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MYRRHA

La contribution du nucléaire à la transition énergétique Et l'apport du Projet MYRRHA dans cette perspective

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Introduction

- Nuclear energy part of the energy mix for transition towards CO_2 neutral society by 2050 is regularly mentioned in the IPCC, IAEA and IEA reports **but rarely said in the general media (nuclear bashing ??).**
- Average lifecycle GHG emissions for electricity production from nuclear energy (6-10 g CO_2[eq]/kWh):
  - comparable to the values of hydropower and windmills.
  - about 20 times less than natural gas
  - and 30 to 40 times less than coal.
  - we need rapidly to improve the paradigm
- End 2023, 418 nuclear reactors are in operation in 32 countries and 59 are under construction. Nuclear electricity represents 10% worldwide, 19,4% for USA and more than 25% for EU, 48% for BE (01.2023).
- In the last COP28 in Dubai, 22 countries declared to commit towards nuclear energy as part of their energy mix for mitigating climate change & Global warming (**x3 installed nuclear by 2050 !**). Confirmed in Brussels on March 2024 @the 1st World Nuclear Energy Summit (IAEA/BE organization) by 36 countries

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Source:

At the Spring Annual Meeting (April 17-21, 2023) of American Physical Society it was said :

- We need to go towards SMRs and come **with acceptable solutions for nuclear waste**
- To have the innovative nuclear energy systems (SMRs) achieving industrial deployment we need:
  - **Establishing an economic viability & competitiveness**
  - **Guaranteeing the safety of the innovative system**
  - Creating a nuclear supply chain including for fuel (HALEU not only)
  - Delivering beyond present electricity application (Heat, H2, fresh H2O)
  - **Reestablishing capabilities and competences of Large projects Mgt**
  - **Establishing a new regulatory Framework**
  - **Showing societal acceptation**
  - **Meeting security and safeguard regulations & requirements**
  - **Dealing with the nuclear waste in agreement with the citizens**
  - Establishing a world market

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Source:

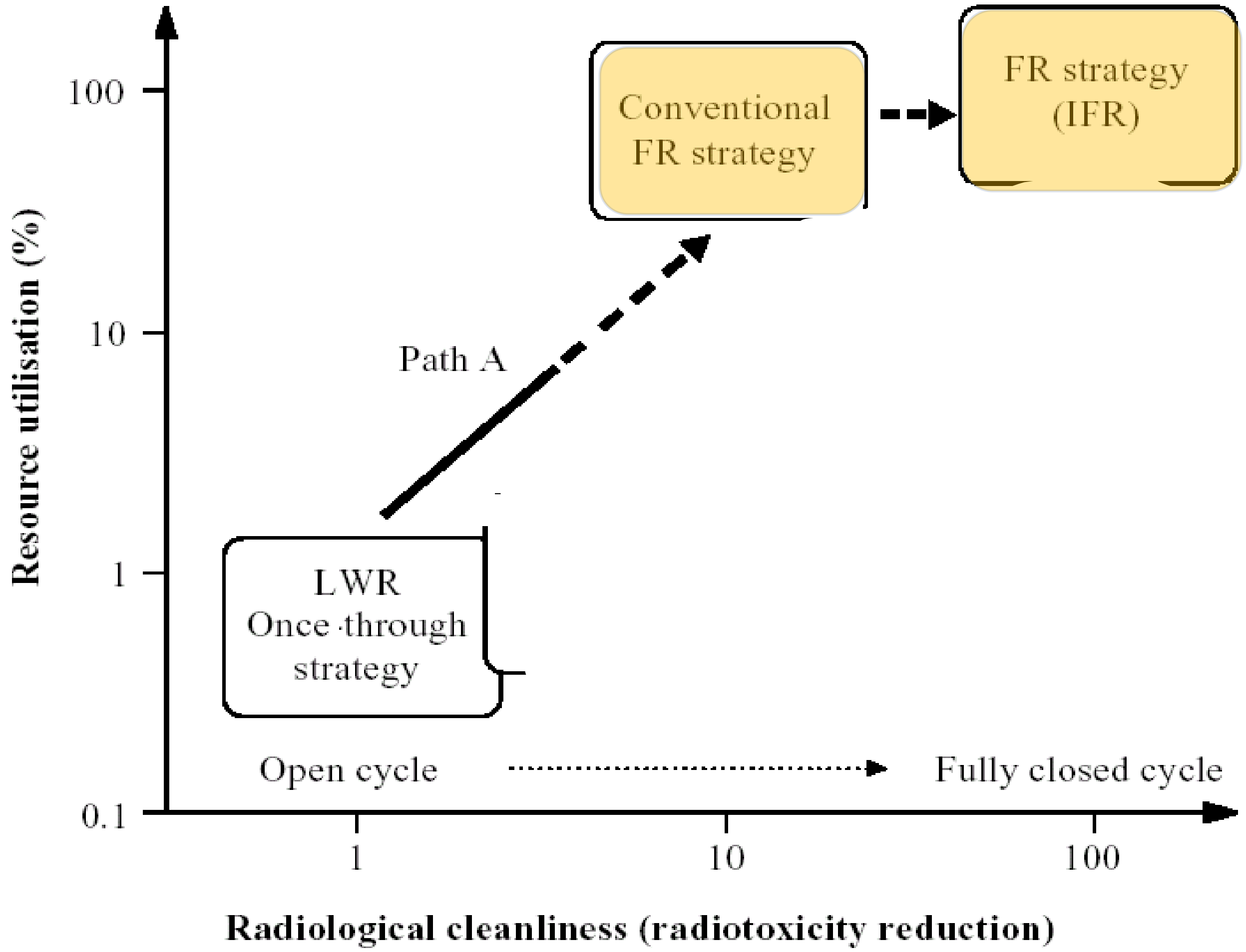
Aspects related to Fuel Cycle and P&T

Source:

- Fuel Cycle or Cycles
- Importance of closing the Fuel Cycle
  - Better use of resources or there is more in it
- Closing the Fuel Cycle in 2020 : opens new avenues
- Role of MYRRHA and it’s importance for opening new avenues

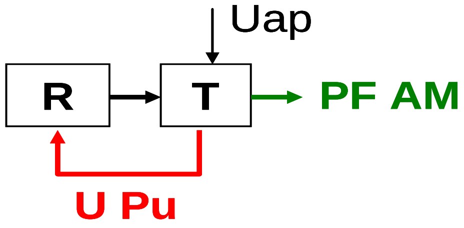
Source:

Fuel Cycle or Fuel Cycles



Sodium Fast Reactor (SFR)

- Fast reactor in combination with closed fuel cycle: recycling of its own generated Pu → sustainable implementation of nuclear energy



- SFR: large experience and technology base but never came to expected deployment level
  - France (MASURCA, RAPSODIE, PHENIX, SUPERPHENIX, ASTRID)
  - Japan (Joyo, Monju)
  - Russia (BOR-60, BN-300, BN-600, BN-800, BN-1200)
  - Germany (KNK, SNR-300)
  - UK (DFR, PFR)
  - Europe (EFR Design)
  - China (CEFR, …)
  - India (FBTR, FBR (EFR))

Fuel Cycle or Fuel Cycles

U_{nat} = 99,3% ^{238}U + 0,7 % ^{235}U

- Potential with todays Tech ~200y

Full Fuel Recycling → 100/0,7

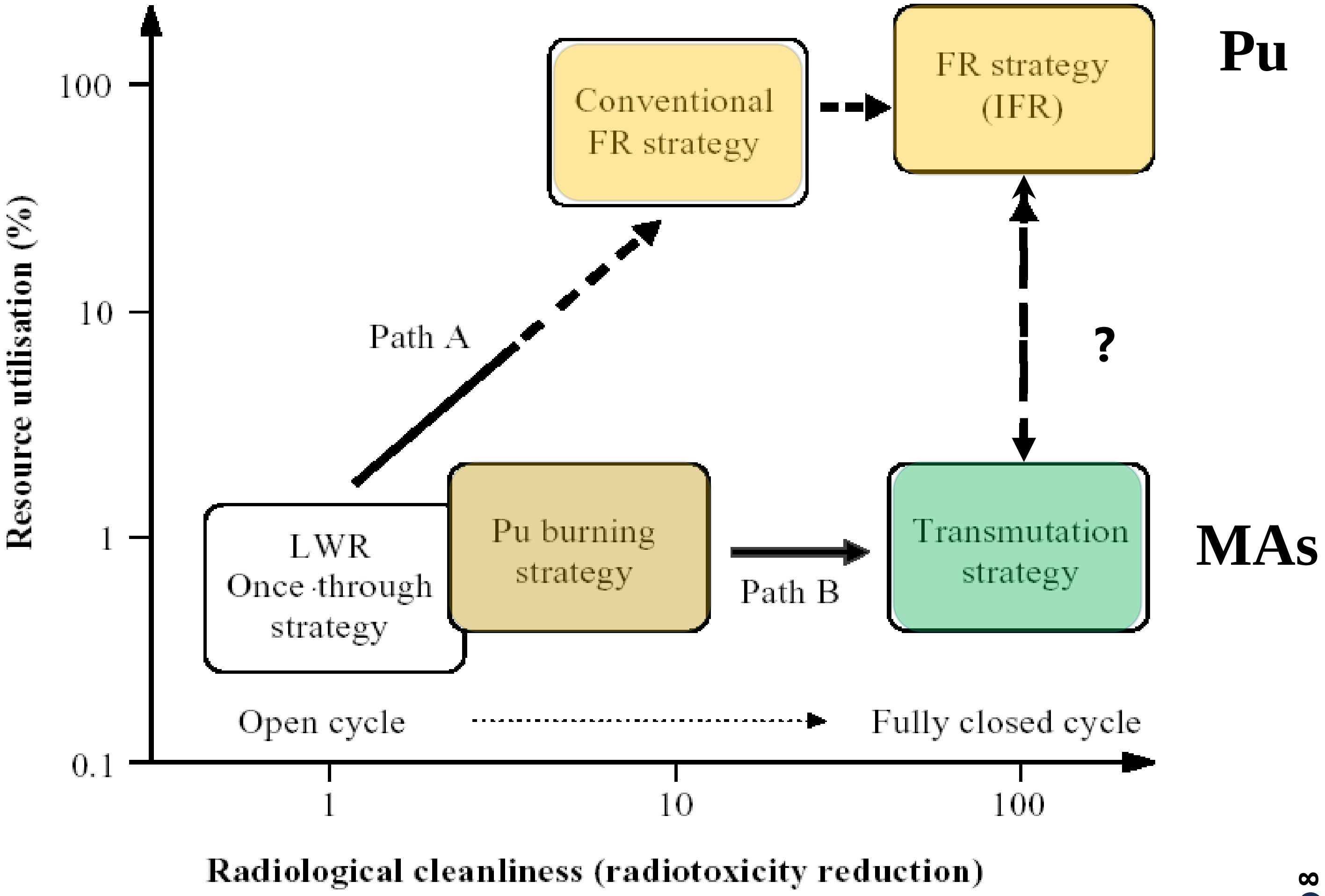
In theory 145,82 more energy by using Fast Reactors than in Thermal ones (in practice we target 100)

- Potential with FR 200y x 100 = 20,000y

Route towards sustainability

later stage why not Th (5x more abundant than U)

- Extra Potential with Th 20,000y x 5 =100,000y !

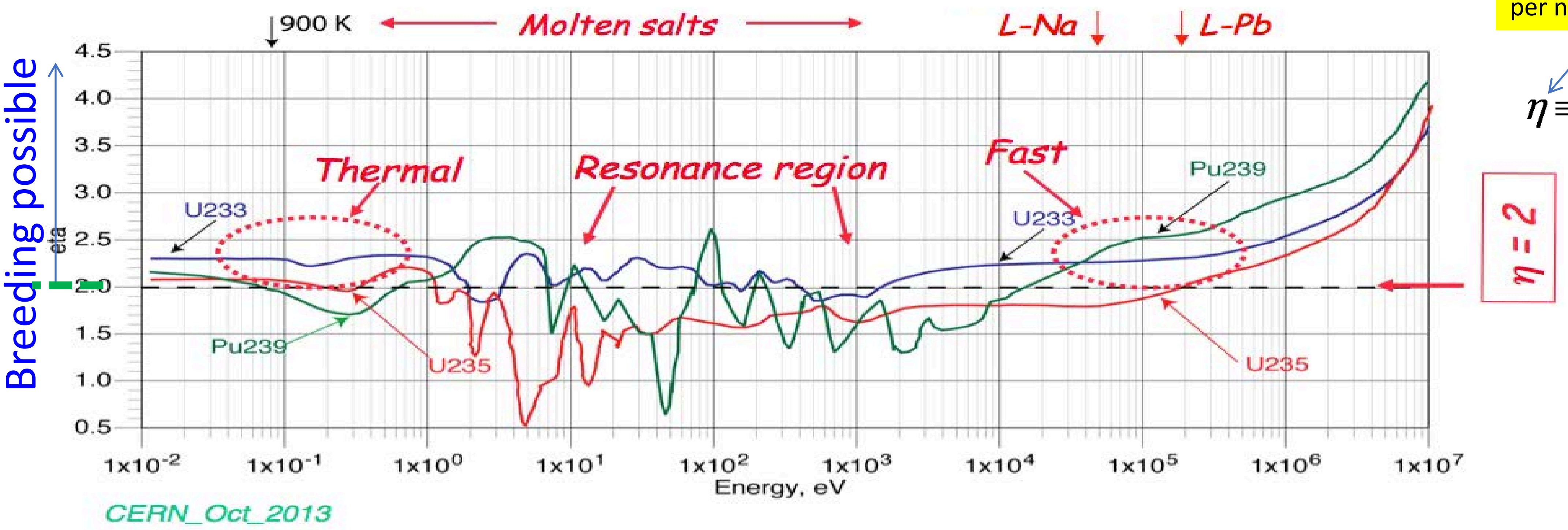


Nuclear energy even more sustainable
Fission energy from ^{232}Th

- ^{233}U is an excellent fuel for a breeder system, especially with fast neutrons

Neutrons produced per neutron absorbed

$$\eta \equiv \nu \frac{\sigma_f}{\sigma_f + \sigma_c}$$



- But the environment has to be taken into account (^{232}Th, ^{238}U). Thorium + ^{233}U cannot be substituted simply to PWR fuel because of neutron inventory issues (capture rate on thorium and long half-life of ^{233}Pa)

Recycling Pu in LWR worsening the MAs case (1)

LWR-UO2 50GWd/tHM

Product	Kg/tHM	% isotopic composition				
U	935	^{238}U	^{235}U			
		99%	1%			
Pu	12	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
		3.5%	51.9%	23.8%	12.9%	7.9%
Np	0.72	^{237}Np				
		100%				
Am	0.66	^{241}Am	^{243}Am			
		58.1%	41.7%			
Cm	0.11	^{242}Cm	^{244}Cm			
		8.8%	91.2%			
FPs	50 .7	~3 kg of LLFP				

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Recycling Pu in LWR worsening the MAs case (2)

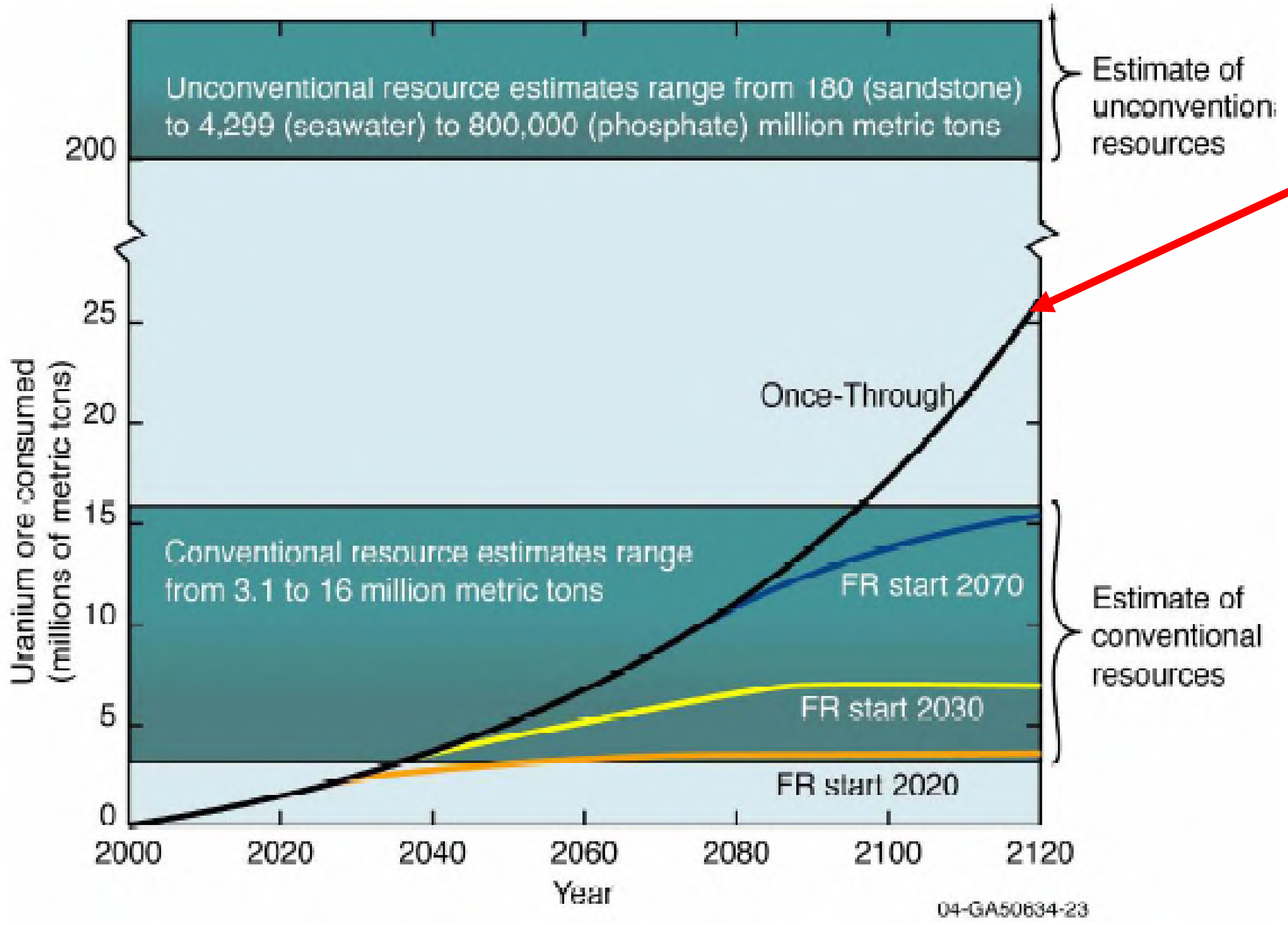
LWR-MOX 50 GWd/tHM

Product	Kg/tHM	%Isotopic composition				
U	887	^{238}U	^{235}U			
		99%	1%			
Pu	56.71	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
		4.74%	36.47%	31.5%	14%	13.4%
Np	7.72	^{237}Np				
		100%				
Am	7.07	^{241}Am	^{243}Am			
		71.8%	28.2%			
Cm	1.042	^{242}Cm	^{244}Cm			
		12.5%	87.5%			
FPs	~49	~3,5 of LLFP				

- Fuel Cycle or Cycles
- Importance of closing the Fuel Cycle
  - Better use of resources or there is more in it
- Closing the Fuel Cycle in 2020 : opens new avenues
- Role of MYRRHA and it’s importance for opening new avenues

Source:

Uranium resources projection



NE growth hypothesis 1.8% /y

Nuclear Energy sustainability doable through FR
➔ **Partitioning**

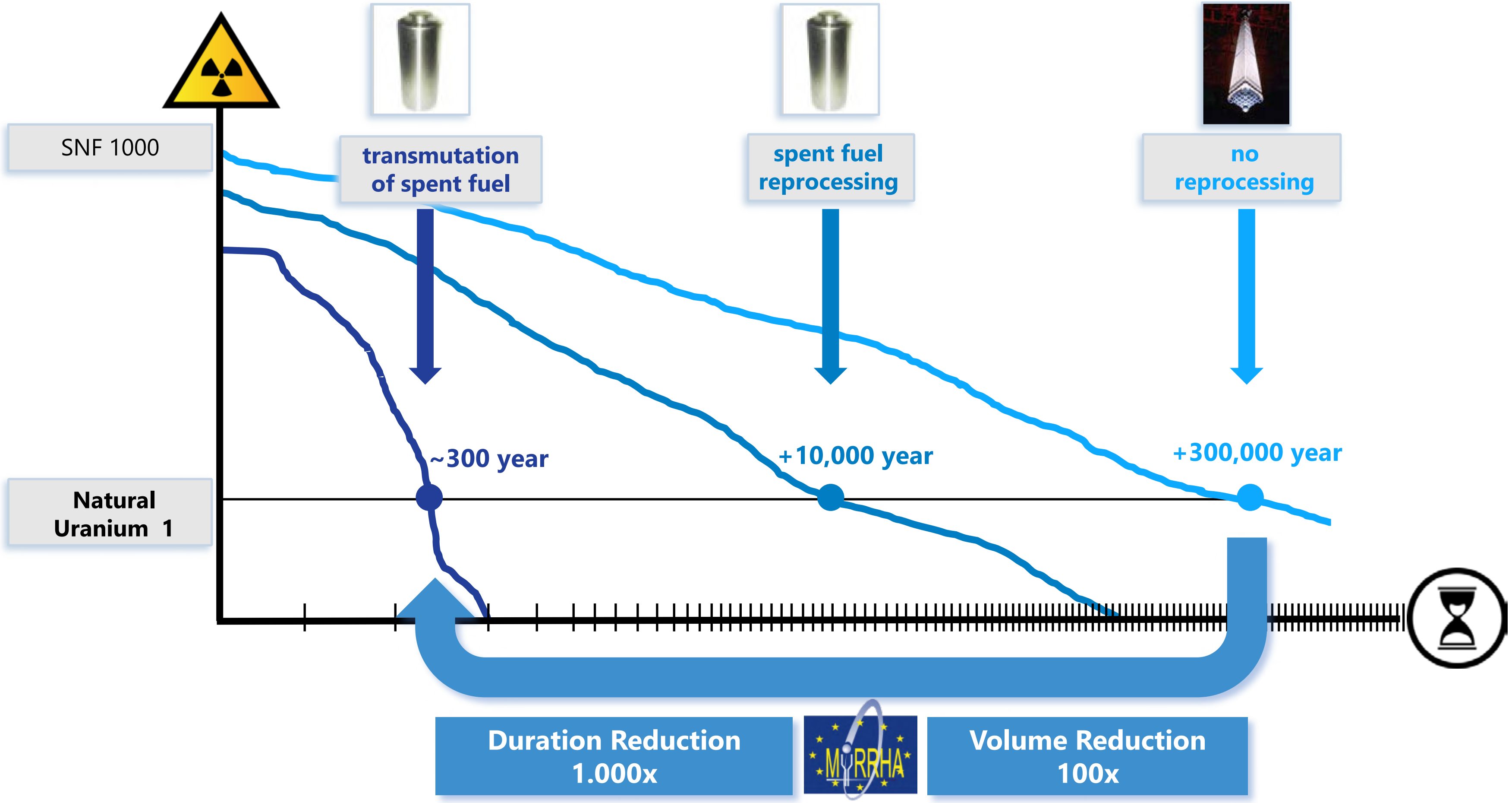
Why do we need Partitioning ?

- Only for For better use of resource

- P&T for transmuting MA’s?

- For environmental reasons

Transmutation of MA's is the better solution for Spent Nuclear Fuel



*SNF = Spent Nuclear Fuel

Source: European Commission Strategy Paper on Partitioning & Transmutation (2005), SCK•CEN MYRRHA Project Team

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Why do we need Partitioning ?

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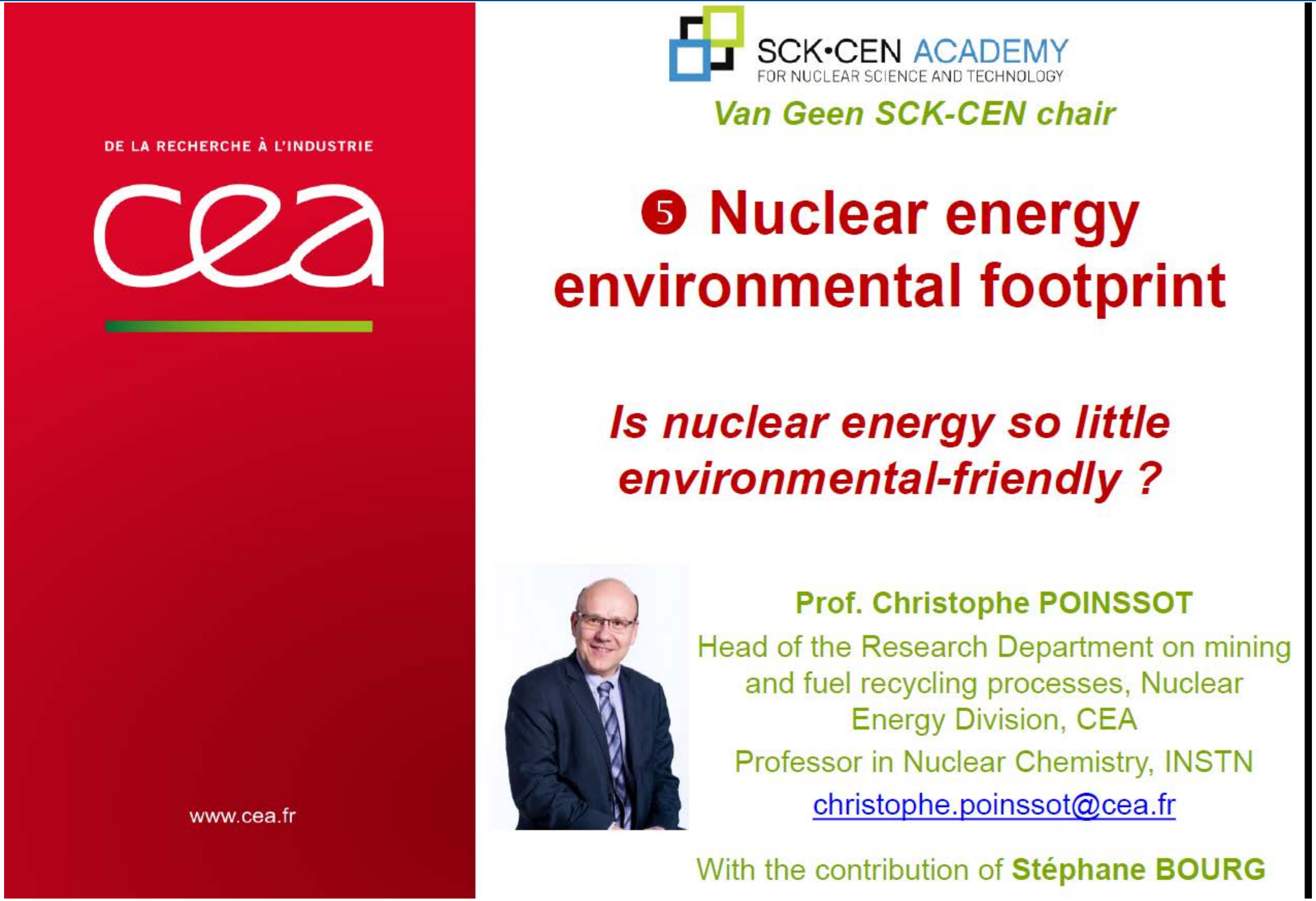
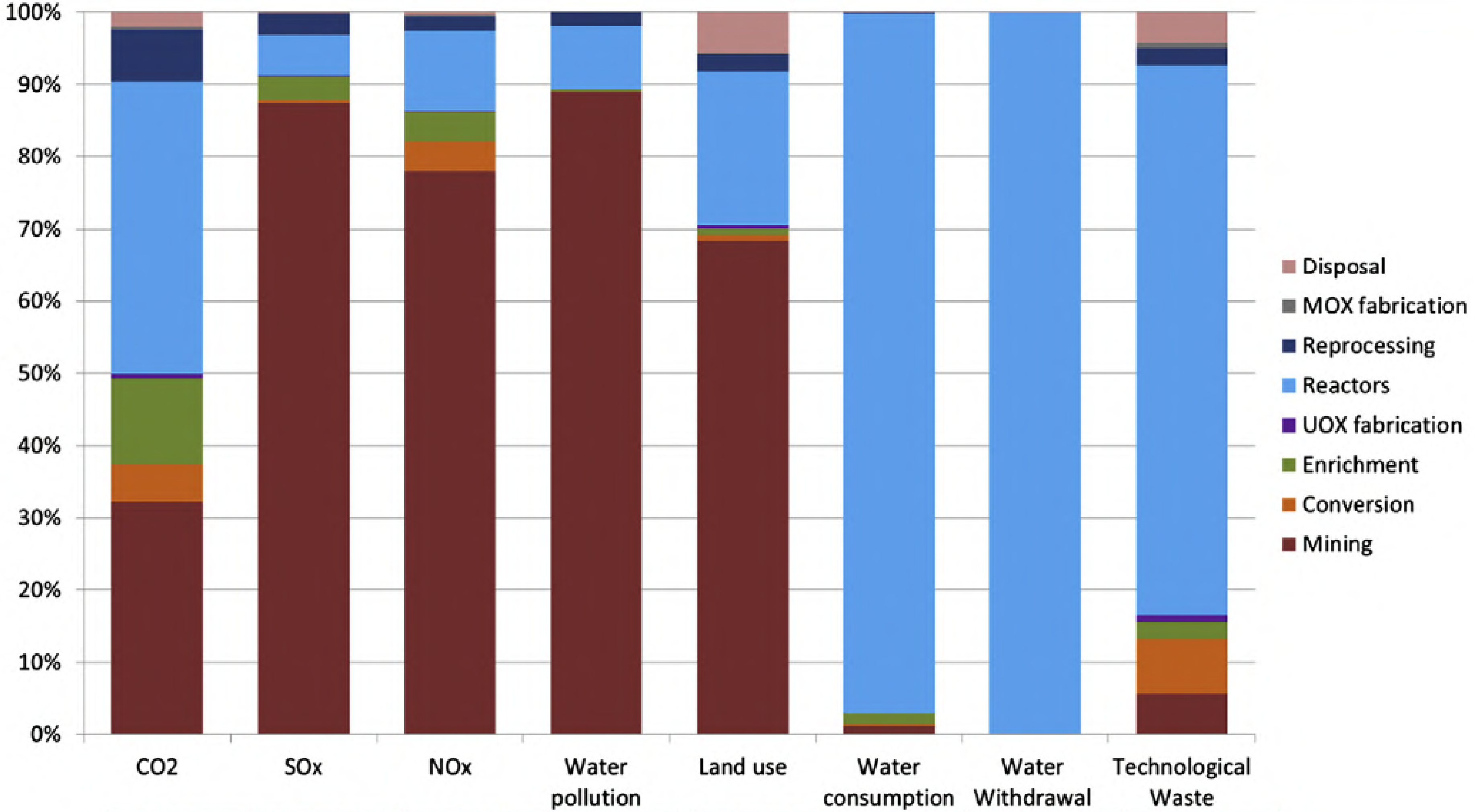
- P&T for transmuting MA’s?

- For environmental reasons

What is the most important part of the fuel cycle for the NE environmental footprint?



The general environmental indicators of the TTC



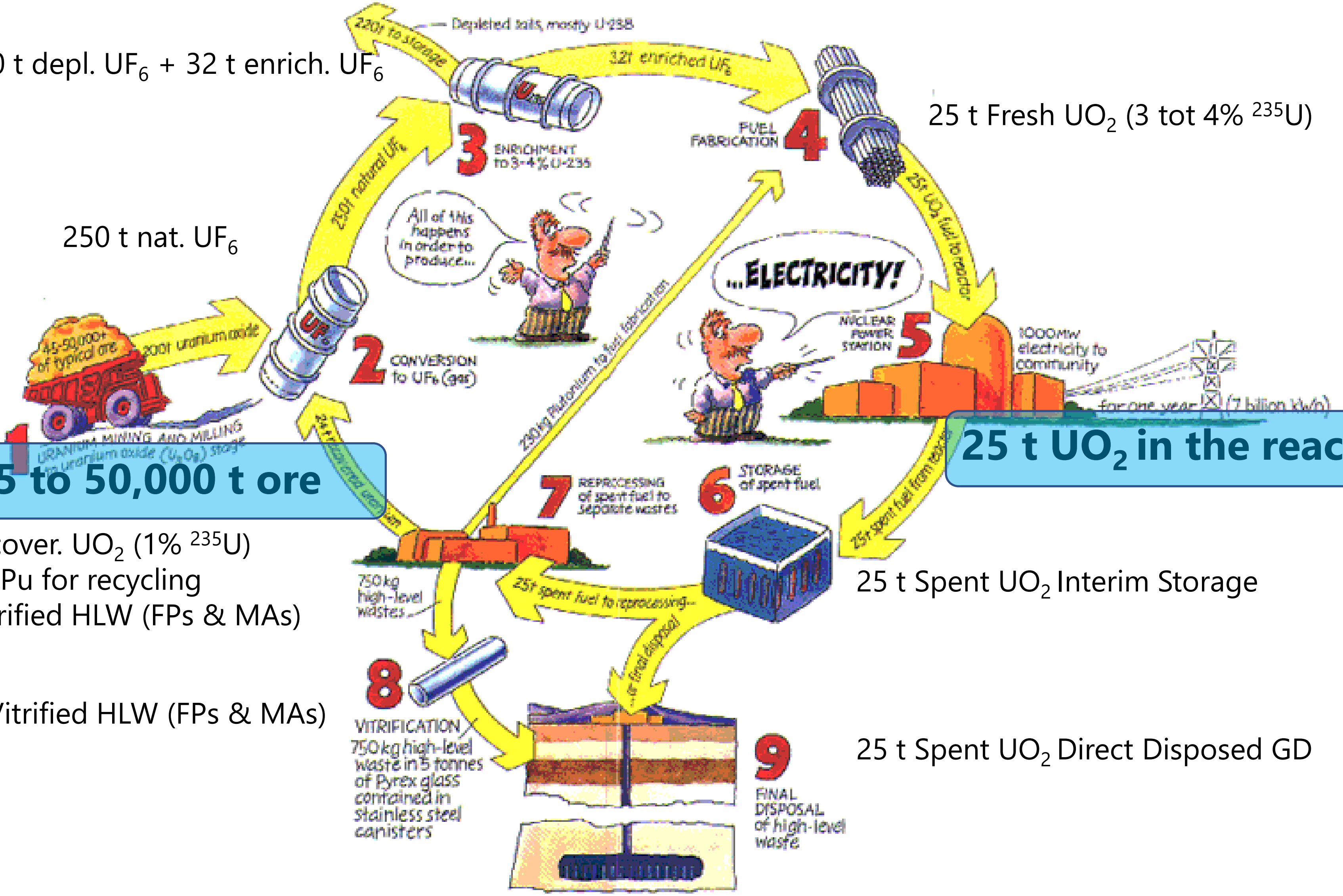
(gCO_2 eq/kWh_e)	(mg/kWh_e)	(mg/kWh_e)	(mg/kWh_e)	(m^2/GWh_e)	(L/MWh_e)	(L/MWh_e)	(g/MWh_e)
5,29	16,276	25,30	287,53	211,0	1507	72364	93,9

Quantities at different stages for 1GWe PWR

220 t depl. UF_6 + 32 t enrich. UF_6

25 t Fresh UO_2 (3 tot 4% ^{235}U)

250 t nat. UF_6



45 to 50,000 t ore

25 t UO_2 in the reactor

24 t recover. UO_2 (1% ^{235}U)
230 kg Pu for recycling
750 Vitrified HLW (FPs & MAs)

25 t Spent UO_2 Interim Storage

750 Vitrified HLW (FPs & MAs)

25 t Spent UO_2 Direct Disposed GD

- Fuel Cycle or Cycles
- Importance of closing the Fuel Cycle
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- Role of MYRRHA and it's importance for opening new avenues

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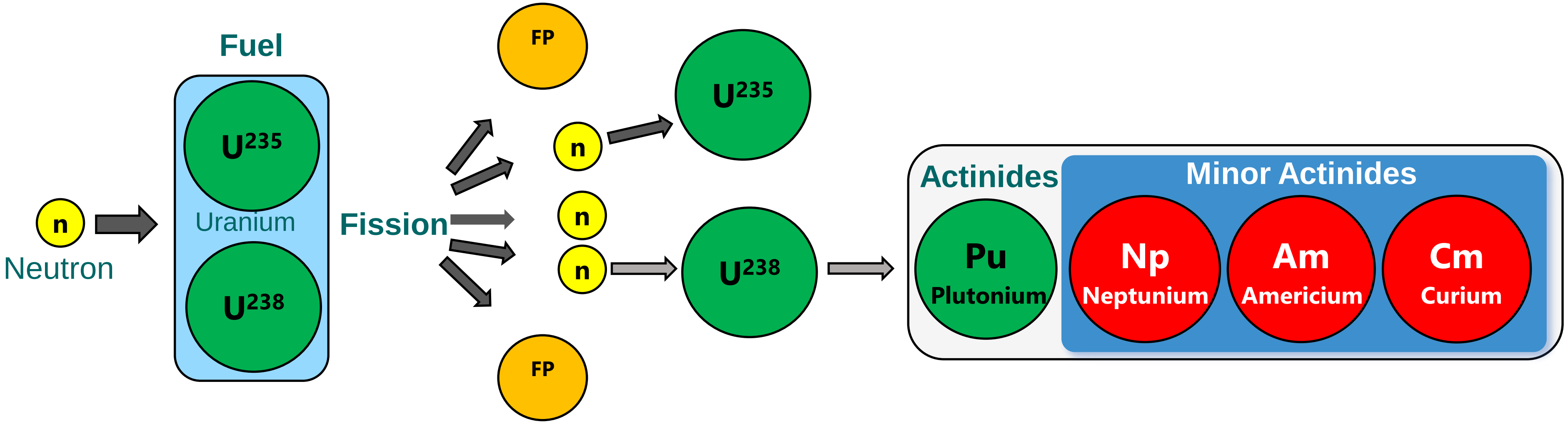
Source:

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 (sorting)**
  - Separate the ingredients of the spent fuel in “similar” categories we can treat in a similar way
- **Transmutation (valorizing)**
  - Use intense neutron field to transmute isotopes into others, less “nasty” and producing energy (**circular economy**)

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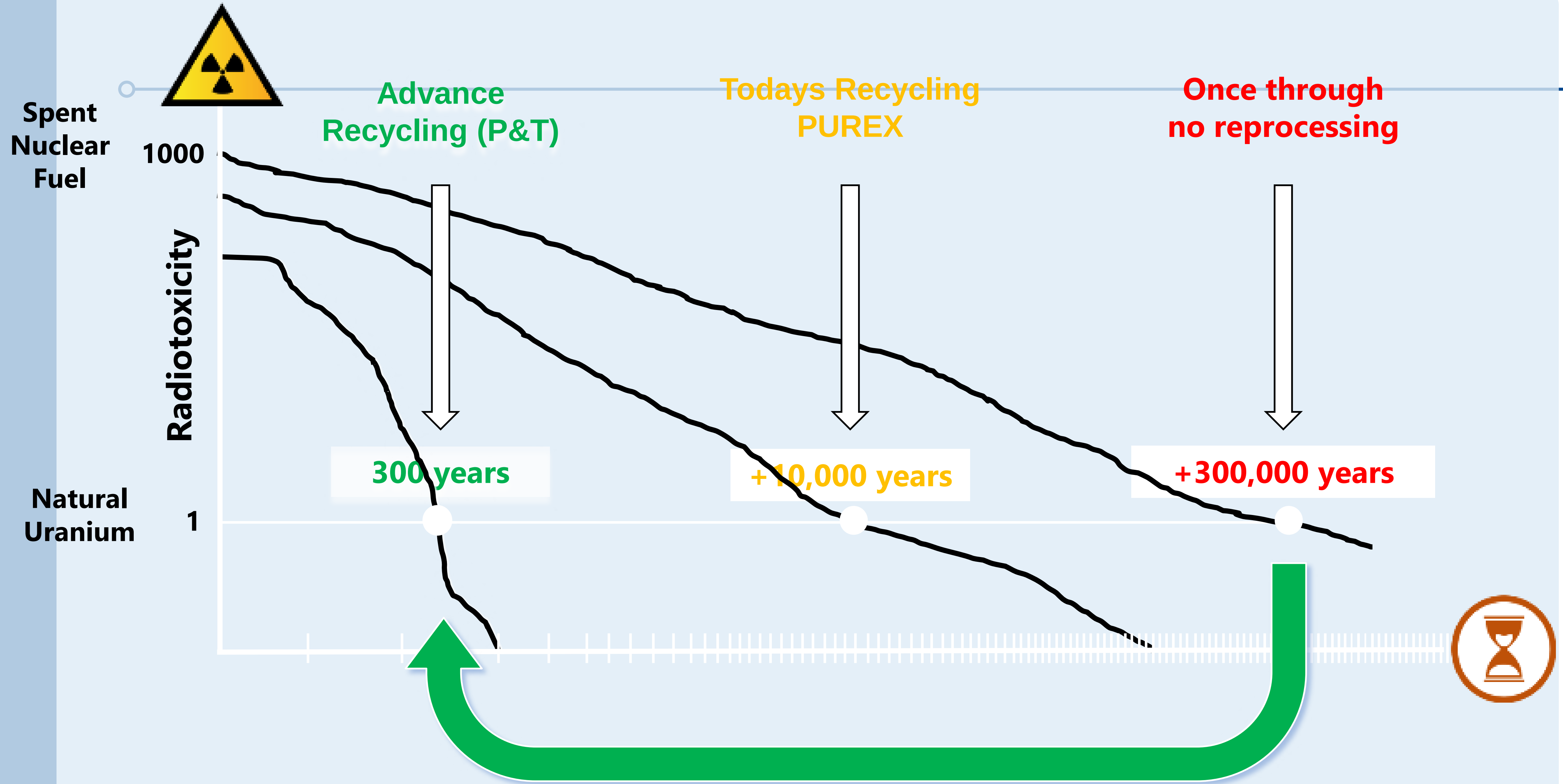
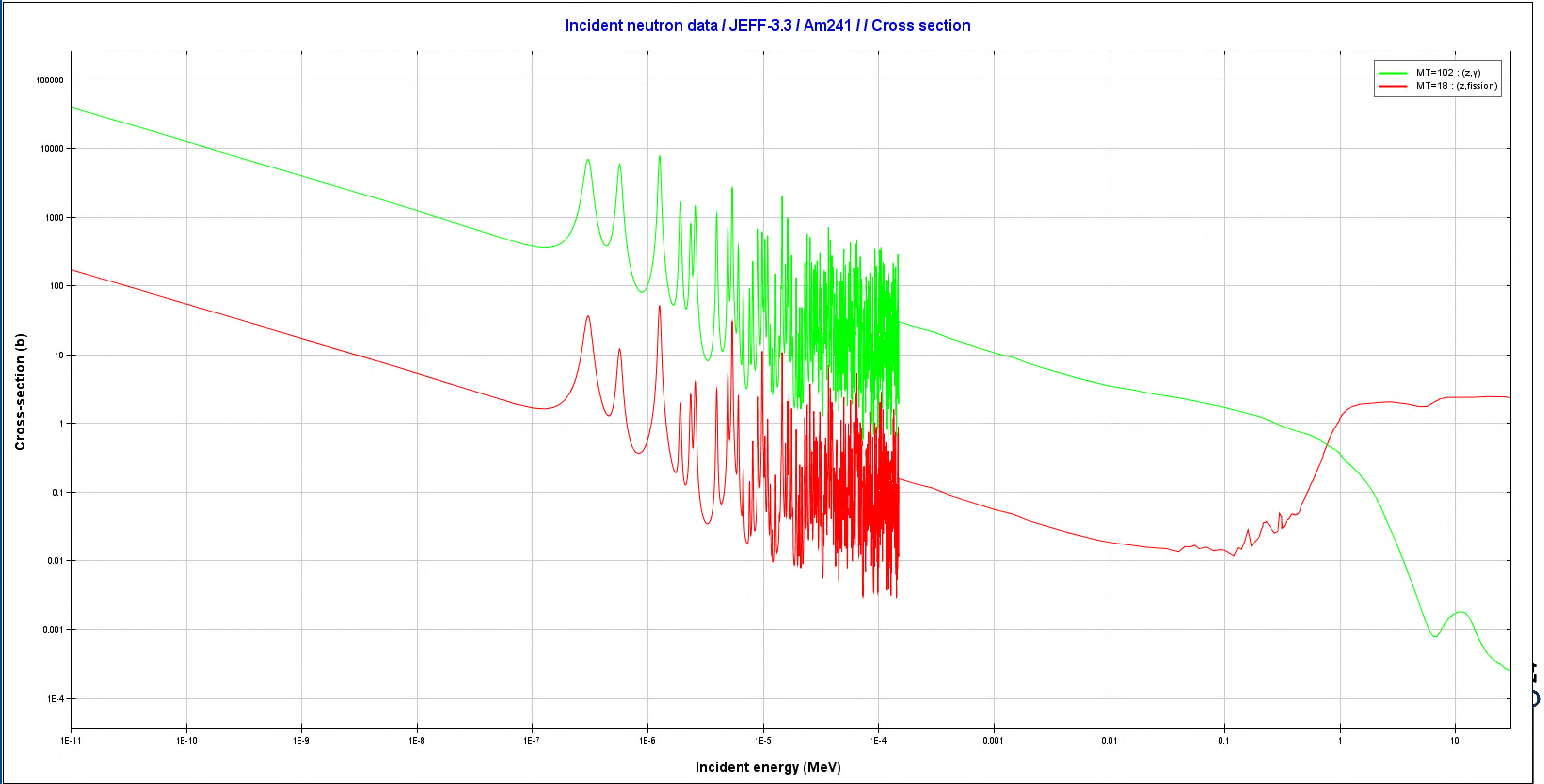


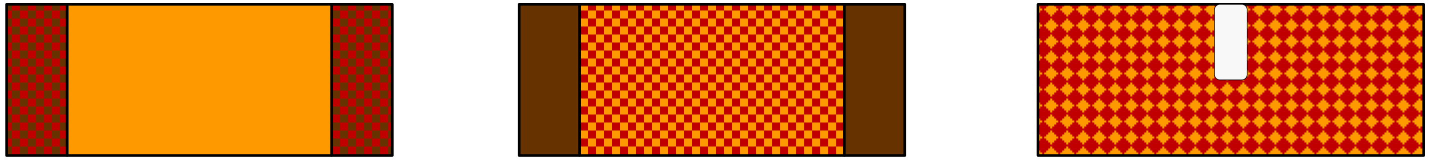
Spent
Nuclear
Fuel
1000
Advance
Recycling (P&T)
Todays Recycling
PUREX
Once through
no reprocessing
Radiotoxicity
300 years
+10,000 years
+300,000 years
Natural
Uranium
1

Transmutation = fast neutrons



Three options for Minor Actinide 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)

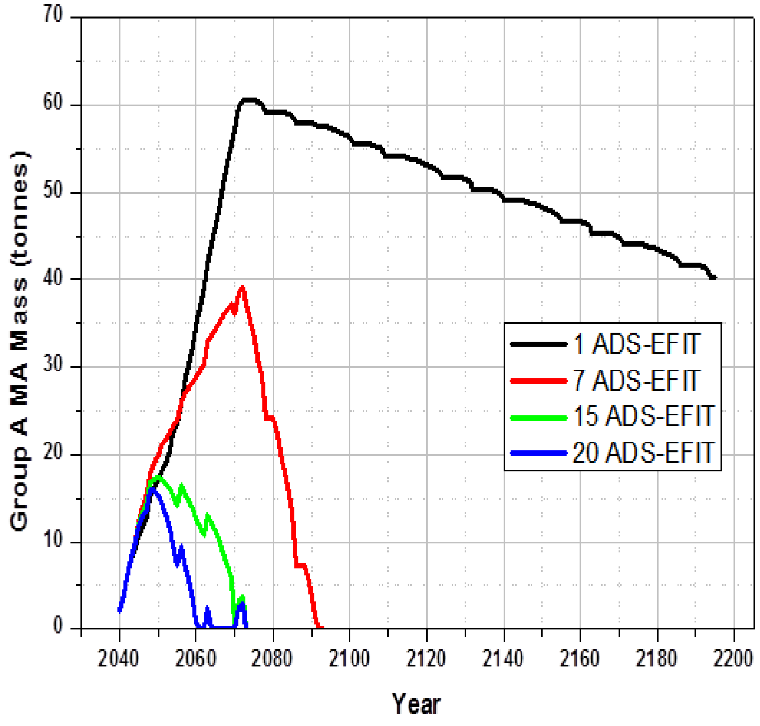
➔ **ADS performs the best**

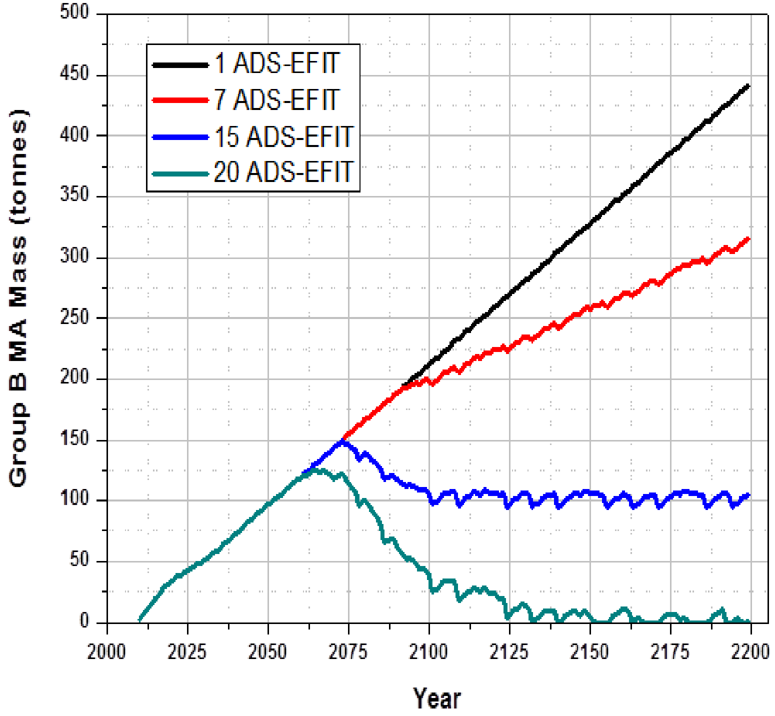
Belgian geological repository: impact on footprint (km²)

	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**

Shared & efficient solution for MA mgt
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]

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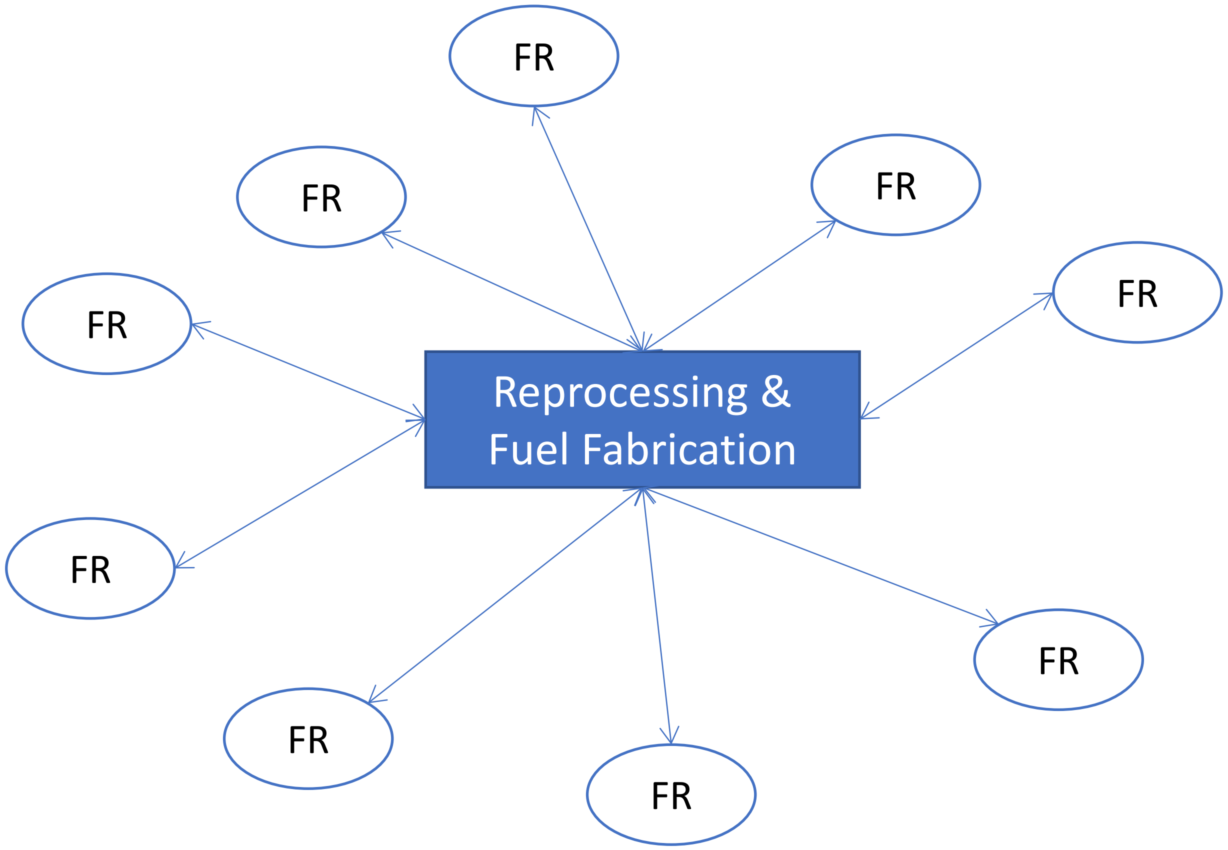
Transport issues of MA-Fuels FR vs ADS

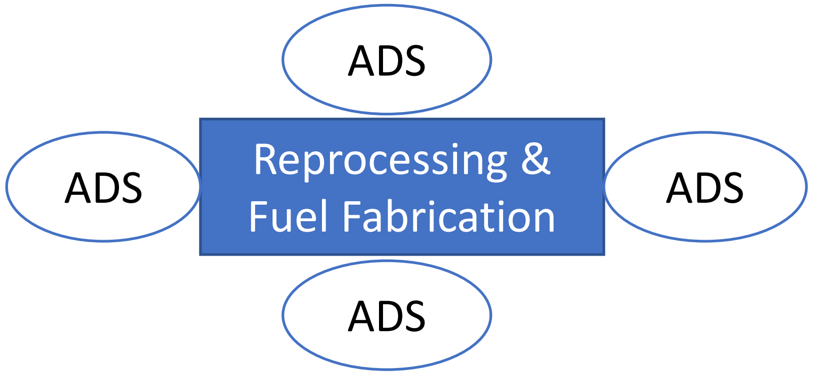
Transmutation in Fast Reactors

- 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

Source:

NEA
NUCLEAR ENERGY AGENCY

Towards Sustainability of Nuclear Fuel Cycles

NEA Task Force on "Demonstration of Fuel Cycle Closure including Partitioning and Transmutation for Industrial Readiness by 2050"

Key Finding and Recommendations

Prof. Hamid AÏT ABDERRHAIM
General Manager, MYRRHA

Motivations and Drivers: The Future We Want

- **Energy is life**
- **Nuclear energy: A necessity for a net-zero economy**
- **Time to transition to a circular economy for nuclear energy**
- **Advancing towards full recycling**

An NEA flagship, policy-oriented Task Force

Goal

- Produce a **“high-level report”** to help policy-makers make informed decisions to **enable the industrialisation of *full recycling* of spent nuclear fuel**
- Stress the need for and the benefit of achieving **a pre-industrial demonstration**

Holistic Approach

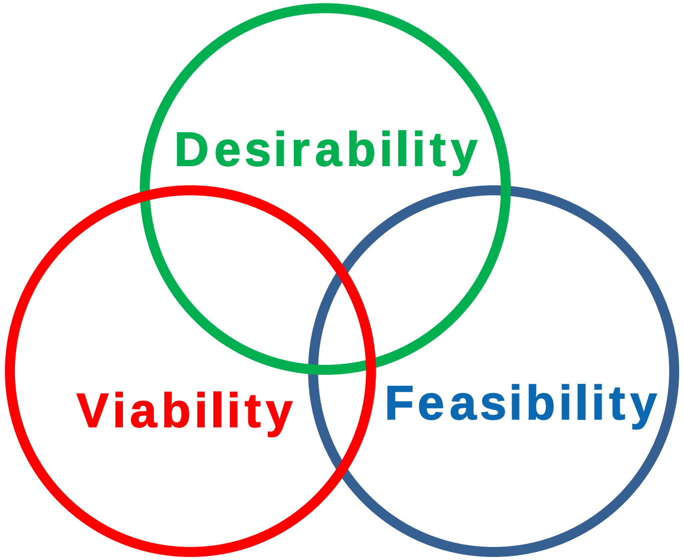
- Societal aspects
- Advanced technologies for *full recycling*
- Economics

Visit [*oe.cd/TF-FCPT*](oe.cd/TF-FCPT)

A Holistic Approach

Societal aspects

- Focus on society's worries and concerns



Advanced technologies for full recycling

- Advanced separation technologies for used fuels from Gen II-III LWRs
- Advanced fuel fabrication and performance
- Transmutation systems: SFR, LFR, **ADS**, MSR
- Reprocessing of advanced fuel
- Advanced fuel technological aspects: transportation, cooling, and handling

Economics

- Identification of the return on investment of the pre-industrial demonstration of full recycling

Securing a Desirable Future

- ***Full** recycling* of nuclear fuel can **optimise** the **use of natural resources** and **waste management**
- **A pre-industrial demonstration is essential** to validate these technologies
- **Engagement from all stakeholders** is crucial for success
- Several systems (SFR, LFR, ADS and MSR) offer the potential for full recycling (plutonium continuous recycling and minor actinide transmutation) but with
  - Varying levels of efficiency at the industrial scale
  - Different logistical challenges, such as transportation
  - Different levels of technology readiness today
- Solutions can be optimised by **combining different technology "building blocks"** depending on national policies and regional strategies *(Note HAA: EURATOM integrated multilateral solution)*
- **Uncertainty reduction:** technology, economics and society's perception *(RoI of pre-industrial demonstration)*

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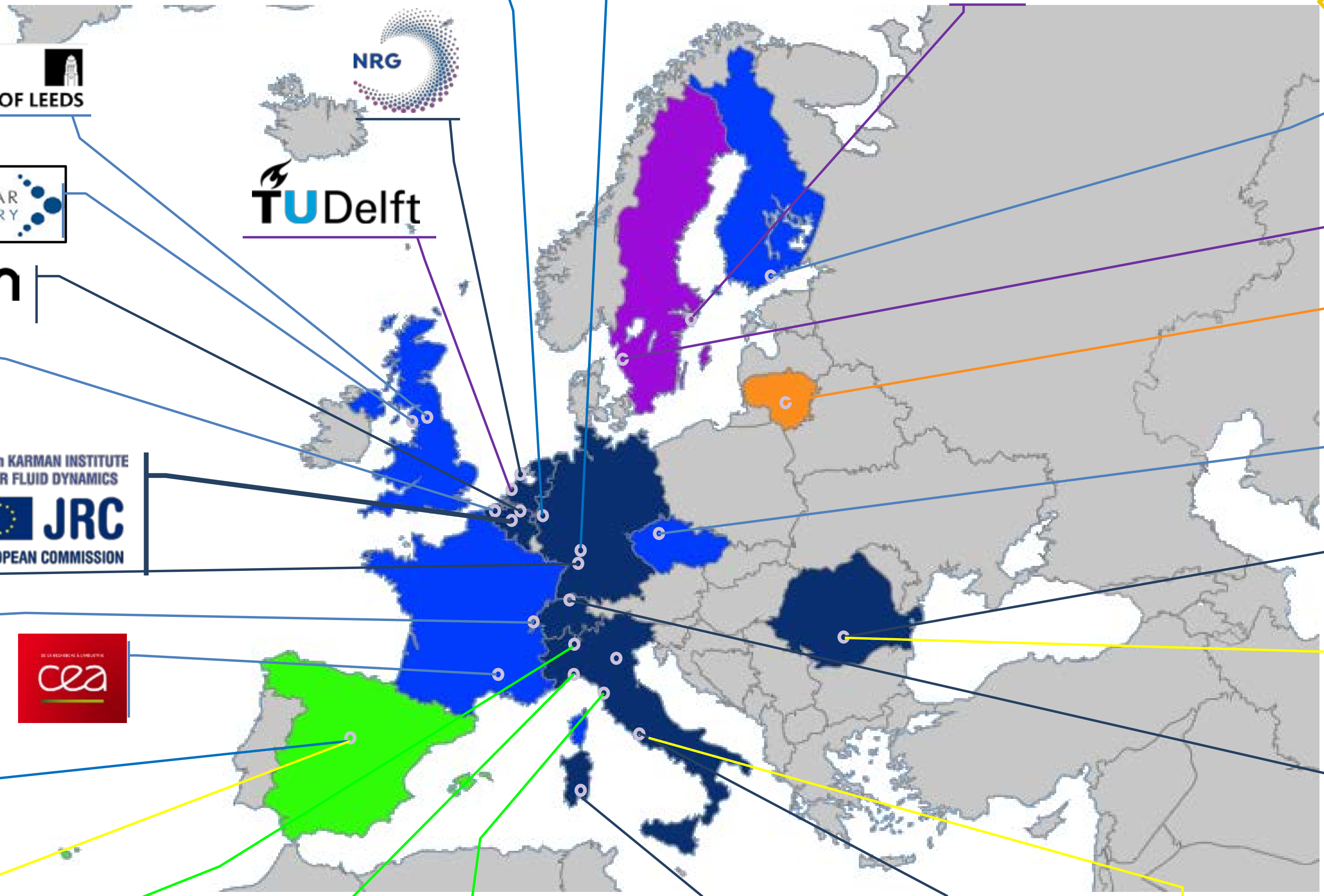

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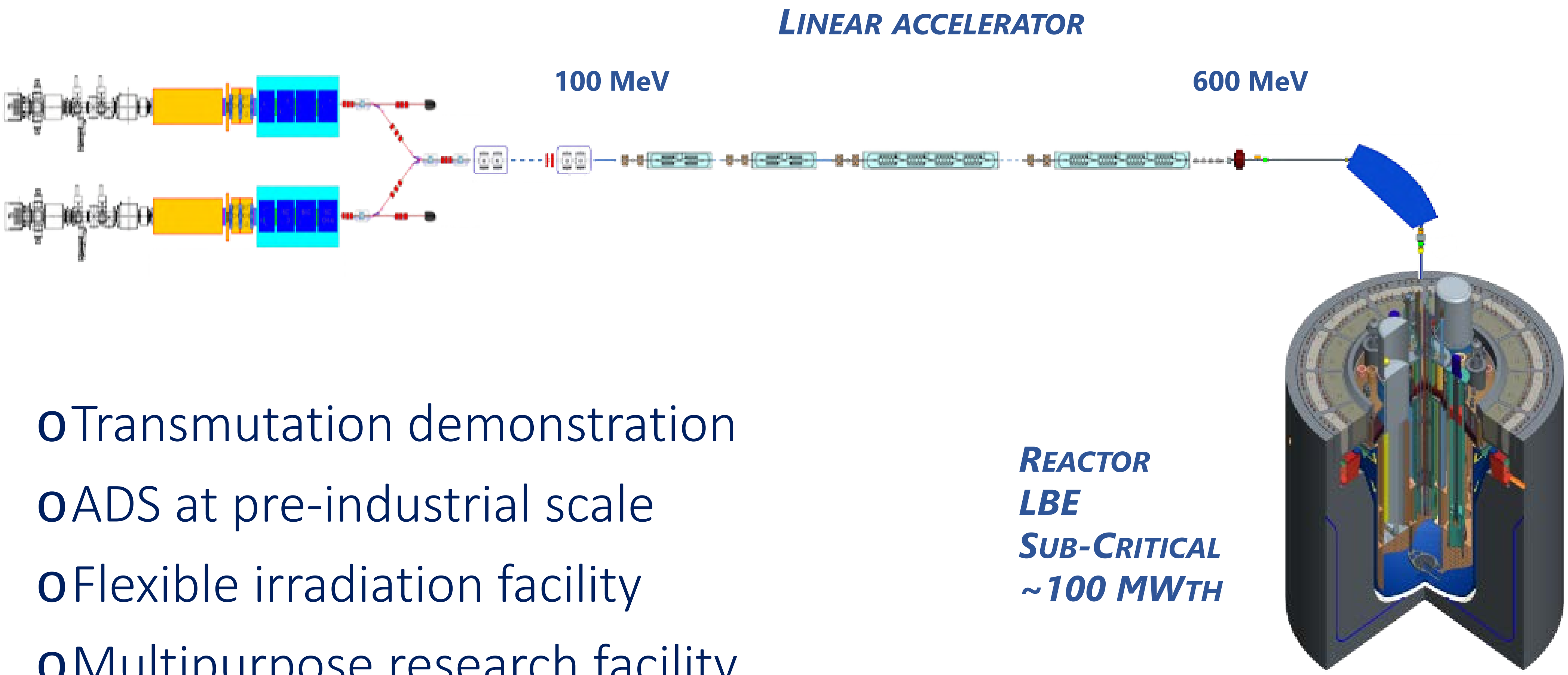
Transmutation systems and R&D: MYRRHA

- A pan-European multipurpose research infrastructure
- A key facility contributing to nuclear innovation & energy transition

Based on Accelerator Driven System (ADS)



- Transmutation demonstration
- ADS at pre-industrial scale
- Flexible irradiation facility
- Multipurpose research facility

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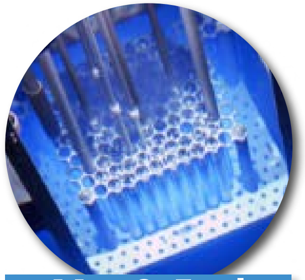
MYRRHA's Application Portfolio

SNF*/ Waste

Radio-isotopes

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

Fusion



Mat.& Fuel
GEN IV

Support to
SMR LFR

Fundamental
research

*SNF = Spent Nuclear Fuel

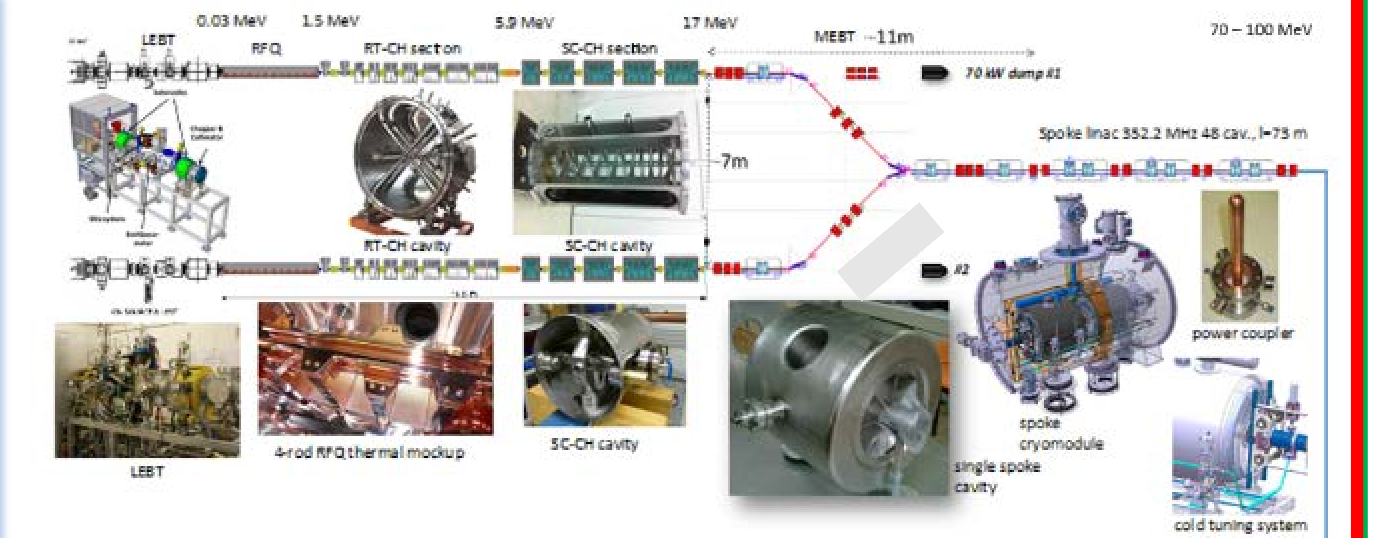
MYRRHA's phased implementation strategy

UNDER CONSTRUCTION

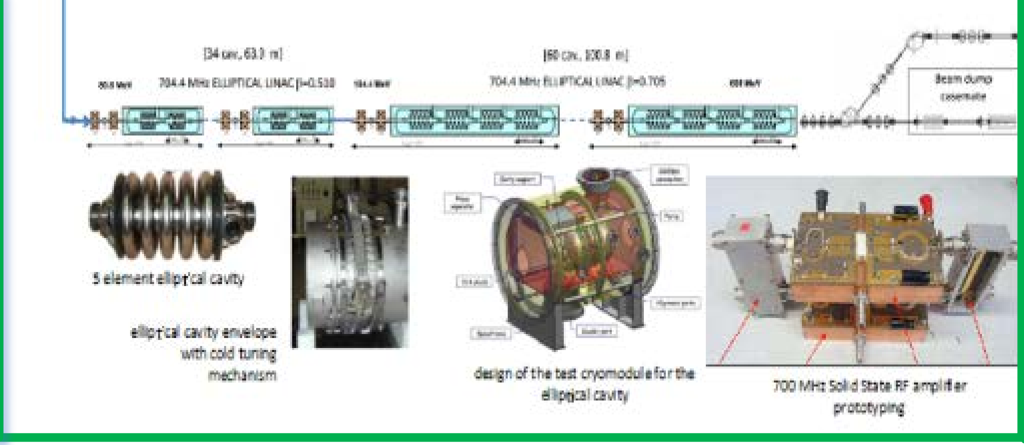
Benefits of the phased approach:

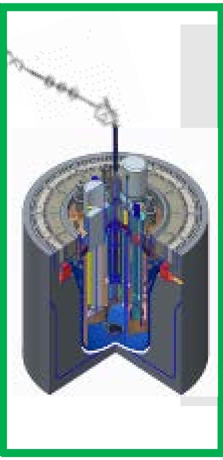
- already a first operational facility available in Mol at **end of 2028**
- spreading the investment costs
- successful milestone then next step >> reducing technical & financial risks

Phase 1 – 100 MeV + Proton Target Facility



Phase 2 – 600 MeV





Phase 3 – Reactor

MYRRHA Phase 1 | MINERVA Facility Layout

Groundbreaking Ceremony on 25 June 2024


MYRRHA | MINERVA Groundbreaking Ceremony
Mol, 25th June 2024

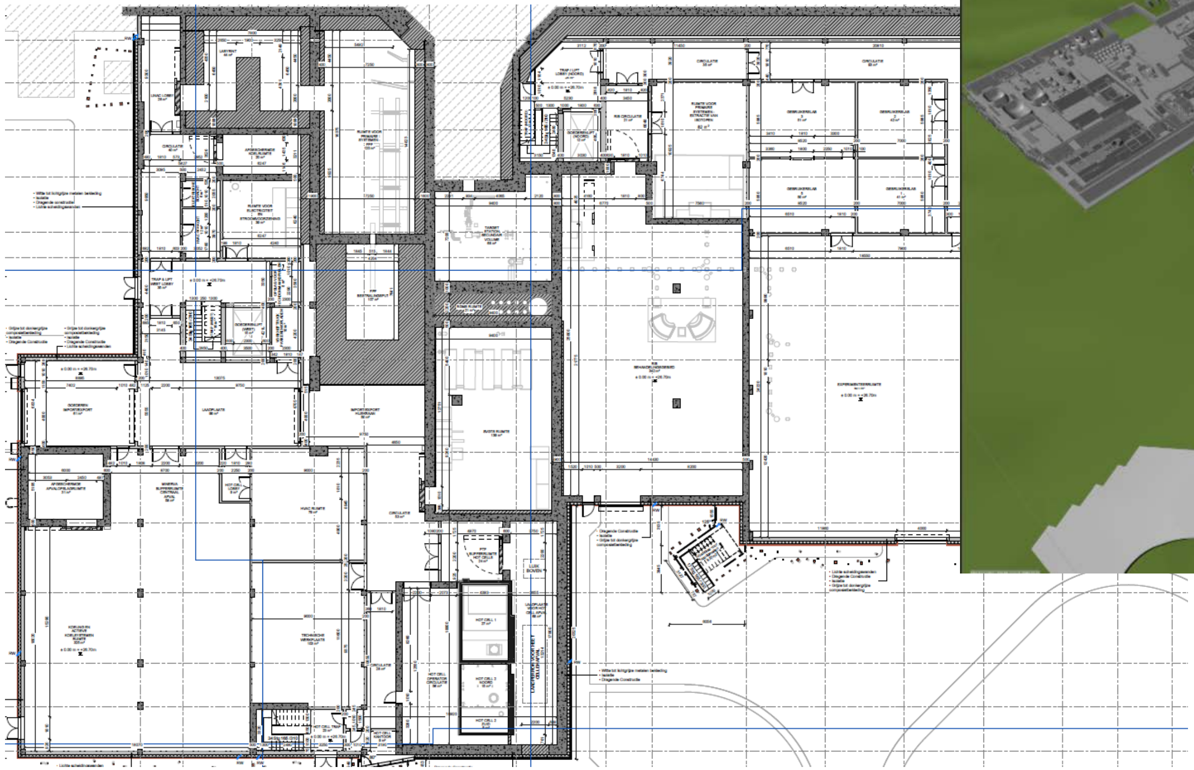
MINERVA implementation by 2027

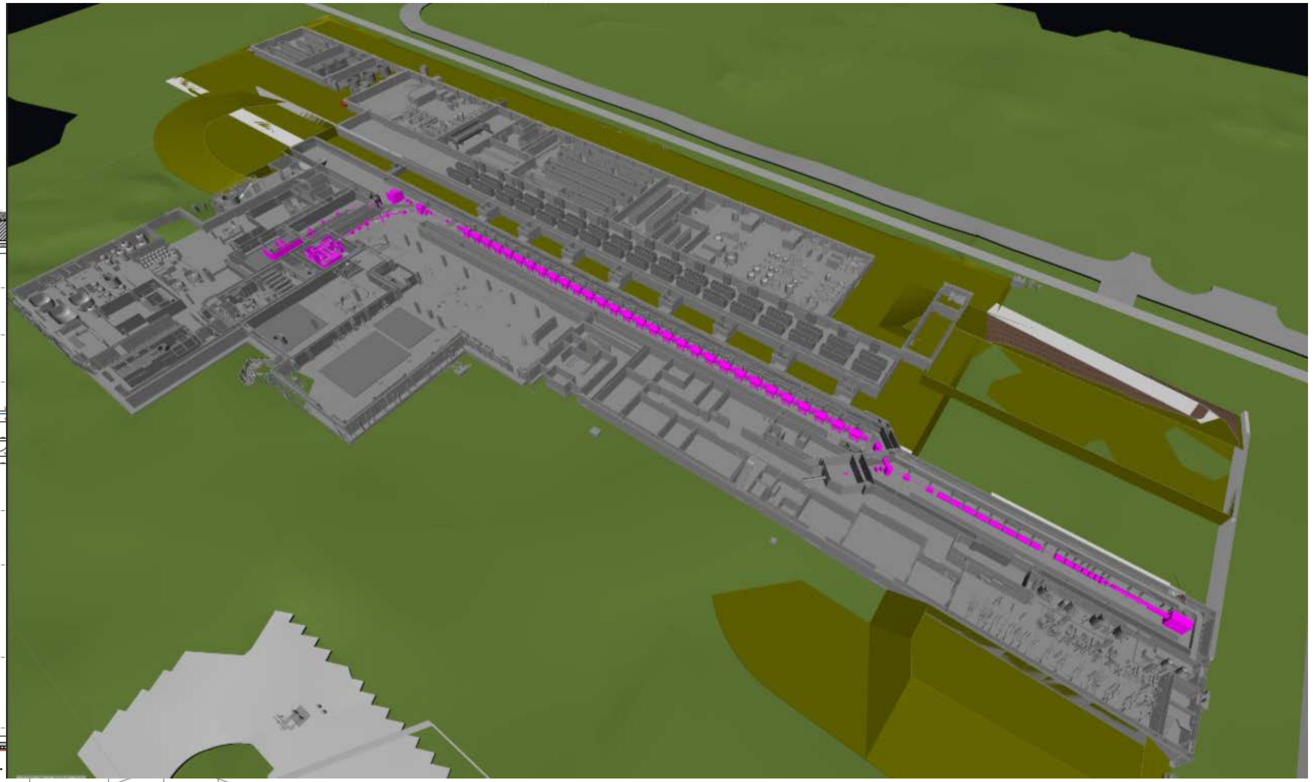
- Overall architecture frozen
- Internal layout frozen

- **Construction started (September 2024)**

Facility Design

- 3D data model
  - links ‘all’ information
  - tool for integration of SSC
- PLM
- Asset management





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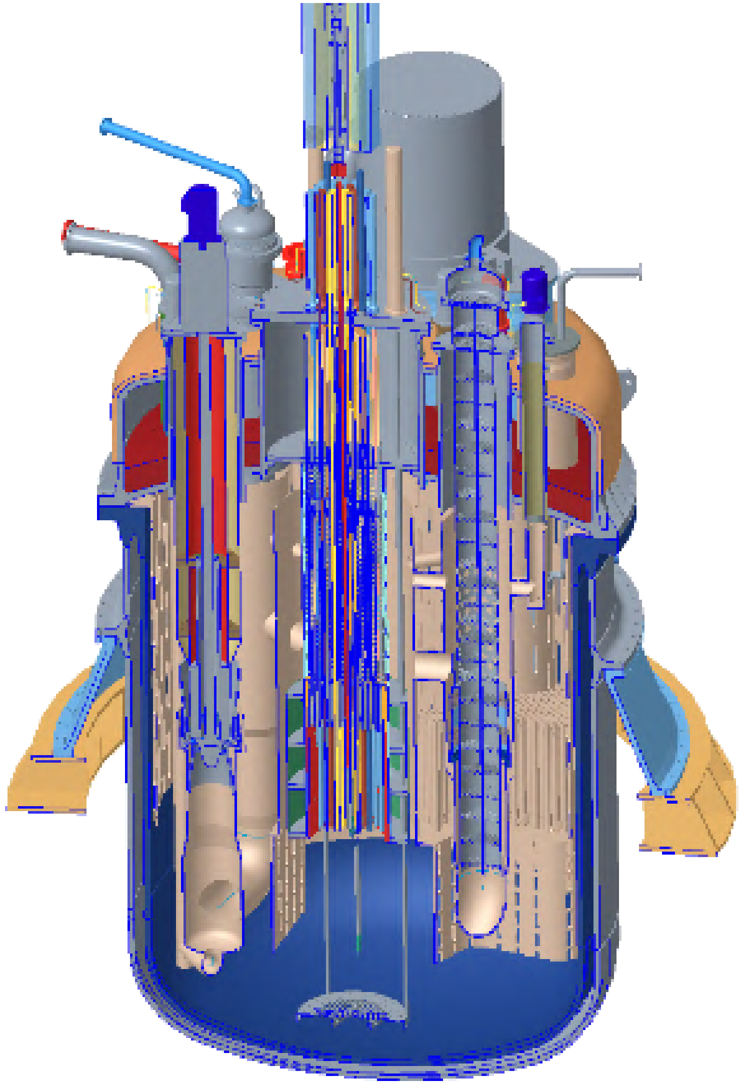
MYRRHA reactor design 1.8, frozen end 2020

Reactor Buildings design under progress at SCK CEN

- 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



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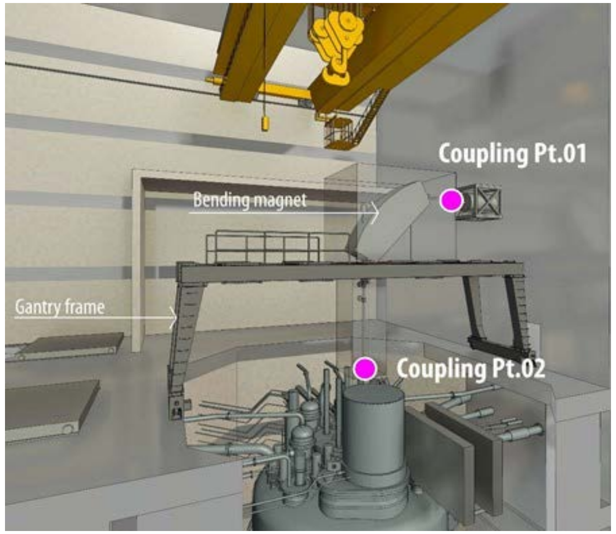
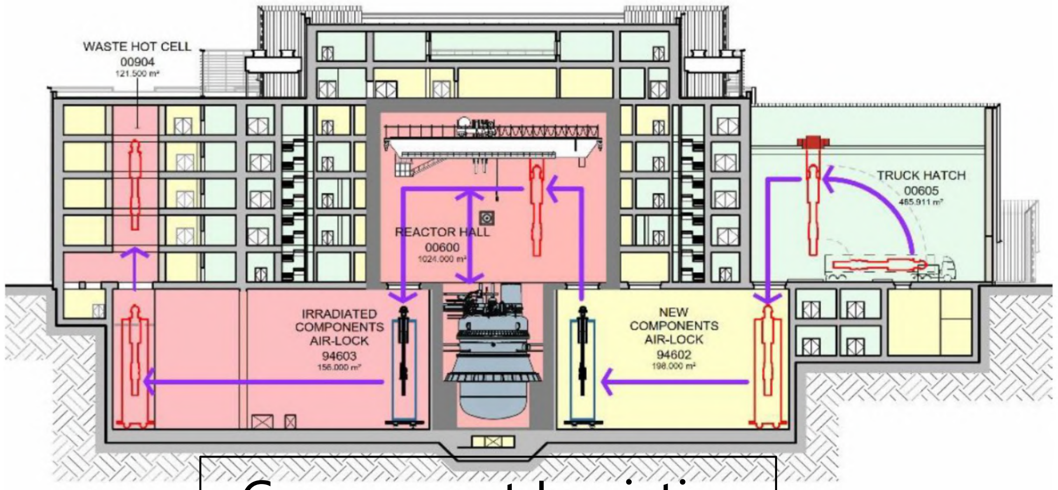
Snapshots of Reactor Buildings integration

In-service Inspection & Repair (ISIR) strategies & concepts, have been defined for the primary system components.

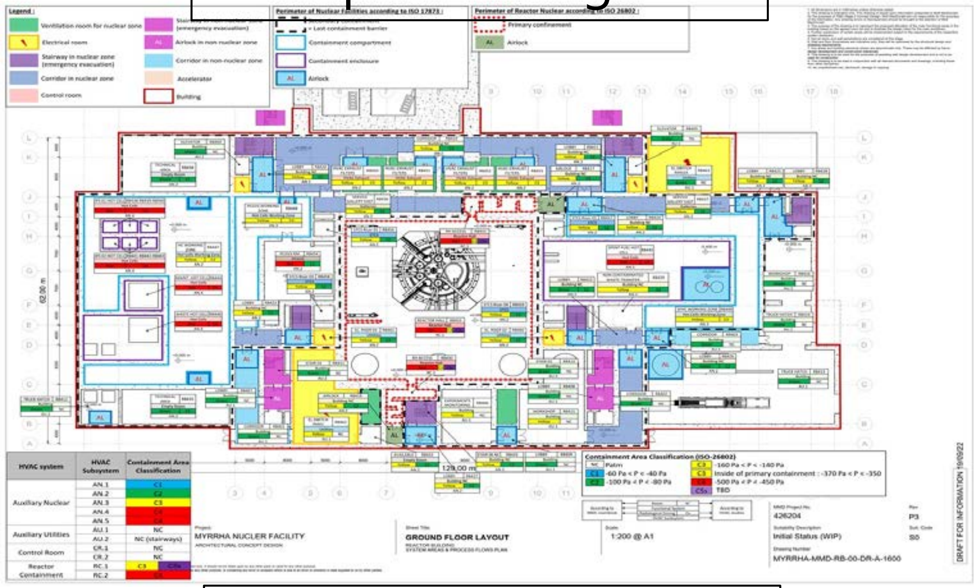
Remote Handling on the cover



Interfacing with the bending magnet and logistics equipment

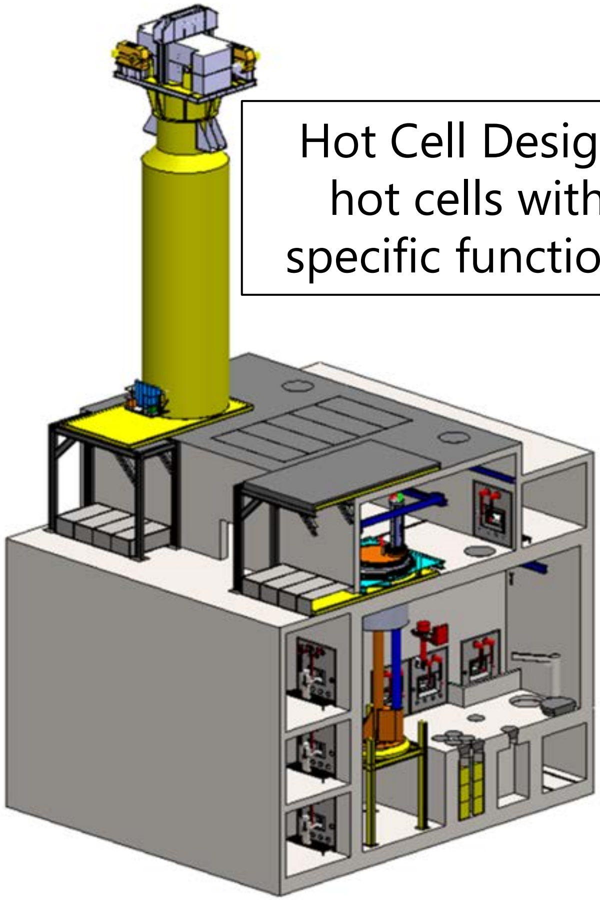


Component Logistics

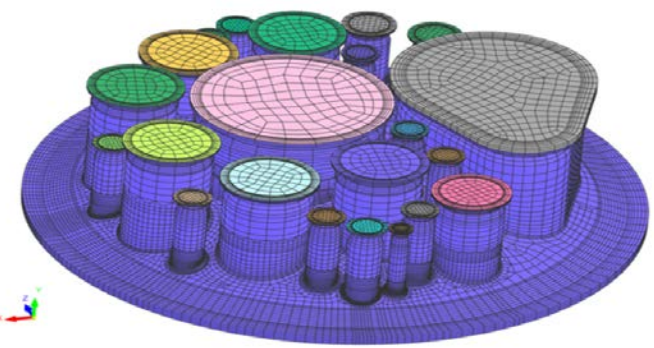


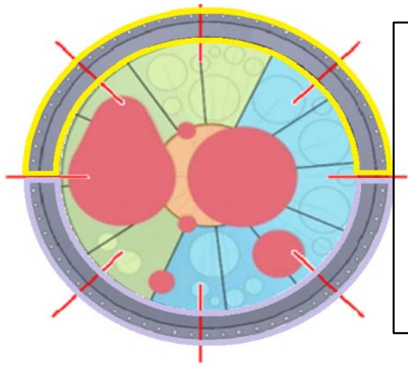
HVAC Zoning

Highlights: Reactor Conceptual Design

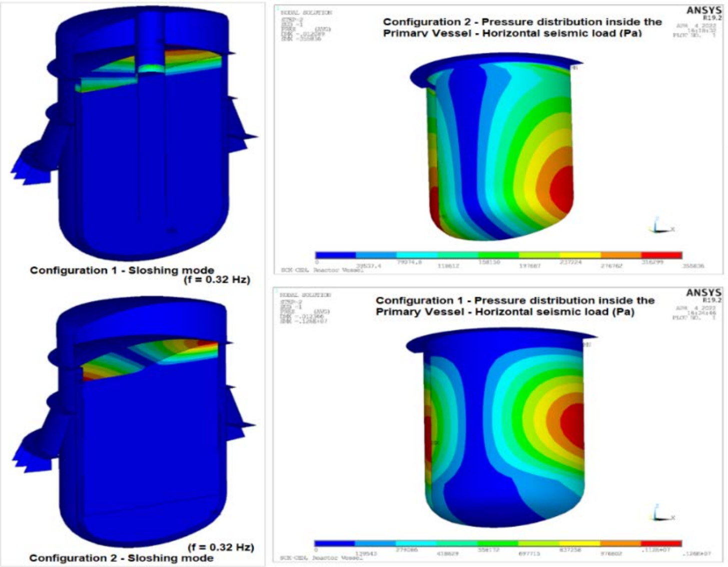


Hot Cell Design: hot cells with specific functions

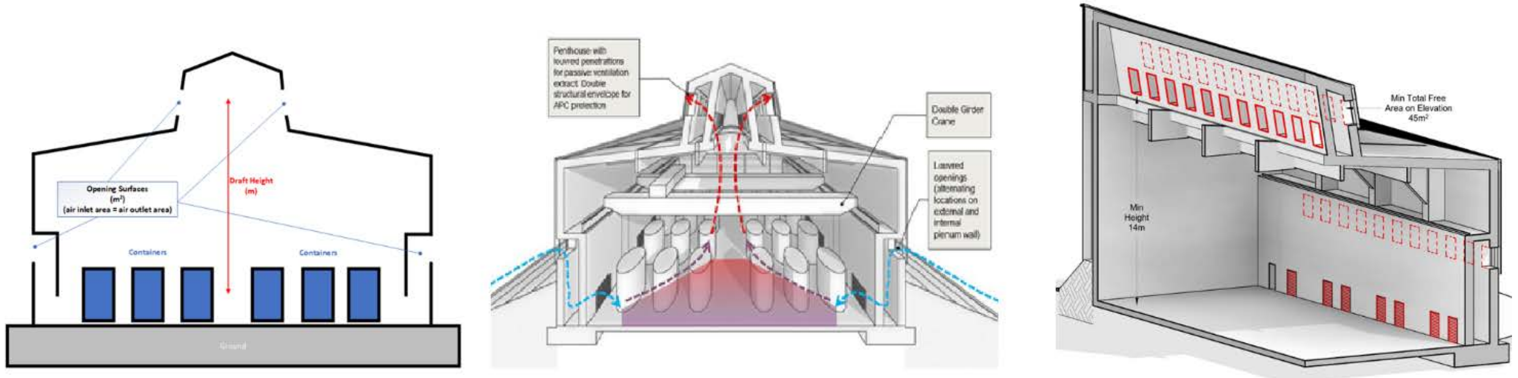




Mechanical and manufacturing analysis of the cover



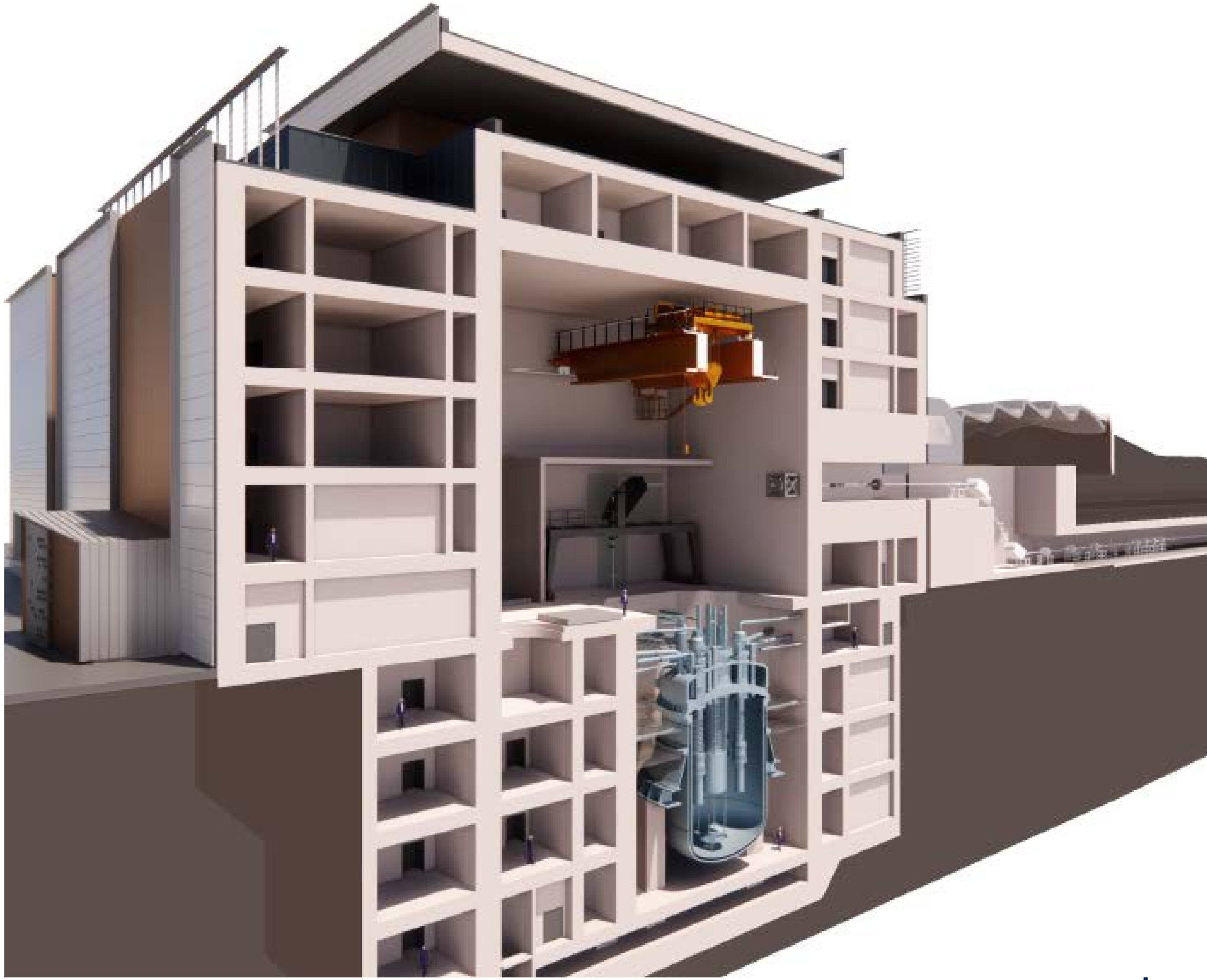
Seismic loading analysis on the vessel



Spent Fuel Building passive cooling storage

MYRRHA Reactor Buildings

- Multi-disciplinary integration
  - Reactor Building
    - Nuclear material handling
    - Ex-vessel remote handling
    - Hot Cells
    - Building Equipment
    - HVAC
    - Utilities
      - Process
      - I&C
      - Electrical
      - Fire protection
  - Accelerator (beam line and bending magnet)
  - Spent Fuel Building
  - Waste Building



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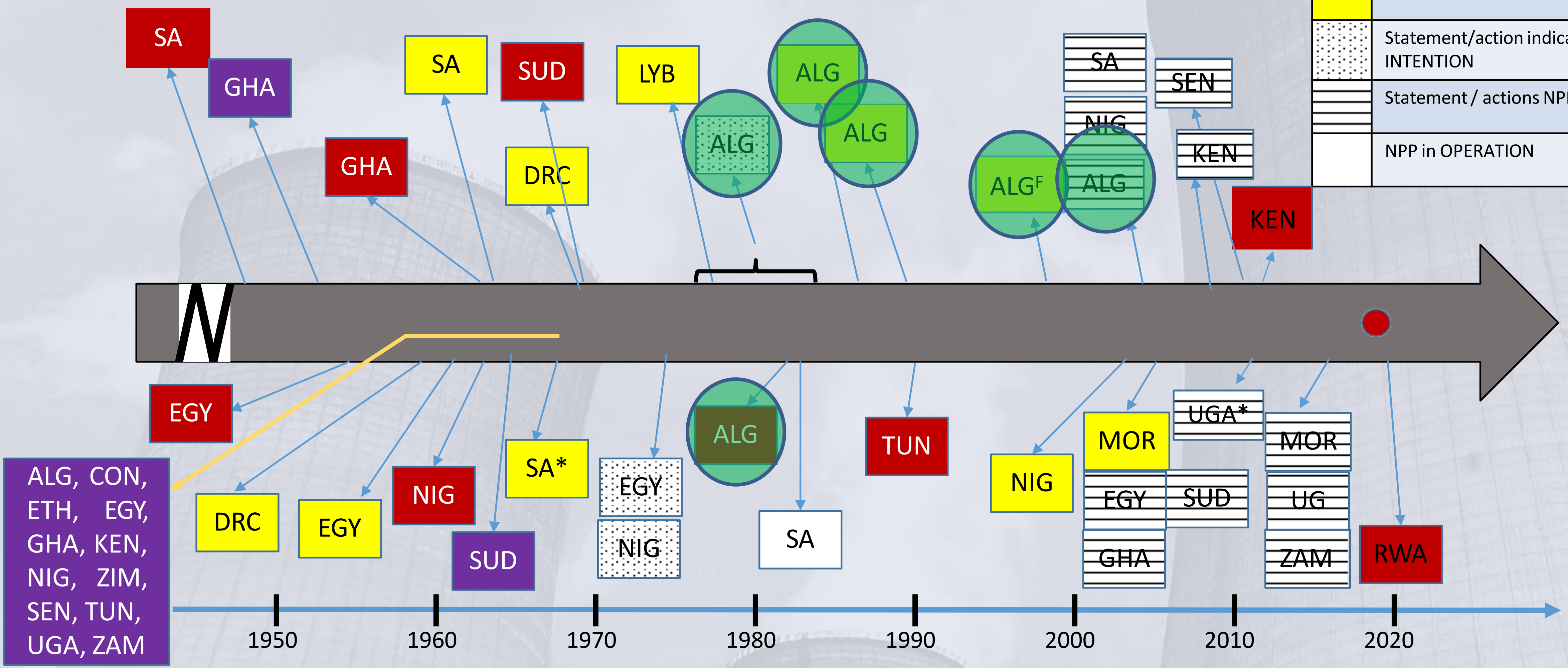
MYRRHA HLM Facilities
for R&D support for Design & Safety

The Nuclear Option for Algeria

- Algeria is pioneering country having considered nuclear power generation in Africa
- Algeria has 4 nuclear research centres with needed technical and technological labs & basics equipment (2 RR’s) for preparing the needed skills & competences as well as mastering the technology
- Algeria has educated enough people to initiate the preparatory phase for implementing nuclear power in the country
- Algeria has created in 2011 the IAGN for securing the E&T within the country of new generations of engineers & technicians expert in nuclear sciences & technologies
- Algeria has an interesting diaspora of experts in nuclear power generation and technology that can contribute to this endeavour

Timeline of Atomic Energy in Africa

COLOUR/PATTERN CODE	
Red	ACT/STATEMENT/ESTABLISHMENT indicating beginning of nuclear Technology
Purple	APPLICATION of nuclear energy
Yellow	RES. REACTOR in operation
Dotted	Statement/action indicative of NPP INTENTION
Horizontal lines	Statement / actions NPP REVIVAL
White	NPP in OPERATION



Nuclear energy in the energy transition towards decarbonisation

- Decarbonisation ➔ less primary carbon-based energy sources use & more electricity consumption
- Todays tendency: Renewables will do the job (not realistic)
- Nuclear energy contributes to the following features
  - Major contribution to **security** of energy supply
  - A **dispatchable production** for a stable and competitive electricity generation
  - Providing **non-electricity energy services** for water desalination, hydrogen production, district heating and process heat
  - Stable prices on the long-term (uranium ore represents **today 6 to 8% of the KWh price**)
  - Providing long-term human resources employment (**economic and well-fare pay back**)
  - Developing **high level technology industries** (important to activate the **local industry in the supply chain**)

The Nuclear Option for Algeria

- Challenges faced by Large Reactors searching for Capital Investment:
  - **Large up-front investment escalation** (France, Finland). Flamanville and Olkiluoto are three times over budget. **But Today both countries are happy having completed the challenge**
  - EPR investment plans in UK illustrate funding size challenge. **Chinese investment needed for financing: which country can still finance LRs? China is today capable to deliver 3 to 4 LRs/year in-time and in budget/same apply for Sout-Korea**
  - Financial distress :
    - Areva in financial distress caused (primarily) by Flamanville and Olkiluoto cost overruns, French Government stepped in to save the company.
    - Westinghouse filed for Chapter 11 protection on March 29th 2017, caused (primarily) by cost overrun of

Increased uncertainty around Large Reactors in terms of Economic requirements (affordability + predictability)

SMR concepts: status & characteristics

- SMRs are not new – present since beginning of the nuclear era
- Initial design in submarines (USS Nautilus 1955), ice-breakers, **BR3 (1st PWR in BE; 11 MWe started in 1962)**
- Today more than 90 designs and concepts are under development in various countries
- The level of development is ranging from conceptual stage to constructed as indicated in next tables :
    - Dark green: SMR in operation, commissioned or finishing construction
    - Light green: under construction
    - Orange: licensed or certified by regulator
    - Red: submitted for permit
    - No color: conceptual design

SMR concepts: status & characteristics (1)

Design	Net output per module (MWe)	Number of modules (if applicable)	Type	Designer	Country	Status
Single unit LWR-SMRs						
CAREM	30	1	PWR	CNEA	Argentina	Under construction
SMART	100	1	PWR	KAERI	Korea	Certified design
ACP100	125	1	PWR	CNNC	China	Construction began in 2019
SMR-160	160	1	PWR	Holtec International	United States	Conceptual design
BWRX-300	300	1	BWR	GE Hitachi	United States-Japan	First topical reports submitted to the US NRC and to the CNSC as part of the licensing process
CANDU SMR	300	1	PHWR	SNC-Lavalin	Canada	Conceptual design
UK SMR	450	1	PWR	Rolls Royce	United Kingdom	Conceptual design
Multi-module LWR-SMRs						
NuScale	50	12	PWR	NuScale Power	United States	Certified design. US NRC design approval received in August 2020
RITM-200	50	2	PWR	OKBM Afrikantov	Russia	Land-based nuclear power plant – conceptual design
Nuward	170	2 to 4	PWR	CEA/EDF/Naval Group/ TechnicAtome	France	Conceptual design
Mobile SMRs						
ACPR50S	60	1	Floating PWR	CGN	China	Under construction
KLT-40S	35	2	Floating PWR	OKBM Afrikantov	Russia	Commercial operation

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SMR concepts: status & characteristics (2)

Gen IV SMRs						
Xe-100	80	1 to 4	HTGR	X-energy LLC	United States	Conceptual design
ARC-100	100	1	LMFR	Advanced Reactor Concepts LLC	Canada	Conceptual design
KP-FHR	140	1	MSR	Kairos Power	United States	Pre-conceptual design
IMSR	190	1	MSR	Terrestrial Energy	Canada	Basic design
HTR-PM	210	2	HTGR	China Huaneng/CNEC/ Tsinghua University	China	Under construction
EM2	265	1	GMFR	General Atomics	United States	Conceptual design
Stable Salt Reactor	300	1	MSR	Moltex Energy	United Kingdom	Pre-conceptual design
Natrium	345	1	SFR	Terrapower/GE Hitachi	United States	Conceptual design
Westing-house Lead Fast Reactor	450	1	LMFR	Westinghouse	United States	Conceptual design
MMRs						
eVinci	0.2-5	1	Heat pipe reactor	Westinghouse	United States	Basic design
Aurora	2	1	LMFR	Oklo	United States	Licence application submitted to the US NRC
U-Battery	4	1	HTGR	Urenco and partners	United Kingdom	Basic design
MMR	5-10	1	HTGR	USNC	United States	Basic design

Source: NEA, IAEA (2020).

How can we be sure to be capable to do it? Compare and learn from others

- New comers :
  - UAE : 4 Large Reactors
    - Declaration of commitment to NE in 2008, with 1st reactor to be finished by 2017
    - 1st 1000 MWe reactor was critical on 2nd of August 2020,
    - 2nd Unit went critical on 22nd of August 2021
    - Strong Top-Down decision making & committment approach by the government
    - Very open to all Stakeholders
  - Saudi Arabia : Co-development of SMR with South-Korea
    - Declaration of commitment to NE in ~2011
    - Choice for Co-development with South-Korea in 2015
    - Choice of SMART (System-integrated Modular Advanced Reactor) SMR of 100 MWe (330 MWt)
    - Initially foreseen to start a Demo in 2017 not yet there
  - Ghana : No choice yet made for LR or SMR
    - Declaration in 2014 for having 1st Reactor around 2030
    - Following the 19 Milestones guidance and progressing along the roadmap
  - Egypt : 4 Large Reactors
    - Declaration of commitment to NE in 2020following the exemple of UAE
    - Insisting on installing a strong local supplier-chain
    - Construction of the 1st two units started

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Conclusions

- Nuclear Energy deployment is feasible within a period of 10 to 15 years
- The development of SMR technology worldwide is an added value for easing this deployment and compatible with the Algerian calendar **but commercial viability of SMRs not yet demonstrated**
- Competences within the country and abroad are available
- The Climate change & the country energy security constraints are urging
- Major actors are present in the country such as utility and energy major company ready for heavy and complex contracts mgt and Nuclear technology specialist such as COMENA
- **This can make it a winning constellation with a nation strong and continuous commitment for Nuclear Power introduction in the energy mix and insuring a real technology transfer and building a strong local chain-suppliers**

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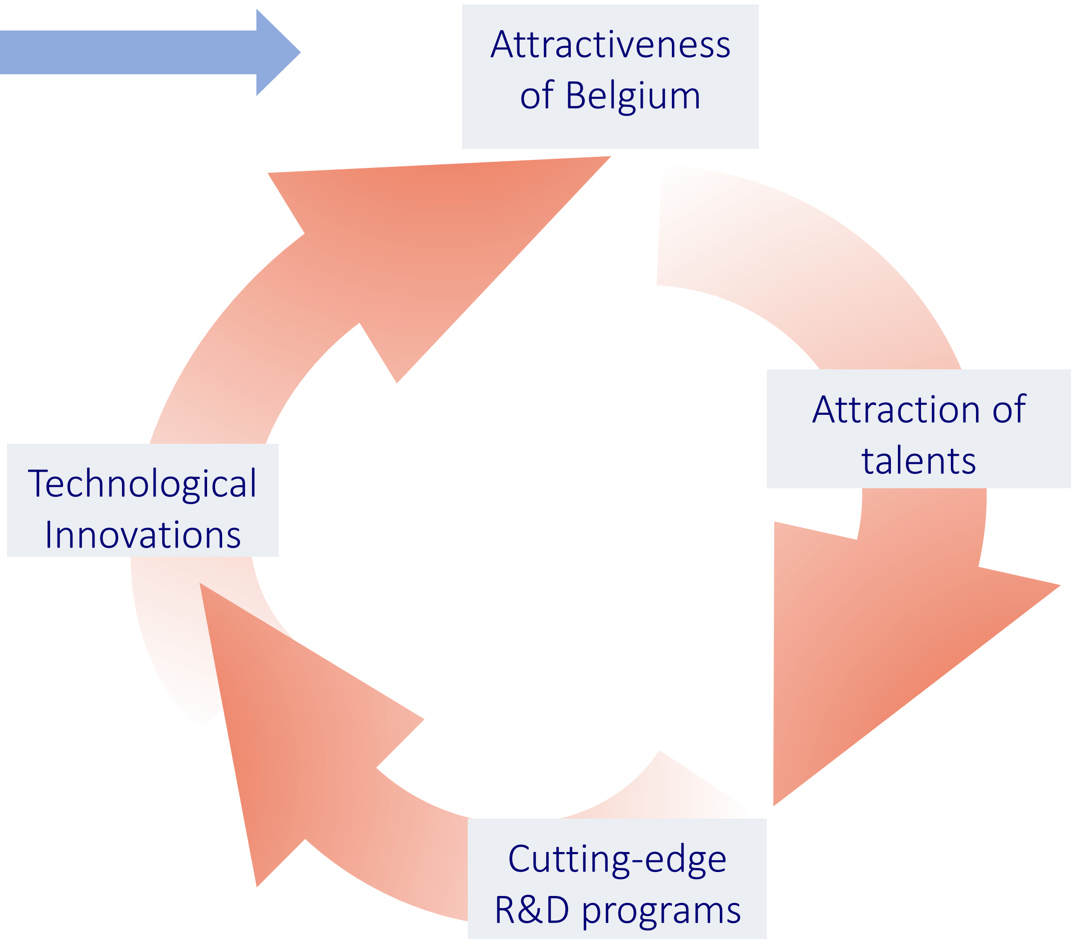
Contribution to nuclear energy sustainability

Since last 22 years:

- In Belgium: 10 thesis/y
- Abroad: + 5 thesis/y

Type of dissertation	1998-2009	2010-2018	2019-2023	2024	Total
PhD	8	35	22	5	**70**
Master after Master (BNEN)	9	14	6	3	**32**
Master / Bachelor	-	52	60	8	**120**
Total	**17**	**101**	**88**	**16**	**222**



Strategic infrastructure fostering continuous innovation

"MYRRHA creates wonder and wonder is the basis of man's desire to understand."

Hamid Aït Abderrahim