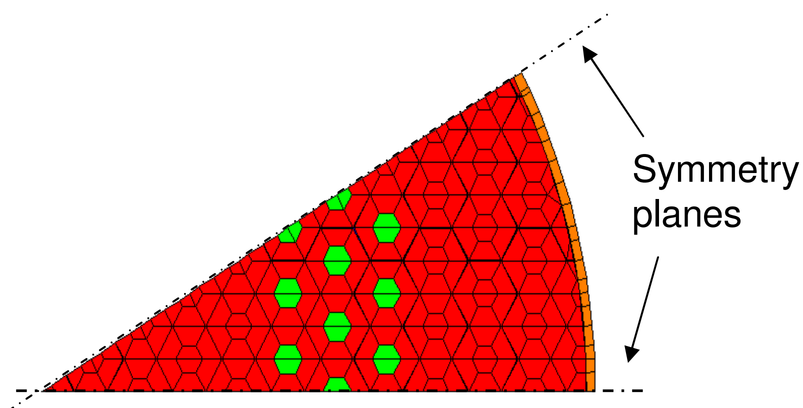


Th/N coupling model

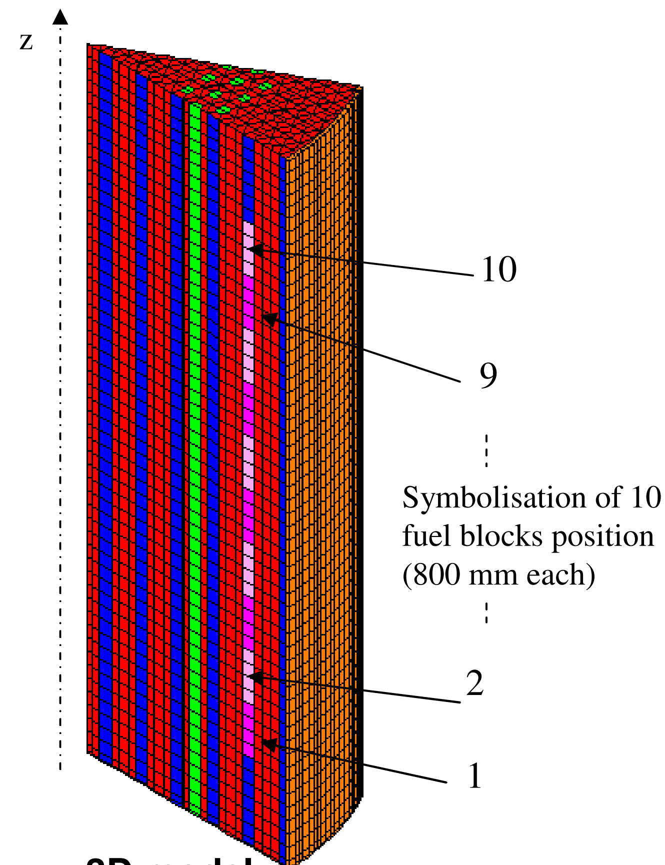
STAR-CD models



Fuel assembly

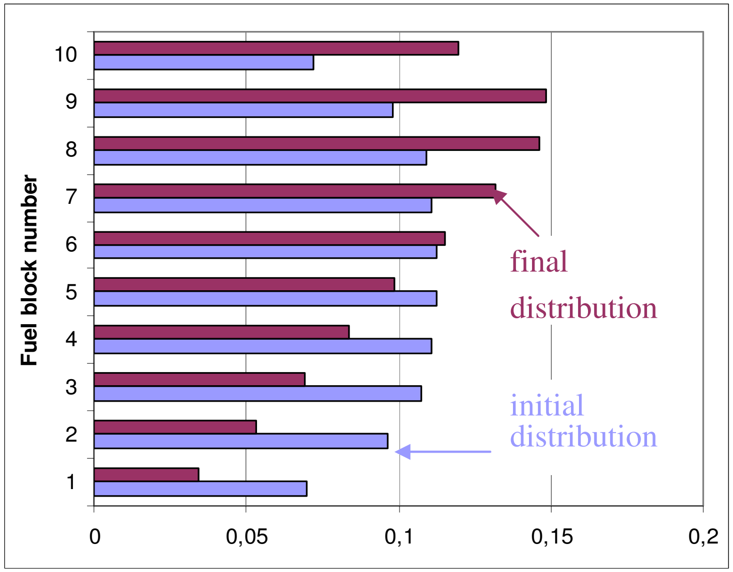


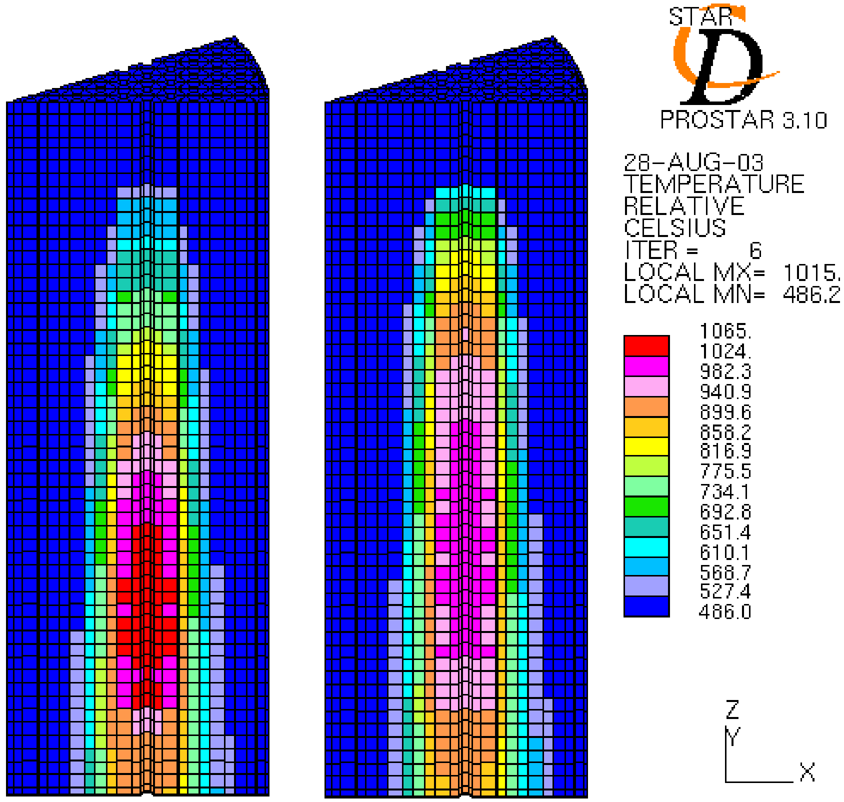
Core model (cut view)



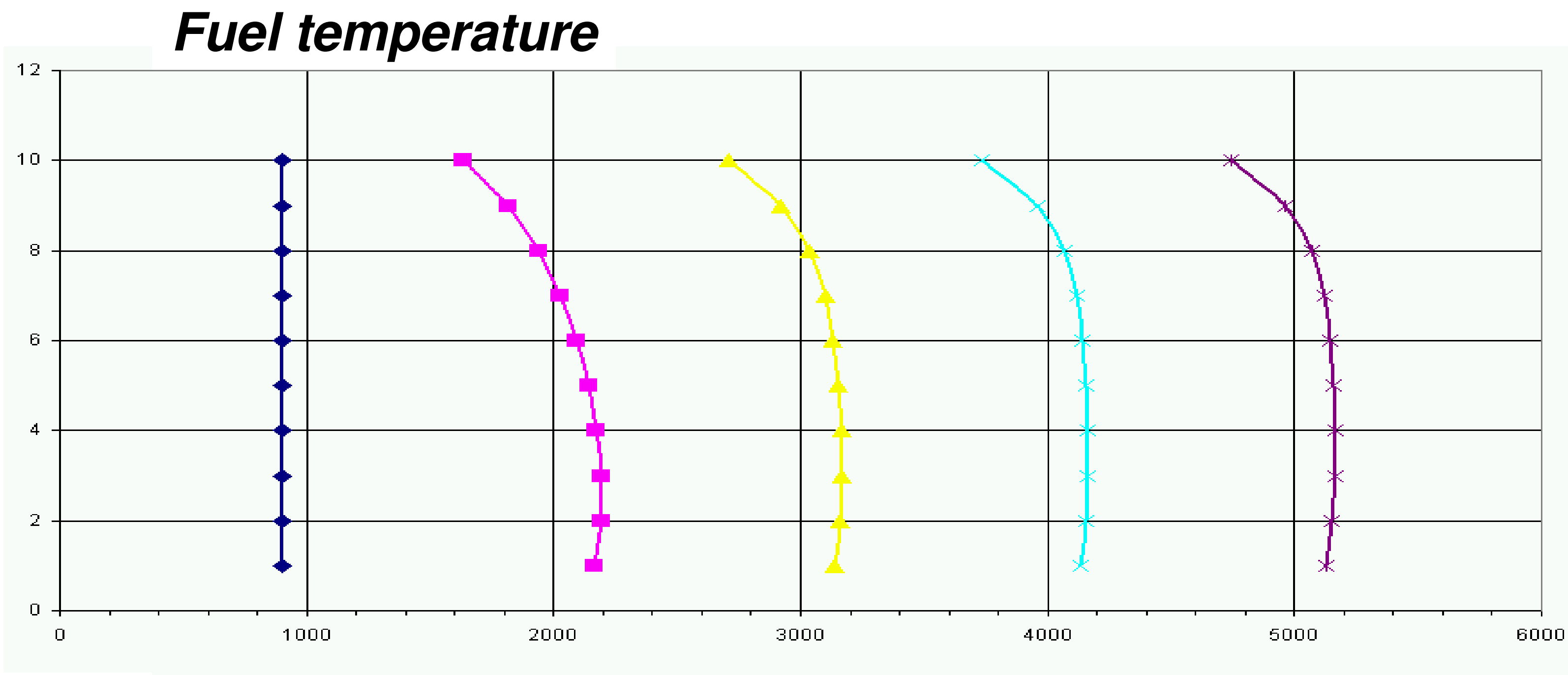
3D model

Example of application





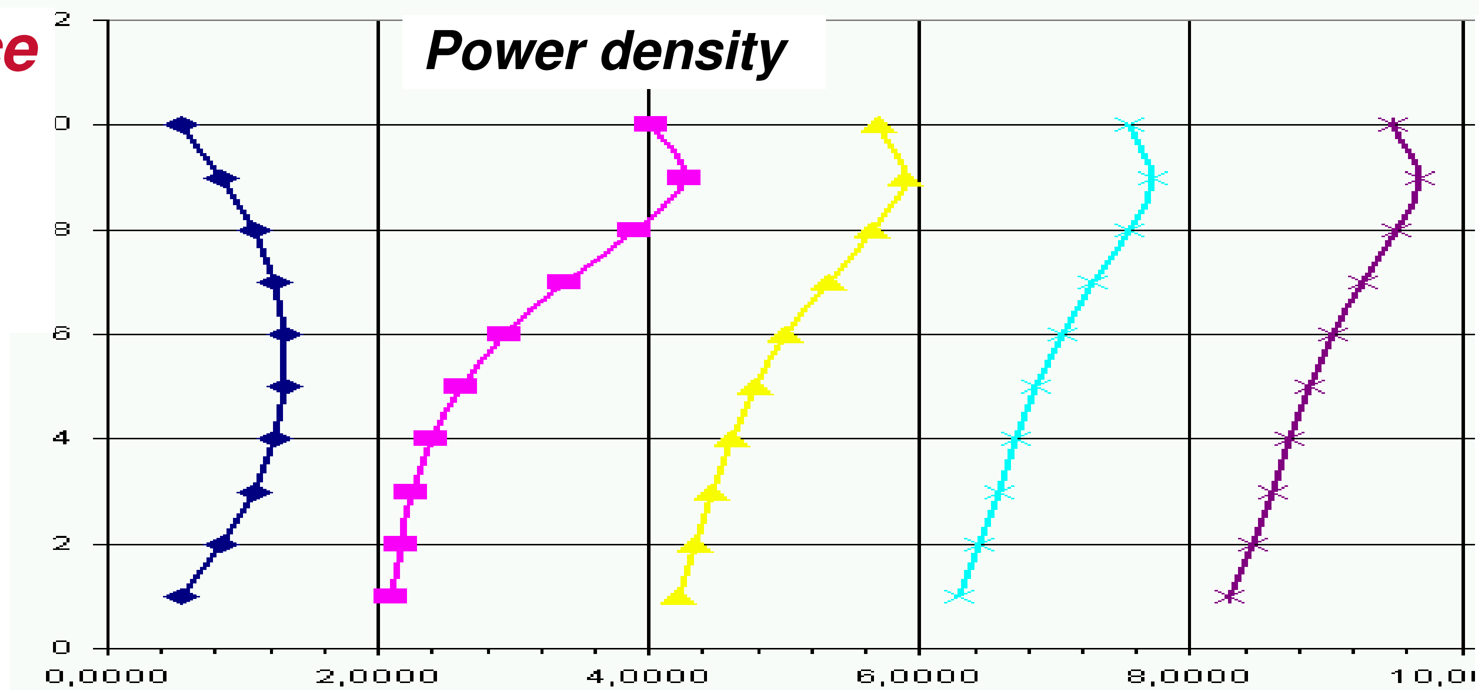
1 iteration ***Converged***



Convergence Process

VHTR

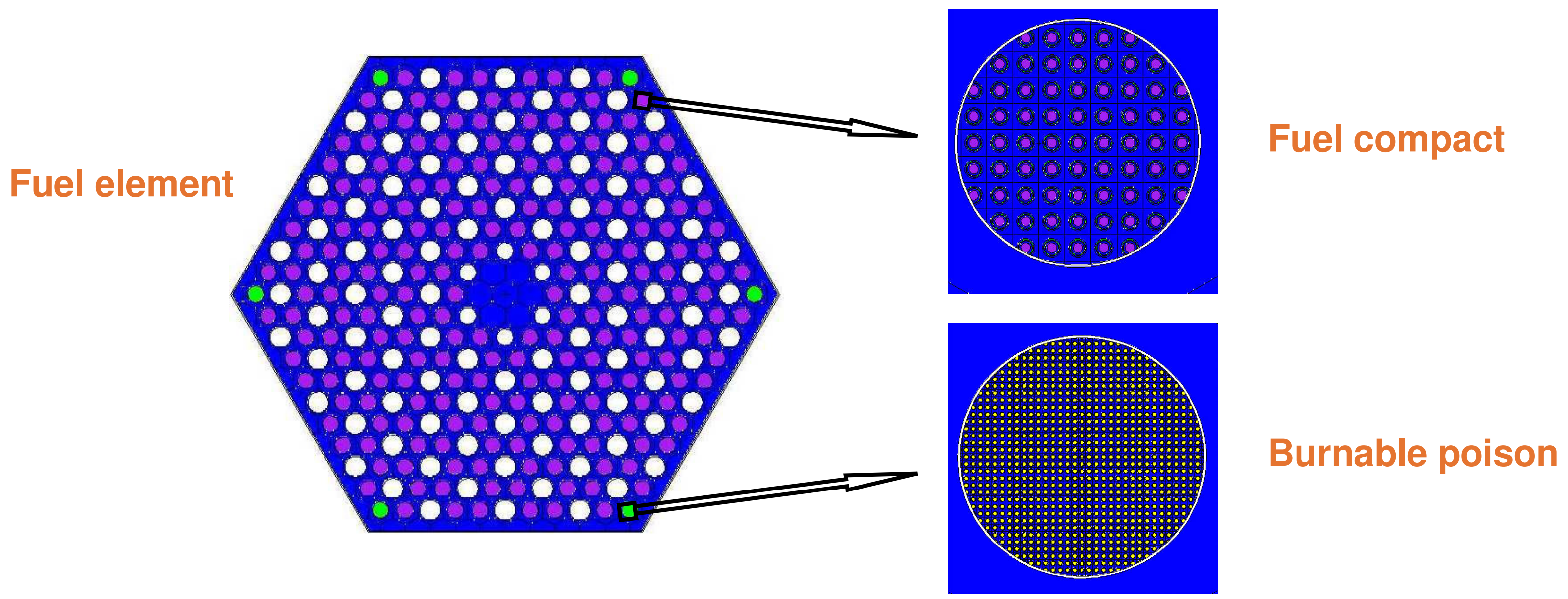
350-950



FRAMATOME ANP METHODOLOGY FOR HTR DECAY HEAT CALCULATION WITH MONTEBURNS

HTR Decay Heat Calculation

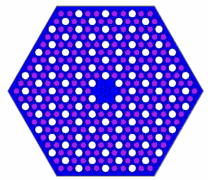
- **Decay Heat assessment is of prime importance for HTR design (concept of passive residual heat removal)**
- **Specificities of HTR fuel must be adequately modelled, in particular the geometric double heterogeneity**



⇨ ***Use of MONTEBURNS (code linking MCNP & ORIGEN2)***

HTR calculations with Monteburns

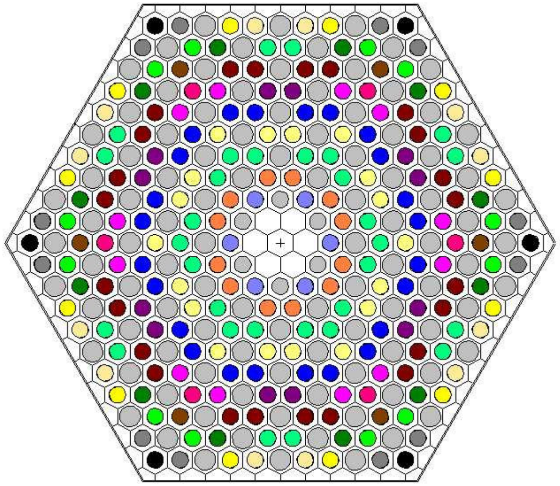
- **Geometry**
  - **2D infinite lattice, prismatic fuel element**



- **Fuel**
  - **UO_2 14% (120 000 MWd/t) and UO_2 20% (170 000 MWd/t)**
  - **Reprocessed Pu (without U) (500 000 MWd/t)**
- **Optimization of calculation parameters / desired accuracy, eg. :**
  - **Number of irradiated materials for the fuel**
- **Comparison finite core geometry / infinite lattice**

Optimization : number of depleting materials

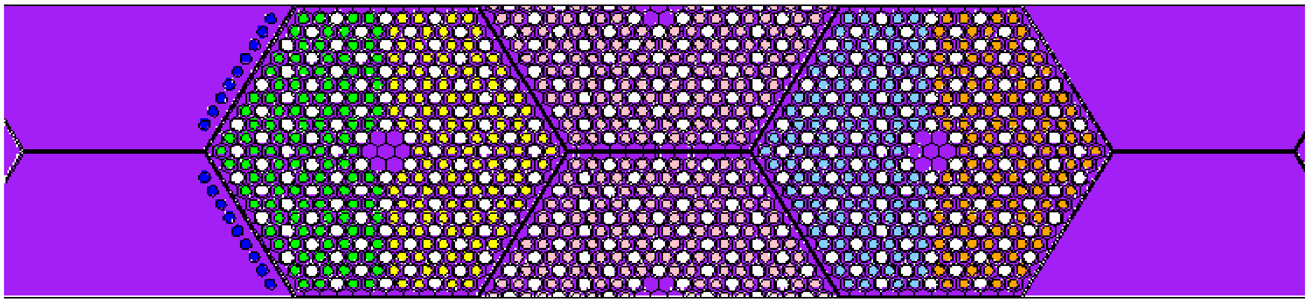
- **MCNP fuel element calculation**
  - **Calculation of the flux and reaction rates in each compact**
  - **Grouping of the compacts for which the results are close (differences < 1%)**
  - ⇨ **16 groups of compacts**



- **Comparison between 1 and 16 depleting materials**
  - **Impact on decay heat < 0.3%**
  - ⇨ **Calculations can be performed with 1 depleting material**

Comparison : Finite core geometry / Infinite lattice

- **Annular active core represented by a slab model with graphite side reflectors**



- **The slab model predicts lower values for decay heat**
  - **More thermal flux in outer fuel element → decrease in Pu240 captures → lower buildup of Pu241**
  - **Impact on decay heat < 3% (<1yr)**