





# **Plutonium and Minor Actinides Management in Thermal High-Temperature Reactors – The EU FP6 Project PUMA**

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*<sup>1)</sup>On behalf of the PUMA consortium*



# Generalities



- PUMA is a 3-year “STREP” from the EURATOM 6th Framework Programme (FP6)
  - **1st September 2006 – 31st August 2009**
- A consortium with **16** partners
  - From **9** countries (8 EU Member States + the USA) + the EC/JRC
  - Coordinated by NRG (The Netherlands)
- A budget of **3.580 M€** with EC funding of **1.850 M€**
  - **255** person-months of work
  - **50** deliverables



# Technical objectives



Provide key elements for the use of contemporary and future (thermal) gas-cooled reactor designs as **burner for plutonium and minor actinides**. Focus on:

- Pu/MA burner reactor physics & optimisation
- Fuel design & manufacturing
- Impact on fuel cycle and economics
- Qualification of analysis tools

→ Main question:

**“Can the HTR be used as transmutation system for Pu and MA?”**



# Consortium



**LISTO**<sub>be</sub>  
Science & Technology Consulting  
Energy Business Consulting



Leader WP3



Coordinator  
Leader WP1 / 4

**EUROPEAN COMMISSION**  
DIRECTORATE-GENERAL  
**Joint Research Centre**  
Institute for Transuranium Elements

Leader WP2



Project Management Office





# Consortium



Partner No.	Partner acronym	Partner name	Country	Main contact Person(s)
1	NRG	Nuclear Research & consultancy Group	The Netherlands	J.C. Kuijper (coordinator)
2	AGH	University of Science and Technology of Cracow	Poland	J. Cetnar
3	BN	Belgonucleaire	Belgium	S. Shihab G. Toury
4	CIRTEN		Italy	N. Cerullo G. Lomonaco
5	EDF	Electricité de France	France	E. Girardi
6	GA	General Atomics	USA	F. Venneri
7	USTUTT	University of Stuttgart	Germany	W. Bernnat
8	JRC-ITU	Joint Research Centre - Institute for TransUranics	EU Germany	J. Somers
9	KTH	Royal Institute of Technology	Sweden	J. Wallenius
10	LISTO	LISTO bvba	Belgium	L. Van Den Durpel
11	NEXIA	NEXIA Solutions	UK	T. Abram
12	NNC		UK	D. Millington
14	LGI	LaGrange Innovation	France	V. Chauvet
15	DUT	Delft University of Technology	The Netherlands	J.L. Kloosterman
16	FZJ	Forschungszentrum Juelich	Germany	H. Werner
17	AREVA	AREVA	France	C. Trakas

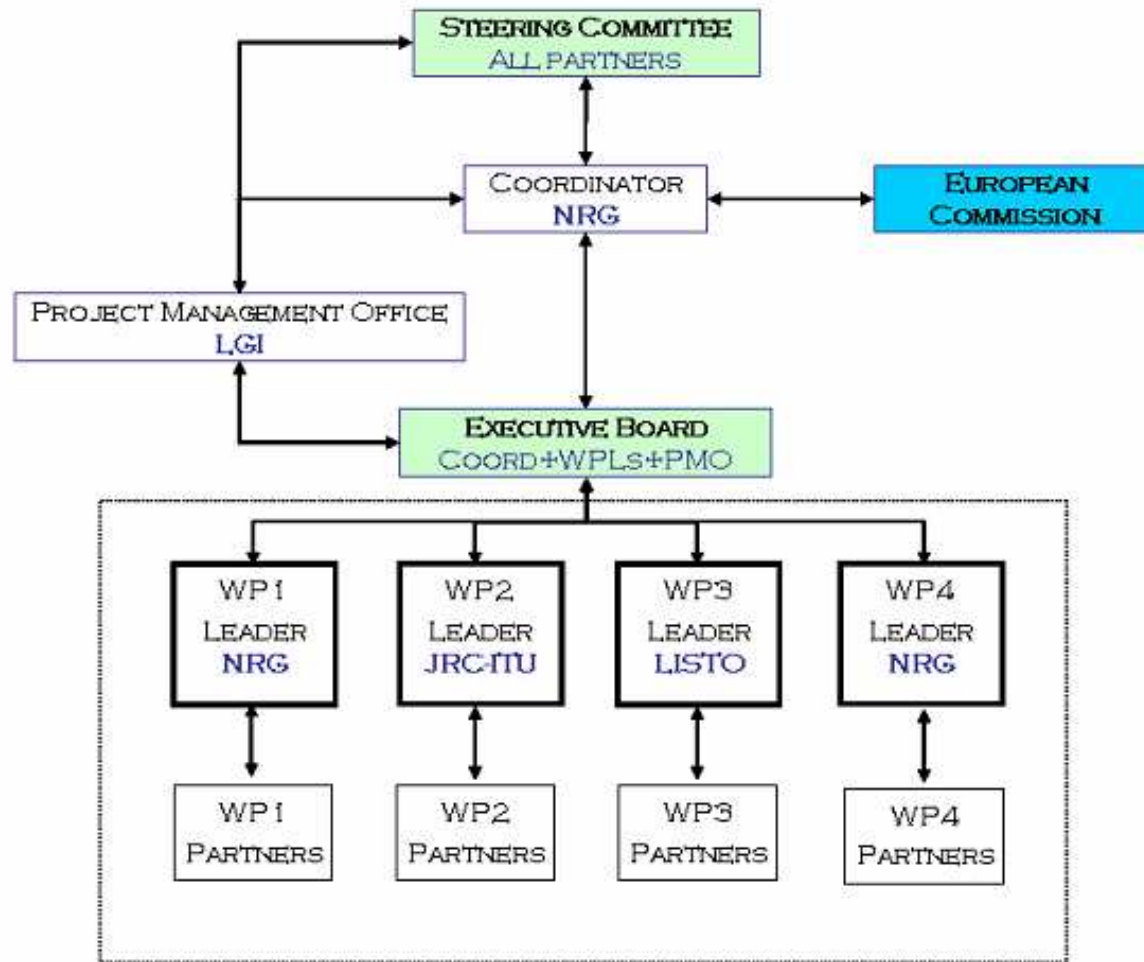
- Clustering foreseen with other EU FP6 projects



- Cooperation foreseen with international institutions



## PUMA MANAGEMENT



- Steering Committee: main management body
- Executive Board: day-to-day management
- Project Management Office (PMO): support to the coordinator
- 3 technical Work Packages + 1 for Management & Communication
- 6-monthly progress meetings of all bodies



# Work Packages



## WP1

“ Pu and MA transmutation/utilisation in HTR  
& additional qualification of analysis tools ”

## WP2

“ Pu and MA fuel for HTRs ”

## WP3

“ Impact on economics and entire fuel cycle ”

## WP4

“ Management, Communication  
and Knowledge Transfer ”



# Description of WP1



## Pu/MA transmutation/utilisation – full core simulation

- Lead: NRG
- Partners: NRG, AGH, BN, EdF, IKE, KTH, UNIPI/CIRTEC, GA, NEXIA/NNC, FZJ, FANP
- Objectives
  - Demonstrate full potential of HTR designs, pebble bed (PBMR) and prismatic block type (GT-MHR) reactors, to utilise/transmute Pu and MA fuel
  - Identify necessary additional qualification of assessment tools (V&V)
- Activities
  - Investigation of HTR core physics for Pu and MA fuel cycles, with emphasis on (transmutation) performance, within constraint of safe operation
  - Calculate helium production and damage in Pu/MA CPs
  - Identify necessary additional qualification of tools and opportunities to obtain experimental data to base it upon
  - Assessment of proliferation resistance
  - Analysis of a reference system (pebble or block type)



## V/HTR core physics investigations



- Pu/MA deep burn in pebble-bed V/HTR (incl. IMF, e.g.  $(Zr, Y, Am)O_2 / (Zr, Y, Ce)O_{2-x}$  or  $(CeAm)O_{2-x}$ )
- Th/Pu fuel cycle in pebble-bed V/HTR
- Pu/MA deep burn in prismatic V/HTR
- Th/Pu fuel cycle in prismatic V/HTR
- Reactivity transients of Pu/MA fuelled V/HTR (safety!)
- Integrated LWR-HTR-GCFR symbiotic fuel cycles



## Objectives

- Obtain reference values for (calculated) parameters characterising (transmutation) performance and safety
- Compensate for differences caused by different code systems (and associated nuclear data)

## Selected reference systems (and fuel cycles)

- Pu-loaded PBMR-400, representing pebble-bed type
- Pu-loaded GT-MHR, representing prismatic block type

Some simplifications to geometry (e.g. “flat bottom”) as emphasis of studies is on “transmutation” performance



## Pu-loaded PBMR-400 (annular core)

PBMR Characteristic	Value
Installed thermal capacity	400 MW(t)
Installed electric capacity	165 MW(e)
Load following capability	100-40-100%
Availability	$\geq 95\%$
Core configuration	Vertical with fixed centre graphite reflector
Fuel	TRISO ceramic coated U-235 in graphite spheres
Primary coolant	Helium
Primary coolant pressure	9 MPa
Moderator	Graphite
Core outlet temperature	900°C.
Core inlet temperature	500°C.
Cycle type	Direct Brayton
Coolant mass flow rate	192.7 kg/sec
Cycle efficiency	$\geq 41\%$
Effective annular core height	11 meters

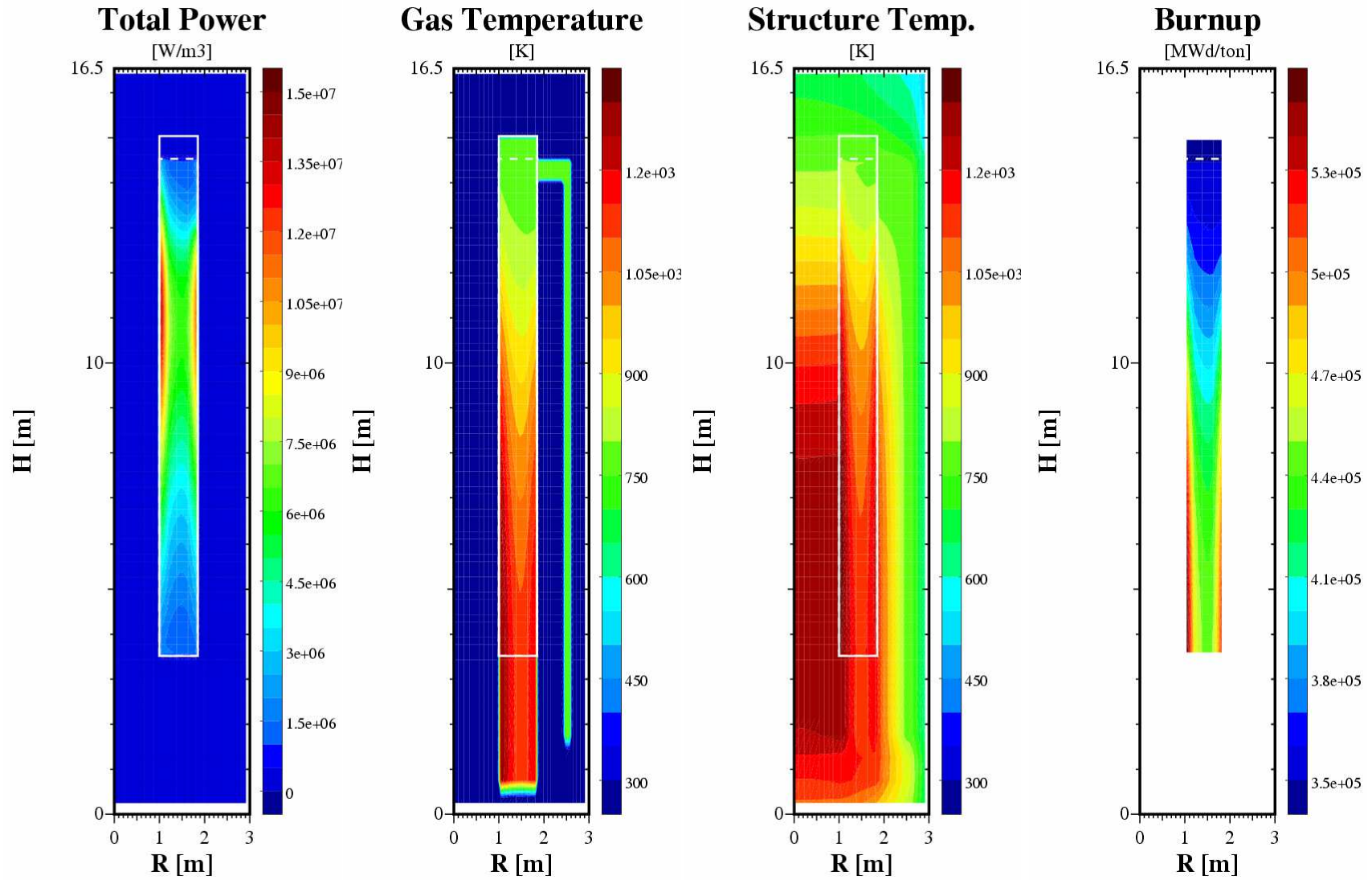


## Reference pebble-bed system



- Multi-pass (“MEDUL”) fuelling scheme
- Recycling: 1500 pebbles/day; 250 fresh pebbles/day (equilibrium)
- Discharge burn-up  $\sim 760$  MWd/kg
- Fuel pebbles:

Diameter	6.0 cm
Diameter of fuelled zone	5.0 cm
Kernel diameter/material	0.24 mm / PuO <sub>2</sub>
Fuel loading	2.0 g Pu <sub>tout</sub> initial per pebble
Pu vector	2.59/53.85/23.66/13.13/6.7
Pu238/239/240/241/242/	8 wt%





## Pu-burning capabilities (example)



### Transmutation capabilities Pu-fuelled pebble bed HTR

Table I Pu-burning capabilities (gram)

Burn-up (MWd/kg)	Pu	Cm	Am	U	Np
0.0	1.0	0.0	0.0	0.0	0.0
7.60E+02	1.457E-01	4.859E-02	3.971E-02	6.711E-04	6.817E-06

Table II Pu vectors for fresh and discharged fuel (fraction)

Burn-up (MWd/kg)	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
0.0	2.590E-02	5.385E-01	2.366E-01	1.313E-01	6.780E-02
7.60E+02	1.598E-02	1.887E-03	7.025E-03	5.372E-03	1.155E-01

The discharged amount of Pu reduces to 14.6 % of the original amount, while the total amount of actinides (U up to Cm) is reduced to 23.5 %. Table II shows the Pu-vector for fresh and discharged fuel. The fissile Pu-fraction is reduced from 67 % to less than 20 %.



# Description of WP2



## Pu and MA fuel for HTRs

- Lead: JRC-ITU
- Partners: NRG, BN, General Atomics, JRC-ITU, KTH, NEXIA, TUD, FZJ
- Objectives:
  - Establishment of helium behaviour in both Pu and MA kernels and PyC and SiC coating layers
  - Development of helium and swelling behaviour models for coated Pu and MA particle fuels
  - Further development of fuel performance models appropriate to HTR CP fuel
  - Design of coated particles suitable for ultra high burn-up of Pu and MA kernels as impregnated Inert Matrix Fuel (IMF)
  - Provision of a limited set of options for detailed neutronic calculations in WP1 and implications on the fuel cycle in WP3
  - Design of an irradiation facility meeting the requirements for a future irradiation test in the HFR Petten



From the fabrication standpoint, it preferred to separate Pu, so that the bulk of the fuel can be manufactured in a facility without excessive shielding. In PUMA, the U/Pu separation philosophy is followed and the fuels for PUMA are considered as heterogeneous of the form:

- PuO<sub>2</sub> (probably with NpO<sub>2</sub>);
- MAO<sub>2</sub> (Cm is excluded and should be separated and stored to permit decay);
- (Pu,MA)O<sub>2</sub>, whereby the Pu:MA ratio is significantly lower than in spent fuel.

As impregnated in a Zr/Y/CeOxyde inert matrix

Actinide infiltration into porous precursor kernel

Diluting inert matrix for HTR actinide (An Pu, Am or Np)

	Matrix	Fuel/target
YSZ	$Zr_{0.85}Y_{0.15}O_2$	$(Zr_{0.85}Y_{0.15})_{1-z}An_zO_2$
YSZ-Ce	$(Zr_{0.85}Y_{0.15})_{1-y}Ce_yO_2$	$((Zr_{0.85}Y_{0.15})_{1-y}Ce_y)_{1-z}An_zO_2$
Ceria	$CeO_2$	$Ce_{1-z}An_zO_2$
PYR (pyrochlore)	$Zr_2Ce_2O_7$	$(Zr_2Ce_{2-z}An_z)O_7$
Zr doped $Y_2O_3$	$(Y,Zr)_2O_3$	$(Y,Zr,An_z)_2O_3$
Graphite	C	C + $AnO_2$

Keep kernel size at 500 micron



# Description of WP3



## Impact on economics and entire fuel cycle

- Lead: LISTO
- Partners: LISTO, NRG, NEXIA, FANP, KTH, GA, NNC, FZJ, CIRTEN
- Objectives:
  - Assess potential future roles for (V)HTRs in delivering energy products, while performing a TRansUranium (TRU) management function in a nuclear reactor park
- Activities:
  - Characterisation of HTR technology , associated fuel cycle infrastructure and waste management technologies
  - Assess the role(s) of HTRs
  - Sensitivity/uncertainty analysis
  - Several scenarios will be investigated and intercompared



# Fuel cycle aspects



- The *technological impact* of HTRs fulfilling a TRU-management function on the whole nuclear energy park and especially on the nuclear fuel cycle within Europe's nuclear reactor park;
- The *economics* and the potential market penetration for such HTRs and especially the economic impact on HTRs when performing a TRU-management role in future nuclear energy systems;
- The *environmental* facet looks into a life cycle inventory analysis for HTRs and especially to the fuel cycle aspects such as (secondary) waste arising, various waste management options, separated fissile material inventories and losses in the nuclear fuel cycle, as well as into non-nuclear material streams;
- The *socio-political* facet focuses essentially on the proliferation risk of nuclear energy systems involving HTRs with TRU-management role



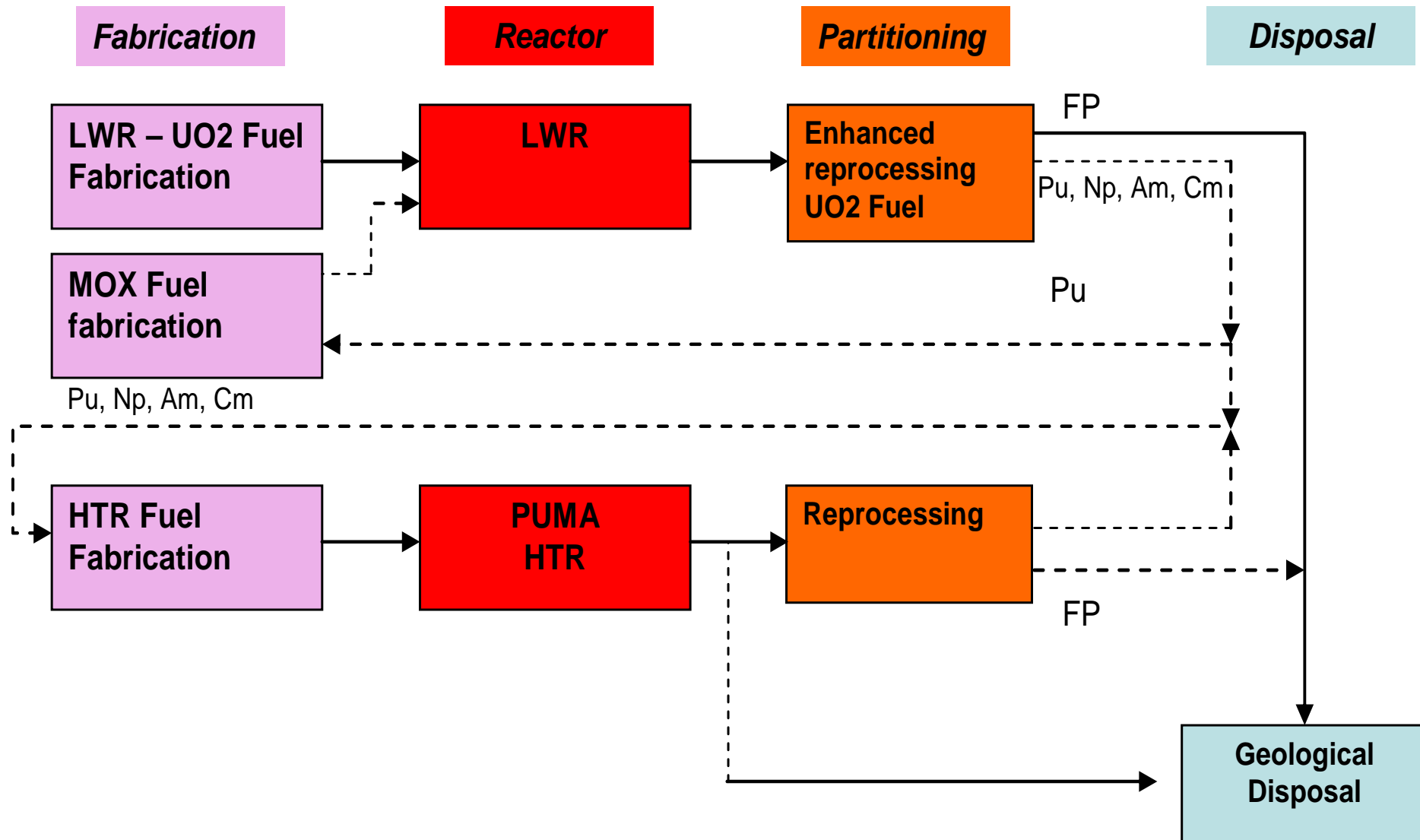
## Scenarios to be investigated



- European LWR park without V/HTR (reference)
- European LWR park without V/HTR + Gen-III LWR with OTC and mono-Pu recycling
- Mixed LWR and V/HTR park, V/HTR in OTC mode
- Mixed LWR and V/HTR park, V/HTR as TRU burner
- Mixed LWR, V/HTR and (S)FR reactor park



# Fuel cycle for PUMA fuel





# Description of WP4



## Management, Communication, Knowledge Transfer

- Lead: NRG
- Partners: NRG, LGI, IKE
- Activities:
  - Define all project management activities of Coordinator and PMO
  - Contractual, administrative and financial management
  - Work progress monitoring
  - Definition of the project's and consortium's internal procedures
  - Organisation, coordination and support for activities of dissemination of knowledge (contribution to RAPHAEL EURO COURSE on V/HTR)



## Conclusion - Summary



- The EU FP6 PUMA project has been underway since 1<sup>st</sup> September 2006
- Main goal: to provide key elements for the use of contemporary and future (thermal) gas-cooled reactor designs as **burner for plutonium and minor actinides**
- Core physics investigations aim at optimising CP fuel and reactor characteristics for Pu/MA loaded V/HTR core
- Explore new CP designs
- Impact of introduction of Pu/MA-burning V/HTRs on entire fuel cycle and future nuclear energy mix
- PUMA contributes to technological goals of Gen IV International Forum