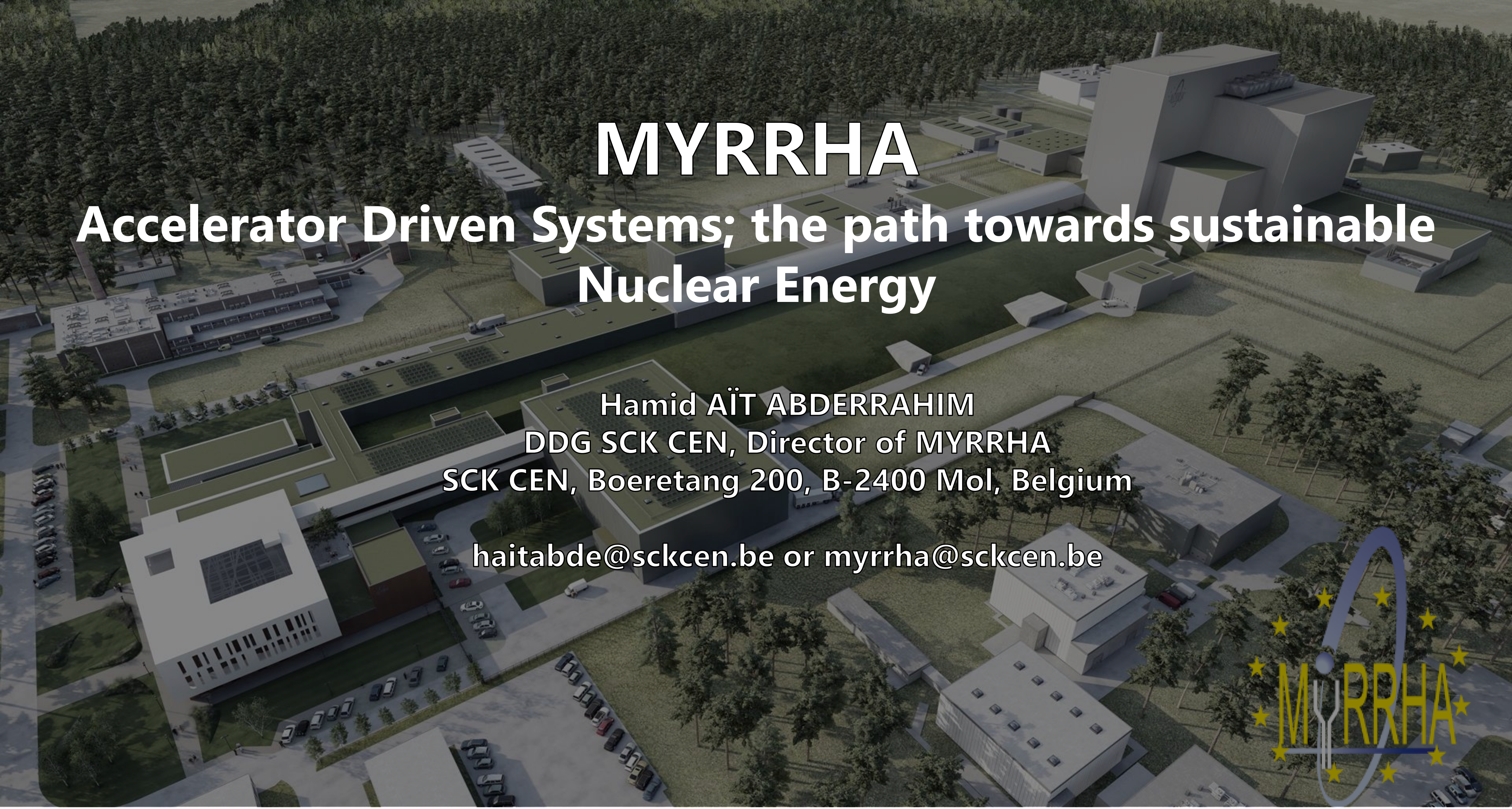


MYRRHA

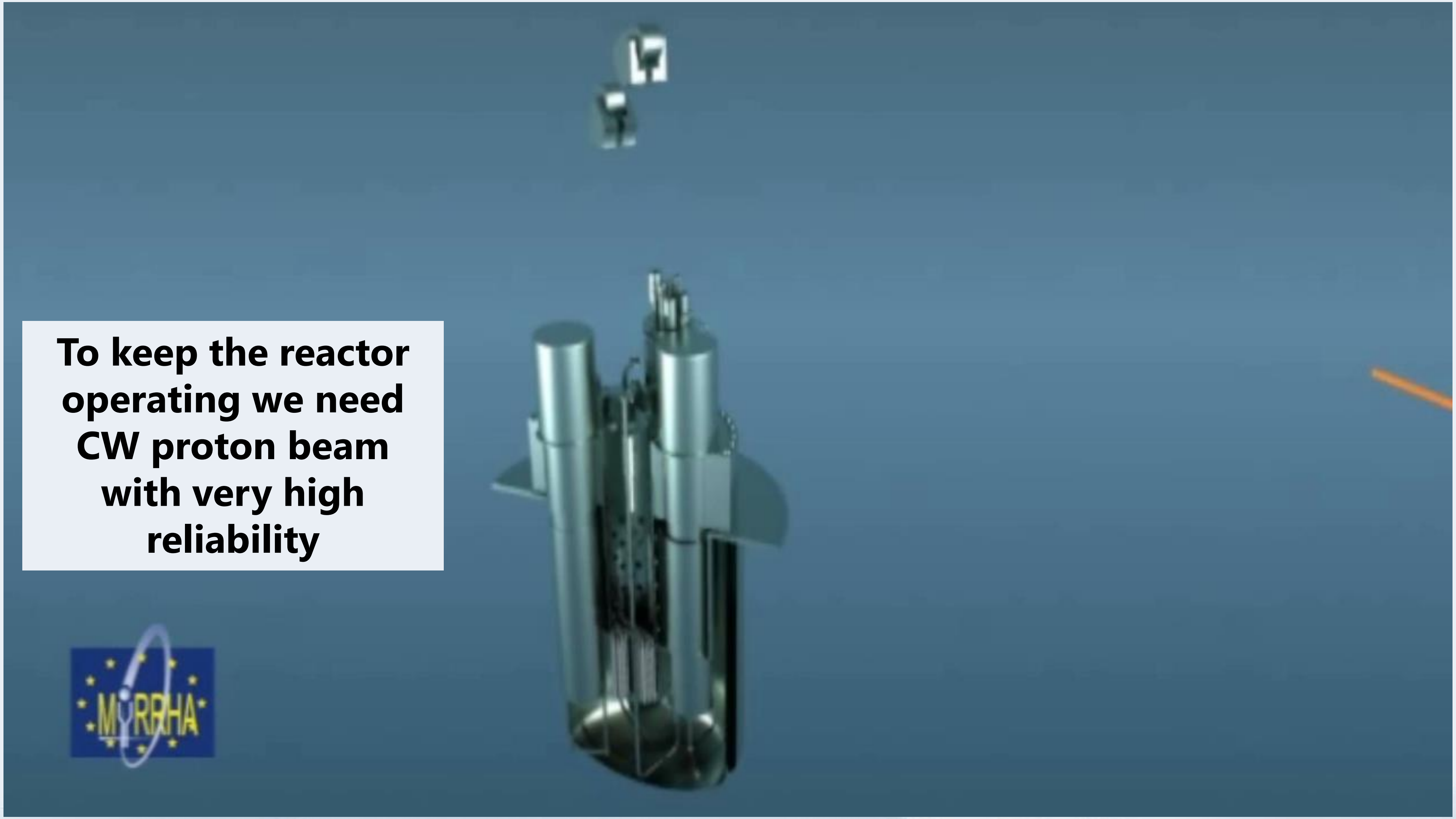
Accelerator Driven Systems; the path towards sustainable Nuclear Energy

Hamid AÏT ABDERRAHIM
DDG SCK CEN, Director of MYRRHA
SCK CEN, Boeretang 200, B-2400 Mol, Belgium

haitabde@sckcen.be or myrrha@sckcen.be

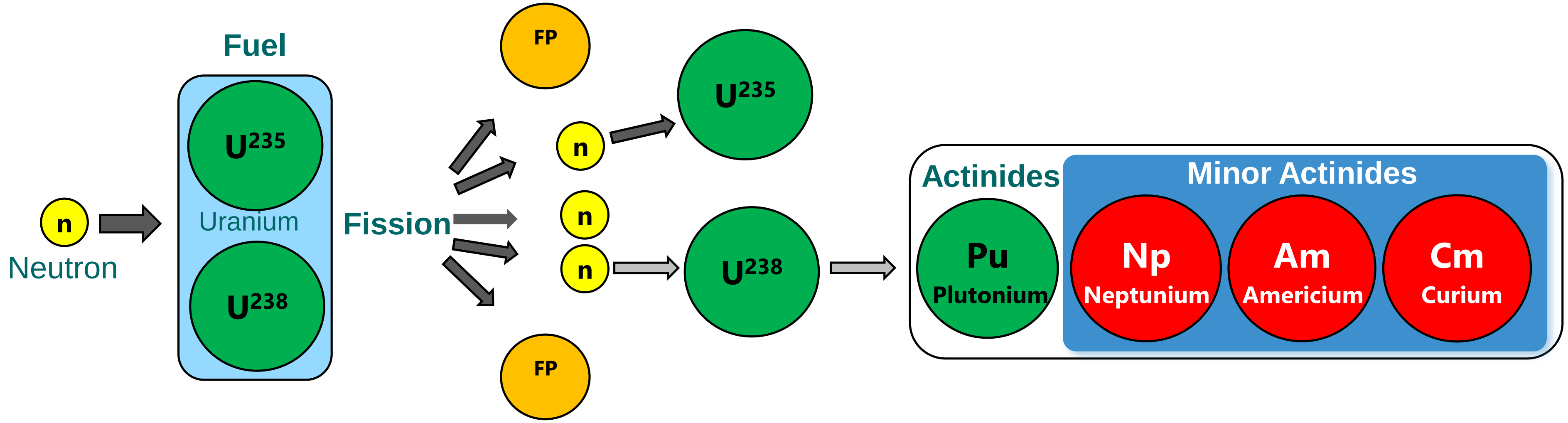
TRIUMF Science Week 2022, July 18-22, 2022, Vancouver (BC), Canada

Accelerator Driven System: intrinsic safety



To keep the reactor operating we need CW proton beam with very high reliability

Fission generates high level radioactive waste



1 ton of nuclear fuel used 4,5 year in commercial PWR reactor **produces electricity for 100,000 Belgian families per year** (3500 kWh/y per family)

➔

After 4,5 years the spent nuclear fuel contains:

- **94,7% of resources we can recycle (U+Pu)**
- **5,1% of nuclear waste with low radiotoxicity (FP's)**
- **0,2% of high radiotoxicity nuclear waste**

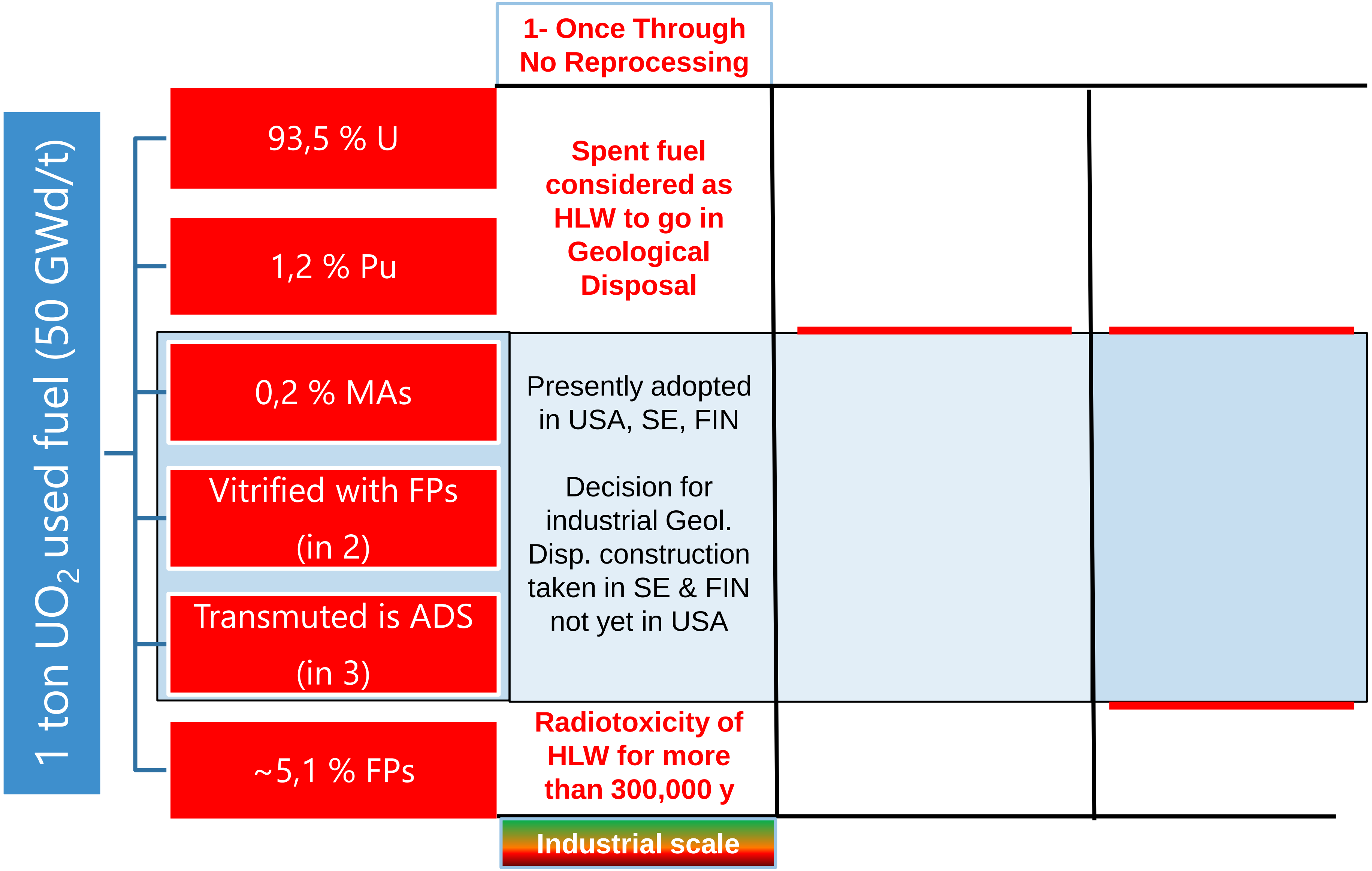
Source: SCK•CEN MYRRHA Project Team

Partitioning & Transmutation

VS

- Just like for classical household waste we need **sorting** and then **valorizing** through recycling
- **Partitioning**
  - Separate the ingredients of the spent fuel in “similar” categories we can treat in a similar way
- **Transmutation**
  - Use intense neutron field to transmute isotopes into others, less “nasty” and producing energy (circular economy)

Possible Fuel Cycles for High Level Waste treatment



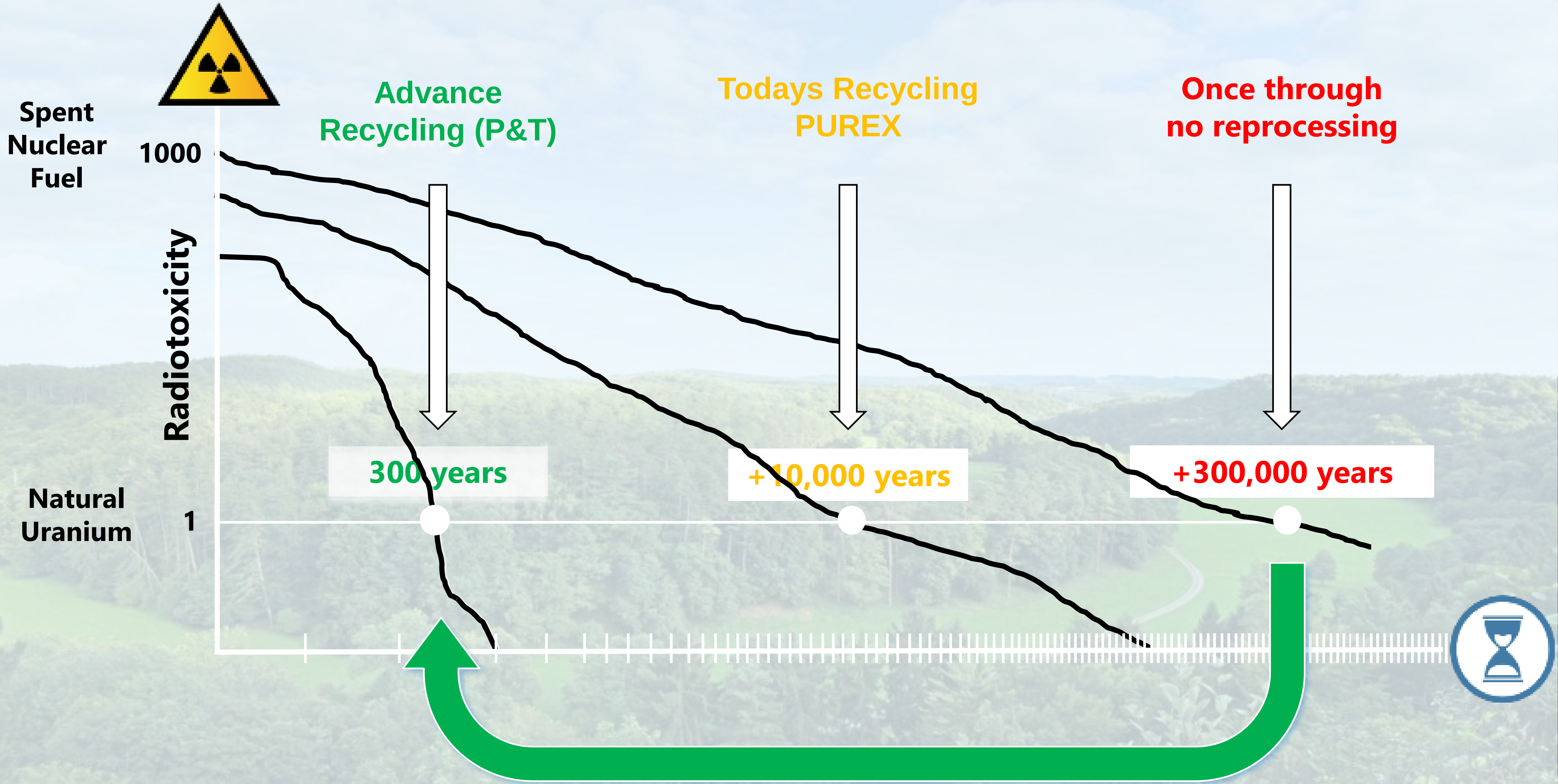
Possible Fuel Cycles for High Level Waste treatment

1 ton UO_2 used fuel (50 GWd/t)	1- Once Through No Reprocessing	2- Todays Recycling PUREX	
93,5 % U 1,2 % Pu	All 1 ton spent fuel considered as HLW to go in Geological Disposal	U + Pu recycled in PWRs or BWRs No recycling of MOX fuels	
0,2 % MAs Vitrified with FPs (in 2)	Presently adopted in USA, SE, FIN Decision for industrial Geol. Disp. construction taken in SE & FIN not yet in USA	FPs + MAs vitrified and to go to Geolo. Disp. Presently adopted in FR, JP, … No formal decision for industrial Geol. Disp. yet	
~5,1 % FPs	Burden of HLW for more than 300,000 y	Radiotoxicity of HLW for more than 10,000 y	
	Industrial scale	Industrial scale	

Possible Fuel Cycles for High Level Waste treatment

1 ton UO_2 used fuel (50 GWd/t)

	1- Once Through No Reprocessing	2- Todays Recycling PUREX	3- Advanced Recycling (P&T)
93,5 % U 1,2 % Pu	**All 1 ton spent fuel considered as HLW to go in Geological Disposal**	U + Pu recycled in PWRs or BWRs No recycling of MOX fuels	U + Pu recycled in PWR or FR MAs in ADS
0,2 % MAs Vitrified with FPs (in 2) Transmuted is ADS (in 3)	Presently adopted in USA, SE, FIN Decision for industrial Geol. Disp. construction taken in SE & FIN not yet in USA	**FPs + MAs vitrified and to go to Geolo. Disp.** Presently adopted in FR, JP, … No formal decision for industrial Geol. Disp. yet	**MA are turned in FPs to go to Geolo. Disp. In specific packaging** Presently R&D programme (FR, JP, BE, **DE**, EU, CN, ROK, USA)
~5,1 % FPs	**Burden of HLW for more than 300,000 y**	**Burden of HLW for more than 10,000 y**	**Radiotoxicity of HLW for ~300 y**
	Industrial scale	**Industrial scale**	**R&D level**


Spent
Nuclear
Fuel
1000
Radiotoxicity
Natural
Uranium
1
Advance
Recycling (P&T)
Todays Recycling
PUREX
Once through
no reprocessing
300 years
+10,000 years
+300,000 years

European Strategy for P&T (2005) with objective of possible industrialisation from 2040

EU P&T Strategy 2005: *"The **implementation of P&T** of a large part of the high-level nuclear wastes **in Europe needs the demonstration of its feasibility at an "engineering" level**. The respective **R&D** activities could be **arranged in four "building blocks"**:*

	P&T building blocks	Description	Name & Location
1	**Partitioning**	▪ Demonstrate capability to process a sizable amount of **spent fuel** from commercial Light Water Reactors to **separate** plutonium, uranium and minor actinides	▪ Atalante (FR)
2	**Fuel production**	▪ Demonstrate the capability **to fabricate** at a semi-industrial level the **dedicated fuel** needed to load in a dedicated transmuter	▪ JRC-ITU (EU)
3	**Transmutation**	▪ **Design and construct one or more dedicated transmuters**	▪ **MYRRHA (BE)** ▪ **ASTRID (FR)**
4	**MA Fuel Partitioning**	▪ Specific installation to process fuel unloaded from transmuter ▪ Not necessarily the same as type to process original spent fuel unloaded from commercial power plants	

The European Commission contributes to the 4 building blocks and fosters the national programmes towards this strategy for **demonstration at engineering level**.

Source: European Commission Strategy Paper on Partitioning & Transmutation (2005)

Technology Readiness Level (TRL)

1. **Advanced partitioning** = "sorting of the waste" beyond classical PUREX

   TRL = 7 ~ 8

2. **Fabrication of dedicated transmutation fuel** (loaded with Minor Actinides)

   TRL = 3 ~ 4

3. **Pre-Industrial sized transmuter demonstration (MYRRHA)**

   TRL (FR = 9, **ADS = 4 ~ 5 after building MYRRHA → 9**)

4. **Advanced reprocessing of transmuter fuel** (≠ from 1, Pyroreprocessing as the most promising)

   TRL = 3

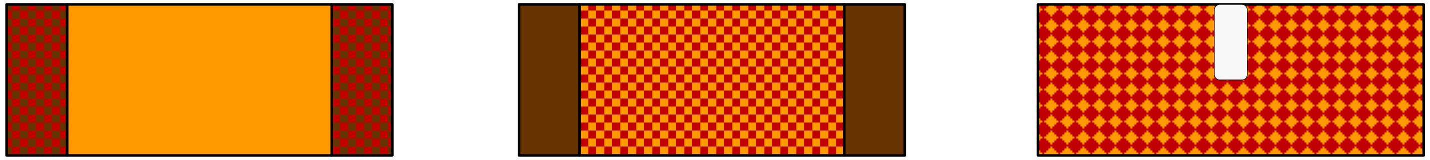
5. **Advanced fuel technological aspects:** transportation, cooling, and handling

   TRL = 3 ~ 4

NSC Task Force on Demonstration of Fuel Cycle Closure including Partitioning and Transmutation (P&T) for Industrial Readiness by 2050 (TF-FCPT) with experts from Belgium, **France**, **Japan, Russia, UK**, **US** and **EC**

Three options for Minor Actinide (MA) transmutation

FR heterogeneous	FR homogeneous	ADS
Driver fuel Blanket with MA	Fuel with MA Blanket	Fuel with MA



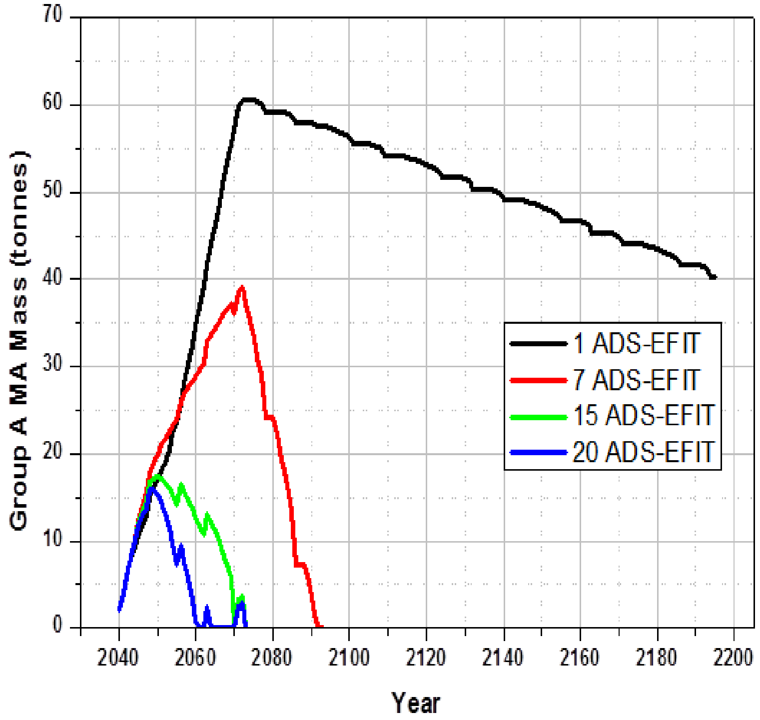
Core safety parameters limit the amount of MA that can be loaded in the critical core for transmutation, leading to transmutation rates of:

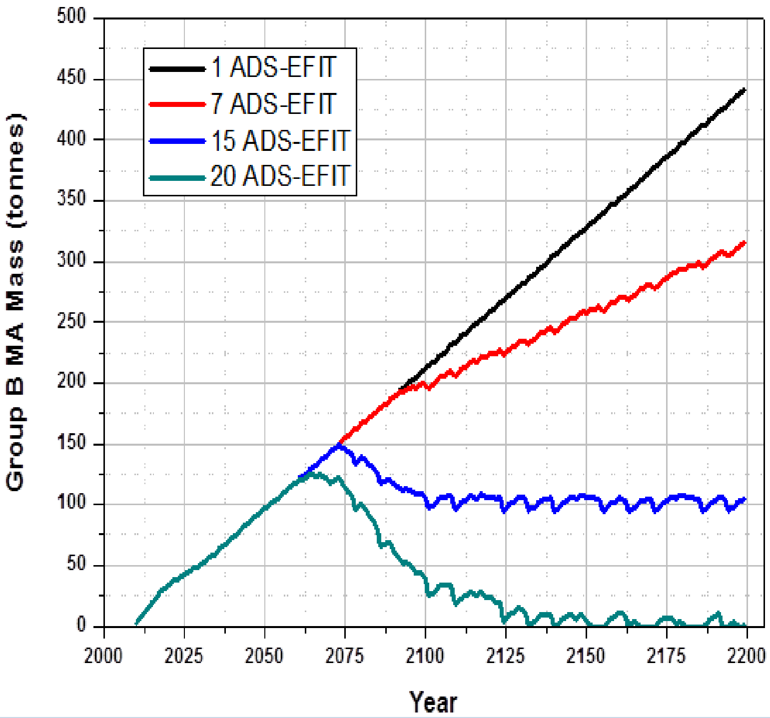
- FR = 2 to 4 kg/TWh
- ADS = **35 kg/TWh** (based on a 400 MW_{th} EFIT design)

→ ADS performs the best

Shared & efficient solution for Minor Actinides management
EU case with 144 power reactors using EFIT 400 MWth

- **Europe should go for a regional approach** (see PATEROS, ARCAS)
- **Countries with different nuclear energy policies to collaborate together**
  - Countries willing to continue Nuclear Energy
  - Countries willing to develop fast reactor systems
  - Countries in nuclear phase out, interested in Partitioning &Transmutation (P&T)





15 EFIT * 400 MWth = 6000 MWth
For all EU HLW treatment

Doel (BE) = 9000 MWth
Tihange (BE) = 9000 MWth

Gravelines (FR) = 17118 MWth

Zaporizhzhya (UA) = 18000 MWth

Bruce (CND) = 18702 MWth

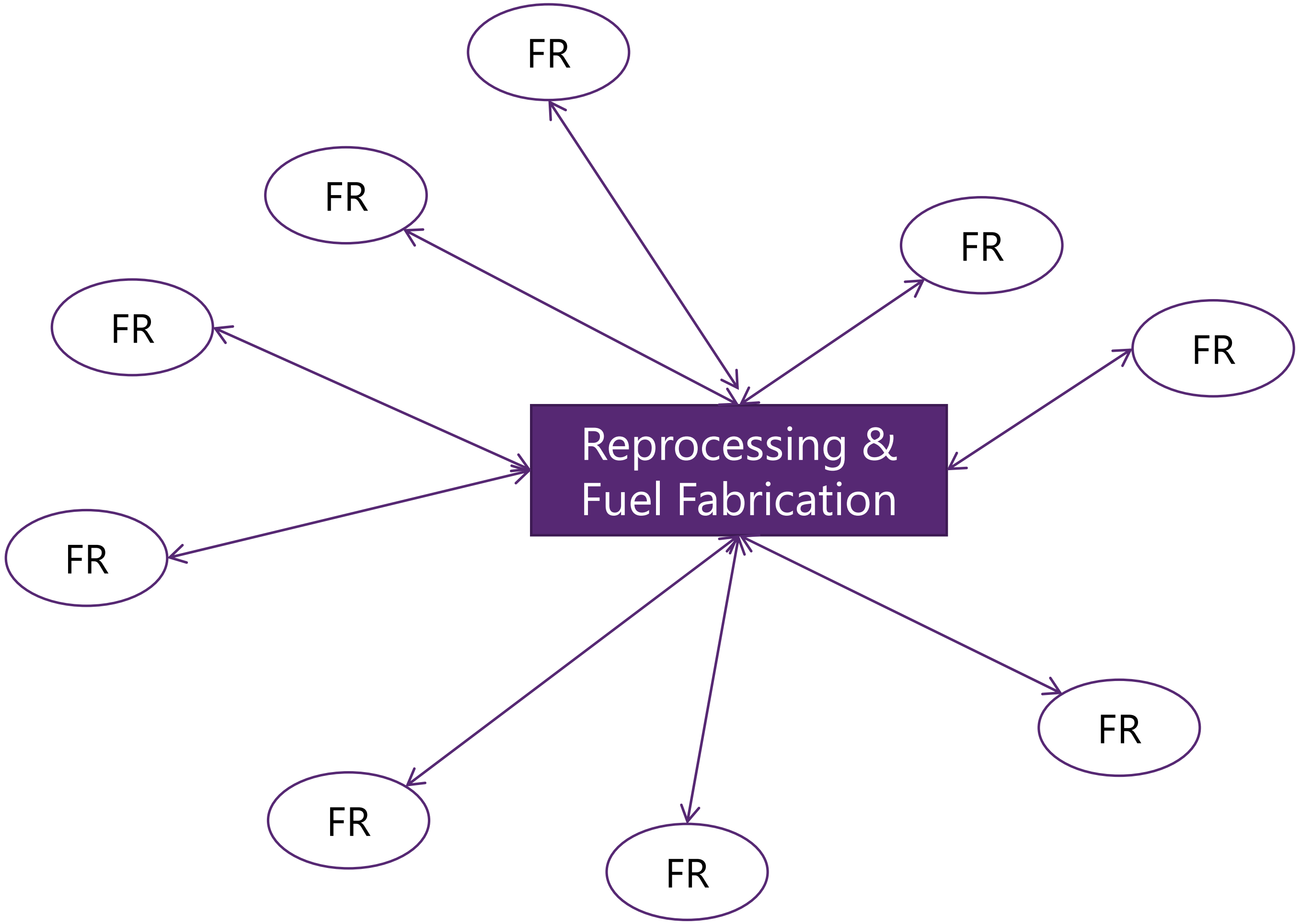
Kashiwazaki-Kariwa = 23895 MWth

Source: [TBD]

Transport issues of MA-Fuels FR vs ADS

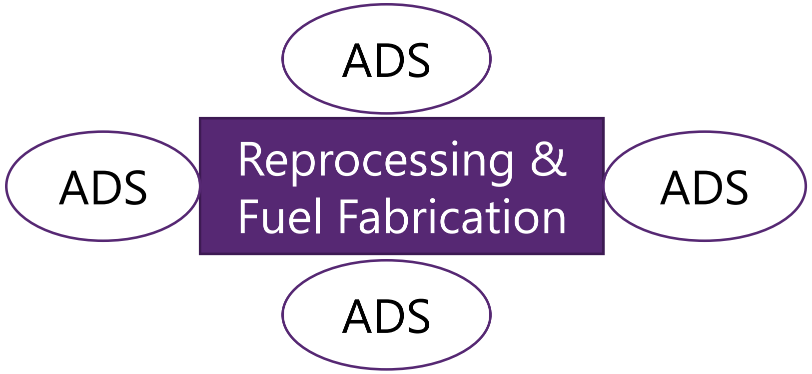
Transmutation in Fast Reactors

- Large number of FRs needed
- Many transport of MA-Fuels on the roads



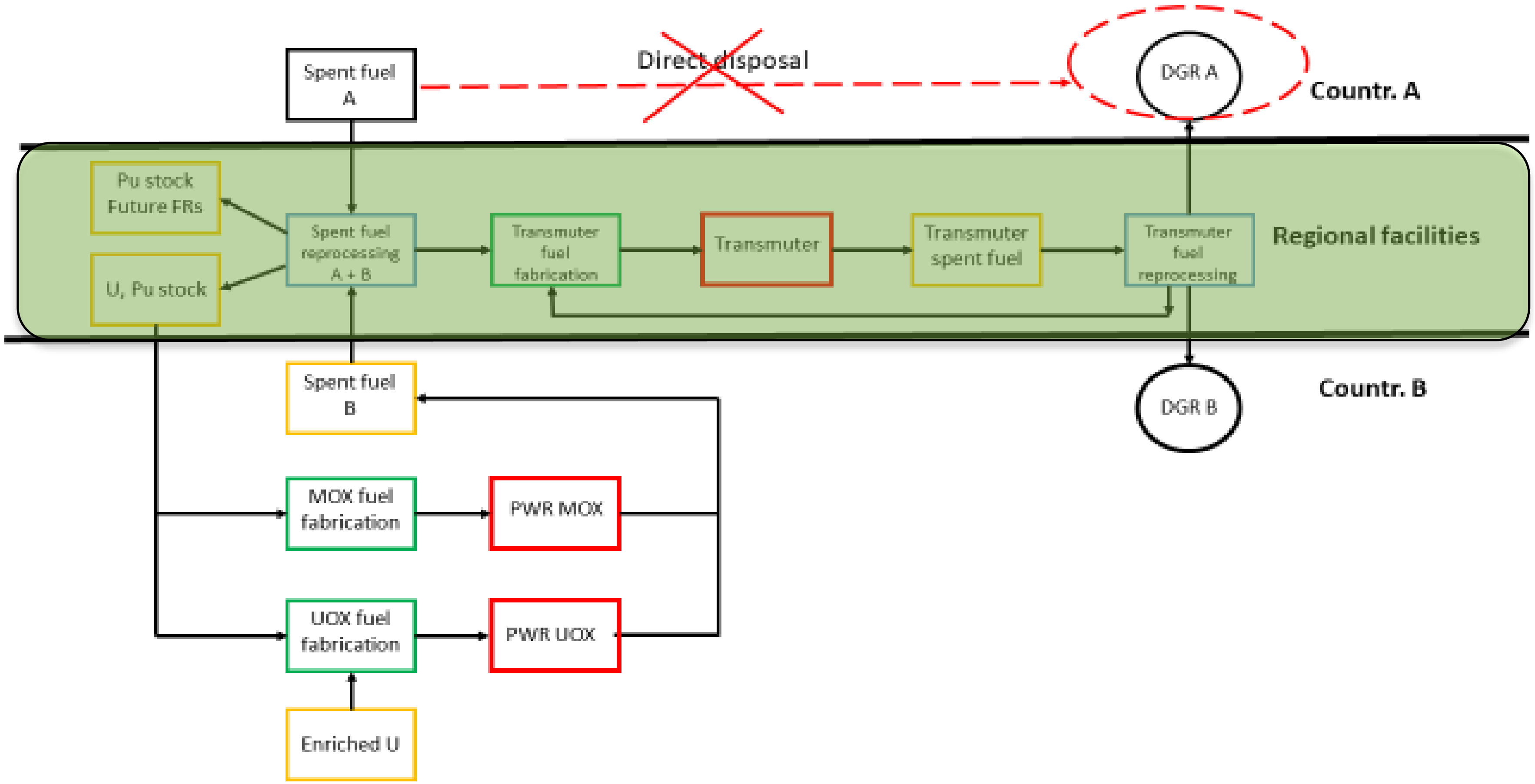
Transmutation in ADS

- Small units in small number ➔ Single site
- Few or no transport of MA Fuel on the roads



no or limited "on-the-road" transport

Even with completely different national NE policies European solution for HLW works with ADS



❑ Advantages for A

- ADS shared with B
- ADS burn A's Pu& MA
- Smaller Fu-Cycle units & shared

❑ Advantages for B

- ADS shared with B
- ADS burn B's MA
- A's uses B's Pu (part) as resource in FR
- FR fleet not contam with MA's
- Smaller Fu-Cycle units & shared

FP6 PATEROS project: Scenario 1 objective: elimination of A's spent fuel by 2100
A = Countries Phasing Out, B = Countries Continuing

National context evolution (3)
2015 -> Today (National Program on waste management)

In **2014** the national policy for the management of spent fuel from commercial nuclear power plants is the safe storage of spent fuel followed by its reprocessing & disposal or direct disposal

2017: Prospective study on the strategies for the management of Belgian nuclear spent fuel

6 different strategies are assessed:

Direct disposal

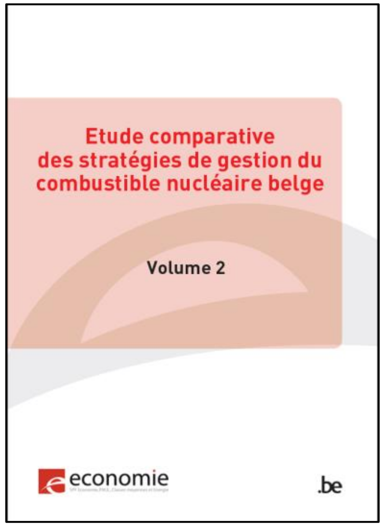
Classical reprocessing of full inventory & disposal

Partial reprocessing

Advanced separation (P&C)

Partitioning & Transmutation (P&T)

Additional research



Belgian geological repository: impact on gallery length (km)

	No further reprocessing	Full reprocessing	MA+FP P&T case
	Disposal gallery length (km)	Disposal gallery length (km)	Disposal gallery length (km)
fuel cycle dependent			
UOX spent fuel	15.43	-	-
MOX spent fuel	0.79	-	-
V-HLW future	-	6.39	1.23
Total C waste	16.22	6.39	1.23
CSD-C future	-	1.40	2.07
Total B&C waste	16.22	7.79	3.30
relative	**1.00**	**0.48**	**0.20**

Belgian geological repository: impact on footprint (km^2)

	No further reprocessing	Full reprocessing	MA+FP P&T case
	footprint (km^2)	footprint (km^2)	footprint (km^2)
fuel cycle dependent			
UOX spent fuel	1.85	-	-
MOX spent fuel	0.10	-	-
V-HLW future	-	0.32	0.06
Total C waste	1.95	0.32	0.06
CSD-C future	-	0.07	0.10
Total B&C waste	1.95	0.39	0.17
relative	**1.00**	**0.20**	**0.08**

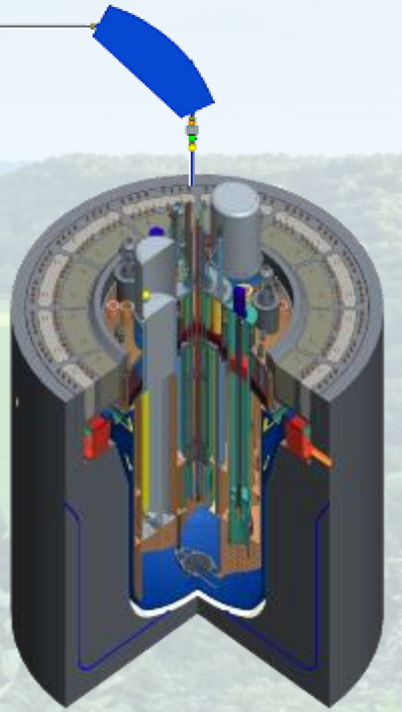
MYRRHA: Accelerator Driven System

Phase 1 — 100 MeV

Linear accelerator

Phase 2 — 600 MeV

Phase 3



Sub-Critical Reactor
Pb-Bi Cooled

- ✓ Transmutation demonstration
- ✓ ADS at pre-industrial scale
- ✓ Flexible irradiation facility

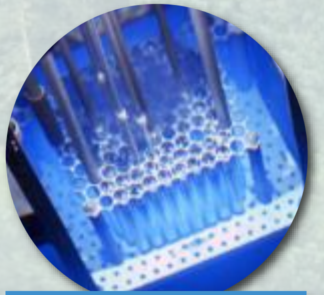
MYRRHA's Application Portfolio

SNF*/ Waste

Radio-isotopes

Fusion

Multipurpose
h**Y**brid
Research
Reactor for
High-tech
Applications



Mat.& Fuel
GEN IV

Fundamental research

Support to SMR LFR

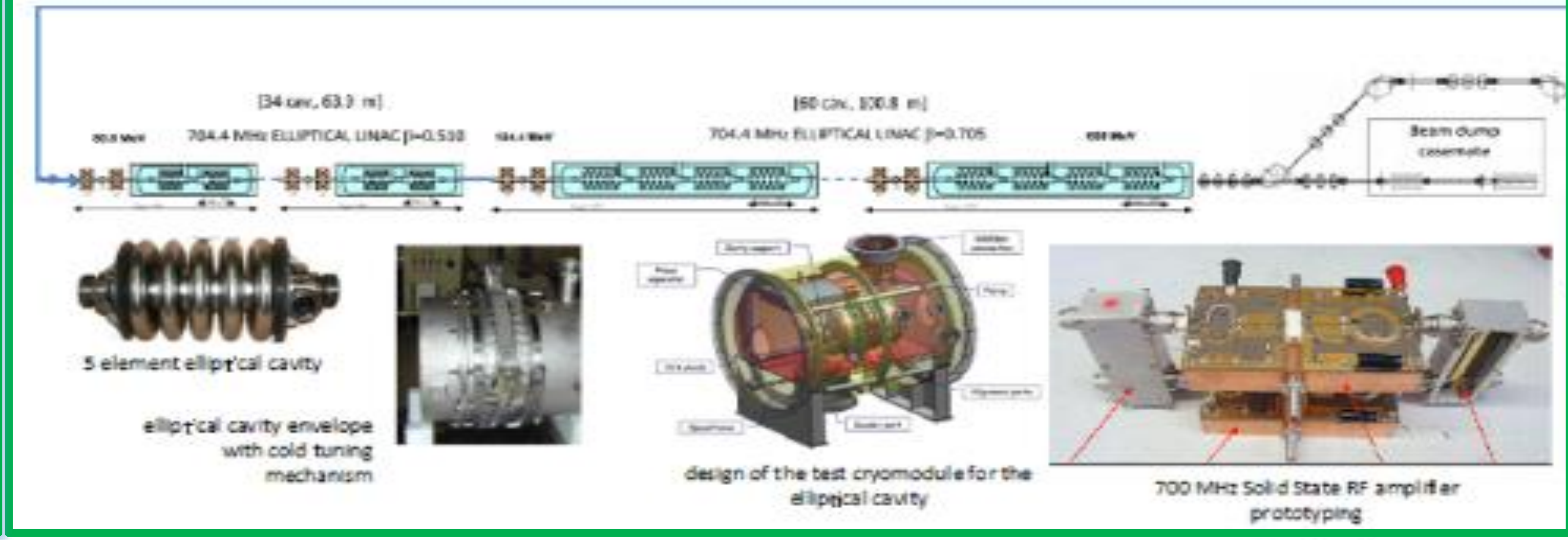
*SNF = Spent Nuclear Fuel

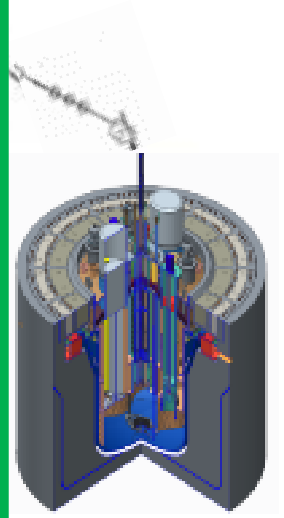
MYRRHA's PHASED IMPLEMENTATION STRATEGY

Phase 1 – 100 MeV + Proton Target Facility

UNDER CONSTRUCTION
MYRRHA phase 1 = MINERVA
(see next presentation by Adrian FABICH

Phase 2 – 600 MeV





Phase 3 – Reactor

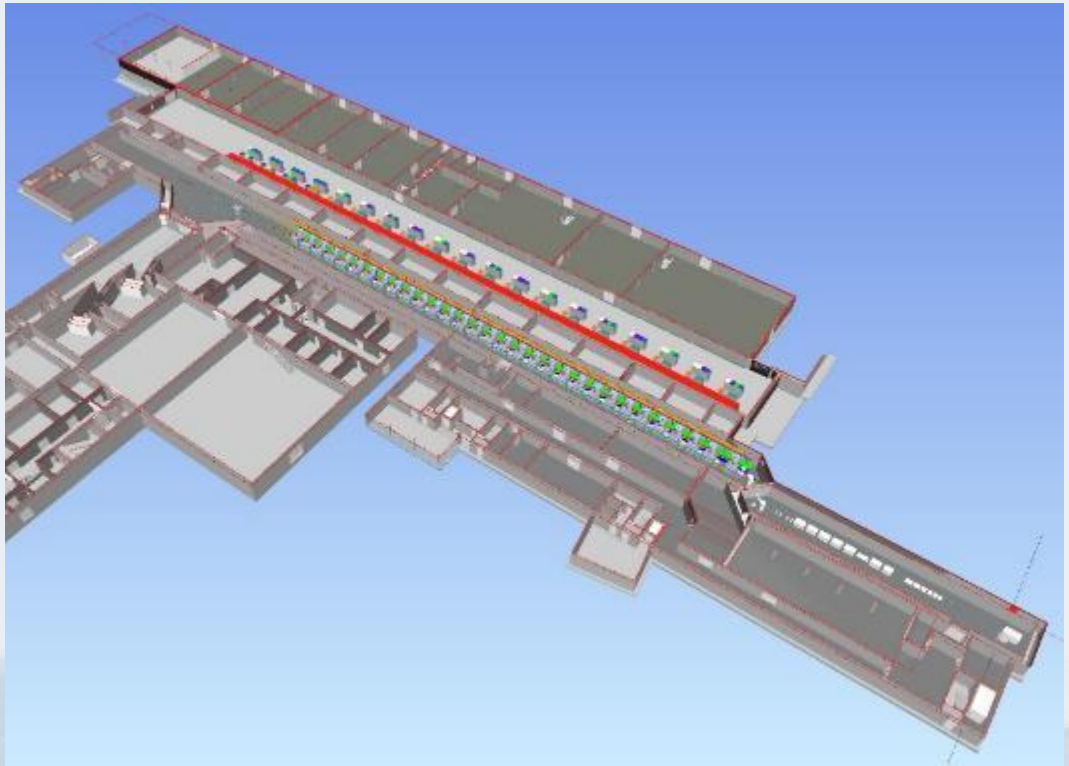
Source: SCK CEN / MYRRHA Project Team

MINERVA implementation by 2026

- Overall architecture frozen, main internal floor plan decisions taken
- PTF design close to level of ACC, FPF catching up

NF ACC

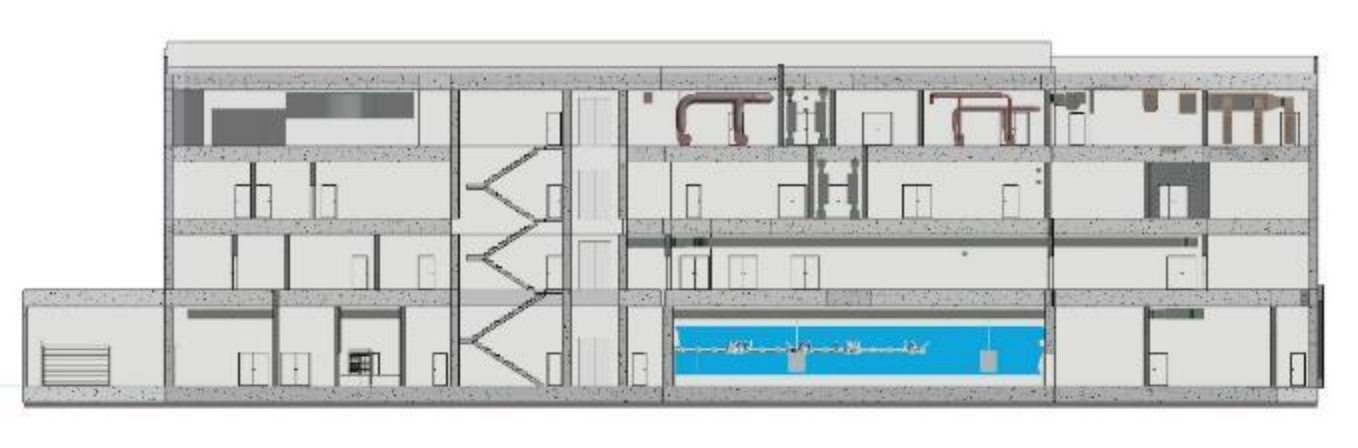
- **Outline Basic Design phase**
  - 3D data model
    - determines <u>minimum</u> level of detail (LOD 100) of all SSC
    - links ‘all’ information
    - tool for integration of SSC

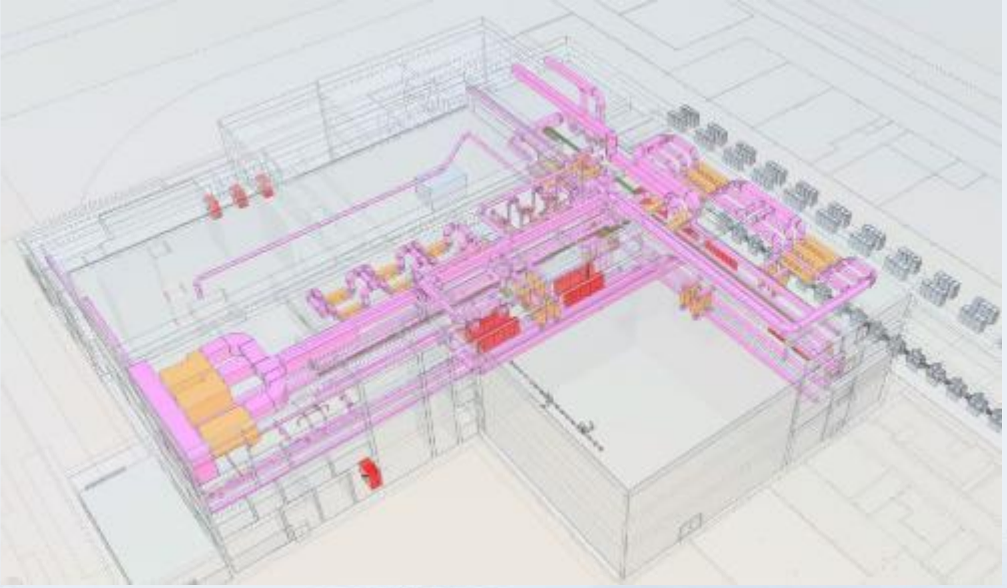


ISC: Restricted

NF PTF

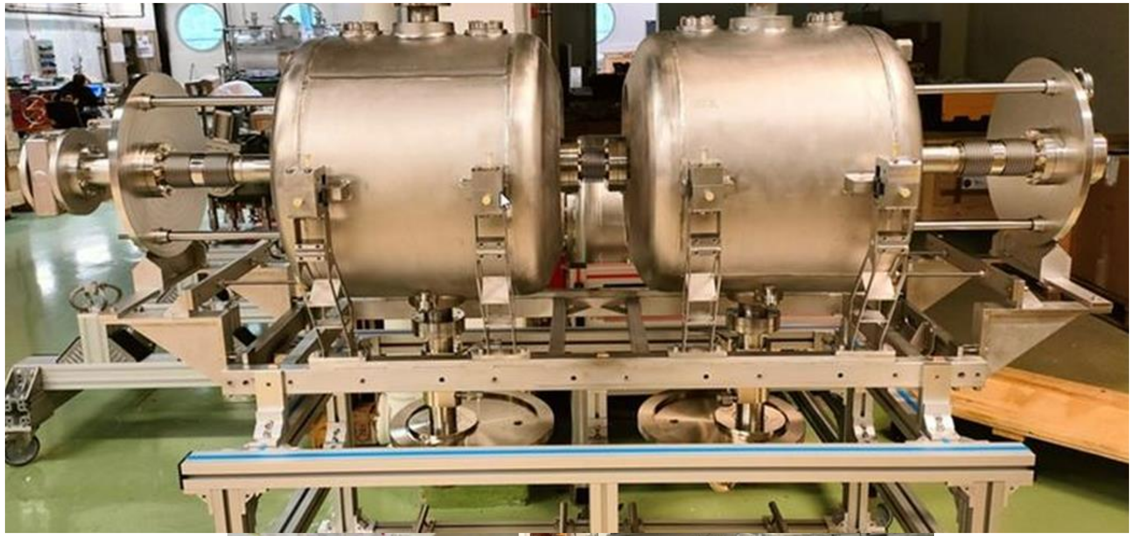
- **Conceptual Design phase**
  - 3D data model
    - minimum LOD 100, higher level reached
    - primary systems included

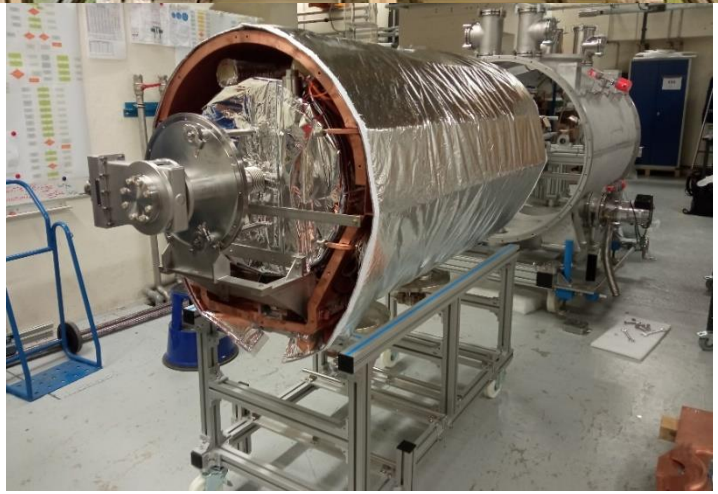




Strong & Fruitful collaboration between TRIUMF and SCK CEN for the development of ARIEL and ISOL@MYRRHA

SC single spoke cavities & cryo module





Prototyping progressing at collaboration partner IJCLab (FR)

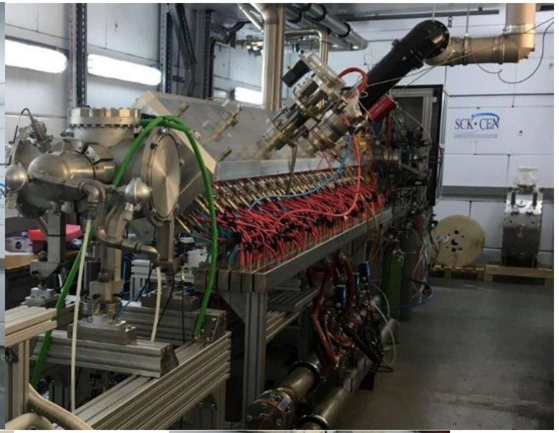
Production of pre-series single spoke cavity parts is ongoing at RI (DE)

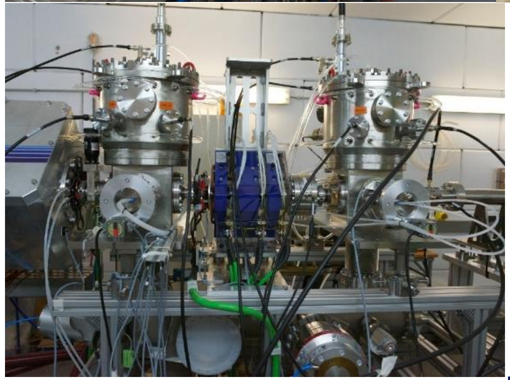
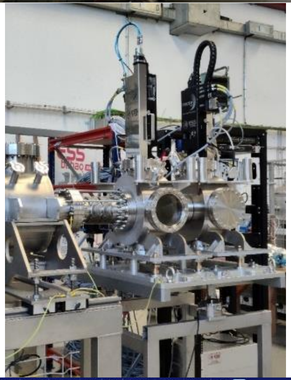
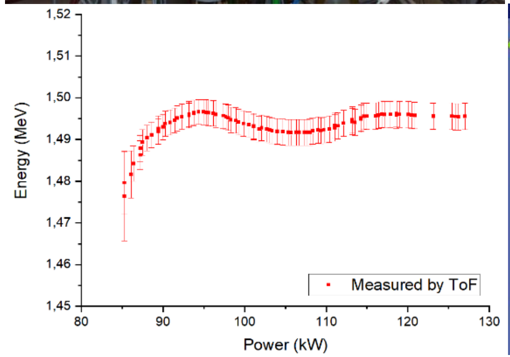
Injector test stand established at CRC (LLN-BE)

SCK CEN operates an injector test-stand consisting of:

- ECR ion source
- LEBT
    - 2 solenoids
    - Alison scanner, Faraday cup,…
    - Fast beam chopper
- RFQ
    - 4 rod design
    - Powered by up to 160 kW RF solid state amplifiers
    - 176.1 MHz
- 2 quarter wave rebunching RF-cavities
- In fall, a emittance meter and a bunch shape monitor will be added

→ Target beam current/cycling achieved
→ RFQ commissioned with >95% transmission
→ Beam energy confirmed after the RFQ by ToF



MYRRHA Reactor: implementation in 2036

Objectives = transmutation + radioisotopes + fusion material R&D + Fission technology platform

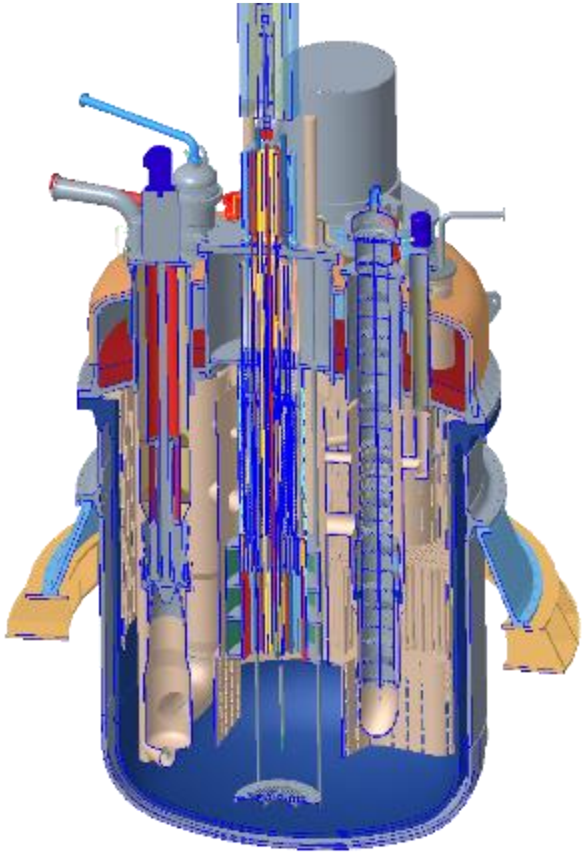
Source:

MYRRHA reactor Highlights

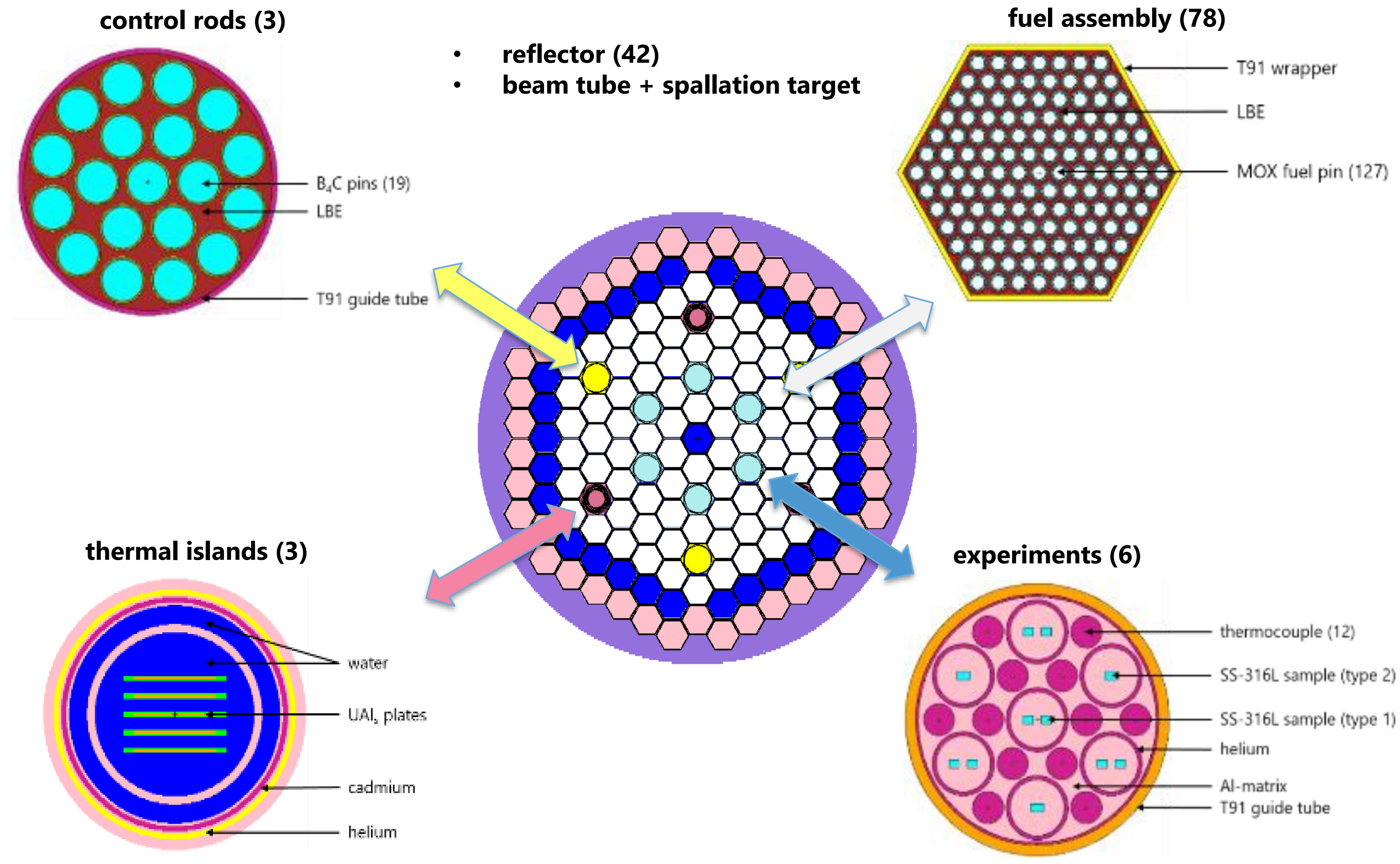
MYRRHA reactor primary design Rev. 1.8, frozen end 2020

- Integrated Pool-type concept with LBE coolant
- Fuel assemblies: hexagonal bundles of cylindrical wire-spaced fuel pins (MOX fuel 30wt.% Pu)
- 4x heat exchangers: double-walled with leak detection; water/steam on secondary side
- 2x primary pumps: vertical shaft mixed-flow design
- Bottom core loading: single in-vessel fuel handling machine (IVFHM)
- Safety vessel integrated into the primary vessel

Parameter	Unit	Value
Maximum core power	MW_{th}	64
Maximum heat sink rated power	MW_{th}	70
Shutdown state LBE temperature	°C	200
Maximum core inlet LBE temperature	°C	220
Maximum average hot plenum LBE temperature	°C	270



MYRRHA Core design for multipurpose R&D : Subcritical core layout

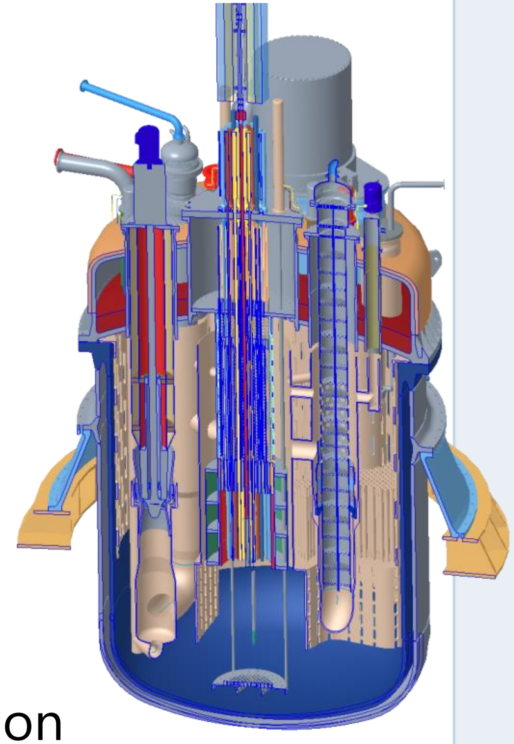


Source: L. Fiorito, 2019

MYRRHA: World Class Technology complex to serve HLM SMR development

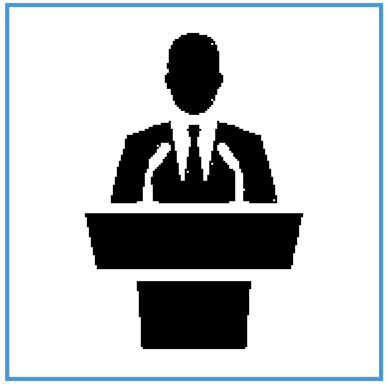
- LiLiPuTTeR-II
- HELIOS 3
- HLM Lab
- MEXICO
- CRAFT
- LIMETS 3
- RHAPTER
- COMPLOT
- ESCAPE
- Ultrasonic Lab
- GUINEVERE

LiLiPuTTeR-II, HELIOS 3, HLM Lab, MEXICO	Lead-Bismuth Chemistry & Conditioning
CRAFT, LIMETS 3	Material development & testing
RHAPTER, COMPLOT, ESCAPE	Component testing & Thermal Hydraulics
Ultrasonic Lab	Instrumentation & Visualisation
GUINEVERE	Lead Zero Power Reactor



Belgian Government decision of 7 September 2018

Confirmed on 23 July 2021 (+ creation of MYRRHA NPO)



Decision to build MYRRHA as large new research infrastructure in Mol, Belgium

Belgium **allocates** € 558 m for 2019-2038

- 2019-2026: construction of MINERVA (linac 100 MeV + PTF & FTS)
- 2019-2026: design, R&D and licensing for Phases 2 (extended linac 600 MeV) & 3 (reactor)
- 2027-2038: MINERVA operations (linac 100 MeV)

Establishment of **international non-profit organisation**

MYRRHA AISBL/IVZW

Decided 23.07.2021

Created 17.09.2021

Government support for establishing MYRRHA partnerships

Belgium appoints tutorship ministers to promote and negotiate international partnerships

Source: Belgian minister of Energy, Environment & Sustainable Development

How to participate in MYRRHA

MYRRHA AISBL/IVZW official from 16 December 2021

Opzoeking in de Kruispuntbank van Ondernemingen (KBO)

Algemene gegevens

Ondernemingsnummer	0778714119	Startdatum	26/11/2021
Type	ELP	Einddatum	
Stopzetting		Inschrijvingsdatum in het KBO	16/12/2021
Duur	0		

Benamingen

Type	Taal	Benaming
Naam	nl	MYRRHA

Rechtsvormen

Rechtsvorm
Internationale vereniging zonder winstoogmerk

Source:

sck cen

ANS MDB

MYRRHA

MYRRHA International nonprofit organisation

MYRRHA AISBL: separate legal entity needed to find external partners/investors

Responsability:

- SCK CEN
  - Design & build MINERVA
  - Conduct R&D for phases 2 ACC-600 & 3 MYRRHA Reactor
  - Obtain licenses for Phase 1 and later on for Phases 2 & 3
  - Being the nuclear operator of MYRRHA/MINERVA
- MYRRHA AISBL
  - Establish the MYRRHA International Consortium
  - Guarding the overall scope of MYRRHA programme

MYRRHA AISBL/IVZW: Membership

- Member categories :
  a) **Founding members** : Belgian State and SCK CEN
  b) **Contributing members** open for :
     - Countries
     - **National Research Organisations, industries of a country**
     - International Institutions or Associations

- Rights & Obligations
  - Contribution in-cash or in-kind to become contributing member
  - from 40 M€ contribution :
    - 1 Director in the Board of Directors (overall maximum of 4)
    - 1 Voting right in the General Assembly per 40 M€ contribution
  - Annual membership fee <100 k€ on proposal of BoD (right of nomination of a representative in the International Scientific and Technical Advisory Board (ISTAB)

Conclusions

Belgium sends a strong signal about its ambitions:

- Maintaining a high level of **know-how** in the nuclear field
- Becoming an **international pole of attraction** for young talents in nuclear applications
- Convert innovations into **solutions** for **societal challenges** (nuclear waste, nuclear medicine, sustainability)
- Encourage and welcome **international cooperation and partnership**

2018
Positive decision

→

Ground breaking
Q2-2023

SCK CEN
Belgian Nuclear Research Centre

Stichting van Openbaar Nut
Fondation d'Utilité Publique
Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – B-1160 BRUSSELS
Operational Office: Boeretang 200 – B-2400 MOL