# PRE-CONCEPTUAL DESIGN OF A HELIUM-COOLED ADS : He-EFIT

**P. Richard[a] – G. Rimpault[a] - J. F. Pignatel[a]**
**B. Giraud[b] - M. Schikorr[c] - R. Stainsby[d]**

a : CEA/DEN/DER Cadarache, 13108 Saint-Paul-lez-Durance, FRANCE

b : AREVA NP, c : FzK, d : AMEC-NNC

e-mail : pierre.richard@cea.fr

# Outline

- EFIT Missions/Basic Characteristics
- Design Approach
- Issues Addressed During the First Half of the Project
- He-EFIT Main Features
- Presentation of the current design : Spallation module, Core, Power Conversion Cycle, DHR Approach
- Conclusions – Next steps

## He-EFIT in the EURTOTRANS Project - Missions

- Within EUROTRANS_DM1, 3 different ADS/ADT are studied and assessed :
  - XT-ADS, Pb-Cooled EFIT, Gas-Cooled EFIT
- EFIT (European Facility for Industrial Transmutation) :
  - Pb-cooled EFIT is the reference solution
  - He-Cooled EFIT is the back up solution
- First mission assigned to EFIT : transmute efficiently Am and Cm
  - A transmutation efficiency for the elimination of minor actinides of 42 kg/$TWh_{th}$ has been defined as target for EFIT
  - In the PDS-XADS Project : achieved with a large power plant (Several Hundreds of MW)
- Electricity Production : goal is to have a plant efficiency higher than 40 % (close to fast neutron reactors) not including the accelerator
- Safety : as any nuclear facility the reactor has to operate safely. But the He-EFIT safety analysis has also to properly address ADT as well as gas-cooled plant peculiarities (MA containing fuels, sub-critical level, absorber/safety rods, He low heat capacity,….).

# EFIT Basic Characteristics

- Some basic characteristics had to be defined early in the plant design process
- Proton beam characteristics : essentially taken as an output from WP1.3
  - Energy set to 800 MeV which is currently considered as an upper limit : over 800 MeV, the radio-toxicity increase rapidly
  - Need for high proton beam intensity 18-24 mA
  - Number of beam trips : 5 per year (progress could be made before EFIT construction ??)
- Operating temperatures (Plant Efficiency) :
  - First assessment made ith Tin/Tout = 400/550 °C
  - Incentive to increase the ΔTcore from 150 °C to 200 °C : Tin/Tout = 350/550 °C Plant efficiency beyond the design objective (43.3 %)
  - Choice of the cladding material : SiC/SiCf to deal with the worst transients (LOCA, LOF)
- Fuel Characteristics (coherently with AFTRA studies) :
  - CERCER (MgO matrix) limit temperature at nominal conditions : 1380 °C
  - CERMET (Mo matrix) considered as back up solution : lower transmutation capabilities and higher cost due to $^{92}Mo$ enrichment

# He-EFIT Design Approach

1 – Spallation module design using the outcome of the PDS-XADS Project

2 - Define the Proton Beam Intensity (for a maximum proton energy of 800 MeV), the reactor power and the $K_{eff}$ (assuming the potential reactivity insertions and burn up swing which have to be checked later)

3 - Design the core taking into account the design objectives (MA burning, Keff,…) and the core design constraints (Fuel composition, cladding composition, pressure drops,…)

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4 - Define the approach for the DHR and design the DHR main components (blowers, HX,…)

5 - Design the primary system

6 - Design the Balance of Plant and Containment and implementation of the plant (cooling loops, confinement building, …)

Steps 2 and 3 required iteration loops with neutronics, T/H and geometry considerations

# Main Issues Addressed during the First Half of the Project (1/2)

- Target : Solid target made of W rods- Cooled by Helium
- S/A Characteristics :
  - S/A outer width over flats fixed to 137 mm : target size corresponding to 19 S/A at the centre of the core
- Core Design :
  - Core power decreased to 400 MWth (600 MWth at the beginning)
  - 3 zones core with different pin diameters
- Peaking factors :
  - Total peaking factor changed from 1.60 to 1.84 : iteration with neutronic calculations
- Other objectives and design constraints :
  - Flat Keff versus Burn Up
  - Reasonably low current requirement ≈ 20- 24 mA
  - Low pressure drop < 1.0 bar
  - Clad temperature limit < 1200°C (nominal cond.), < 1600°C (transient cond.),
  - Coolant speed < 50 m/s
- Others : Wrapper Thickness, Number of grids, …

# Main Issues Addressed during the first half of the Project (2/2)

- Cross-check with partners and modifications of the correlations for heat exchange coefficients, core pressure drops (making use of past projects) and fuel conductivity (According to DM3 recommendations) :
  - Rather good agreement :
    - Core composition $\Delta f < 0.05$ %
    - Fuel Max Temperatures $\Delta T < 20$ °C
    - Cladding Max Temperatures $\Delta T < 6$ °C
    - Pressure drops : incoherency in the Dh calculations but small consequences : $\Delta(\Delta P) < 0.034$ bar

- Safety :
  - Pressure drop limited to 1 bar for the core and 1.5 bar for the whole primary circuit

  $\Rightarrow$ Provisional value to be checked by appropriate transient calculations

  - DHR strategy - Comparison of different two approaches : "XADS-like" approach / GCFR approach
- Other items : to be addressed in the second half of the Project using as much as possible the background of both He-XADS and GCFR studies

# Main Features of the Gas-Cooled EFIT (1/3)

| Design Parameter | Value/Characteristic | Comments |
|---|---|---|
| **PLANT GENERAL CHARACTERISTICS** | | |
| Coolant | Helium at 70 bars | Identical to GCFR value |
| Core Power | 400 $MW_{th}$ | After iterations with neutronic calculations |
| Core Power Density | 55 $MW/m^3$ | 60 $MW/m^3$ proposed in June 2005 |
| Plant Efficiency | 43.3 % without acc. | Requirement : 40 % |
| Core Inlet/outlet Temp | 350°C/550°C | Delta T increased by 50 °C |
| Power conversion | Indirect cycle S-$CO_2$ with re-compression | |
| Accelerator | LINAC<br>E : 800 Mev<br>I : 18-24 mA | Over 800 MeV, Spallation Products have longer half-life ⇒ Upper limit fixed to 800 MeV |
| Target Unit | Window Target<br>Solid Target | W rods cooled by helium – Separate cooling of the window |

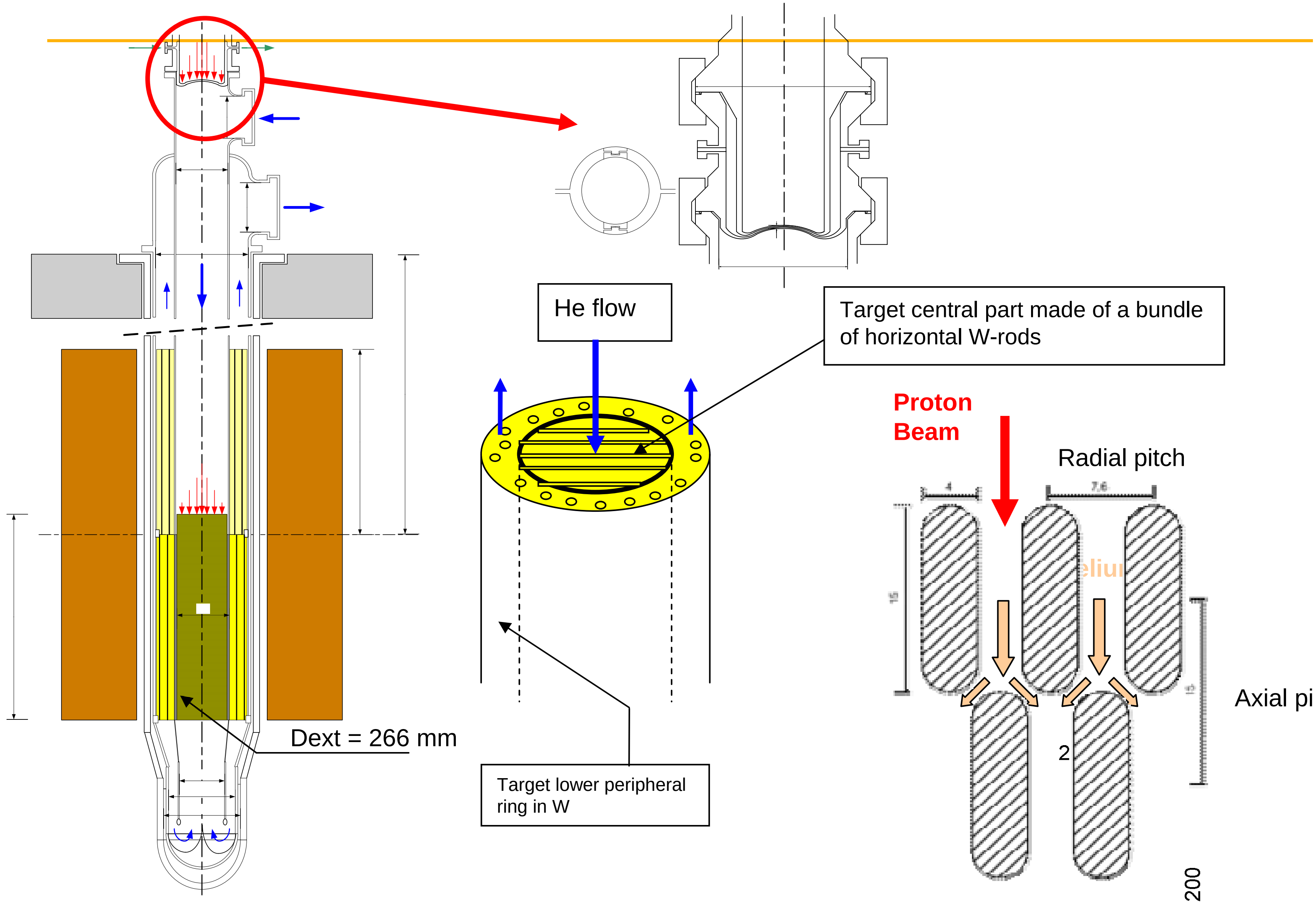
# Main Features of the Gas-Cooled EFIT (2/3)

| CORE GENERAL CHARACTERISTICS | | |
|---|---|---|
| Fuel Composition | (Pu, Am, Cm)$O_2$ + MgO | 50/50 % Fuel/Matrix ratio |
| Fuel (pellet) Power density | App. 200 W/cm$^3$ | To be adjusted after transmutation optimisation |
| Fuel content Ratio | 34 % (Pu/MA+Pu) | To be adjusted after transmutation optimisation |
| Fuel and MA Vectors | The Pu vector used is that resulting from a MOX fuel irradiated in PWRs at 45 GWj/t and cooled for 30 years | CEA hypothesis for the French reactors |
| Fuel Pin Spacer | Grid | 5 grid spacers |
| Fuel Assembly type | Wrapper | 4 mm thickness |
| Fuel Assembly cross section | Hexagonal | |
| Core zoning | 3 Zones | Different pin diameters |
| S/A pitch | 137 mm | Adjusted for an optimum target size |
| Peaking Factor | 1.839 | Same peaking factors considered in the three zones |
| Core height | 1.25 m | |
| Core Pressure Drop | Range 0.7-1 bar | Based on GCFR assessment. To be checked at a second stage by transient calculations |

# Main Features of the Gas-Cooled EFIT (3/3)

| | | |
|---|---|---|
| **PIN CHARACTERISTICS** | | |
| Cladding material | SiC/SiCf | |
| Cladding thickness | 1 mm | Thickness limited for Feasibility reasons (could be reduced to 0,.8 mm if necessary) |
| Fuel/Cladding Gap | 100 µm for 5.8 mm in Diameter – Changed proportionally to the pellet diameter | Provided by AFTRA |
| **DESIGN CRITERIA** | | |
| $T_{fuelmax}$ | 1380 °C | DBC cat. I |
| $T_{fuelmax}$ | 1580 °C | DBC cat. II |
| $T_{fuelmax}$ | 1780 °C | DBC cat. III |
| $T_{cladmax}$ | 1200 °C | DBC cat. I |
| $T_{cladmax}$ | 1300 °C | Long-term transient(>24h) |
| $T_{cladmax}$ | 1600 °C | Short-term transient(<24h) |
| **SAFETY ISSUES** | | |
| Protected transients | The plant shall be designed to accommodate PLOF/PLOCA | The analysis of protected transients similarly to the XADS is to be done (transient list to be checked with WP1.5) |
| DHR | Under nominal pressure : Nat. circulation<br>Depressurised cond. : active DHR systems to remove Decay Heat | Decay Heat Curve deduced from the benchmark carried out within WP1.1 |

# Solid Target with “Cold” Window Concept

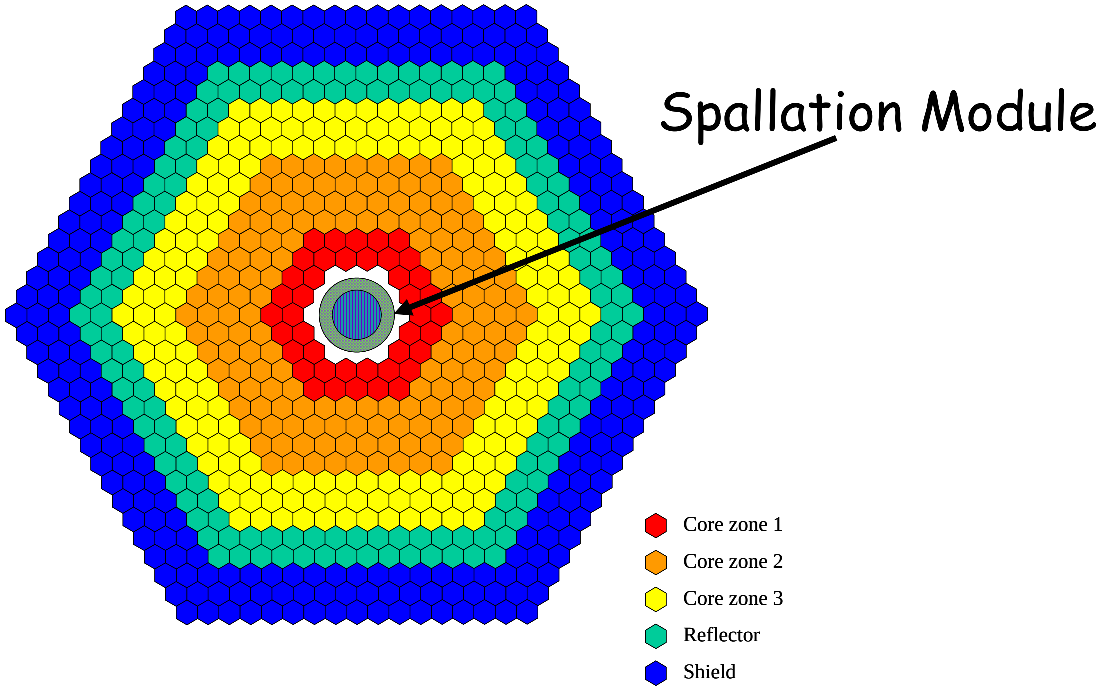


# Current Design – Core (1/2)

- A three zone core has been preliminarily studied :
  - Zone 1 (inner) : 45 MWth, 42 sub-assemblies
  - Zone 2 (intermediate) : 165 MWth, 156 sub-assemblies
  - Zone 3 (outer) : 191 MWth, 180 sub-assemblies

- The main design features considered are the following :
  - Core height : 125 cm
  - External width over flat : 137 mm
  - Matrix volumic fraction in the fuel pellet : 50 %
  - Fuel (fuel+matrix) fraction in the different zones : 11%, 21.5 % and 35 % (for respectively zone 1, 2 and 3)
  - The total form factor was assumed to be the same in the three zones (1.839)

# Current Design – Core (2/2)




He-EFIT Core design

Remarks :

1 - Core pressure drops are not equilibrated (too many design constraints). They are respectively 0.84, 0.74 and 1 bar in zone 1, 2 and 3 ⇒ some gagging will be necessary

2- The pellet diameter in zone 1 is rather small (2.3 mm). To be increased to 4-5 mm according to AFTRA recommendations (the number of pin rows per S/A can be reduced to 11 or even 10)

# Current Design – Detailed Characteristics (1/2)

| **EFIT Type** | **He-EFIT** | | |
|---|---|---|---|
| **Thermal Power ($MW_{th}$) - Volumic Power** | **400 - 55 $MW/m^3$** | | |
| Coolant Type | He | | |
| Coolant Pressure (bar) | 70 | | |
| Inlet Temperature (°C) | 350 | | |
| Outlet Temperature (°C) | 550 | | |
| Plant Efficiency | 43.3 % - Indirect S-$CO_2$ cycle with re-compression | | |
| Cladding Type - Thickness | SiC/SiCf -Thickness = 1 mm | | |
| Spallation module | Solid W He cooled | | |
| Accelerator | LINAC - E = 800 MeV - I = 24 mA | | |
| **Zone** | **1 (inner)** | **2 (intermediate)** | **3 (outer)** |
| **Matrix Type** | **MgO** | **MgO** | **MgO** |
| Matrix Fraction | 50% | 50% | 50% |
| **Core Geometry** | | | |
| Number of fissile sub-assemblies | 42 | 156 | 180 |
| Fissile Height (H) | 1.25 m | 1.25 m | 1.25 m |
| Wrapper Width over outer Flats | 137 mm | 137 mm | 137 mm |
| Wrapper Thickness | 4.0 mm | 4.0 mm | 4.0 mm |
| Inter-Wrapper Gap | 5.0 mm | 5.0 mm | 5.0 mm |
| **Coolant Volumic Fraction (%)** | **49.80%** | **44.75%** | **37.19%** |
| **Fuel + Matrix Volumic Fraction (%)** | **11.16%** | **21.70%** | **34.98%** |
| **Structure Volume Fraction (%)** | **39.05%** | **33.56%** | **27.83%** |

# Current Design – Detailed Characteristics (2/2)

| Zone | 1 (Inner) | 2 (Intermediate) | 3 (Outer) |
|---|---|---|---|
| **Sub-Assembly Bundle Geometry** | | | |
| Number of Pin rows per S/A - Pin per S/A | 12 - 469 | 8- 217 | 5 - 91 |
| Pin outer Diameter | 4.38 mm | 6.87 mm | 11.57 mm |
| Pitch | 5.89 mm | 8.60 mm | 13.20 mm |
| Pellet/Cladding Gap | 0.040 mm | 0.081 mm | 0.160 mm |
| Pellet Diameter | 2.30 mm | 4.71 mm | 9.25 mm |
| **Core Thermal-Hydraulics** | | | |
| Average Coolant Speed in the Fissile Core | 30 m/s | 35 m/s | 45 m/s |
| Max Pin Linear Power | 33 W/cm | 72 W/cm | 171 W/cm |
| **Total Core Pressure Drop** | **0.84 Bar** | **0.74 Bar** | **1.01 Bar** |
| **Hottest Channel Thermics** | | | |
| **Max Cladding Temperature in the Hottest Channel** | **686 °C** | **700 °C** | **711 °C** |
| **Max Fuel Temperature in the Hottest Channel** | **792 °C** | **950 °C** | **1310 °C** |

➢Under nominal conditions :
- ❖Large Margins on cladding temperature (1200 °C under normal operating conditions)
- ❖Reasonable margins the fuel temperature (1380 °C)
- ❖On pressure drops : GCFR studies show the potential to increase the pressure drop ??

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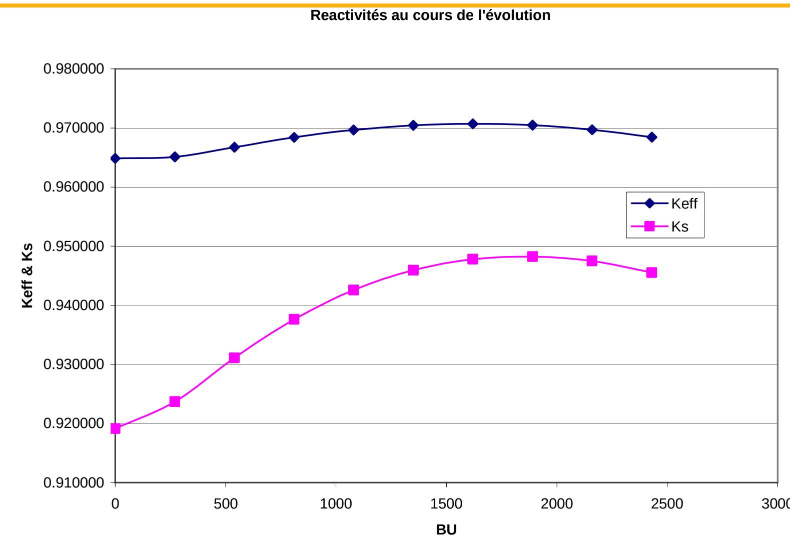
# On-going Neutronic Assessment

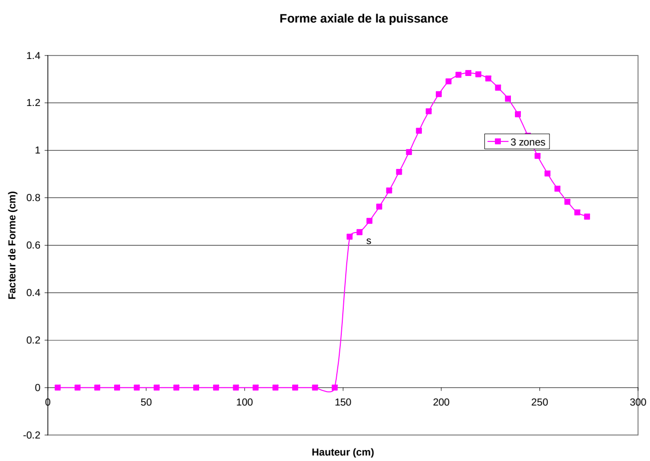
Monte-Carlo (MCNPX) simulation
ERANOS evolution calculation

| ELEMENT | Kg | Kg/TWhth |
|---|---|---|
| U | 27.42 | 1.02 |
| Np | -30.32 | -1.13 |
| Pu | 176.47 | 6.59 |
| Am | -1463.36 | -54.64 |
| Cm | 178.90 | 6.68 |
| TOTAL | -1110.89 | -41.48 |

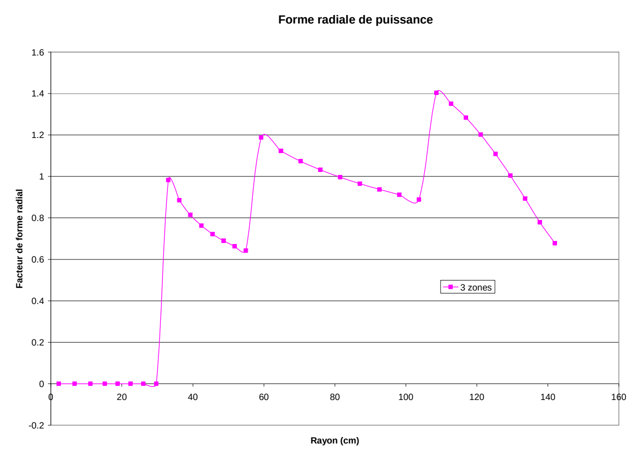
Transmutation rate : close to the target value




Keff evolution versus Burn up




Axial Peaking Factor




Raxial Peaking Factor

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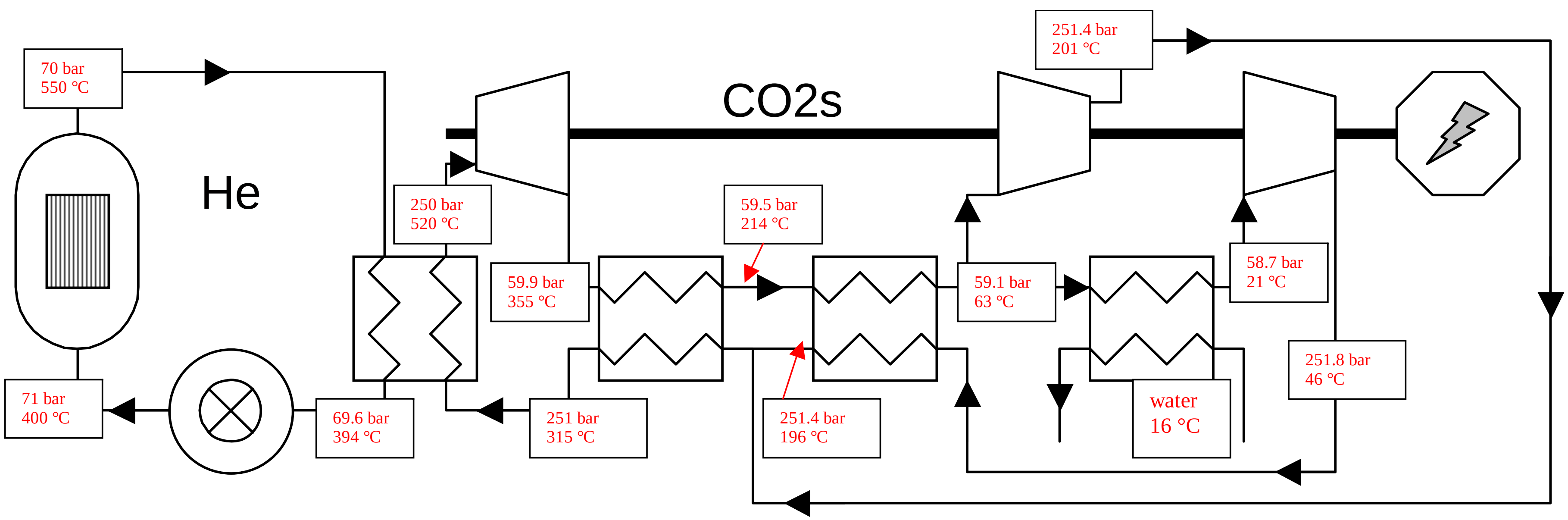
# Power Conversion Cycle

- Assumptions :
  - Indirect Supercritical $CO_2$ cycle with re-compression
  - $CO_2$ remains super-critical : $CO_2$ characteristics above the Critical Point (74 bar/32 °C). This avoids the presence of water in the compressors (badly known behaviour of the components)

- Parametric study on the core inlet temperature : +/- 50 °C

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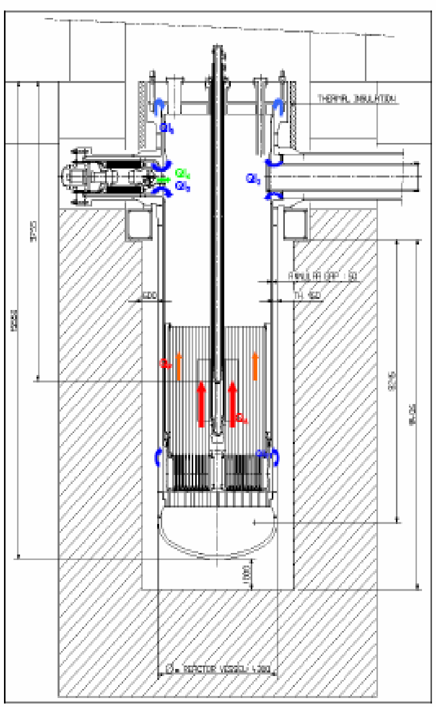
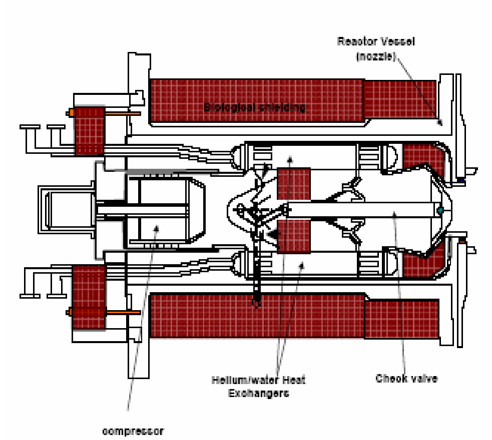
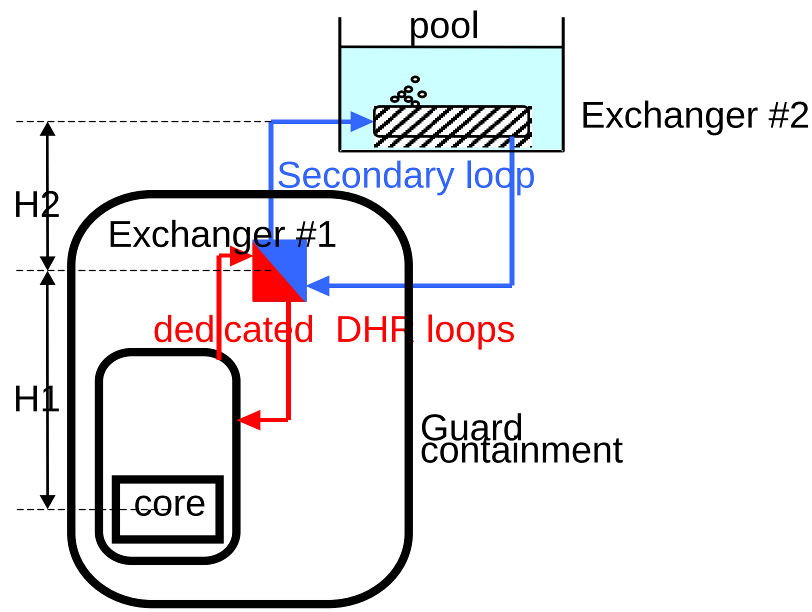
# Decay Heat Removal Strategy

- Approach Compare different strategies :
  - Active/Passive
  - Guard Containment/No guard Containment
- Background :
  - PDS-XADS (He-Cooled XADS)
  - GCFR Approach





# DHR for EFIT

**For He-EFIT:**

→The PDS-XADS solution seems better

→Proton beam +Spallation module →complexity → Guard containment not suitable

**If the full depressurization is chosen, a strategy must be defined** :

→The blowers must work 1 to 70 Bars : Requires High Power and a complex Blower Design (or 2 systems : 1-10 bars and 10/70 bars? )

OR

→Blowers can work only at low pressure :

→ Action for fast depressurization System systematically used (safety)

→ SIMPLIFICATION of procedures

**System implementation :**

→ 3 DHR loops designed for 100 %

→ 2 Solutions : Loops integrated on the vessel/Ex-vessel loops

## Conclusions (1/2)

**Current Design :**

- A three zone core has been preliminarily studied :
  - Zone 1 (inner) : 45 MWth, 42 sub-assemblies
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- The main hypothesis and/or design objectives accounted are the following :
  - Core height : 125 cm
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  - Fuel (fuel+matrix) fraction in the different zones : 11%, 21.5% and 35 % (for respectively zone 1, 2 and 3)
  - Matrix volume fraction in the fuel pellet : 50 %
  - The total form factor was assumed to be the same in the three zones (1.839)

- DHR Approach defined

## Conclusions (2/2)

- Detailed neutronic calculations :
  - Neutron source behaviour by the mean of MCNPX Calculations
  - Core neutronics by the means of MCNPX and ERANOS calculations.

**Next steps :**

- Another iterative loop will be required on the core design to fully fit with the He-EFIT Objectives and Design Criteria (Transmutation rate, pin size in the inner zone,….)

- Even if the current core design is not fully defined, He-EFIT main characteristics (core power, main core dimensions) are sufficiently precise to go ahead with :

  - Safety Approach/DHR strategy :
    - Pre-sizing of the DHR loop components
    - CATHARE/SIM-ADS modelling
  - Remontage – System Integration