GIF Webinar Series

2016-2024 EDUCATION AND TRAINING WORKING GROUP

GEN IV International Forum

Expertise | Collaboration | Excellence

International Molten Salt Research in Support of MSR Development

Your Presenters

Mr. Aslak Stubsgaard, Copenhagen Atomics

Mr. Edward Pheil, Exodys Energy

Ms. Isabelle Morlaes, Orano

Dr. Jeremy Pearson, San Rafael Energy Research Center

Dr. Markus Piro, McMaster University

Our Moderator

Dr. Patricia Paviet, GIF ETWG

28 August 2024

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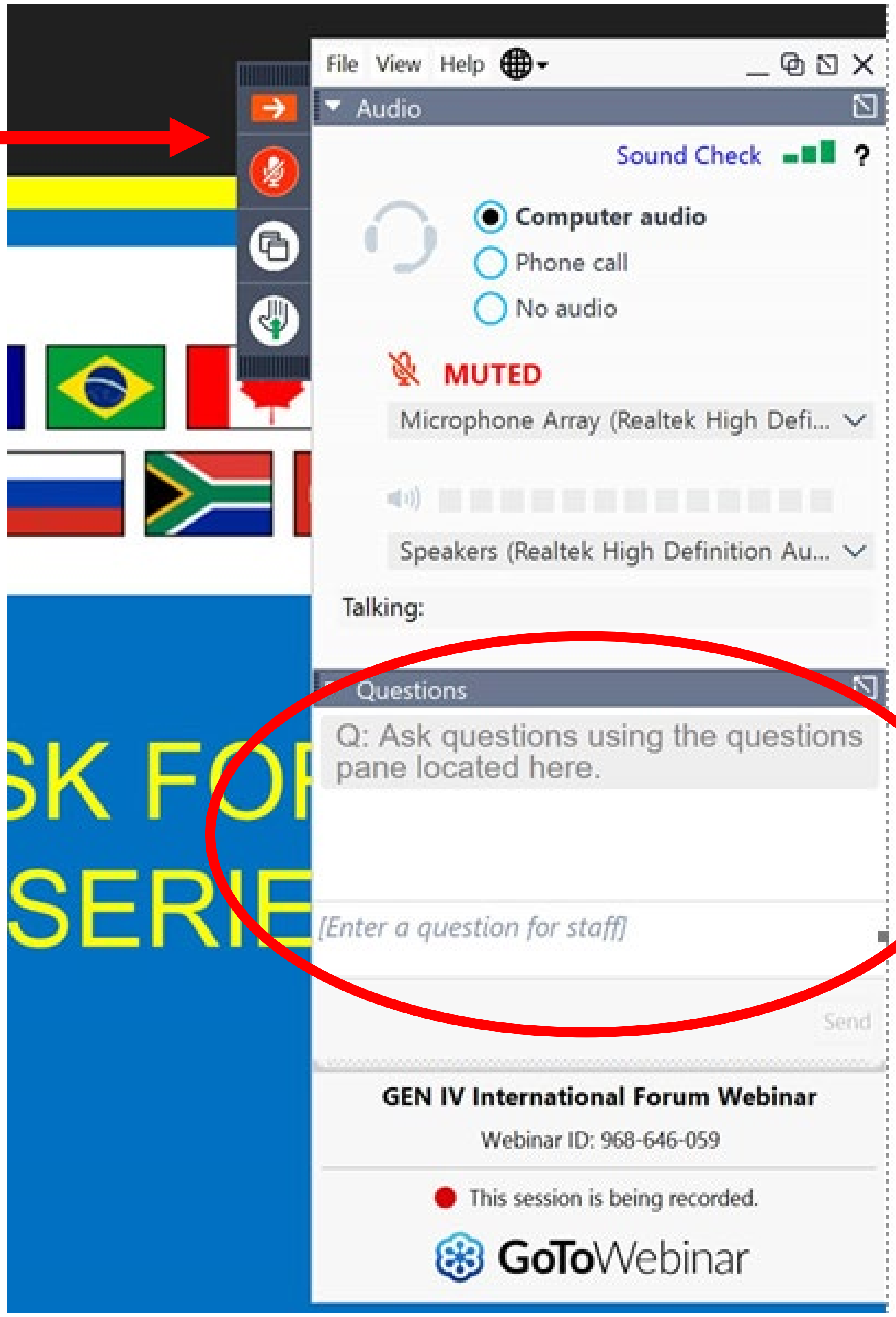

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Meet our Moderator

Dr. Patricia Paviet is the National Technical Director of the Molten Salt Reactor program for the US Department of Energy, Office of Nuclear Energy managing research and development to support development of Molten Salt Reactor Systems across six US national laboratories. In addition, she is the Chair of the Generation IV International Forum Education and Training Working Group, which she has managed since November 2015. Efforts of this group focus on the GIF webinar series, the Pitch your Gen IV Research competition, as well Knowledge Management and Knowledge Preservation of advanced reactor systems. She has 30 years of experience on the nuclear the fuel cycle, actinide chemistry and repository sciences. She earned her B.S. and M.S. in Chemistry from the University of Sophia Antipolis, Nice, France and a PhD in Radiochemistry from the University Paris XI, Orsay, France.

Email: patricia.paviet@pnnl.gov

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Meet the Presenter

Aslak Stubsgaard is the Co-founder and Chief Technology Officer of Copenhagen Atomics, in Copenhagen Denmark. Aslak earned a Master of Sciences in theoretical and mathematical physics from Aarhus University. In addition to the distinctive approach to thorium energy - using molten salts, Copenhagen Atomics fabricates and then sells to other players some of unique components both in molten salt energy storage, concentrated solar power and molten salt reactor industries.

Email: aslak.stubsgaard@copenhagenatomics.com

Copenhagen Atomics

molten salt reactor development

copenhagen
atomics

Aslak Stubsgaard
CTO & Co-founder

The goal

Mass manufacturing thorium reactors

copenhagen
atomics

copenhagen
atomics

Reactor Production Facility

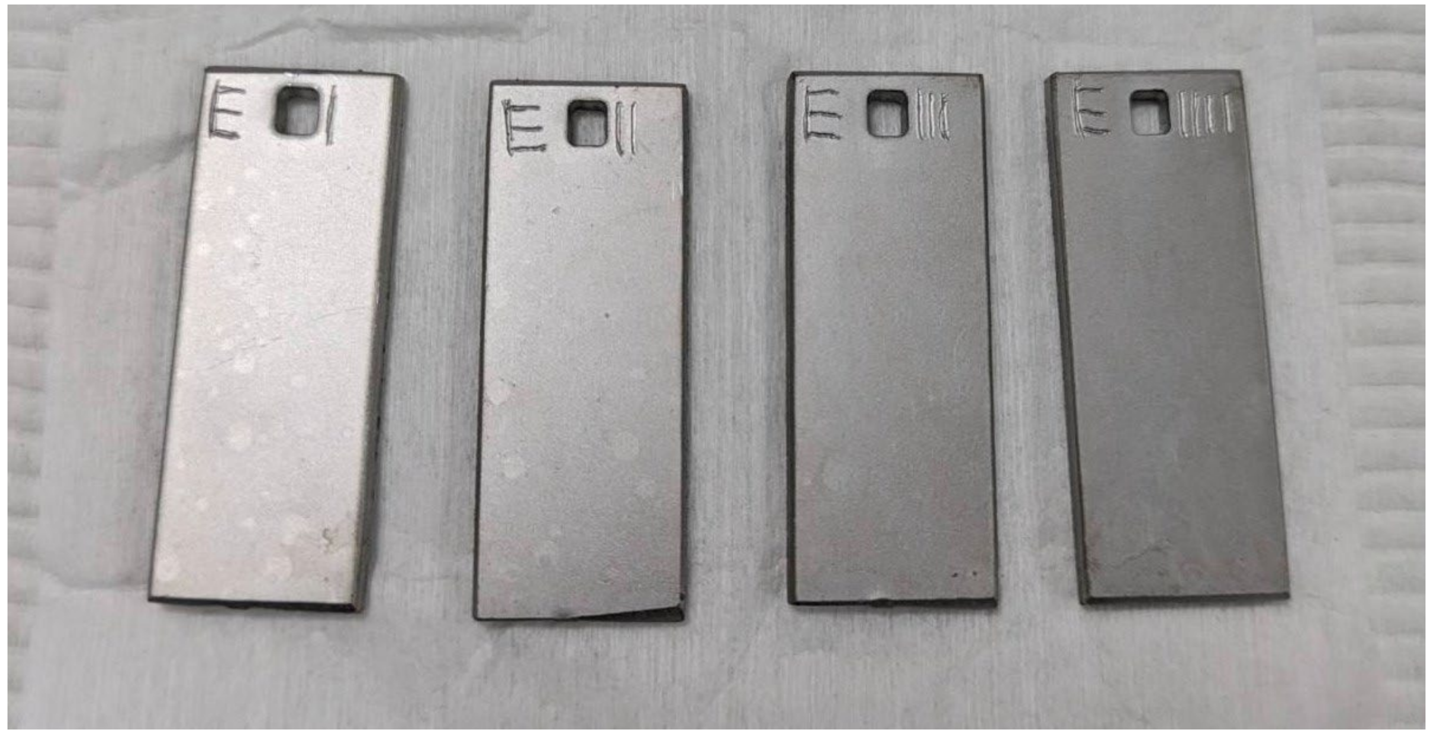
11.000 m^2

Copenhagen, Denmark

70+ Employees

copenhagen atomics

Large-scale salt production



1000L batch size of purified FLiNaK, FLiTh, FLiThU, etc.

Purified salt specs:
<100ppm of oxide species
<500ppm of transition metal species

Available for purchase

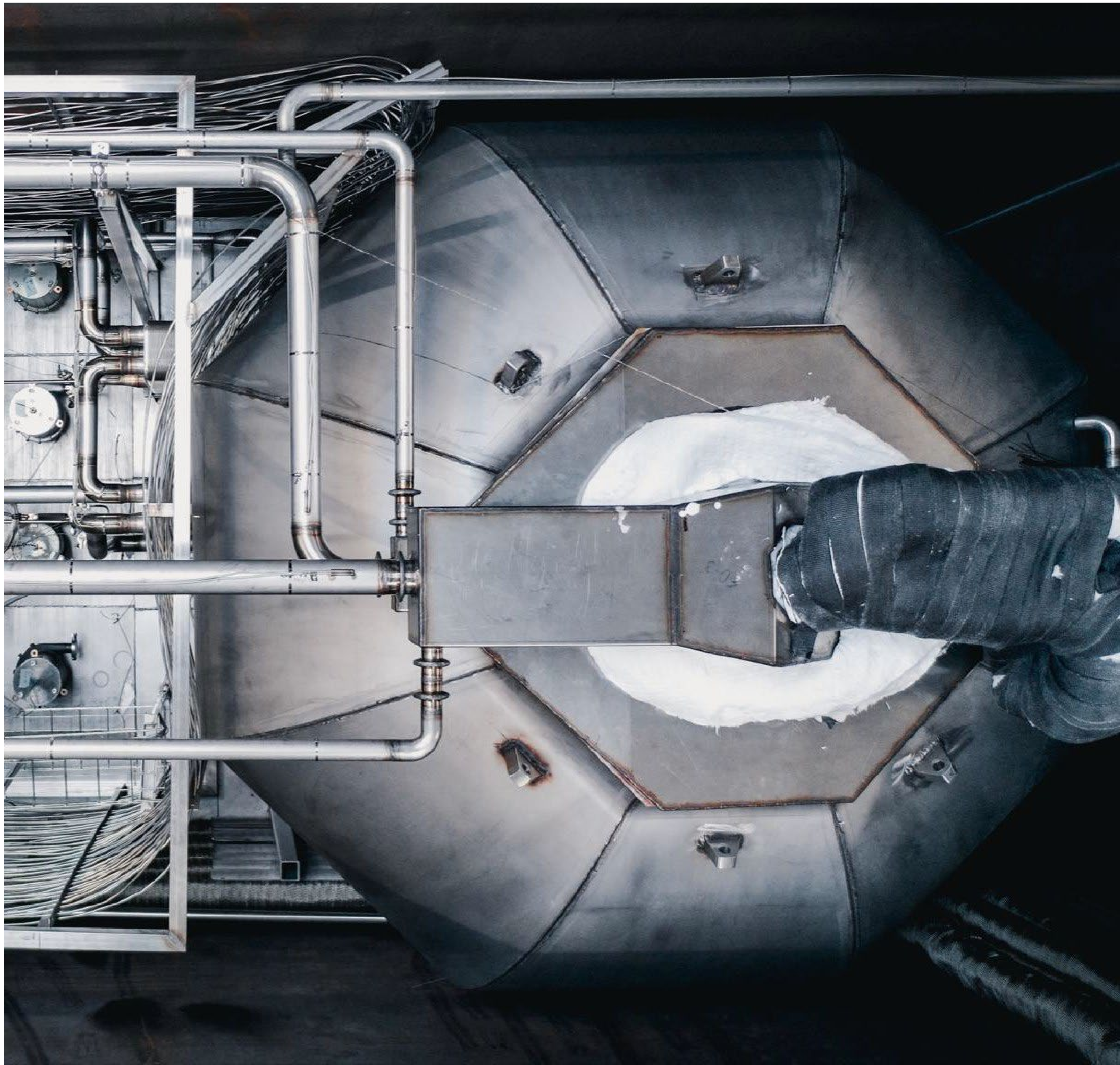
Static corrosion study

SS316L in purified FLiTh salt
@ 700C & 3000h

1-5 µm/y corrosion rate

copenhagen atomics

Non-fission prototypes



Valves

copenhagen atomics

Pumps

copenhagen
atomics

Loops

Specs

Pump
Valve
Flow meter
Pressure sensor
Salt leak sensor

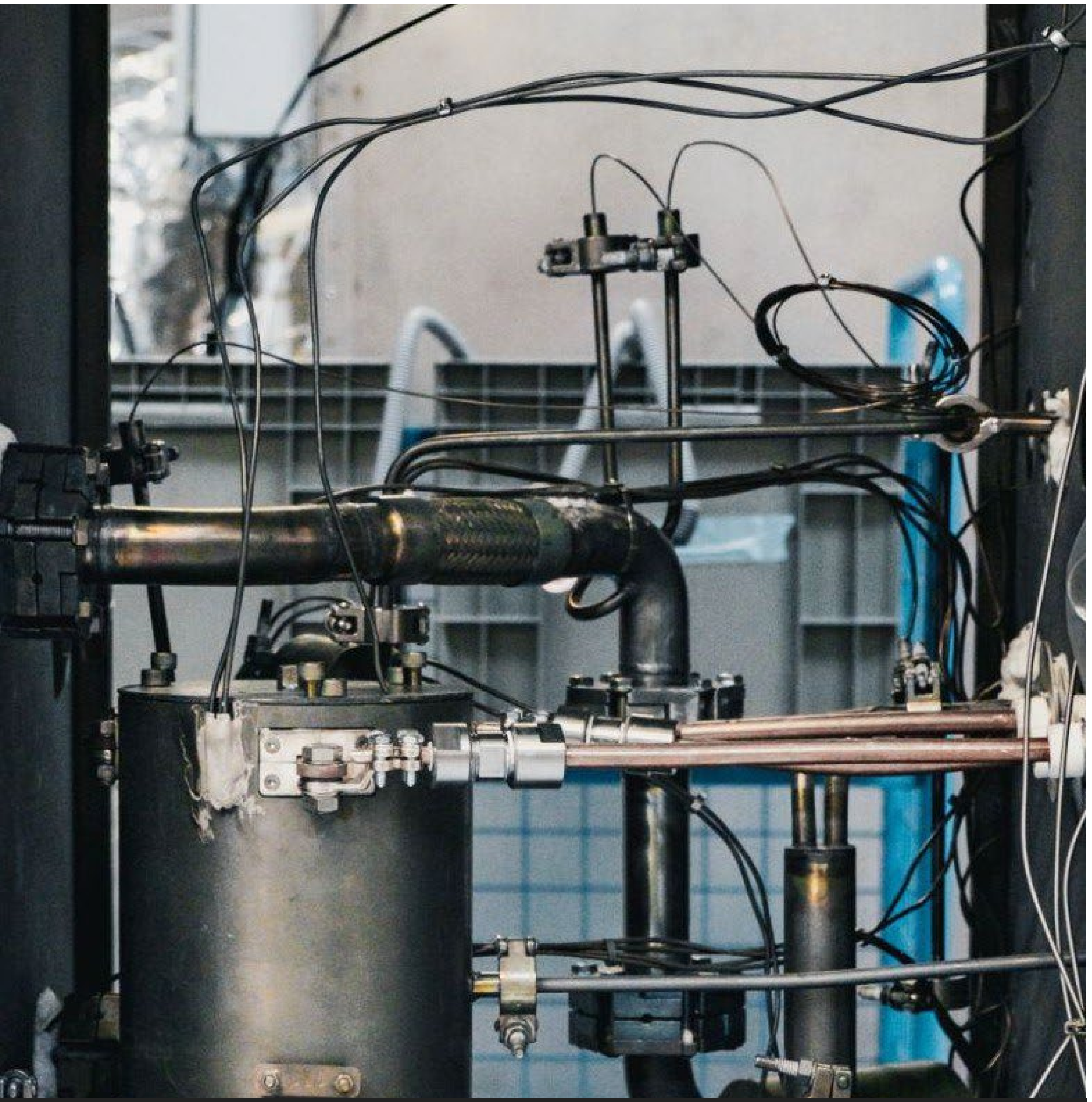
Available for purchase with 1000h warranty

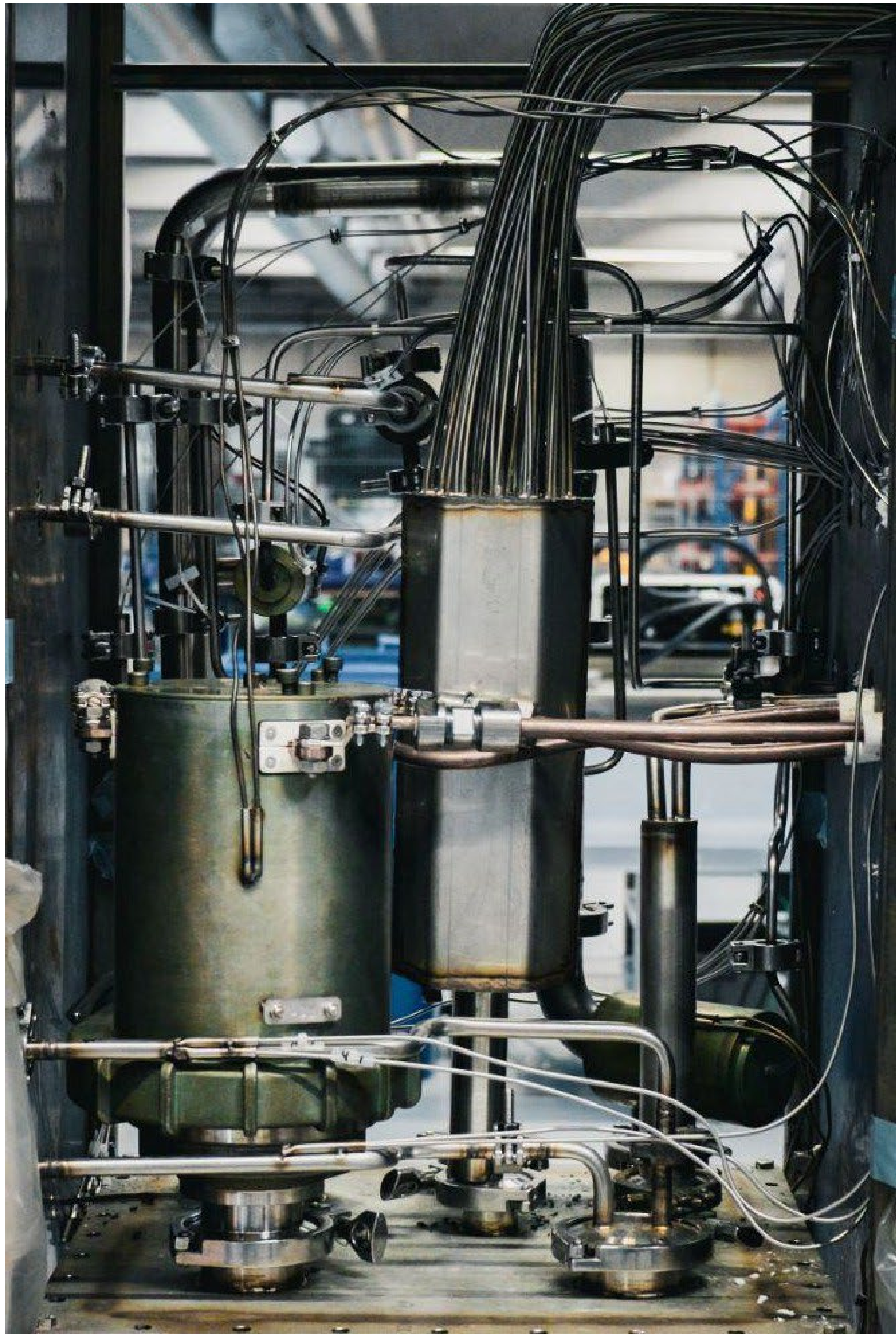
Upcoming

Online salt chemistry monitoring

copenhagen atomics

Loops





copenhagen atomics

copenhagen
atomics

Meet the Presenter

Edward Pheil, Chief Technology Officer & Founder at Exodys Energy, graduated from Penn State University with a Nuclear Engineering Fusion degree. He has 32 years of experience earned in multidisciplinary reactor technologies at the Naval Nuclear Laboratory, KAPL. Ed has spent the last 9 years dedicated to the development of molten salt reactors, first with Elysium Industries and now with Exodys Energy.

Email: EdPheil@ExodysEnergy.com

GEN IV International Forum

EXODYS ENERGY

Nuclear Waste is our Clean Energy Solution

International Molten Salt Research in Support of MSR Development

August 28, 2024

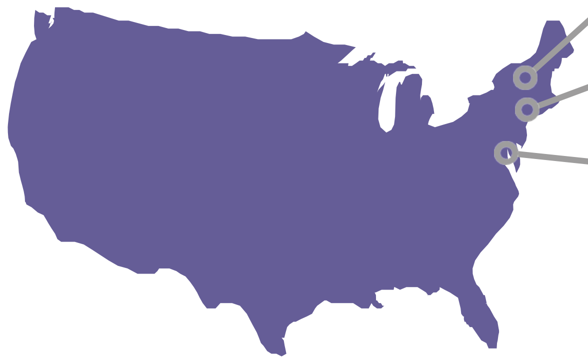
Company Overview

Exodys Energy is dedicated to converting UNF liabilities into valuable assets for nuclear site owners

Founded in October 2022 as a nuclear reprocessing vendor, we are currently developing **UPCYCLE modules: a capital-efficient and deployable recycling solution.**

The Exodys team is composed of **nuclear power and waste recycling experts**, stemming from both civilian and defense sectors.

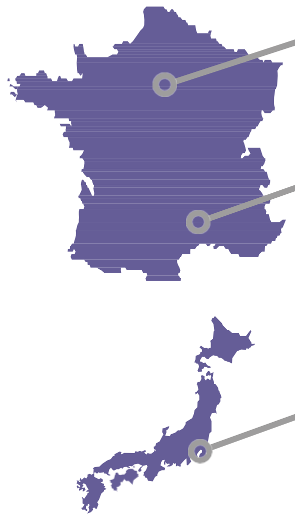
With our global presence, we are uniquely positioned to leverage recycling best practices to **treat all types of fuel - independent of age, burnup, enrichment, cladding, & damage.**



Schenectady, NY - Design & Engineering

New York, NY - Global Headquarters

Washington DC - Government Relations



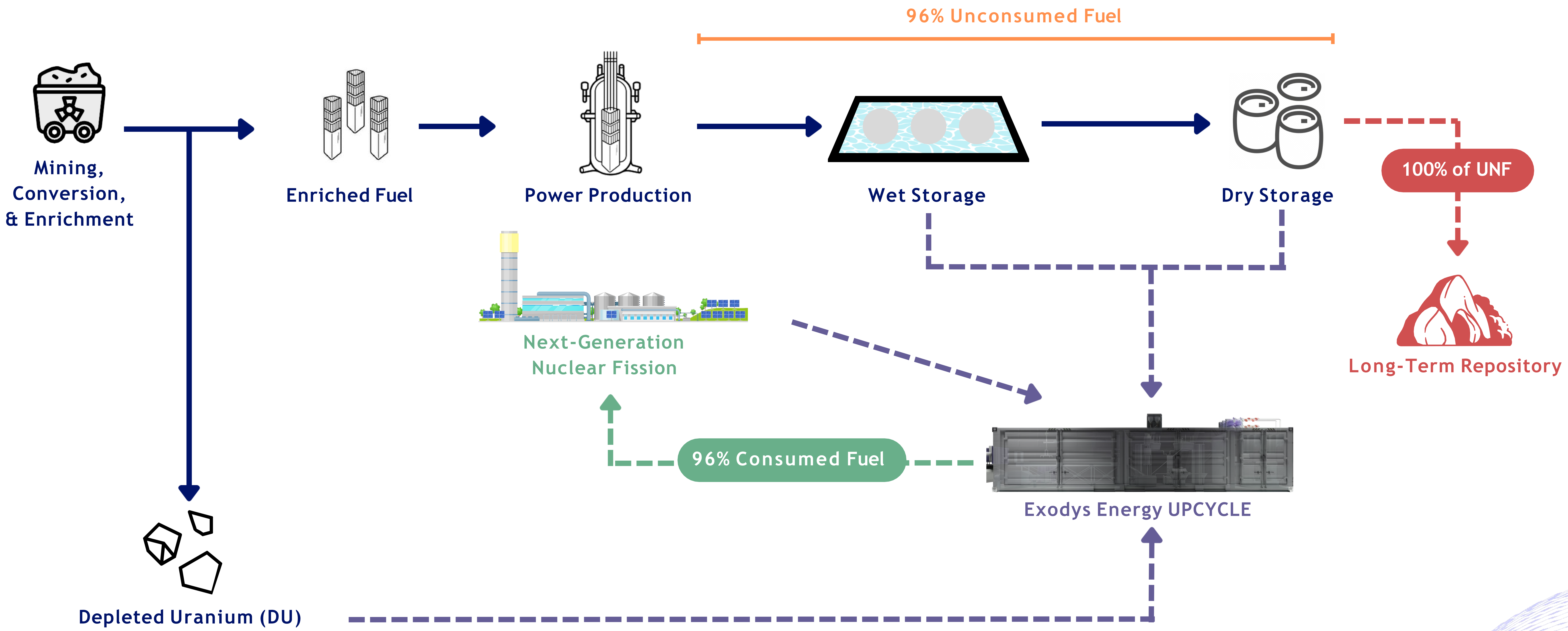
Paris, France - Business Development

Uzès, France - Design & Engineering

Tokyo, Japan - Business Development

Nuclear Fuel Lifecycle

Enabling a Circular Economy through a Closed Fuel Cycle

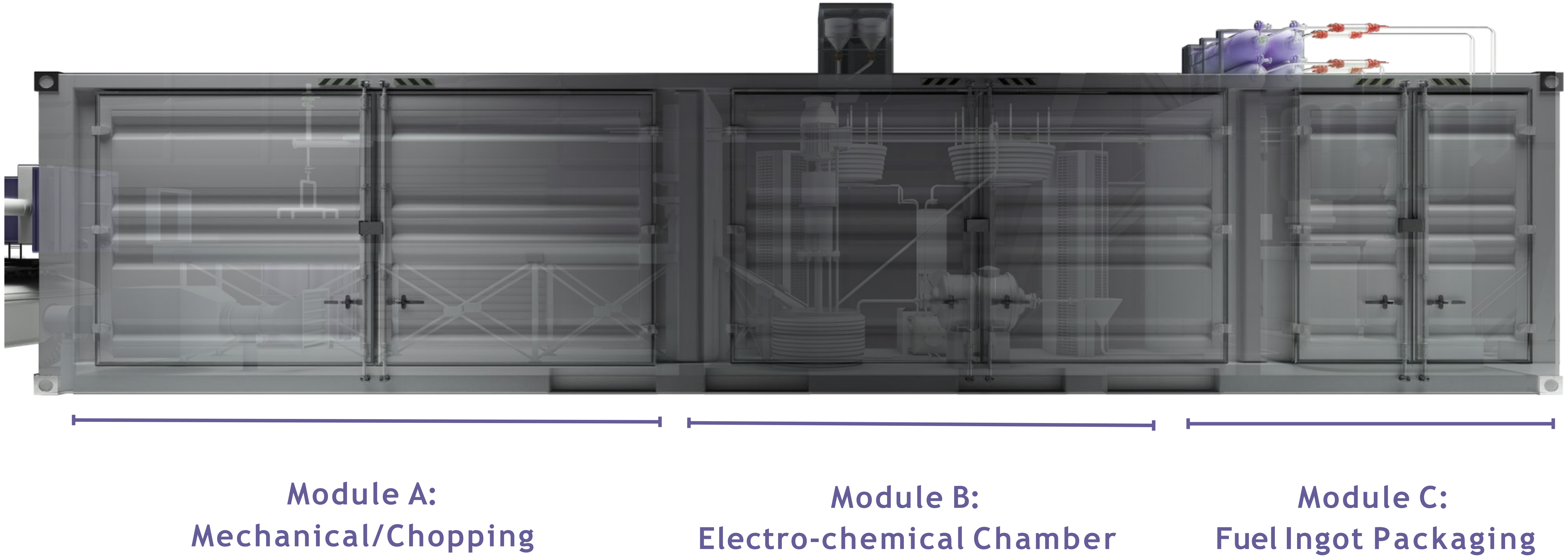


UPCYCLE Technology

Secure, Scalable, and Deployable Pyroprocessing Modules

Fuel Input

- Used Nuclear Fuel (UNF)
- MOX UNF
- Depleted Uranium (DU)
- CANDU UNF
- Separated Pu (RG+WG)



Note: Fast spectrum MSRs allow for the use of natural or depleted uranium at steady-state, thereby allowing countries without enrichment infrastructure to fuel its reactors.

This could also facilitate fuel take-back programs for countries without fuel infrastructure.

Used Fuel Chlorination

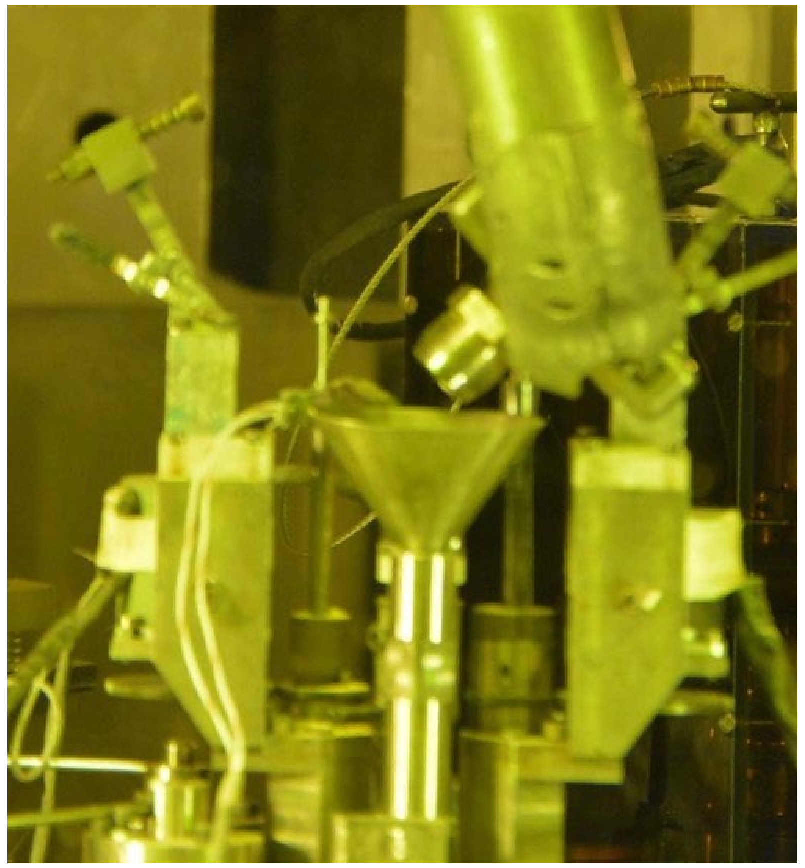
Experiment at Idaho National Laboratory's Hot Fuel Examination Facility in April/May 2018

<u>Highlights:</u>

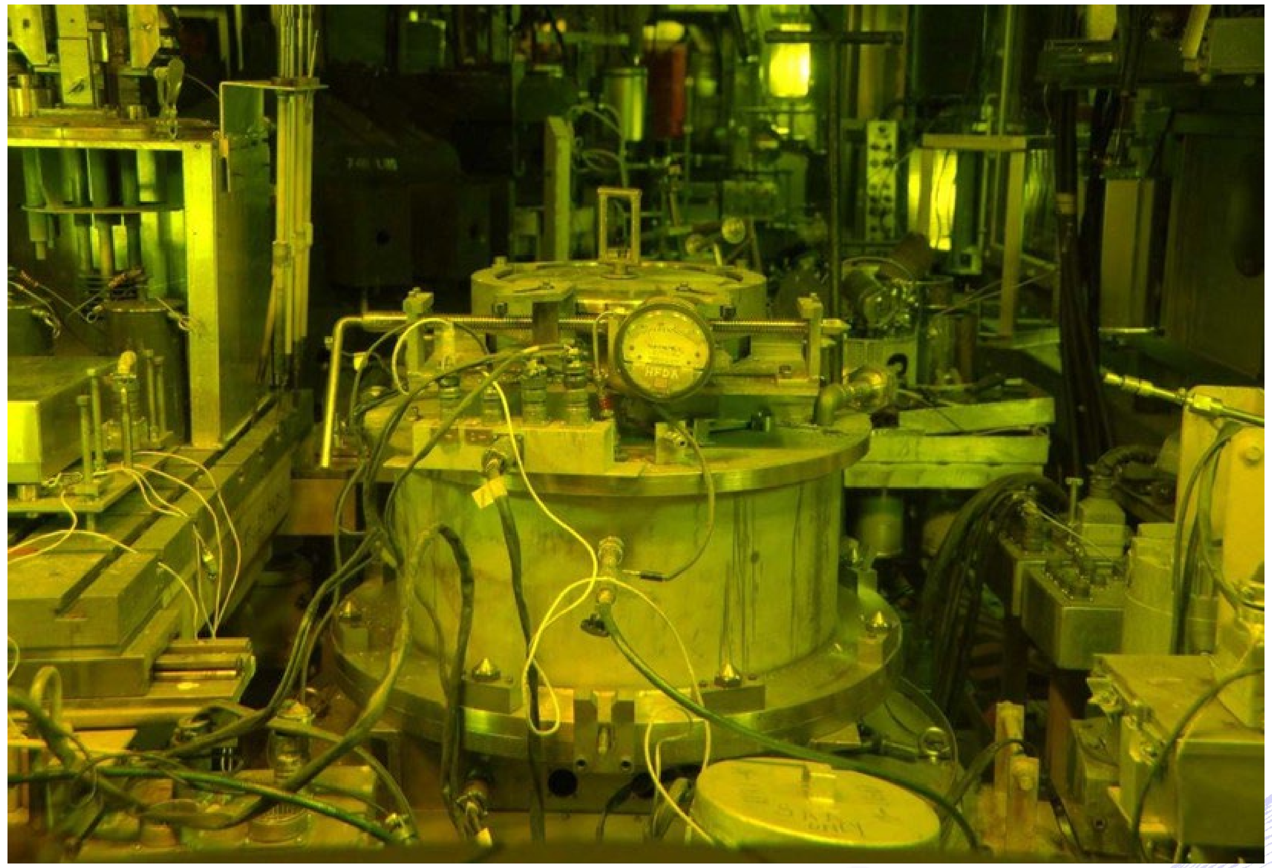
- 150g of MOX UNF
- Use of non-Li chloride salts
- Great agreement between modeled & measured concentrations of Pu (0.1–5%)

(1) Molten Salt + Used Fuel

(2) Chlorination Process



(3) Hot Fuel Dissolution Apparatus



U.S. Development

The United States has been gradually increasing its investment and focus on molten salt reactors

- The US market is fortunate to have significant R&D capacity with **17 national laboratories** working on various types of nuclear technologies.
- At least **9 US national laboratories are working on molten salt-related research** in 2024, whereas it was only 3 in 2015.
- **x2 Liquid-fueled MSRs are in process for potential operation before 2030.**
  - Abilene Christian University will receive the NRC decision for their safety assessment and construction permit on September 30, 2024.
  - TerraPower will build and operate its Molten Chloride Reactor Experiment at INL.

Challenges of International Collaboration

Each country and program also have their own priorities

- **Navigating national priorities:**
  - Nuclear programs typically benefit from significant government investment with a focus on local development (workforce and industry).
  - Several vendors have encountered difficulty balancing the benefits for each host country (e.g. UAE Barakah).
- **Difference in regulatory regimes/standards:**
  - e.g. France authorizes larger amounts of Krypton emissions, in comparison to the U.S. EPA., which affects design choices.
- **Export Control complicates cross-border technical conversations:**
  - There is a significant amount of data on molten salts, whether from national laboratories or from the MSR Experiment, that is redacted from publications.

Advantages of International Collaboration

Each country and program have varied skillsets and specializations

- **Exodys is a US company with a French subsidiary** to bridge US expertise in reactor development with French expertise in recycling and waste management.
    - Most MSR vendors have embraced an international approach with headquarters/offices in multiple countries.

- **Diversification of workforce specialization:**
    - European counterparts in Italy, Switzerland, and France developed the initial multiphysics tools to couple neutronic and CFD calculations for MSR design.
    - International team allows for input on diverse regulatory frameworks, allowing to meet for international acceptance.

- **Increased buyer power from a larger supplier base:**
    - France 2030 has invested a higher proportion of its resources in several MSR concepts, in comparison to other countries. Thus, France/EU-based suppliers supporting these concepts can also benefit foreign MSR programs.

Nevertheless, Recycling is a Team Sport

UPCYCLE, combined with the deployment of fast reactors, can considerably reduce fuel lifecycle costs

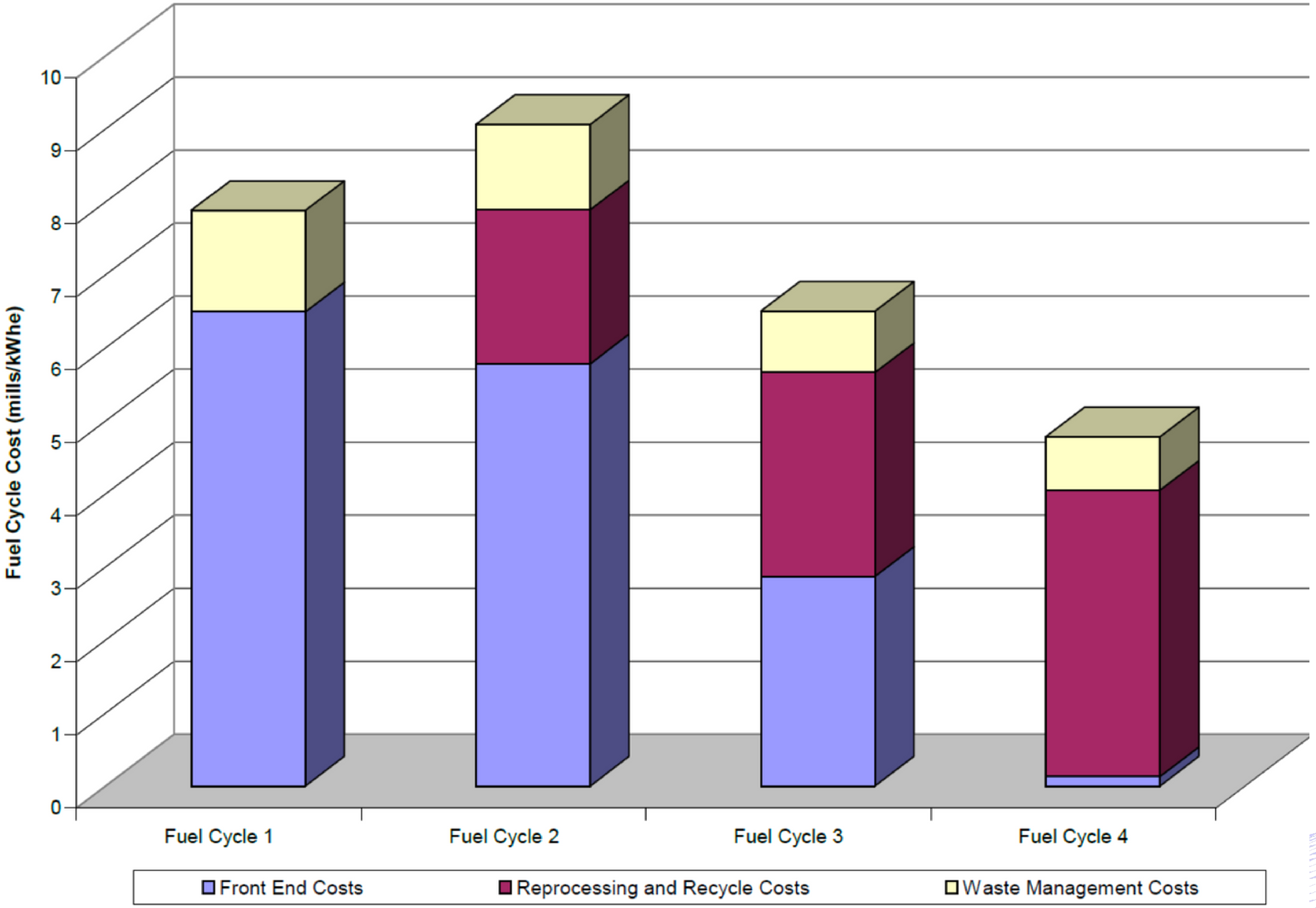
Comparison of overall fuel cycle costs using nominal unit costs for fuel cycles 1-4:

- **Fuel Cycle 1:**
Once-through

- **Fuel Cycle 2:**
Single recycle of UOX UNF converted into MOX fuel to be used in PWRs

- **Fuel Cycle 3:**
Multiple recycles of UOX & MOX UNF to be converted into MOX fuels appropriate for a combination of PWRs and fast reactors

- **Fuel Cycle 4:**
Multiple recycles using exclusively fast reactors



Source: Nuclear Fuel Reprocessing: For the Advanced Nuclear Era. EPRI, Palo Alto, CA: 2023. 3002026537

Areas for Potential Collaboration

Storage & Transport
Casks for SNF + New Fuel

Accountancy & Safeguards
(e.g. Sensors, Probes)

Advanced Reactor
Vendor Fuel Input

OPPORTUNITIES

info@exodysenergy.com

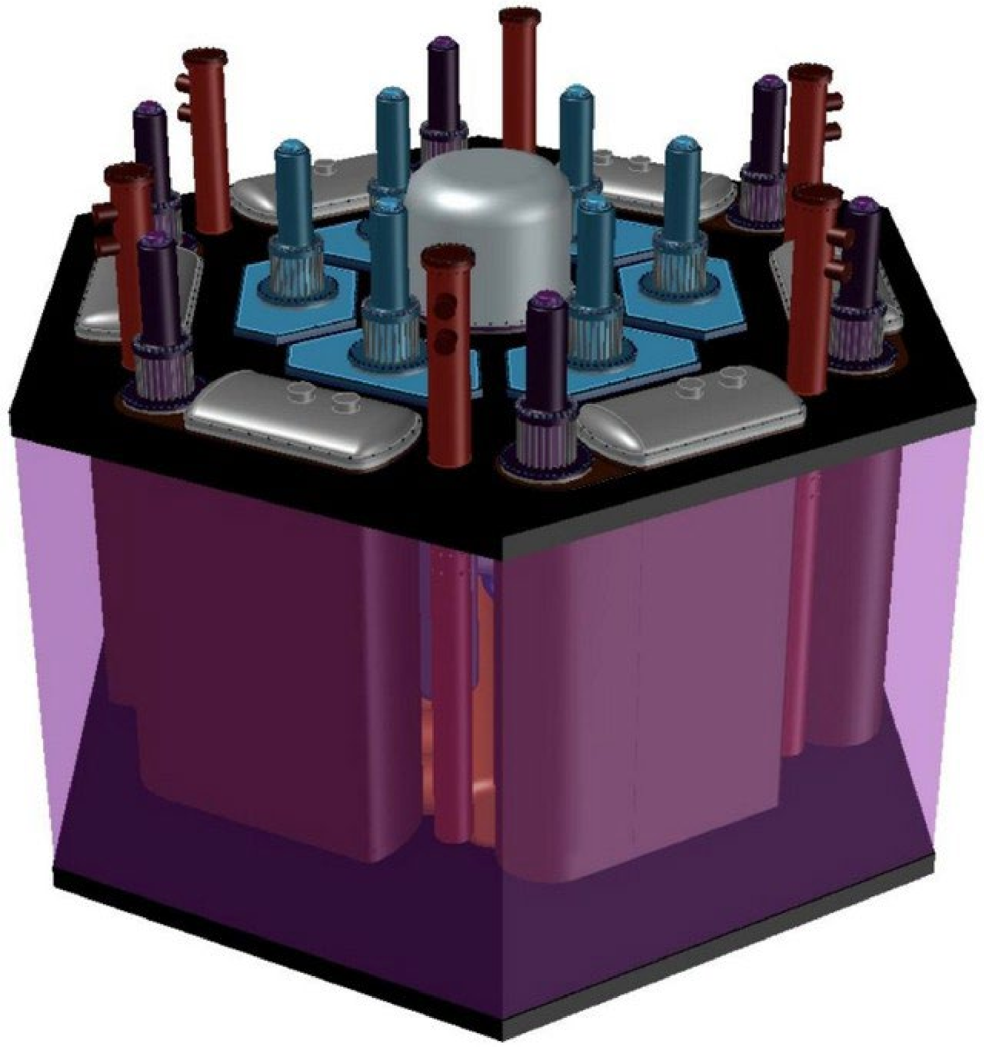
Experimental Facility
(Hot Cell/Glovebox)

Electro & Pyro - Processing
Engineering Expertise

Regulatory Experience
(ex: Yucca, ISFSI, Dry Cask)

EXODYS ENERGY

Nuclear Waste is our Clean Energy Solution



Ed Pheil
Chief Technology Officer
edpheil@exodysenergy.com

For Additional Enquiries

EXODYS ENERGY INC.
115 Broadway, 5th Fl, New York, NY 10006
info@exodysenergy.com

Meet the Presenter

Isabelle Morlaes has 30 years of experience in the nuclear business, in both reactor design & maintenance field and fuel cycle field (both front and back ends). She holds several management and strategy positions in different business units of AREVA and Framatome, then Orano. Since 2000 she is the Senior Vice President, MSR Project Manager in Orano. She works in the Innovation Department of Orano. Her mission includes the exploration of new business models for Orano on the fuel cycle using MSR "burning" capabilities, the coordination of initiatives to develop partnership and business with MSR designers, and the search for international collaborations and co-financing schemes, to accelerate the development of the MSR technology and its fuel cycle, in synergy with the La Hague plant.

Email: isabelle.morlaes@orano.group

Value of MSRs for Fuel Back-End management

GIF Webinar

August 28, 2024

I. Morlaes

orano

01 Orano - World expert in the nuclear fuel cycle

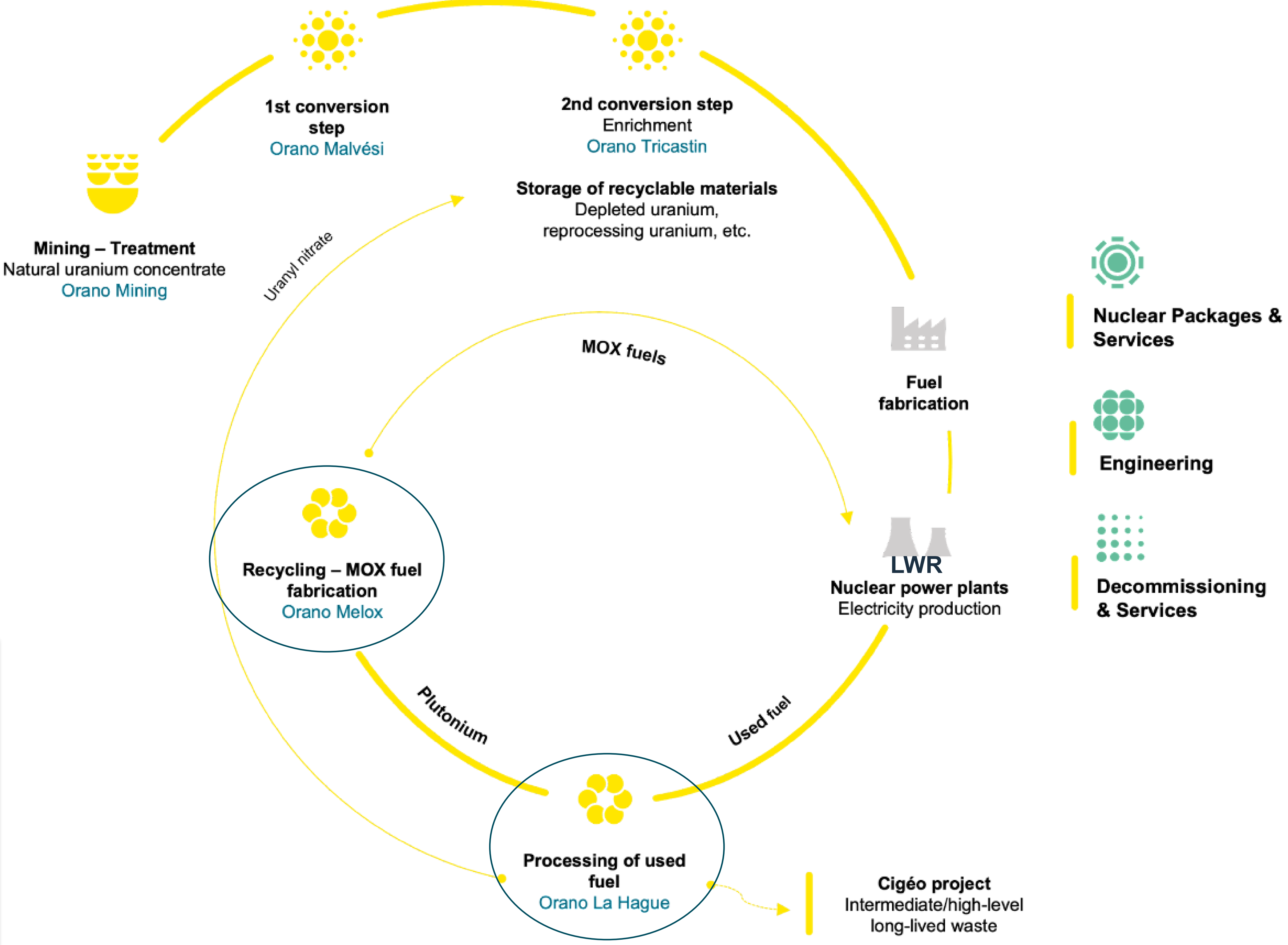
The Orano Group offers its customers high-performing products and services, in mining, conversion, enrichment, recycling, logistics, engineering and decommissioning.

Orano is also **a major force in nuclear medicine and targeted alpha therapy using ^{212}Pb,** through its subsidiary Orano Med.

Its know-how across every stage of the fuel cycle and its ability to innovate are key success factors

Orano fundamental purpose:

To develop know-how in the transformation and control of nuclear materials, to protect the climate, health, and for a resource-efficient world now and tomorrow.



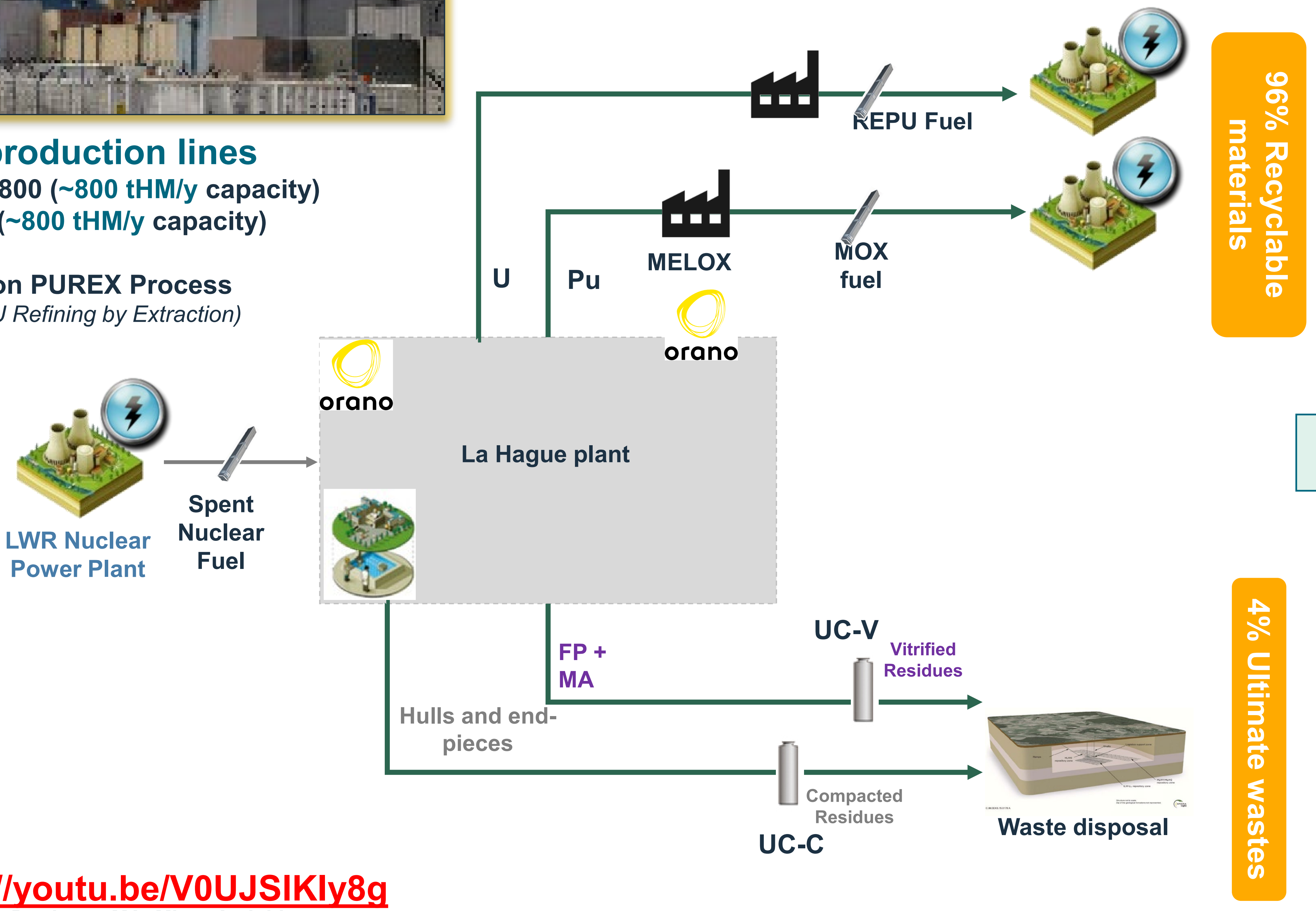
The La Hague plant is a strategic asset which has addressed Back-End challenges for LWRs spent nuclear fuels for 50 years

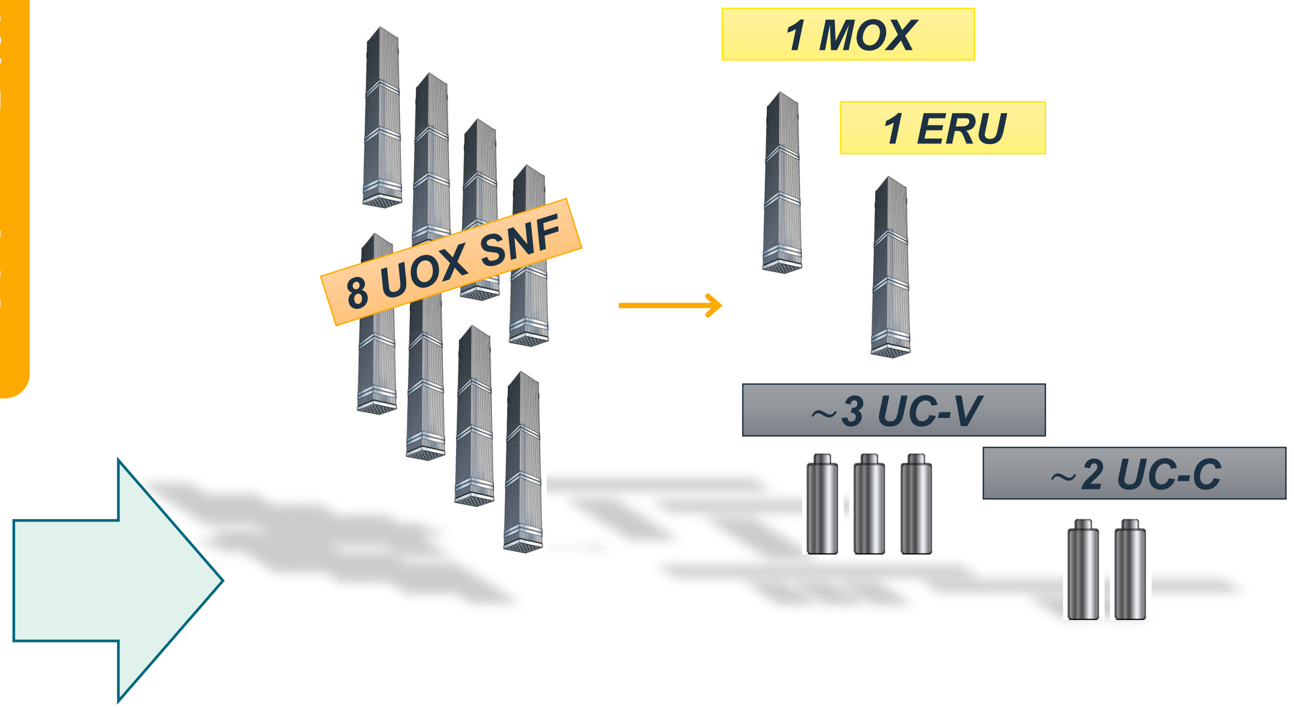
Two production lines

- UP2-800 (~800 tHM/y capacity)
- UP3 (~800 tHM/y capacity)

Based on PUREX Process
(Pu and U Refining by Extraction)

~27,000 tHM reprocessed for France
~10,500 tHM reprocessed for 6 other countries





- *96% recycled materials*
- *Up to 25% savings in Natural U*
- *HLW volume reduction by 5*
- *HLW radiotoxicity reduction by 10*
- *Safe & secure ultimate waste (without Pu)*

https://youtu.be/V0UJSIKIy8g

FP: Fission Products; MA: Minor Actinides
UC-C/V : Universal Canister – compacted / vitrified

6 other countries : Germany, Belgium, Spain, Japan, Switzerland, Italy, the Netherlands

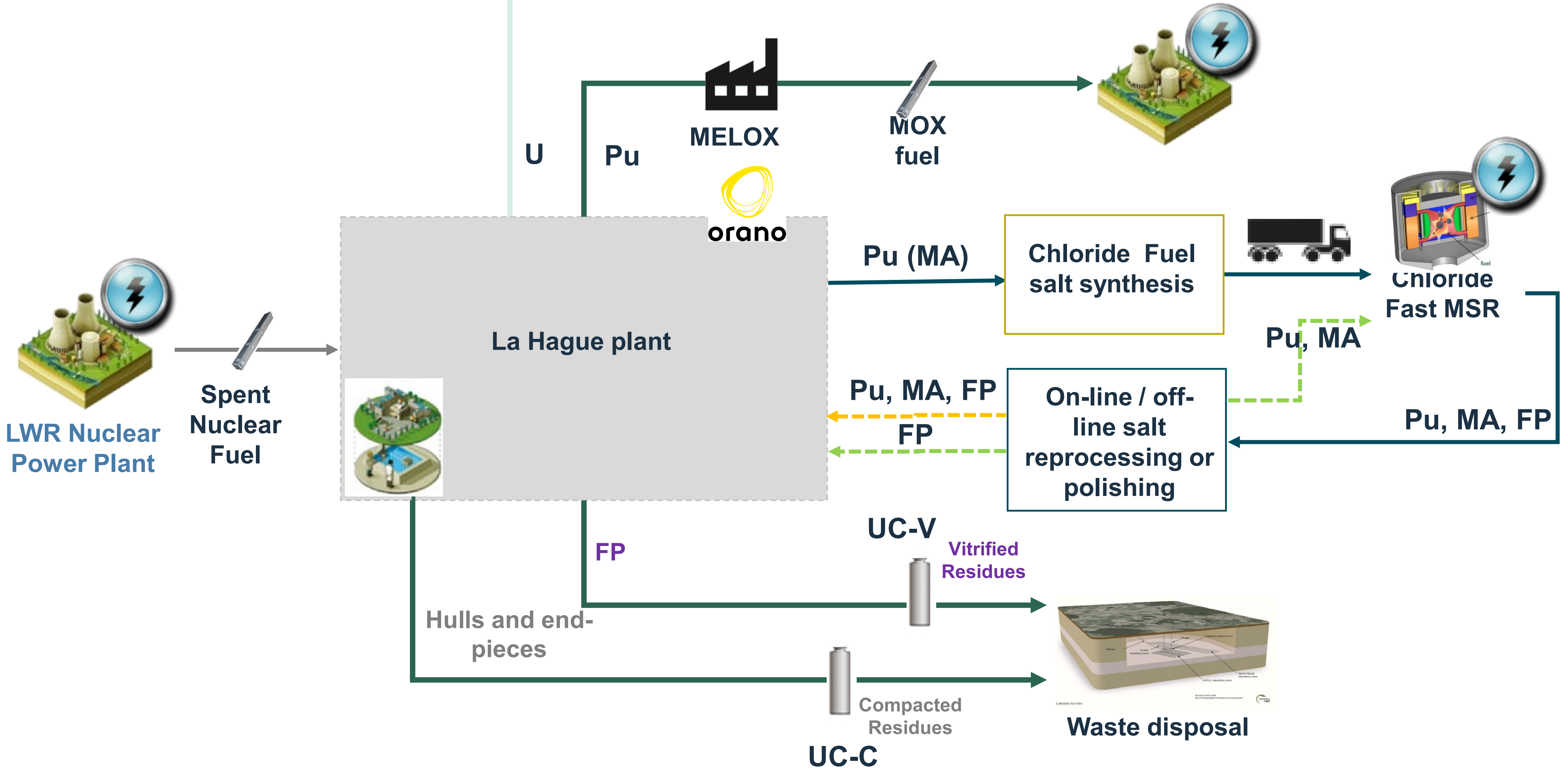
orano

03 Since 2019 Orano has been exploring the potential of fast Chloride MSR to add value to the utilities : use Pu + MA as fuel and provide a global solution where the customer is left with vitrified residues with FP only

Beyond U/Pu multi-recycling in LWR, coupling with Fast MSR offers an additional service to LWR operators to close their fuel cycle and reduce their High-Level Waste

- Treatment of spent nuclear fuel with no return of Pu
- Transmutation of MA ➔ less ultimate waste, reduced long term radiotoxicity

The molten salts could be produced and recycled in La Hague, and FP vitrified in La Hague



2 options / 2 steps approach:

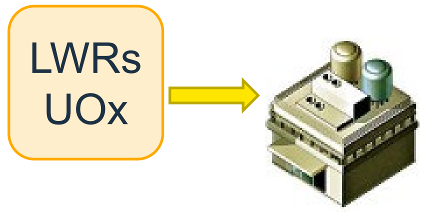
- **Option / Step 1** : irradiated salt (Pu+FP+MA) sent to La Hague for recycling and vitrification of FP
- **Option / Step 2 :** on-site salt polishing ➔ FP-only salt transportation to La Hague for vitrification

04 The comparison of 3 scenarios(*) illustrates the potential of MSR in reducing the volume and long-term radiotoxicity of High-Level Waste (HLW)

"Symbiotic fleet" (@10 TWhe/year)

Impact on waste to be emplaced in a Deep Geological Repository

1 Open cycle

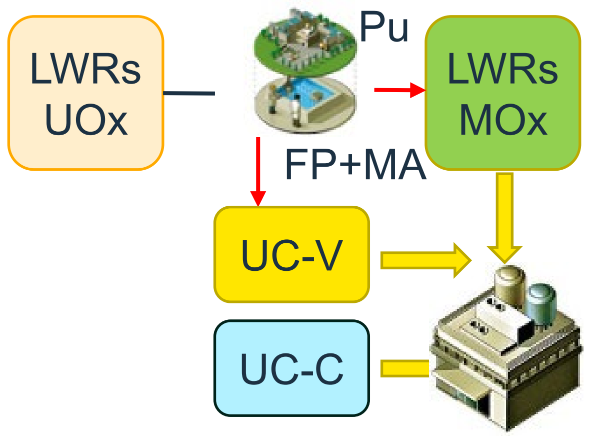


Power generation:
100% from UOX

130 used UOx fuel assemblies per year

2 Mono-recycling of Pu in LWRs (MOx)

Pu stream balanced in MOx fuels



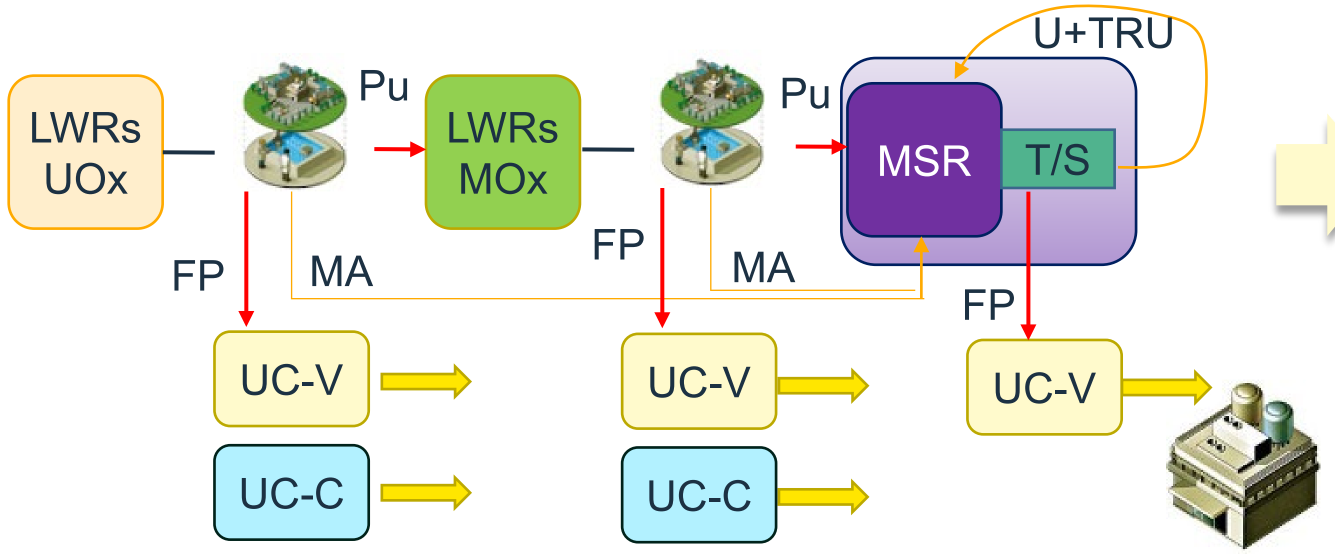
Power generation:
63% from UOX
37% from MOX (*)

14 used MOx fuel assemblies + 20 UC-V + 23 UC-C per year

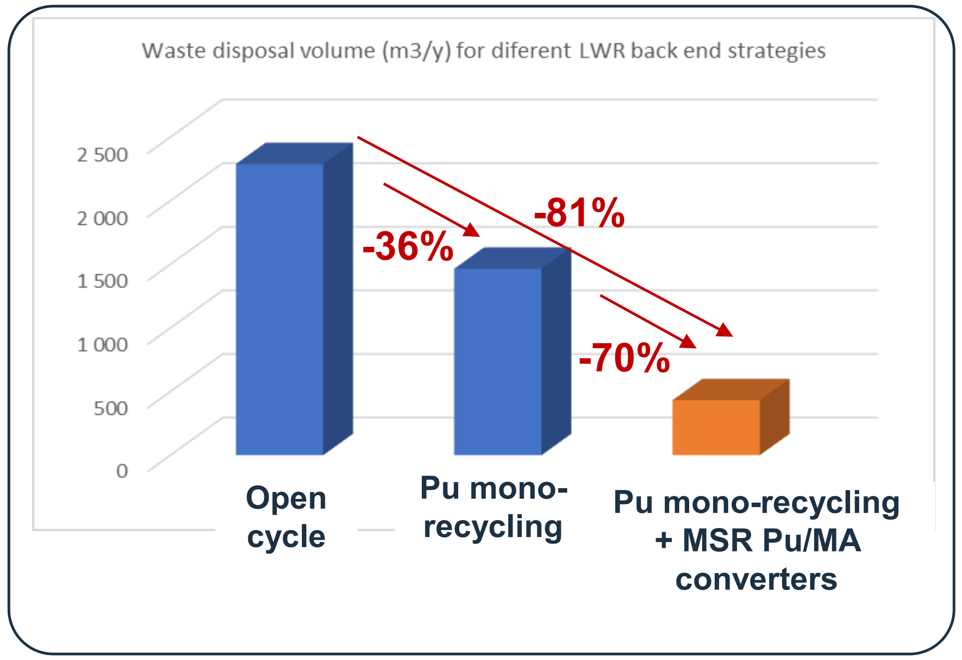
3 Mono-recycling of Pu in LWRs (MOx) + MSR as Pu+MA convertors

Pu ex-MOx & MA ex-UOx/MOx streams balanced in MSR

Power generation:
51% from UOX
30% from MOX (*)
19% from MSR



20 UC-V without MA + 21 UC-C per year



No MA in UC-V → strong reduction of both thermal impact and requirements for the Geological Repository

T/S : on-line treatment / separation of salt

(*) Assumptions in this example: LWR are SMR @100 MWe, MSR are @135 MWe, In scenario 2, SMRs are loaded at 30% of MOx fuel

orano

05

Orano's strategy is to enable the emergence of Chloride Fast MSR models, with a first demonstrator of Cl Fast MSR in the 2030'

R&D on technological issues and key topics

First Critical mock-up

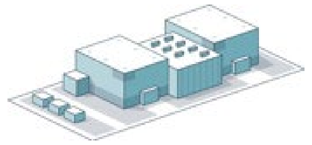
today

~2027

orano · cea · Euratom Horizon2020 · France Relance · cnrs · JRC Joint Research Centre · ARDP

orano · CORE-POWER · TerraPower · Southern Company

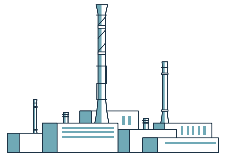
International cooperation is vital to succeed in the R&D programs leading to commercial Cl MSRs



First experimental small Chloride Fast MSR

2030-2040

orano



Pu Salt production pilot in La Hague

Commercial deployment of Chloride Fast MSRs

Industrial Pu salt production plant in La Hague

orano

Fast Cl MSR are ideal candidates to close the fuel cycle and reduce Long-lived HLW

Using synergies with the industrial capabilities of La Hague can accelerate the development and deployment of such Back-End solutions for LWR (including LW-SMR) fuel

» ***a unique value in terms of sustainability and public acceptance of nuclear energy in the future***

Meet the Presenter

Dr. Jeremy Pearson serves as the Director of the San Rafael Energy Research Center in Emery County, Utah where he works with local leadership and universities to research and commercialize groundbreaking sustainable energy technologies. Dr. Pearson earned an undergraduate degree in Chemical Engineering from Brigham Young University and a Ph.D. in Chemical Engineering from the University of California Irvine studying used nuclear fuel recycling. Dr. Pearson has worked in the energy field in nuclear energy and advanced unconventional fossil fuels, as well as in energy policy having served in 2015 in Washington D.C. as an AAAS American Association for the Advancement of Science - Science and Engineering Fellow in the office of Senator Orrin G. Hatch.

Email: jeremy.pearson@usu.edu

Forging the Future of Energy

STATE U BYU EMERY COUNTY

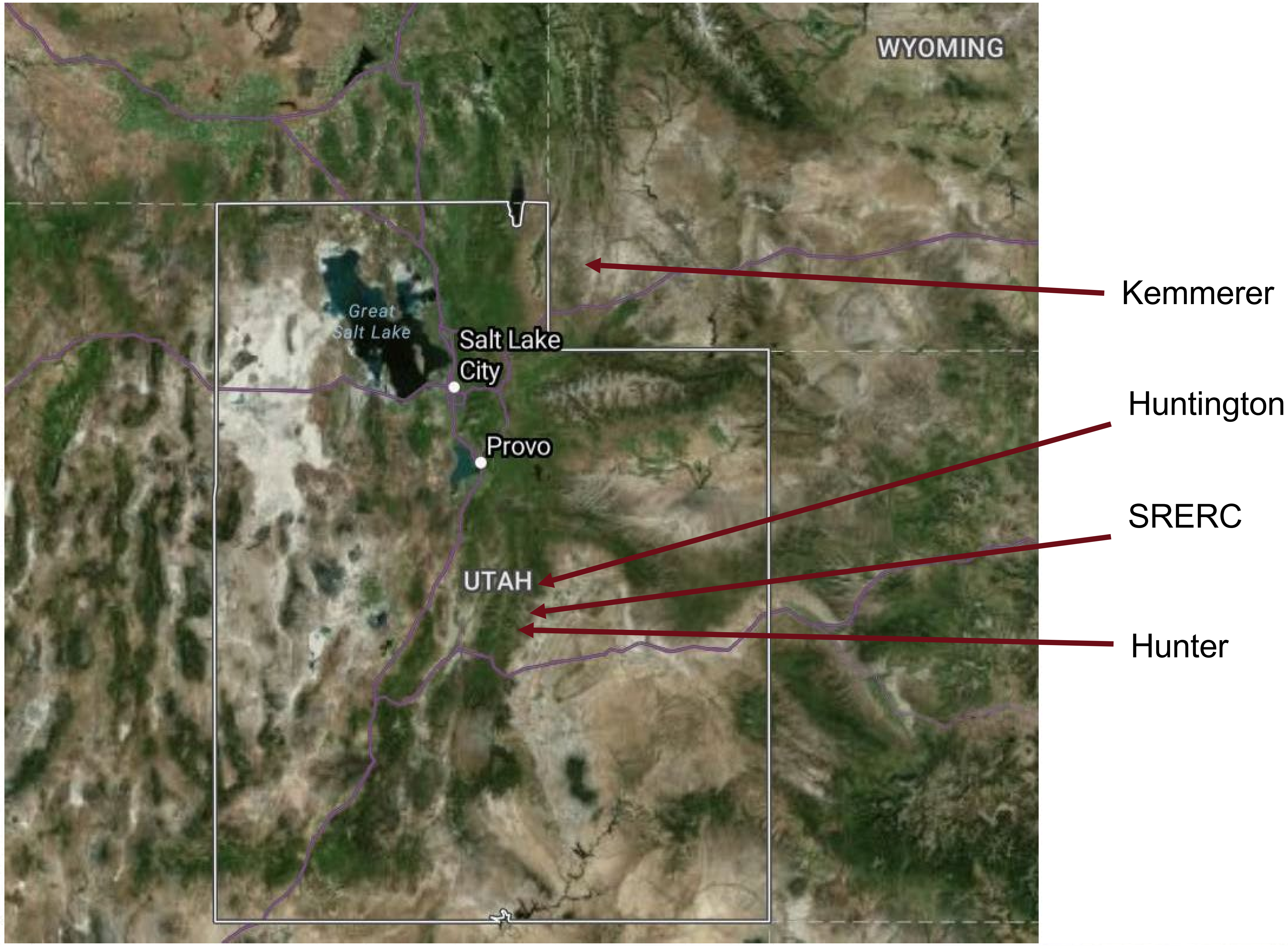
UTAH OFFICE OF ENERGY DEVELOPMENT

What is the San Rafael Energy Research Center?

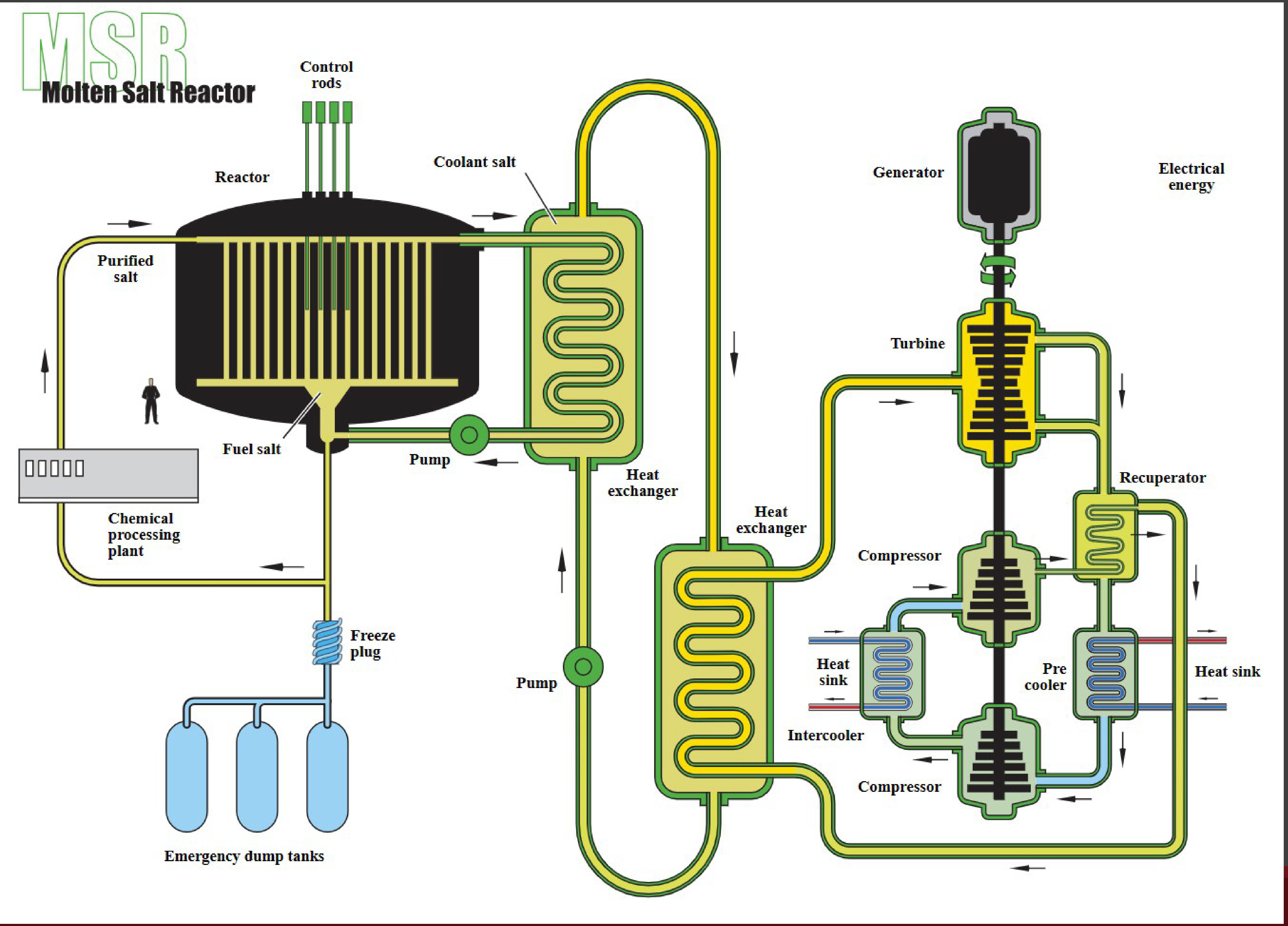
- A miniature national lab
- An R&D site for large-scale energy research
- A nuclear energy materials laboratory
- An accessible facility for researchers everywhere
- A heroic effort to revitalize a coal community

The San Rafael Manufacturing and Industrial Park

- 130 Acres in Orangeville, UT
- Industrial Park already owned, zoned, and planned by Emery County, UT
- $1.8M already invested to run utilities to the site
  - Power, water, gas, sewer
  - More infrastructure plans underway
- Emery County local leadership is working hard to make these projects happen



Molten Salt Nuclear Reactor

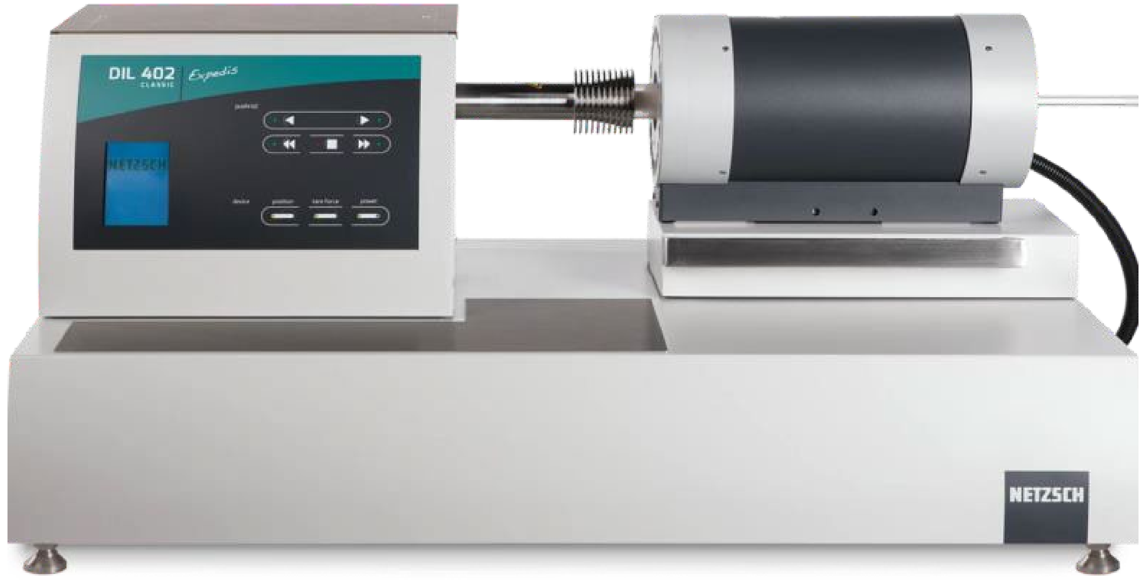


Laboratory Facility

- LC Technology Gloveboxes
  - Argon Atmosphere
  - 3 bay extended height
- Chemical and Radioisotope fume hoods
  - Contained experiments with dedicated ventilation
- Beryllium capability
- DEQ Limited Scope Nuclear Materials License

Netzsch Analytical Equipment

- STA 449 F3
  - Heat Capacity
  - Mass Loss
  - Melting Temperature
- LFA 467 HT
  - Thermal Conductivity
  - Thermal Diffusivity
- TMA 402 F1
  - Coefficient of Thermal Expansion
  - Density curve
- DIL 402
  - Coefficient of Thermal Expansion
  - Density curve



Revolutionary Molten Salt Classification

- Anton-Parr MCR 702E
  - Viscosity
- Biologic VMP 300 & VSP 300
  - Electrochemistry experiments
- Bruker G6 Leonardo
  - Oxygen concentration
  - Hydrogen concentration
  - Nitrogen concentration

Elemental Analysis

- Agilent 8900 ICP-MS
  - Elemental analysis
  - High TDS capability
- ThermoFisher Neoma ICP-MS
  - Multicollector ICP-MS
  - Isotopic analysis
- CEM MARS 6
  - Intelligent microwave digestions

Microscopy

- ThermoFischer FIB-SEM
  - Helios 5 Hydra UX Plasma Dual Beam
  - Focused Ion Beam Milling Attachment
  - 3D EDS
  - Carbon Coater
  - Computer Controlled SEM

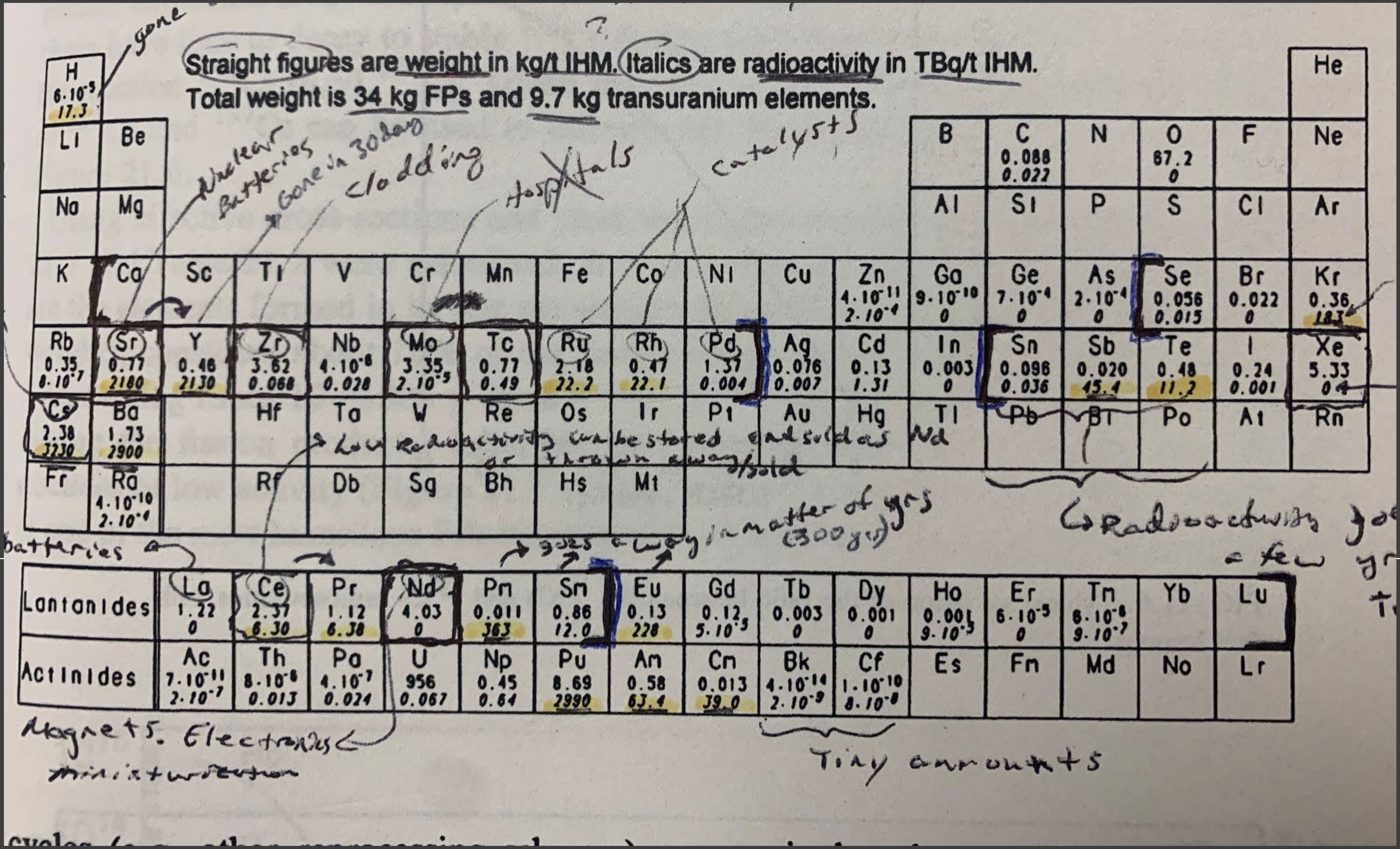

G6 LEONARDO


EXIT
BOX 3-03
STA 449
Jupiter
open
close


GLASS

High Bay Room

Separations, Extraction and Used Fuel Recycling



ANL/NE-Landmark-CRADA-12
Revision 1

Summary Report
Conceptual Design of a Pilot-Scale Pyroprocessing Facility

Prepared by

Argonne National Laboratory
Merrick and Company

for

The Landmark Foundation

May 1, 2015
Updated April 10, 2018

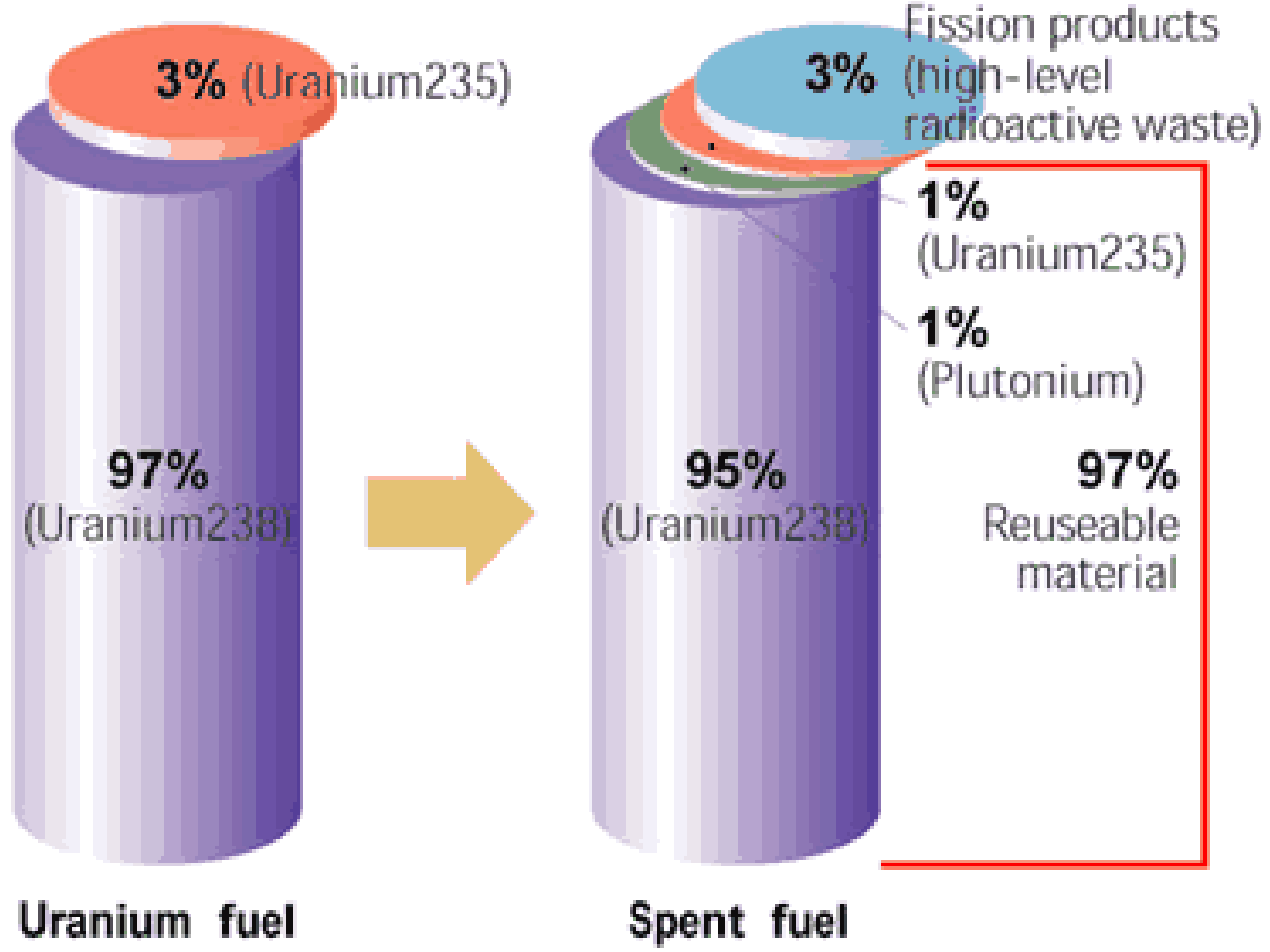


Figure 3 Processing Facility

ACES Delta Project

Hydrogen Power

World's Largest Renewable Energy Storage Project

Energy Solutions

Kemmerer

Huntington

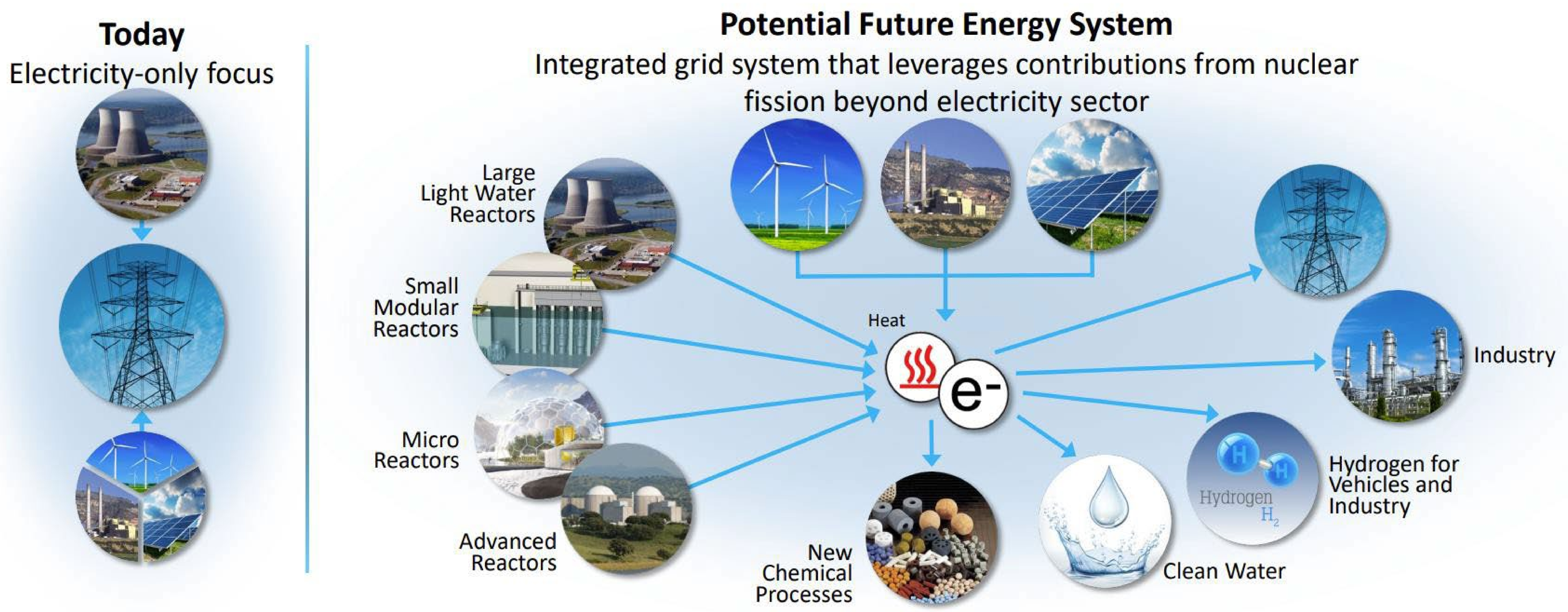
SRERC

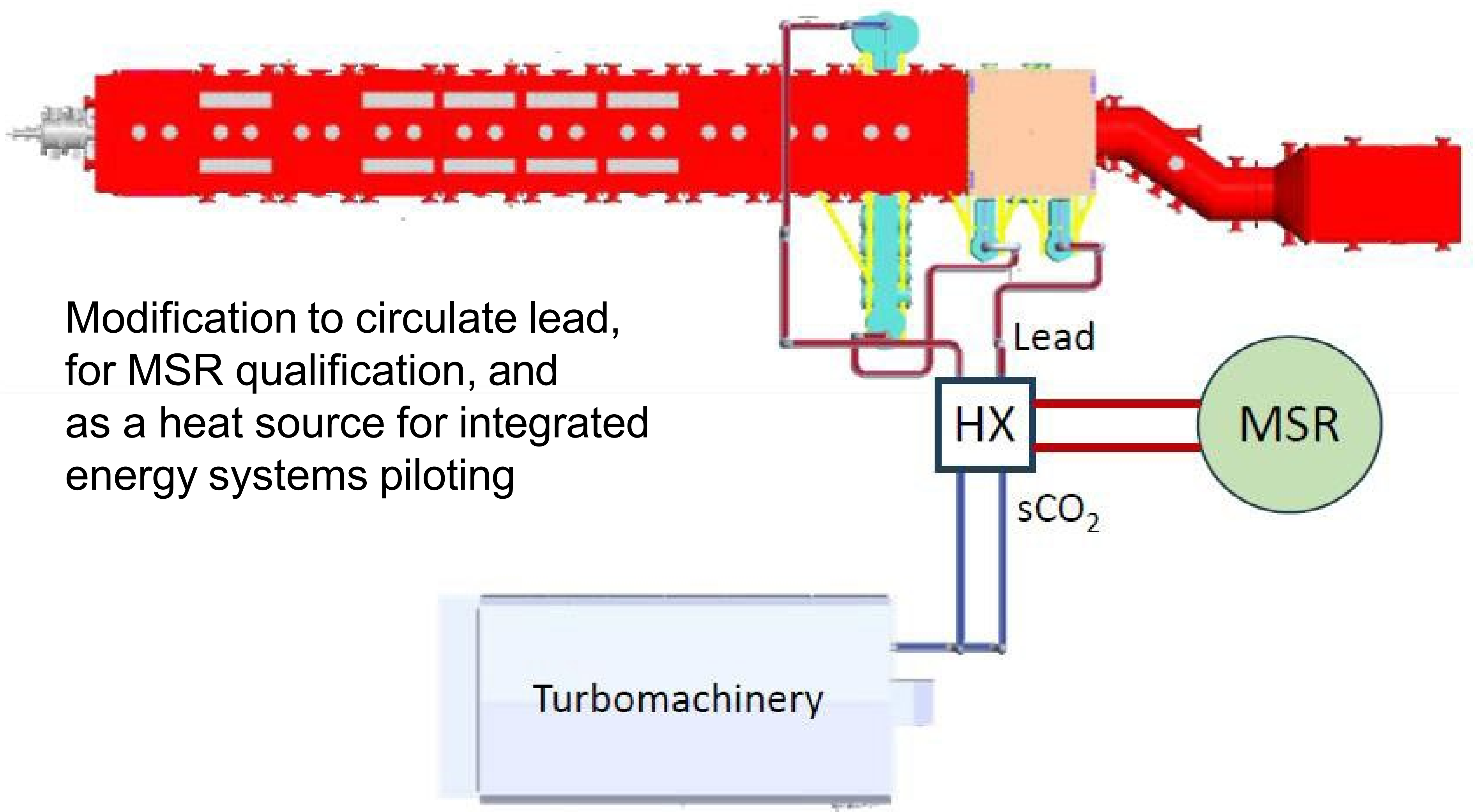
Hunter

Delta

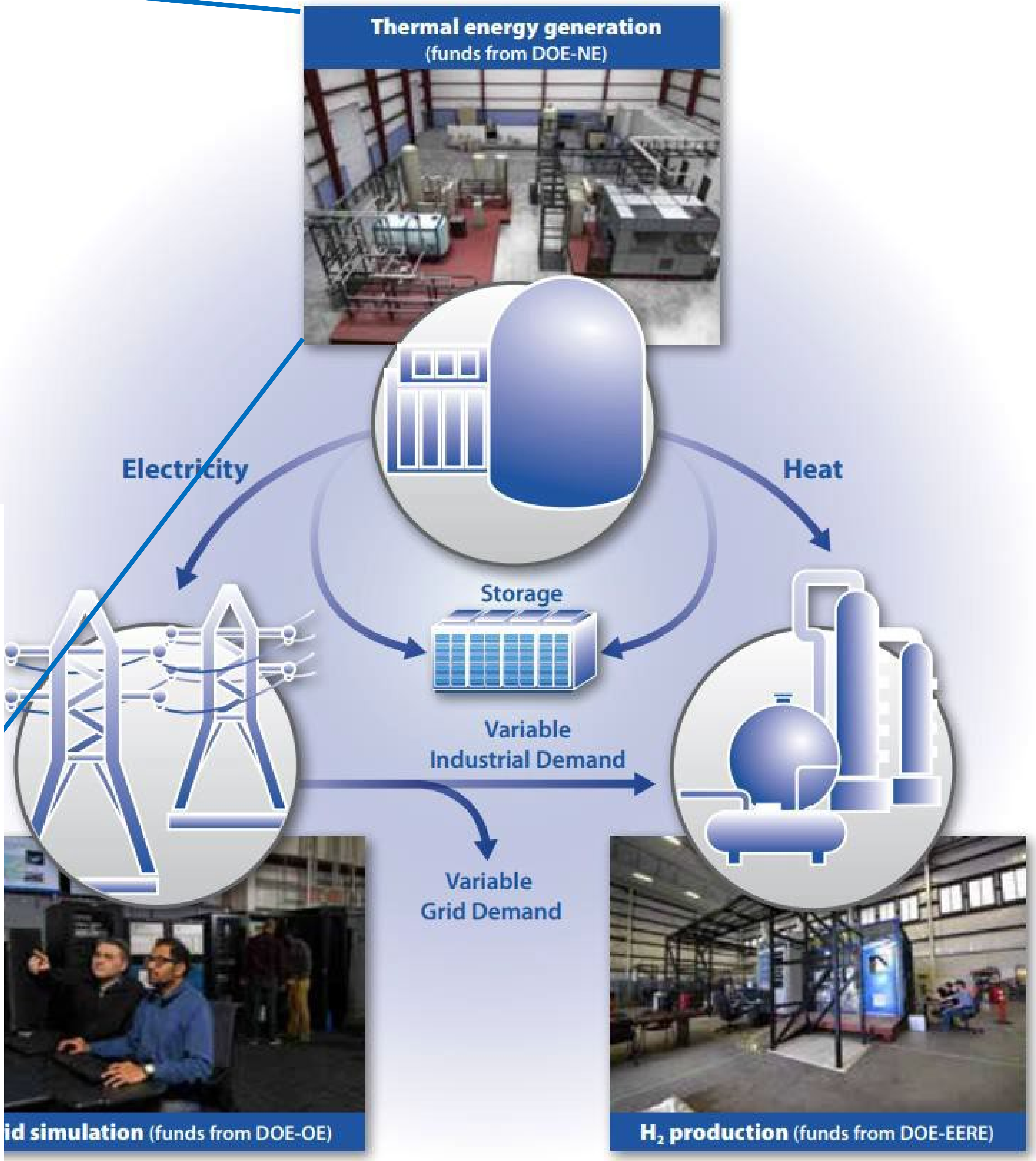
1.5 MW_{th} Pulverized Coal Flame Furnace with supercritical CO_2 loop

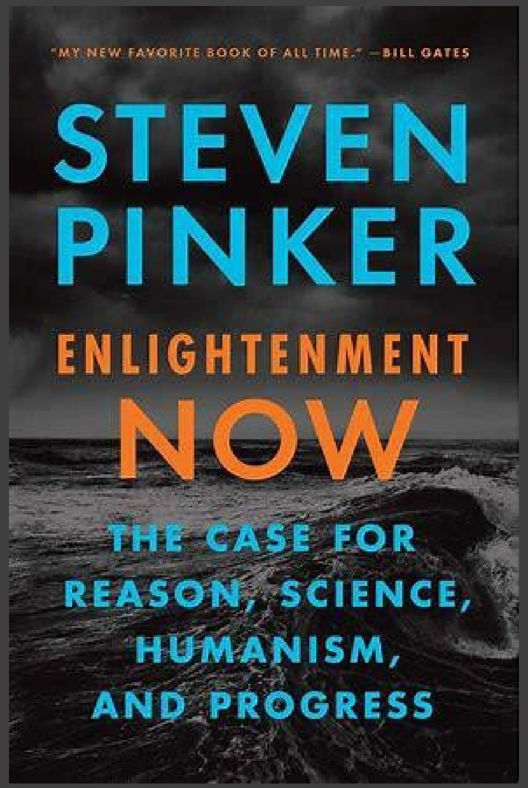
Integrated Energy Systems: A Key Opportunity for Nuclear Energy





Modification to circulate lead, for MSR qualification, and as a heat source for integrated energy systems piloting





The Humancentric Energy Approach

"Disagree Better"

-Governor Spencer Cox

"Energy channeled by knowledge is the elixir [of life]"…[Entropy is the enemy of life]"

-Author Steven Pinker

"One of the biggest challenges the world has ever faced is the transition to sustainable energy and to a sustainable economy. That will take some decades to complete." -Elon Musk

QUESTIONS?

Meet the Presenter

Dr. Markus Piro is currently an Associate Professor at McMaster University where he is conducting research in nuclear fuels and materials for conventional and advanced reactors. Previously, he was the Chair of the Energy and Nuclear Engineering Department and Canada Research Chair in Nuclear Fuels and Materials at Ontario Tech, and Head of the Fuel Modelling Section at the Canadian Nuclear Laboratories. He earned a PhD in Nuclear Engineering from the Royal Military College of Canada and did a Post Doc at the Oak Ridge National Laboratory. In addition to research in academia, he is the President of Piro Consulting, a consulting firm supporting the nuclear industry primarily in safety and licensing.

Email: pirom@mcmaster.ca

An Academic Perspective on MSR Education and Training

Markus H.A. Piro

Dept. Eng. Phys., McMaster University

Inter. Molten Salt Research in Support of MSR Development

Aug. 28, 2024

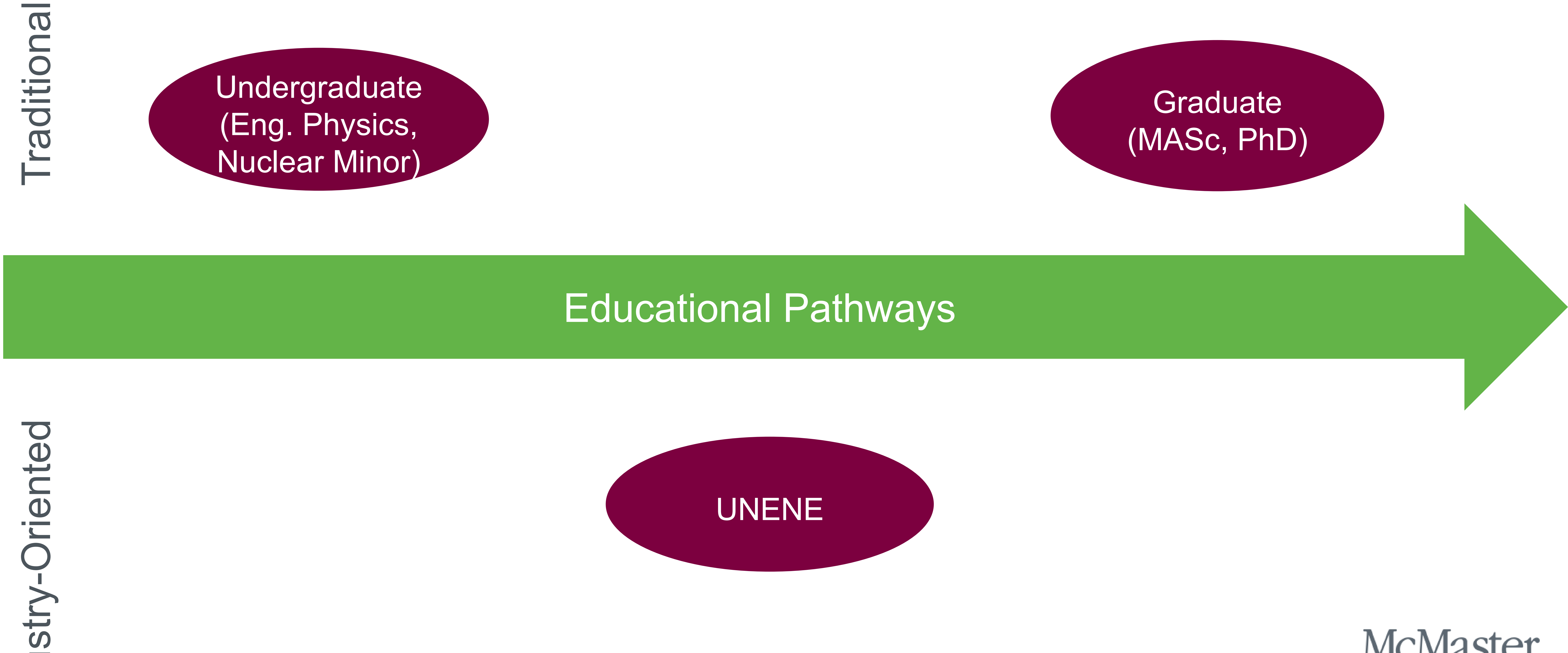
Acknowledgements

- First, I would like to thank Patricia for the kind invitation to participate in this panel discussion. Thank you, Patricia!
- Technical discussions with many colleagues is greatly appreciated.
- Thank you to the students and post docs (both current and former) for your excellent work.

Disclaimer

- Please note that the opinions expressed in this presentation are my own and do not reflect my current (or former) employer.

Nuclear Education and Training Pathways



Who's Hiring Our Students?

- Mostly utilities.
- To a lesser extent suppliers, national labs, and regulator.
- An even smaller fraction are hired by SMR vendors.
- Since our mission is to train students so they can enter the workforce, programs are designed for the needs of the nuclear sector.
- The nuclear talent supply chain in Canada is a major concern right now.
    - Large anticipated growth in industry; not enough talent to meet job growth.

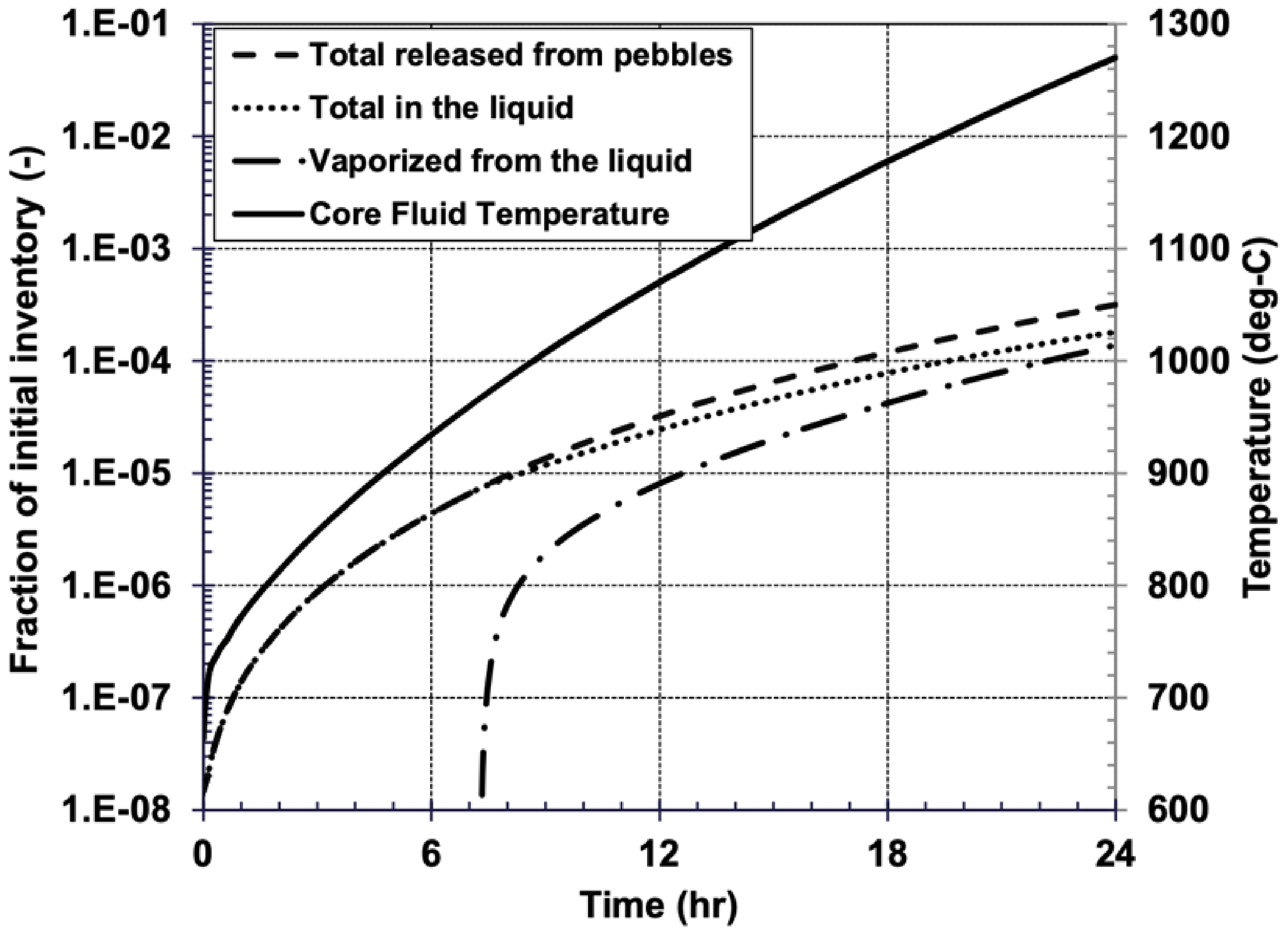
Incorporating MSR Content in Education

- Undergraduate programs:
  - Limited MSR content sprinkled in a few courses.

- Graduate programs:
  - Again, limited MSR content.

- Research is the primary pathway…

Graduate Student Research



Simulations identify knowledge gaps

Experiments inform models

F. Gelbard, B.A. Beeny, L.L. Humphries, K.C. Wagner, L.I. Albright, M. Poschmann, M.H. A. Piro, Nucl. Sci. Eng., 197(10) (2023).

Opportunities in Academia

PhD Student Visiting JRC for Salt Experiments

- Great way to get students engaged on MSR technologies.
- Perform R&D to support MSR programs – fill knowledge gaps, develop new capabilities, etc.
- Train the next generation of scientists and engineers.

JRC Karlsruhe, Germany

Challenges in Academia

- It is impractical to cover all nuclear technologies in any meaningful depth in our undergraduate program.
    - *How do we balance different nuclear technologies?*

- Instructors need to be sufficiently trained & competent in a particular technology.
    - *How do we train instructors?*

- Catch 22 effect:
    - *Industry needs vs student needs – not always aligned.*

Summary

- Our current approach is to provide a solid foundation in nuclear science and engineering (technology agnostic), primary application is CANDU, and to expose students to other technologies.
- The best pathway for MSR technology into education is via student research.
- International collaborations have been extremely valuable.
- The nuclear job market is highly competitive right now for companies to hire students. Companies need to be strategic in their hiring.

Questions?

pirom@mcmaster.ca

McMaster University

Upcoming Webinars

Date	Title	Presenter
25 September 2024	Overview and Update of Sodium Fast Reactor Activities within the Gen IV International Forum	Yoshitaka Chikazawa, JAEA, Japan
02 October 2024	Prospects and Challenges of the GFR Technology	Petr Vacha, UJV, Czech Republic
26 November 2024	Overview and Update of SCWR Activities within GIF	Armando Nava, CNL, Canada