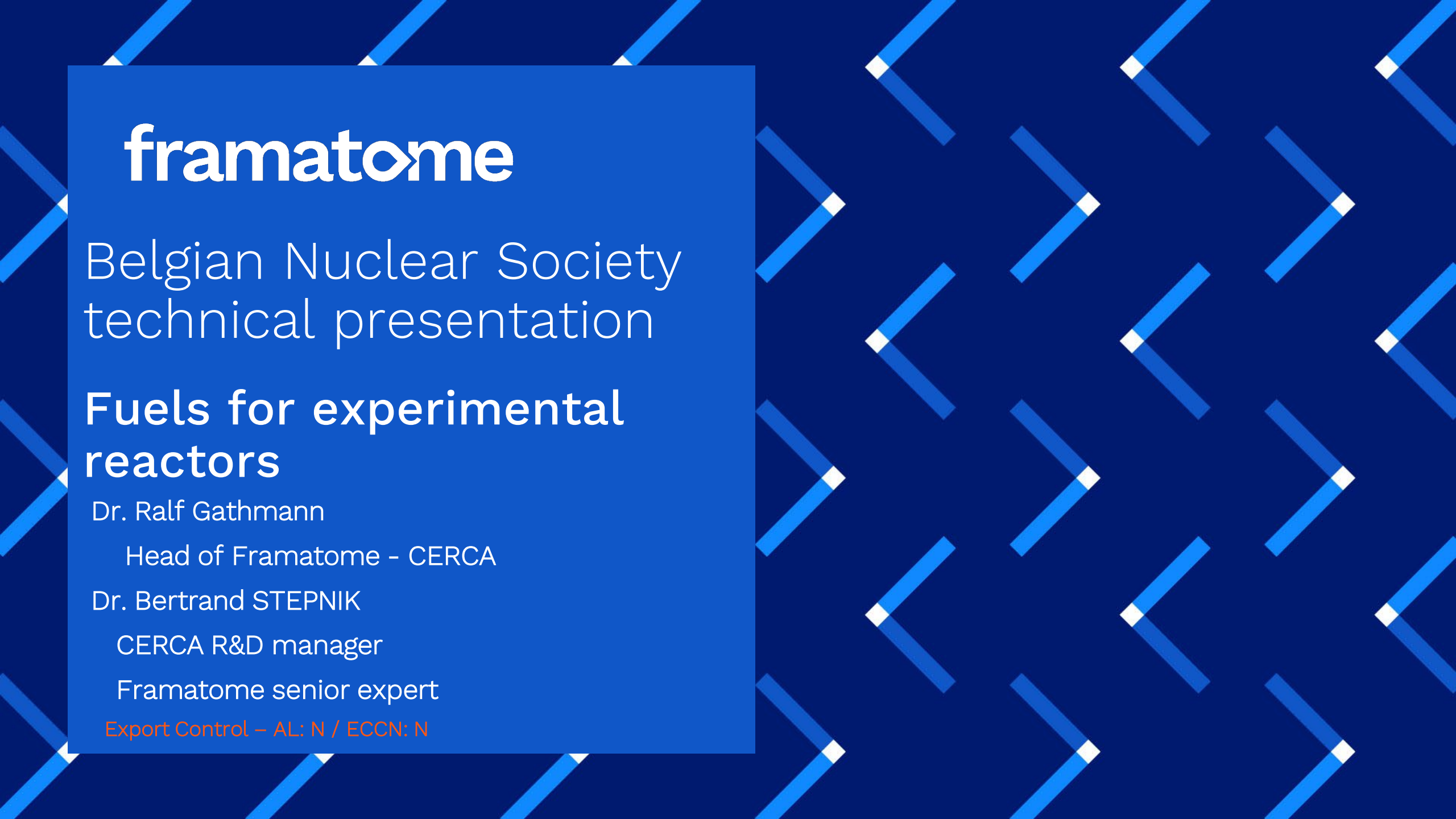




framatome

Belgian Nuclear Society
technical presentation

Fuels for experimental reactors

Dr. Ralf Gathmann

Head of Framatome - CERCA

Dr. Bertrand STEPNIK

CERCA R&D manager

Framatome senior expert

Export Control – AL: N / ECCN: N

Content

1. Framatome-CERCA introduction
2. Industrial & R&D capacities
3. Research Reactor & Power Plant fuel comparisons
4. HALEU fuel conversion
5. Activities in Belgium
6. Ongoing R&D projects

1

Framatome-CERCA



Framatome at a glance

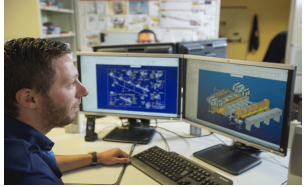
For over **60** years, Framatome's teams have been involved in developing safe, competitive, clean, low-carbon nuclear energy worldwide by:

- designing nuclear power plants,
- supplying nuclear steam supply systems,
- designing and manufacturing components and fuel assemblies,
- integrating automation systems,
- and servicing all types of nuclear reactors.

Framatome's presence around the globe includes:

- Original equipment manufacturer of **92** nuclear power plants
- Provides services to more than **380** reactors worldwide
- Generated **€4 billion** revenue in 2023

Our activities in a nutshell



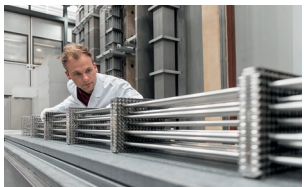
Engineering & Design Authority: Development, design and licensing of Nuclear Steam Supply System (NSSS) and associated services, including worldwide Technical Centers



Projects and Components Manufacturing: Design and manufacturing of heavy and mobile components for nuclear islands. Management and execution of nuclear reactor new build projects, as well as component replacement projects



Instrumentation & Control (I&C): Design and fabrication of safety I&C and automation systems for nuclear power plants



Fuel: Development, design, licensing and fabrication of fuel assemblies and core components for power reactors (PWR, VVER, BWR) and research reactors. Development of zirconium products



Installed Base: Products, maintenance and engineering services for existing nuclear fleets and reactors under construction

Fuel activities



■ MISSION

- Supply innovative safe fuels performing more efficiently than ever before to our utility customers
- Technology provider, technology transfers and licensing
- Offer an extended range of fuel-related services
- Maintain a worldwide integrated platform close to markets and customers

■ SCOPE

- Design, develop, fabricate and commercialize fuel assemblies and the associated technologies
- Production of zirconium and its alloys
- Fabrication and supply of fuel for research reactors
- Offer engineering services, on-site services and all fuel services associated

Framatome CERCA – Fuel for Research Reactors

Division of the Fuel Business Unit of Framatome

Established in 1957 to develop and industrialize uranium-metal alloys for nuclear and medical applications

- 3 locations in France
- ~200 employees

PARIS
Head Office



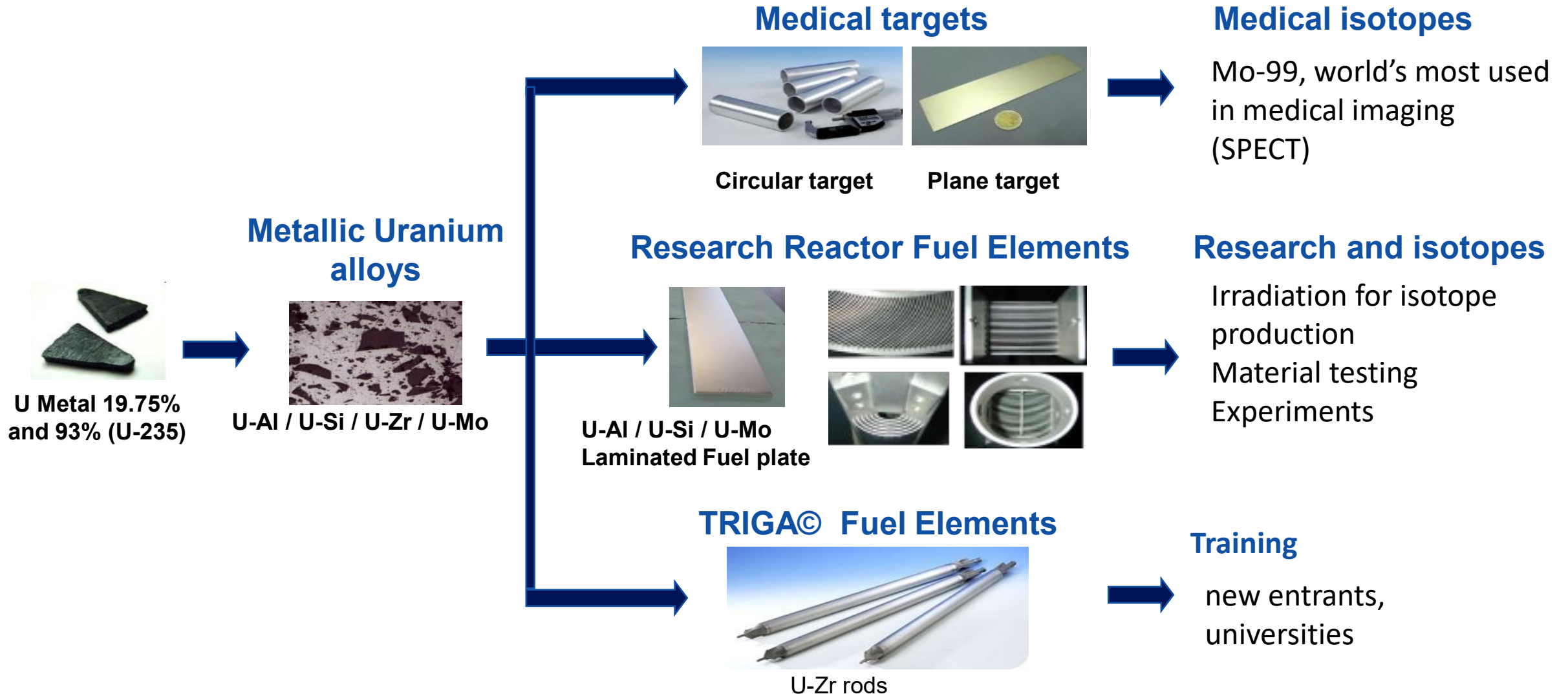
LYON
Marketing & Sales



ROMANS-SUR-ISÈRE
Manufacturing - R&D

framatome

CERCA Products and Applications



CERCA™ products



Medical target for
Mo-99 production
~200 x 45 x 1.6 mm



Fuel plates for
Research Reactors
~600 x 60 x 1.3 mm



Fuel elements for
Research Reactors



CERCA Production History

■ CERCA created in 1957

- 60 years of experience in fuels and metal uranium production.
- > 450 000 fuel plates produced.
- > 20 000 fuel elements of 70 designs.
- Delivered to > 40 research reactors in around 20 countries.

■ HEU Mo-99 targets

- Since 1970.
- > 50 000 targets produced.

■ LEU Mo-99 targets

- Since 2008.
- > 30 000 targets produced.

■ Partner for new product developments

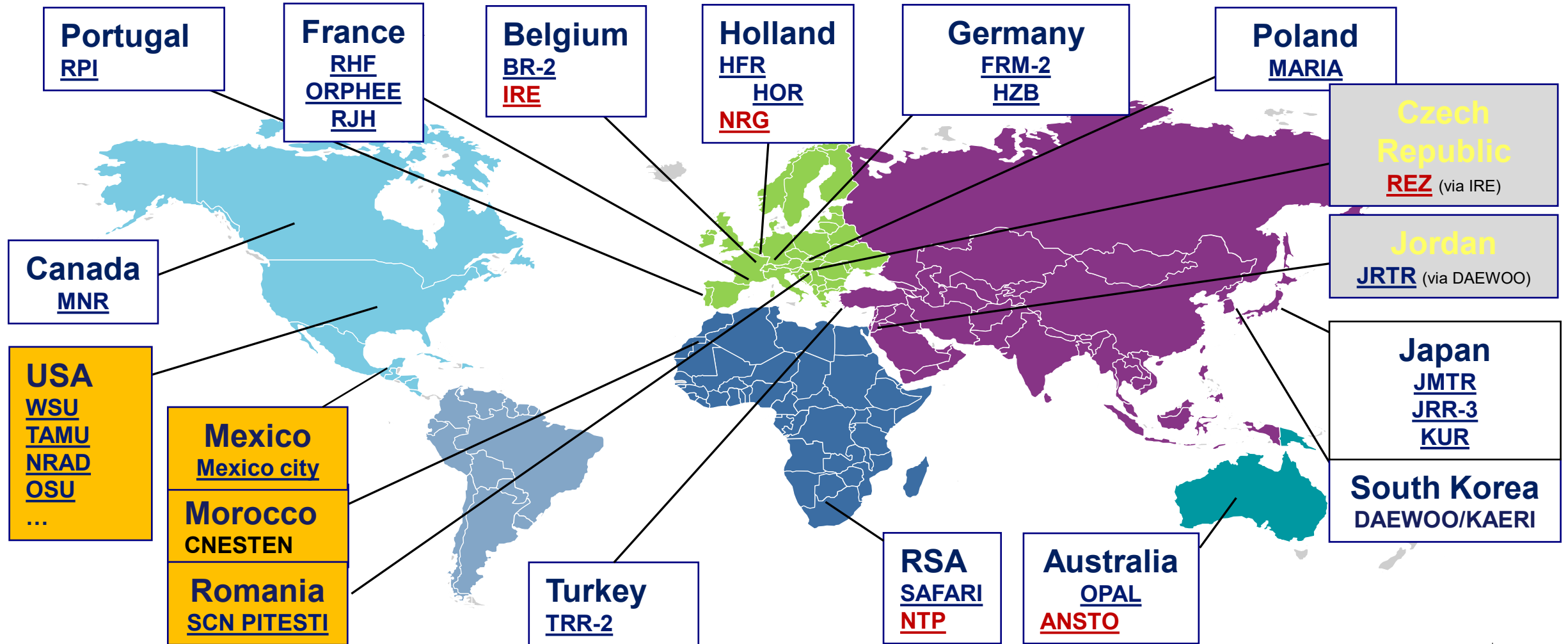
- LEU targets.
- LEU fuel (KUCA coupons, MARIA fuel, UMo dispersed and monolithic,...).
- Fuel for new and recent reactors (JRTR, OPAL,...).
- Fuel for future reactors projects (JHR, PALLAS, TRIGA type,...).



19 countries on 4 continents
23 customers (out of TRIGA)
18 reactors (out of TRIGA)

LEU & HEU Fuel customers
 TRIGA Fuel customers
 NTP Medical targets Customers

CERCA™ customer's



2

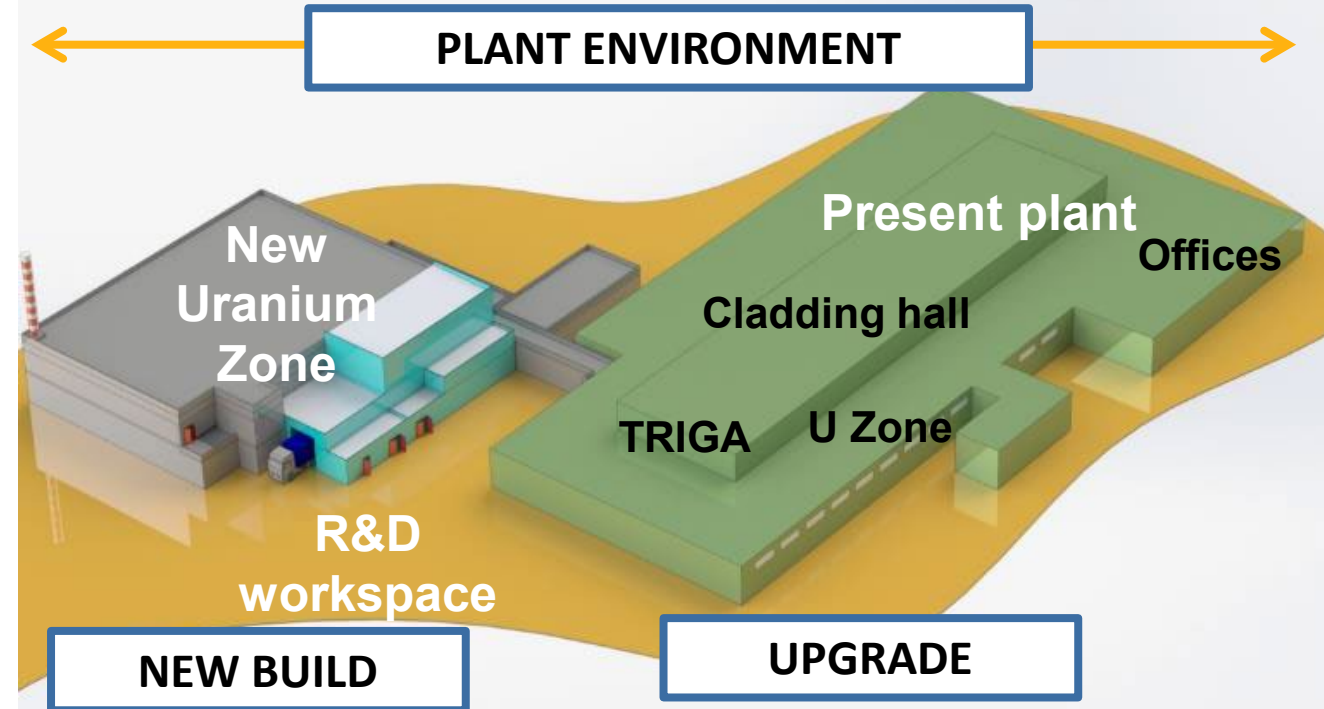
Industrial & R&D Capacity

Industrial capacity upgrade

- € 180 millions investment
 - To increase capacity, to comply with safety and security requirements, to renew process equipment
 - 20 sub-projects to address CERCA facilities and plant environment
 - Present plant upgrade
 - New Uranium Zone
 - TRIGA facility
 - R&D workspace
- To ensure European Fuel capabilities for the decades to come

Framatome - CERCA

PROJECT OVERVIEW - ILLUSTRATIVE



New Uranium Zone

- New Build to host uranium alloy fabrication activities.
 - Maintain existing capacities
 - U Material Storage
 - Safety and security upgrades
 - Designed to resist extreme weather and seismic events
 - Containment in case of fire outbreak and criticality accident
 - Physical Protection
- Building complete.
- Commissioning and Uranium storage in 2022.
- Equipment qualification in Uranium should start in Q4 2024



R&D Capacity - CRIL

CERCA Research and Innovation Laboratory

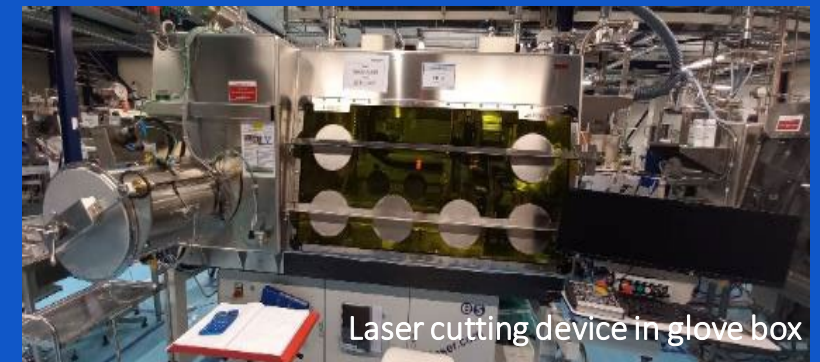
- R&D capacity designed for developing fuels for research and advanced reactors
 - 40 years of R&D experience in fuel developments
 - New facility opened in 2019 and fully equipped by 2021
 - 500 m² of URANIUM LAB :
 - Depleted Uranium, Natural Uranium
 - Low Enriched Uranium
 - High Enriched Uranium
- Facility optimized to develop any type of Uranium based nuclear fuel

Framatome - CERCA



R&D Capacity - CRIL

- State-of-the-art manufacturing equipment
 - 17 glove-box; 4 hoods
 - Arc melting, induction melting, annealing furnaces
 - Powder atomization ; powder grinding / sieving / mixing
 - Compaction presses ; hot rolling mill ; cold rolling mill
 - Laser welding ; laser marking, 3D Printing equipment
- In-house sampling and characterization equipment
 - Laser cutting devices ; diamond wire ; rotating disk
 - SEM – EDX ; mechanical tests in GB (tensile & compression)
 - X-ray inspection ; UT inspection ; acoustic microscopy
 - Thermal measurements (TGA, DSC...)
- Strong partnership with Lille university
 - XDR, microprobe ; FIB / SEM ; TEM / AFM ...



3

Research Reactor & Power Plant fuel comparisons

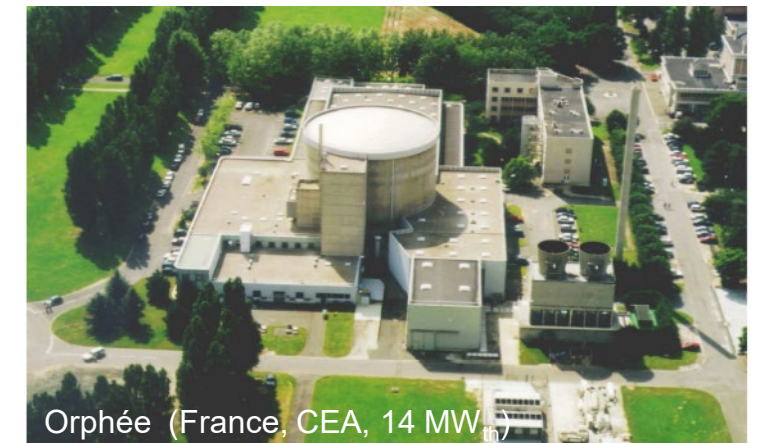
General figures

Reactor core

	Power Plan	Research Reactor
■ Size	4 x 4 x 4 m ³	→ 0.5 x 0.5 x 0.5 m ³
■ Water temperature	300°C	→ 60°C
■ Thermal neutron flux	9 10 ¹³ n/cm ² .s	→ 5 10 ¹⁴ n/cm ² .s
■ Thermal flux to cool down	80 kW/liter	→ 600 kW/liter

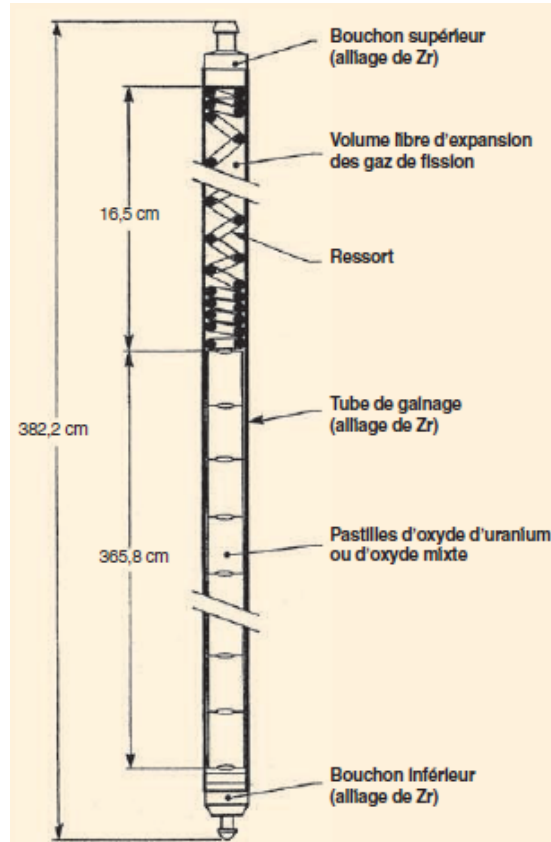
Fuel

■ Uranium 235 enrichment	≤4.5%wt	→ ≤93%wt (19.75%wt)
■ Uranium alloy	UO ₂ – Ceramic	→ UO ₂ – Ceramic <u>OR</u> U-Al, U-Si, U-Zr, U-Mo– Metallic
■ Meat shape	Sintering pellet	→ Compacted powders
■ Cladding	Zr-Nb pin welded	→ Al plates co-rolled <u>OR</u> extruded
■ Element structure	Stainless Steel & Zr-Nb	→ Al alloys

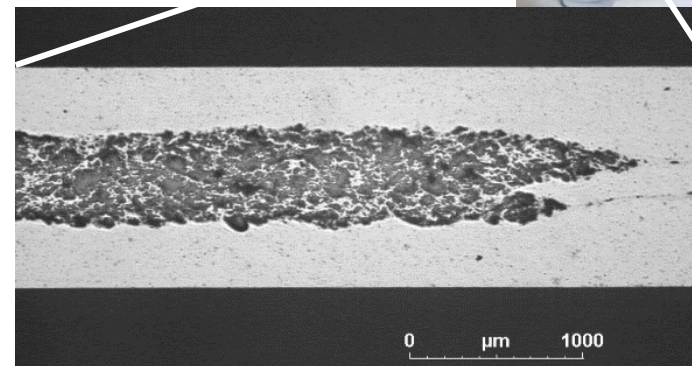


Fuel core

Power plant fuel pin

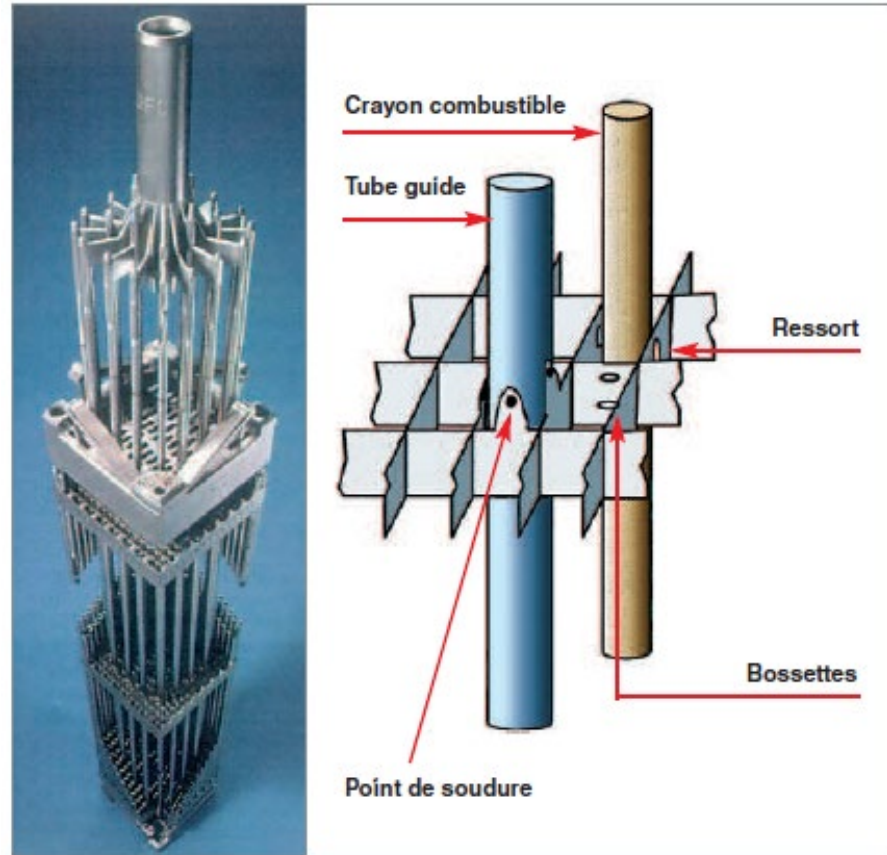


Research Reactor fuel plate

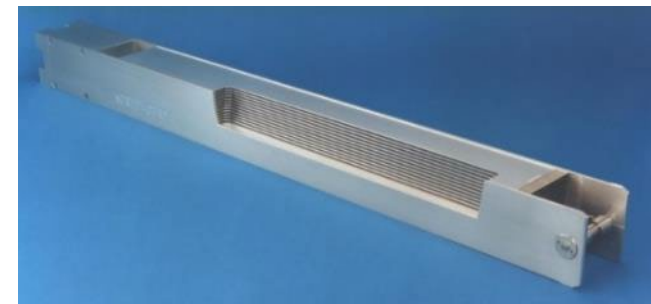
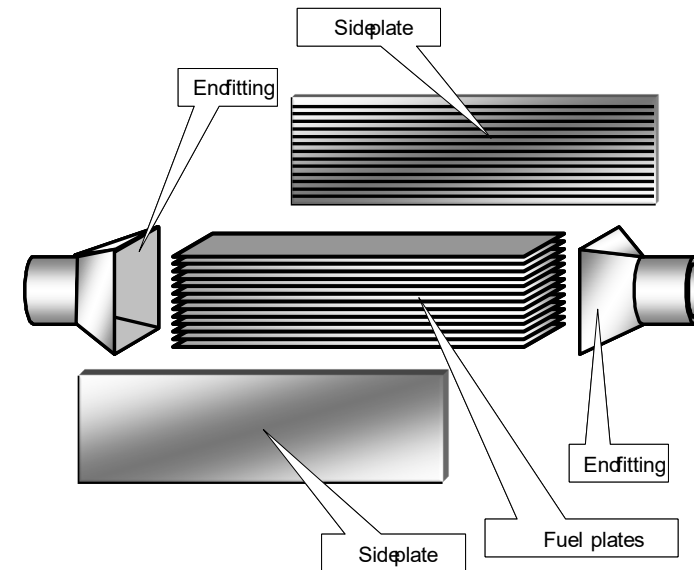


Fuel element

Power plant fuel element

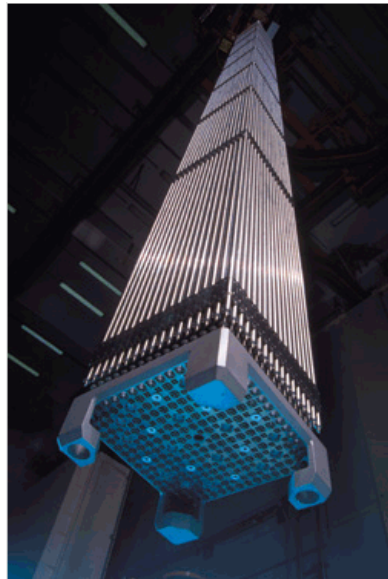


Research Reactor fuel element



Reactor core

- **Power Plant reactor (EDF 1300 Mwe, France):**
 - 1 fuel element: 773 kg UO_2 4%wt enrichment (681 kg U_{tot} , 27 kg U235)
 - Reactor core: **118 t UO_2 4%wt enrichment** (104 t U_{tot} , 4.2 t U-235)
- **Research Reactor (Orphée 14MWth, France):**
 - 1 fuel element: 1.1 kg UAl_x 93%wt enrichment (0.8 kg U_{tot} , 0.7 kg U-235)
 - Reactor core: **8.9 kg UAl_x 93%wt enrichment** (6.3 kg U_{tot} , 5.9 kg U-235)

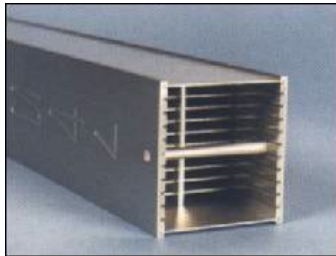
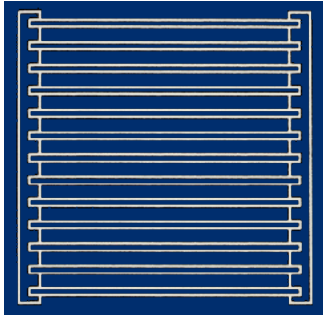


Research Reactor fuel elements

Plate types

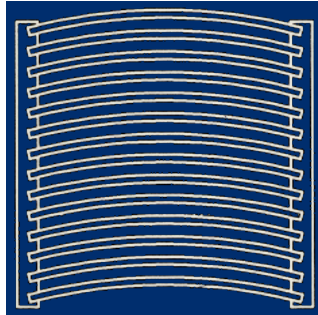
SQUARE

FLAT PLATES



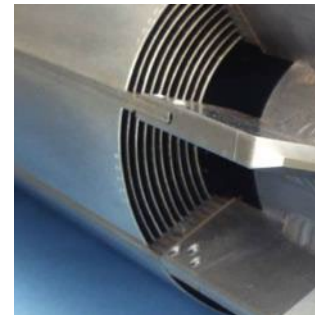
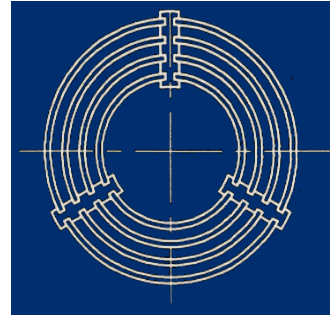
OSIRIS – ORPHEE
GKSS – BER II
JMTR – JRR3 – JRR4
(SAFARI 1) – RPI – OPAL

CURVED PLATES



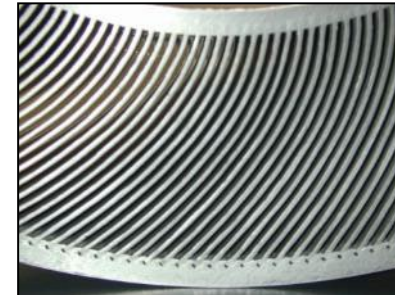
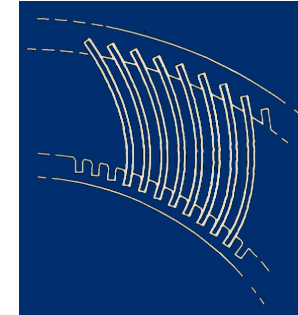
HFR – R2
MNR

TUBULAR



BR2 - RJH
FRJ2 - MARIA

RING-SHAPED

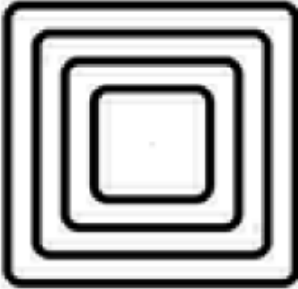
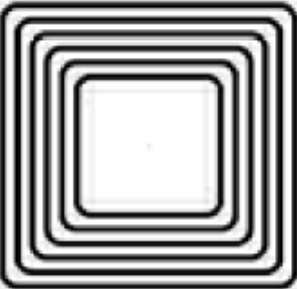


RHF
FRM II



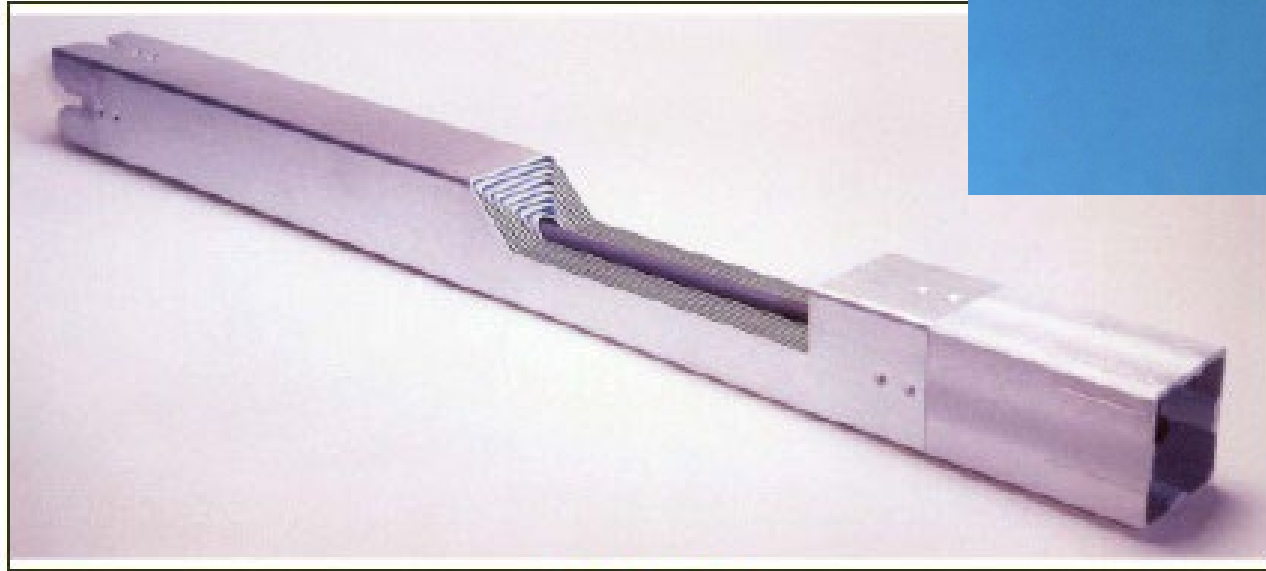
Research Reactor fuel elements

Tube types

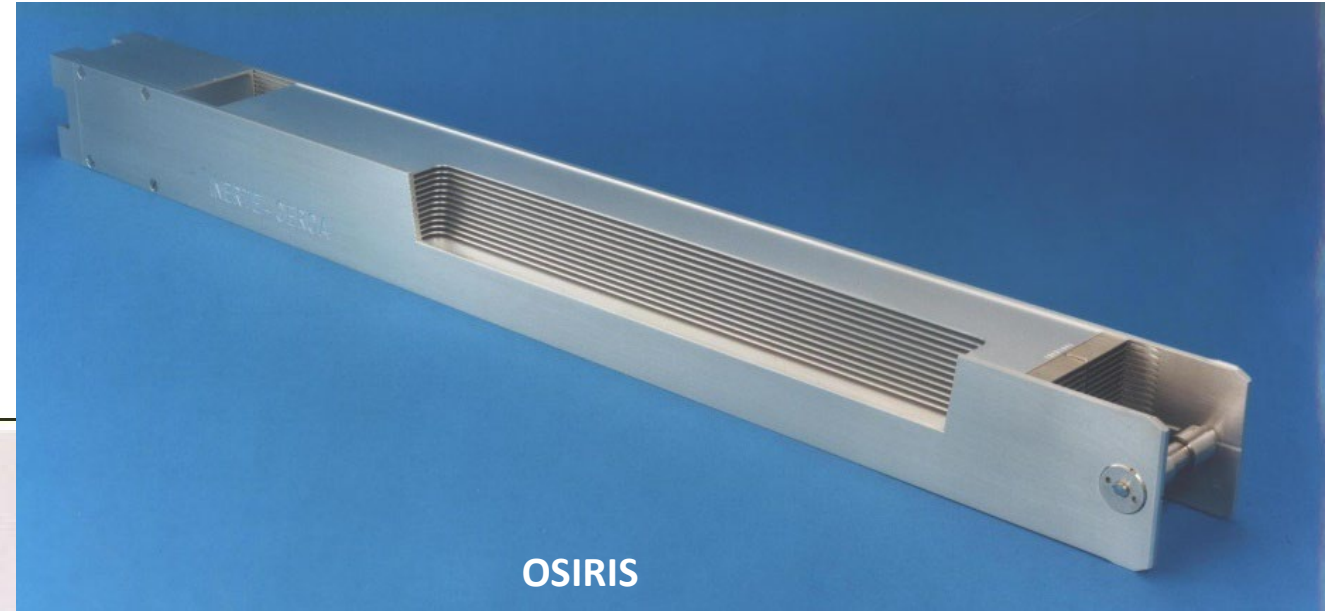
WWR-M2	IRT-2M	IRT-3M	MR-6	WWR-TS
				
Ukraine, Hungary, Vietnam, Germany	Czech Republic, Libya, Bulgaria, N. Korea	Uzbekistan, Czech Republic	Poland	Kazakhstan

Research Reactor fuel elements

Plate and tube types



FA IRT 4M



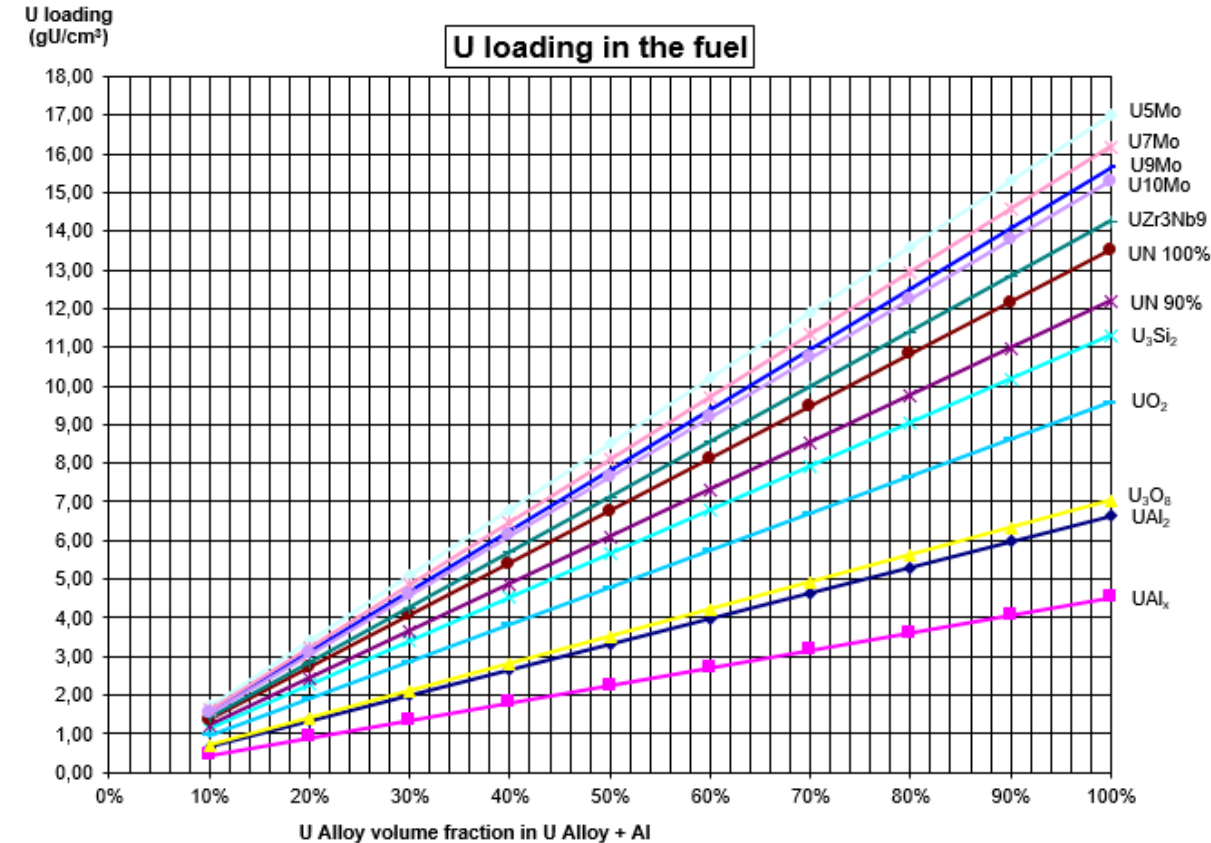
OSIRIS

4

HALEU fuel conversion

Treaty on the Non-Proliferation of Nuclear Weapons (NPT)

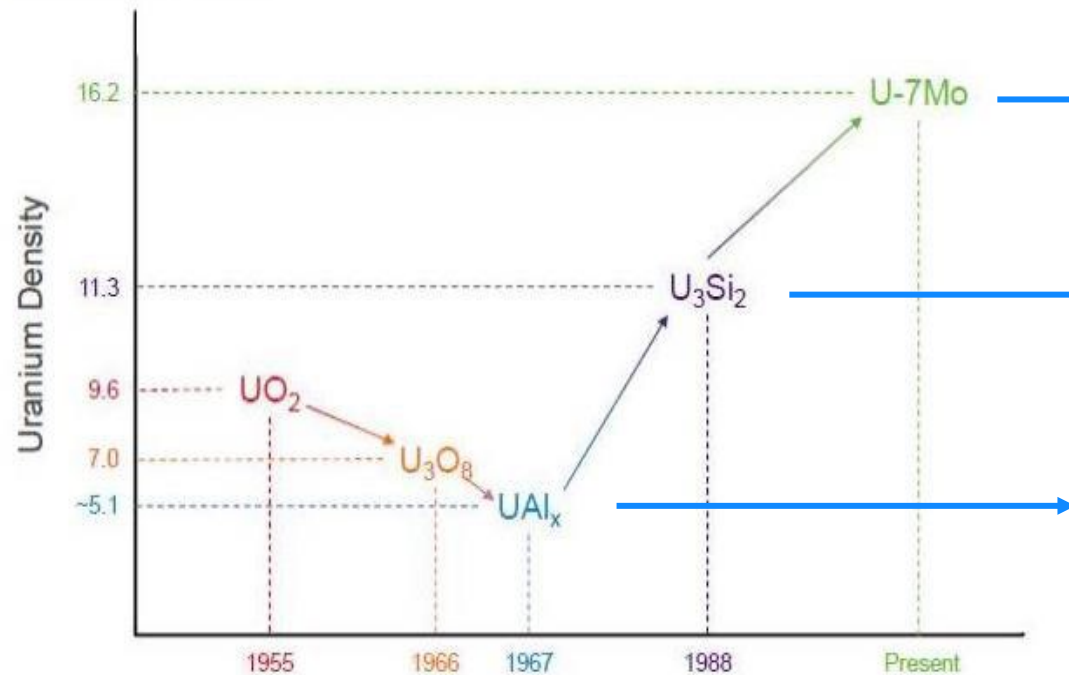
- Signed from 1968 – 189 countries – Under IAEA
- Application for RR:
 - 1978: Global Threat Reduction Initiative (GTRI)
 - LEU or HALEU : ^{235}U enrichment < 20%
 - HEU : ^{235}U enrichment $\geq$ 20%
 - From 1978 conversion process occurred
- Conversion from HEU → HALEU:
 - To decrease the enrichment by a factor 5
 - To increase the U total quantity by more than a factor 5
 - Use denser U alloy and more volume in the same element geometry
 - $\text{UAl}_x \rightarrow \text{UO}_2 \rightarrow \text{U}_3\text{Si}_2 \rightarrow \text{UMo}$



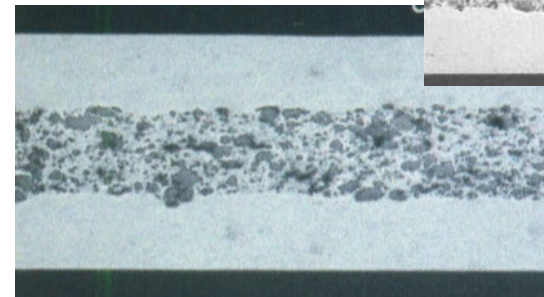
Dispersion fuel development history

- Development of high-density U-base alloys and fuel plates

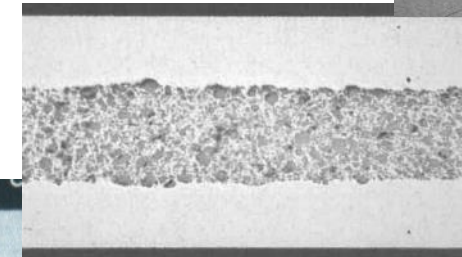
Uranium Density



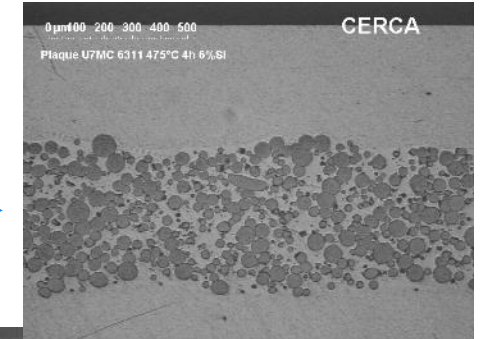
Uranium density fuel fabrication [HOF-09]



UAl_x Fuel



U_3Si_2 Fuel

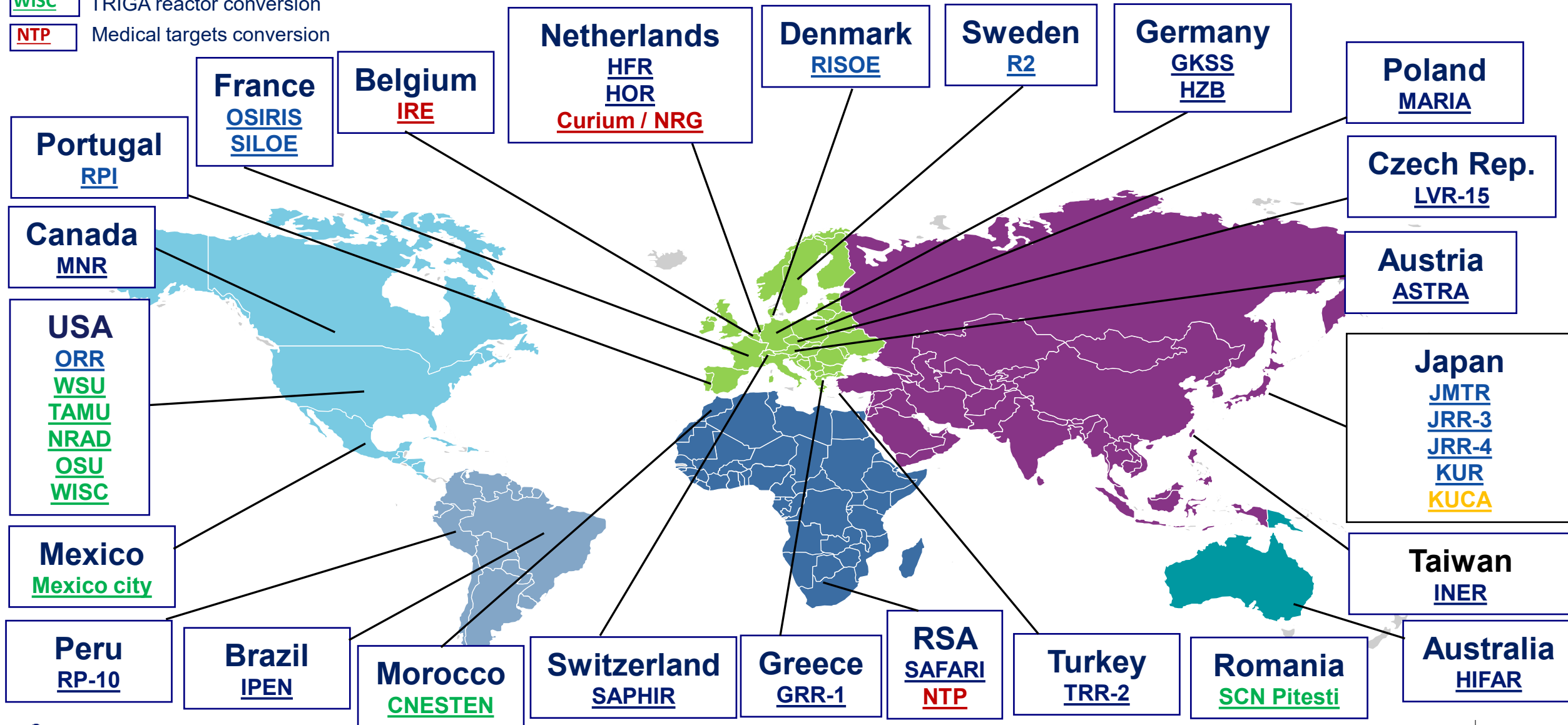


U7Mo Fuel

➤ High density alloys to maintain neutron performances

- HOR** Research reactor conversion
- KUCA** Critical facility conversion
- WISC** TRIGA reactor conversion
- NTP** Medical targets conversion

38 conversion to HALEU

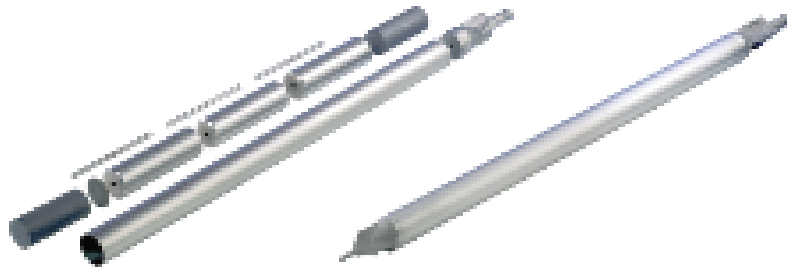


38 conversions of fuels or targets to HALEU

■ HALEU U_3Si_2 fuel for low/medium power reactors

- 27 fuels converted to HALEU between 1988 and 2023
- Customers all over the world
- More than 100 fuel elements produced each year
- More than 100 000 plates and 5 000 elements produced

HALEU U_3Si_2 has been the reference conversion fuel for HEU UAl_x and HEU U_3O_8

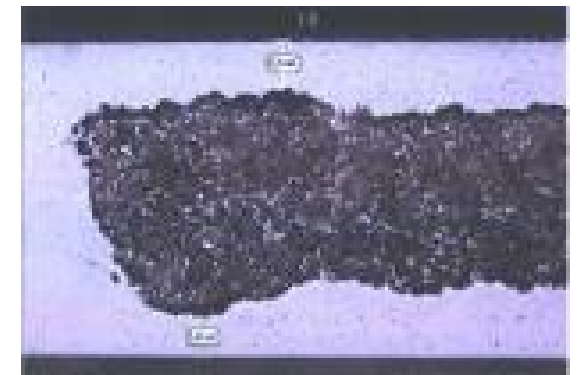


■ HALEU U-Zr for TRIGA reactors

- 8 reactors converted to HALEU between 2005 and 2012
- Strong partnership with US-DOE
- Unique TRIGA fuel producer

■ HALEU UAl_2 for $^{99\text{m}}\text{Mo}$ targets

- 3 targets converted to HALEU between 2007 and 2020
- More than 50 000 HALEU targets produced
- Since 2014, 30 millions patient diagnostics per year



4 European high power reactor conversions ongoing

■ 4 reactors and a fuel manufacturer

- TUM (FRM II) ; CEA (RJH) ; ILL (RHF) ; SCK CEN (BR2) + Framatome
 - With the support of US-DOE, US National Laboratories
- Since 1999: FROG, U-Mo group, ALPS, LEONIDAS
- Since 2013: HERACLES gathers all European efforts towards European reactors conversion (manufacturing, irradiation, fuel behavior understanding)
- Several EURATOM contracts, HERACLES contracts, bilateral contracts
- High power reactor fuels are the more complex and more performant fuels
- Long time conversion developments 1999 – 2030
- 3 fuel options under development

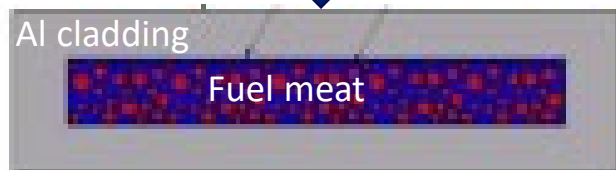
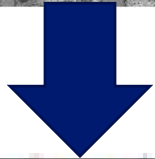
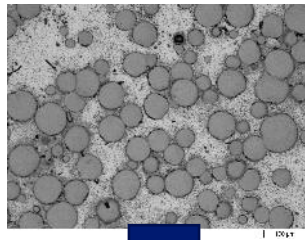


Fuel candidates for HALEU conversion of HPRR

- 3 Fuel candidates developed with high density

UMo Alloy (7-10 wt.%Mo)

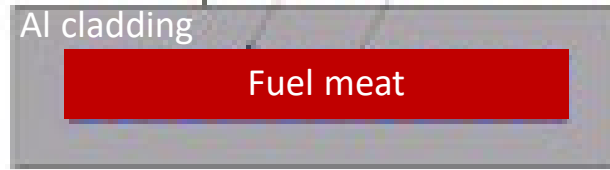
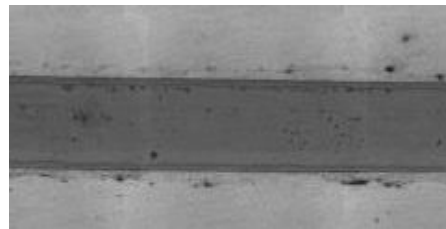
Disperse fuel



8 gU/cm³

JHR (CEA, France)

Monolithic fuel



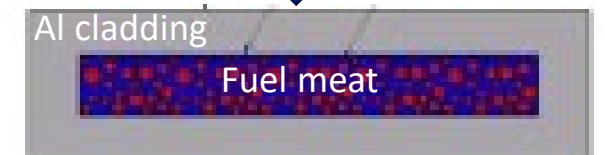
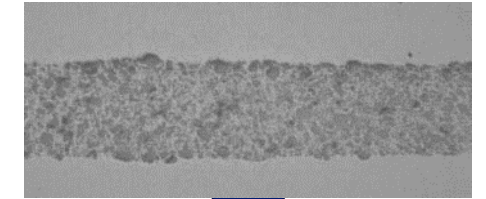
16 gU/cm³

FRMII (TUM, Germany)

U₃Si₂ Silicide

Disperse fuel

(Standard or High Density fuel)



4.8 – 5.3 gU/cm³

BR2 (SCK.CEN, Belgium)

RHF (ILL, France)

5

CERCA activities in Belgium

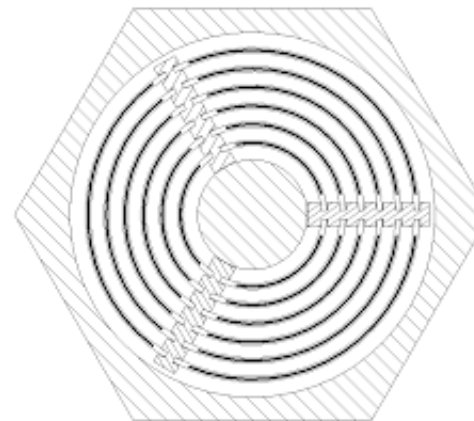
IRE targets for ^{99}Mo & ^{131}I production

- Framatome is producing for IRE (*Institut National des Radioéléments*, in Fleurus)
- Deliveries in several research reactors in Europe (BR2, HFR, LVR15, MARIA)
- HEU targets (93%wt in ^{235}U)
 - Since ~1970
 - Tubular, UAl_3 - UAl_4
- HALEU targets (19.75%wt in ^{235}U)
 - Since 2013-2020
 - Plane, $\text{UAl}_2 \rightarrow \text{UAl}_3$ - UAl_4



BR2 reactor fuels

- Framatome was producing the HEU elements for BR2 reactor operated by SCK.CEN (Belgian Nuclear Research Centre, in Mol)
- Tubular element type, with 6 plate rings
- HEU elements (93%wt in ^{235}U)
 - 600 elements : 1999 - 2018
 - Bend plates, $\text{UAl}_3\text{-UAl}_4$, 1.3 gU/cm^3
- HALEU plate & elements (19.75%wt in ^{235}U)
 - Conversion program ongoing (European program)
 - Bend plates, U_3Si_2 , 5.3 gU/cm^3



6

R&D and Fuel industrialisation

UMo monolithic fuel development

- Challenge: To develop UMo monolithic fuel in a short time schedule & in competition with US
- 2023: Production of 12 LEU UMo foils & optimization & industrialization
 - UMo foil R&D achieved; 12 LEU UMo monolithic foil prototypes produced
 - UMo monolithic plate in development with C2TWP process
 - **Patent published** about C2TWP process (#170117; WO2023280897)
 - 40 plates processed
- 2024: Production of 3 LEU UMo monolithic plates for irradiation in BR2 in 2025



LEU UMo monolithic foils

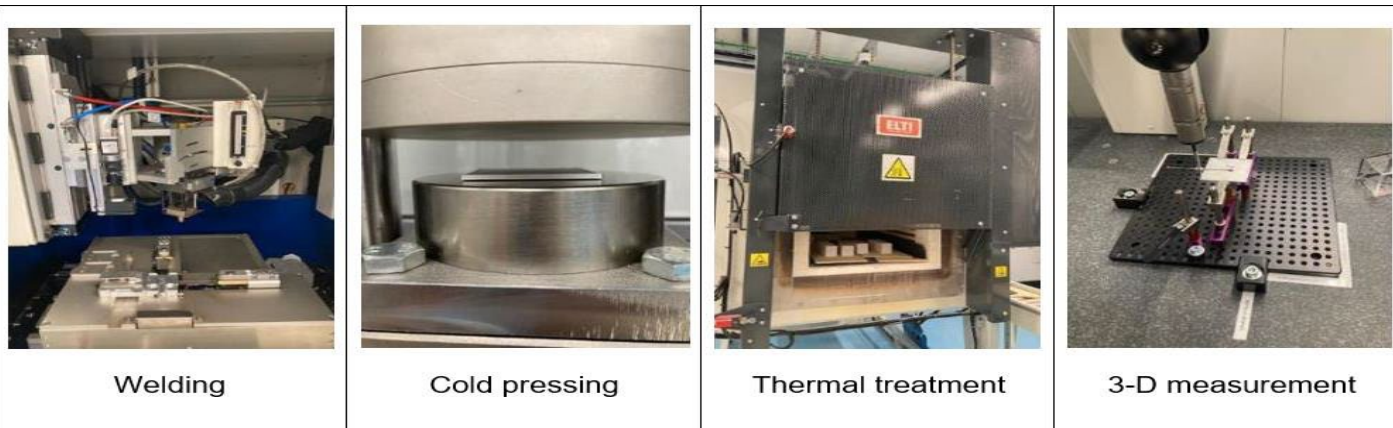
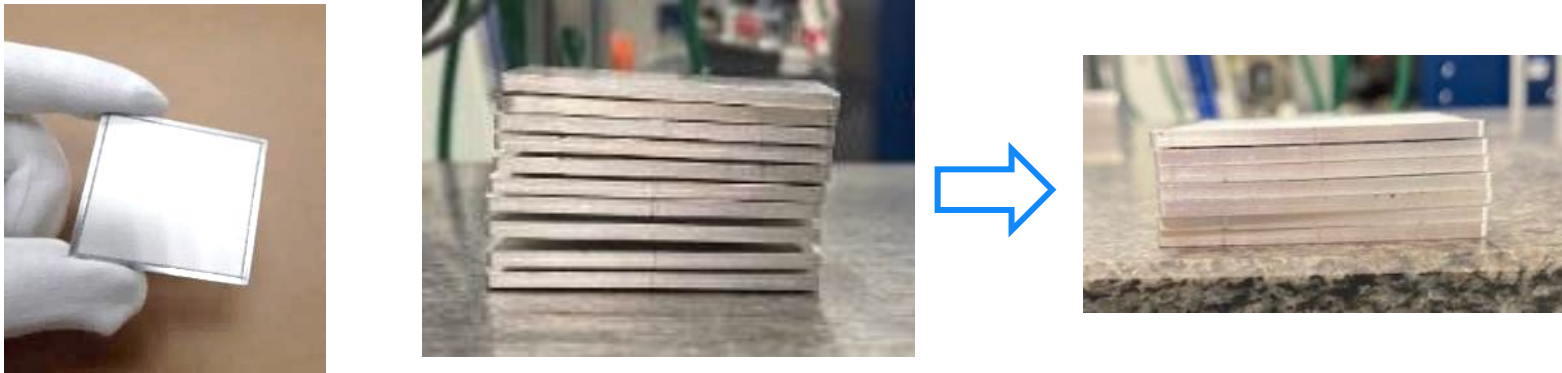


DU UMo monolithic plate ; Ultrasound picture (top); Visual picture (Bottom)

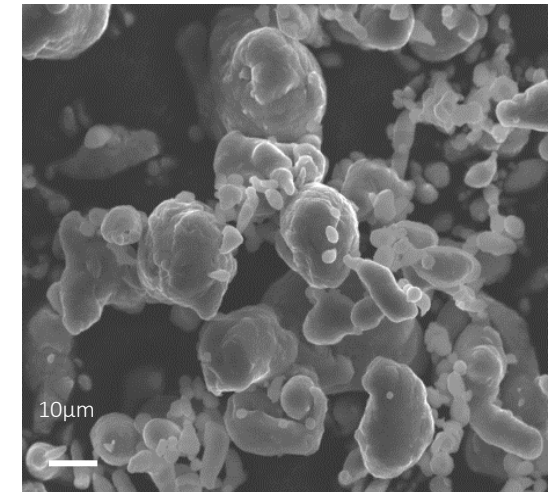
KUCA conversion in Japan

➤ Challenge: Industrialization an UMo dispersed fuel

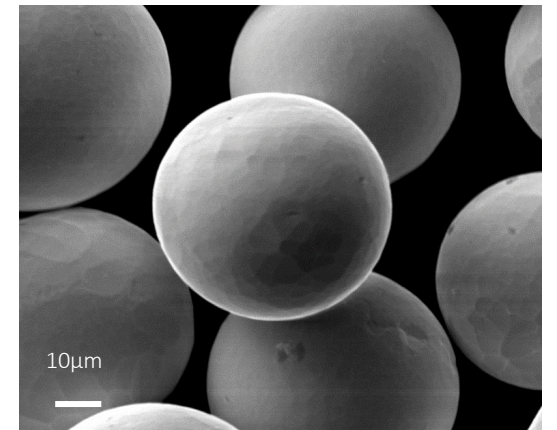
- To minimize dimensional deformation due to welding
- To homogenize the UMo atomized & Al ground powders



Al: $d_{50} \sim 20 \mu\text{m}$;
non spherical; $2,7\text{g/cm}^3$



+



UMo: $d_{50} \sim 80 \mu\text{m}$;
spherical; 18g/cm^3

UMo powder atomization & heat treatment

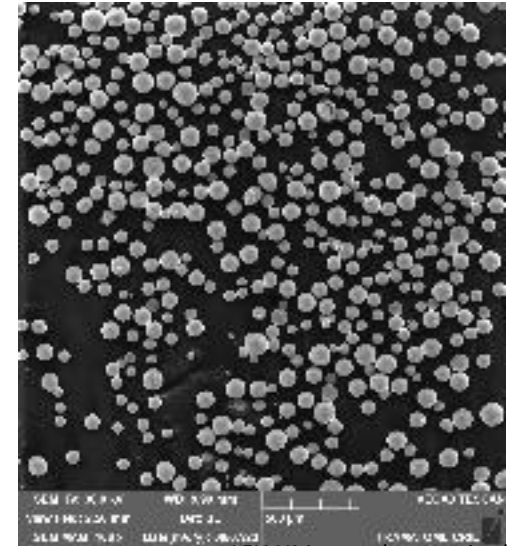
➤ Challenge: To reach high quality powder with atomization process

■ **2023:**

- UMo LEU powder atomization complete
- UMo powder heat treatment in glovebox and operational
- 1000°C; Ar atm; 10^{-3} mbar; rotational mixing; glove box

■ **2024:**

- UMo powder heat treatment qualification with uranium
- E-FUTURE 3 irradiation experiment in BR2
- To produce and to transport 3 LEU UMo dispersed plate prototypes



LEU UMo powder atomized

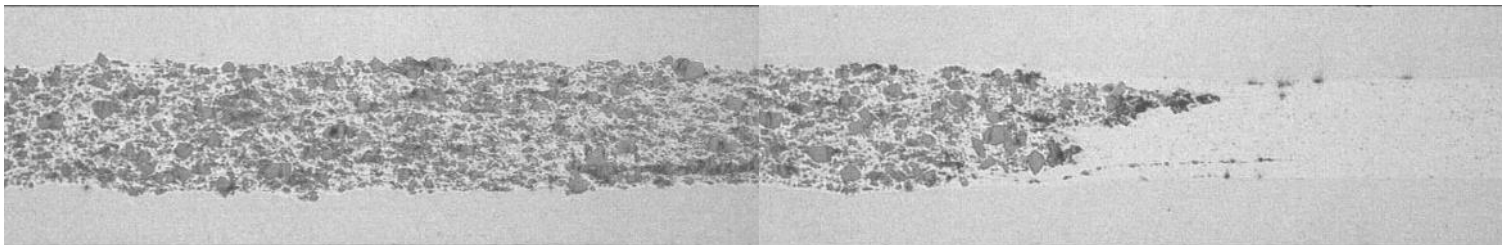


UMo powder heat treatment furnace

U_3Si_2 High density fuels

➤ Challenge: To develop conversion fuels for EU high performance reactors

- 2023:
 - Manufacturing & transportation of the mixed elements ME-DEUS (SCK) and ME-CHARTREUSE (ILL)
 - EU CONVERSION proposal submitted to EURATOM
 - **Patent published** about U_3Si_2 high density plates (#170120)
- 2024:
 - To produce 3 COBRA elements (SCK) for mid-2025
 - U_3Si_2 atomization developments



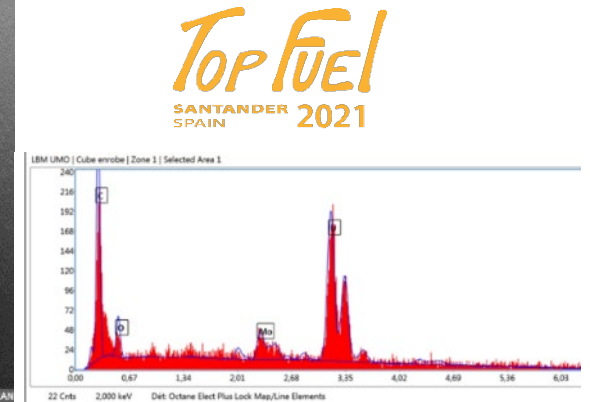
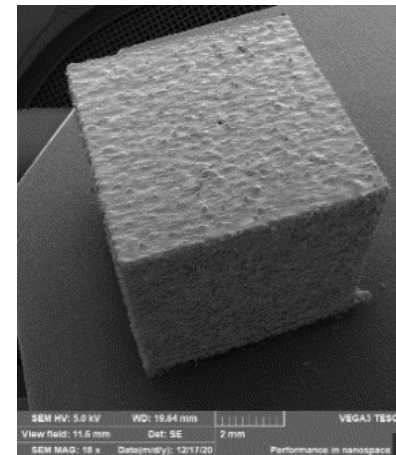
ME-CHARTREUSE LEU plate n°CHAP6102



3D printing with Uranium

➤ Challenge: Nuclearize a 3D printing device

- 2021:
 - First 3D printing of UMo and U₃Si₂ by Framatome
 - Publication in Top Fuel 2021
- 2022:
 - SFEN (*Société Française d'Énergie Nucléaire*) innovation award



Conclusion

- Framatome – CERCA is a worldwide producer of research reactor fuels & ^{99}Mo targets
- Its industrial and R&D infrastructure have been upgraded
- We are expert in fuel conversion from HEU to HALEU with 38 success

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Thank
you

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