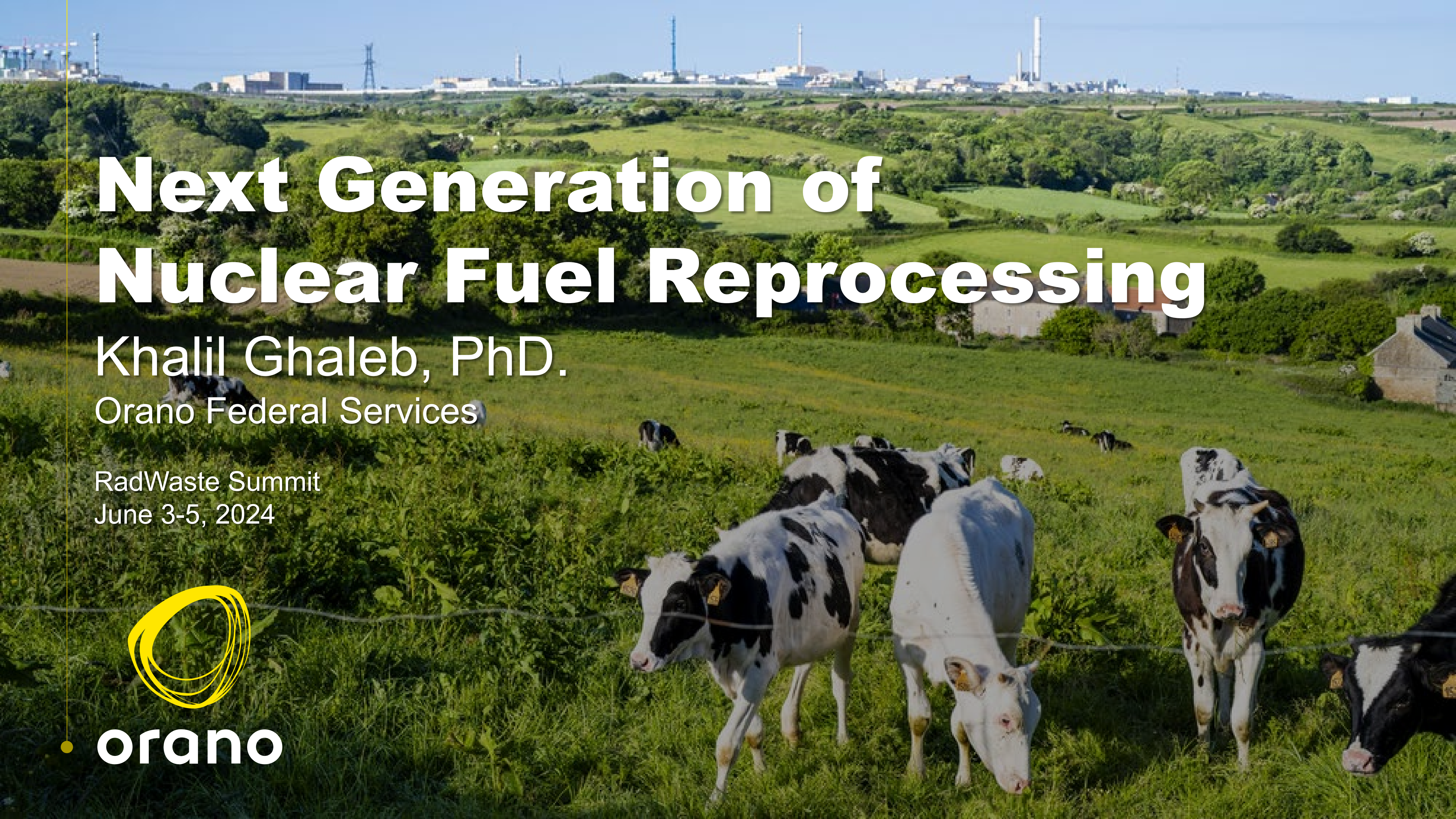

Next Generation of Nuclear Fuel Reprocessing

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Orano Federal Services

RadWaste Summit
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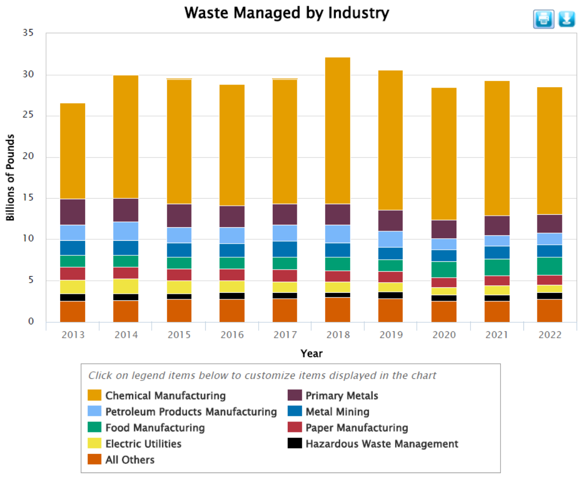
01 Introduction

- Chemical manufacturing generates 54% of the waste created in the U.S. or the equivalent of 7,000,000 MT a year
- Electric utilities that combust coal or fuel oil generate 3% or the equivalent of 500,000 MT a year
- Nuclear reactors in the U.S. generate around 2,100 MT of used fuel a year
- The current U.S. inventory hovers above 80,000 MT of used nuclear fuel



www.epa.gov

02 • Current Status: Post-irradiation Composition of Used Fuel Assembly

PWR fuel assembly before irradiation: ~ 500 kg of U (~ 480kg of U-238 & ~ 20 kg of U-235)

After irradiation*

* percentages depend on fuel burnup

~ U_f 470 kg (94 %)

~ U-235 5 kg (1 %)

~ Pu 5 kg (1 %)

~ FP & MA 20 kg (2 - 5 %)

… and 14 to 22 g became energy

02 From an Energy Point Perspective

On average, the fission of one (1) kilogram of U-235 produces 82,800 GJ or the equivalent of 23,000 MWh of thermal energy

- The fission of Pu-239 produces 5% more energy than the fission of U-235
- The 1% of the U.S. current stockpile of used fuel containing up to **800 MT** of Pu* represents more than **4000 terawatt-hours** of electric energy
- Equivalent to 450 years of electricity produced by a 1000 MWe LWR nuclear reactor operating 365 days per year

03 Existing Solutions for Recycling

Orano's recycling platform with 50 years of experience, offered internationally …

Transportation by Train, Truck & Ship

Used fuel shipments to La Hague plant

7,500 shipments in France

2,500 international shipments

La Hague Reprocessing Facilities (only western-operating commercial-scale facility)

Amount of reprocessed fuel (PWR, BWR, RTR, FBR, UNGG)

36,000+ tHM for France

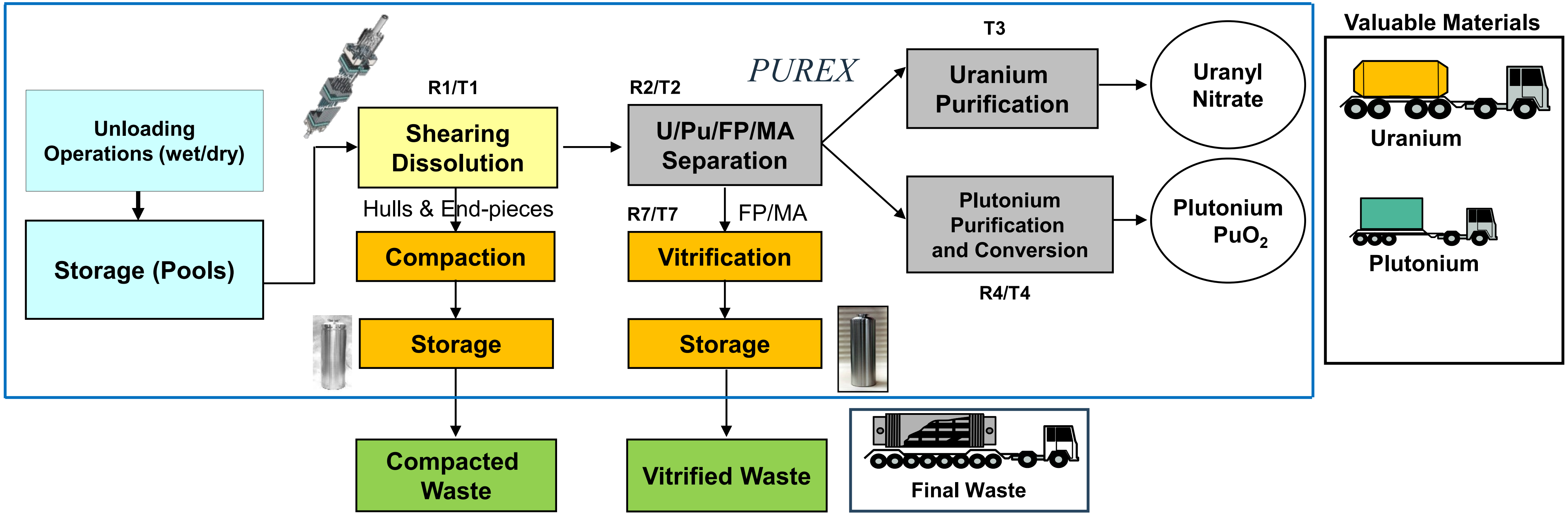
10,000+ tHM for 6 other countries

MELOX Fuel Fabrication Facility

Produced MOX Fuel:

3,000+ tHM of MOX fuel loaded in 43 reactors

03 Reprocessing, Conditioning, and Recovery



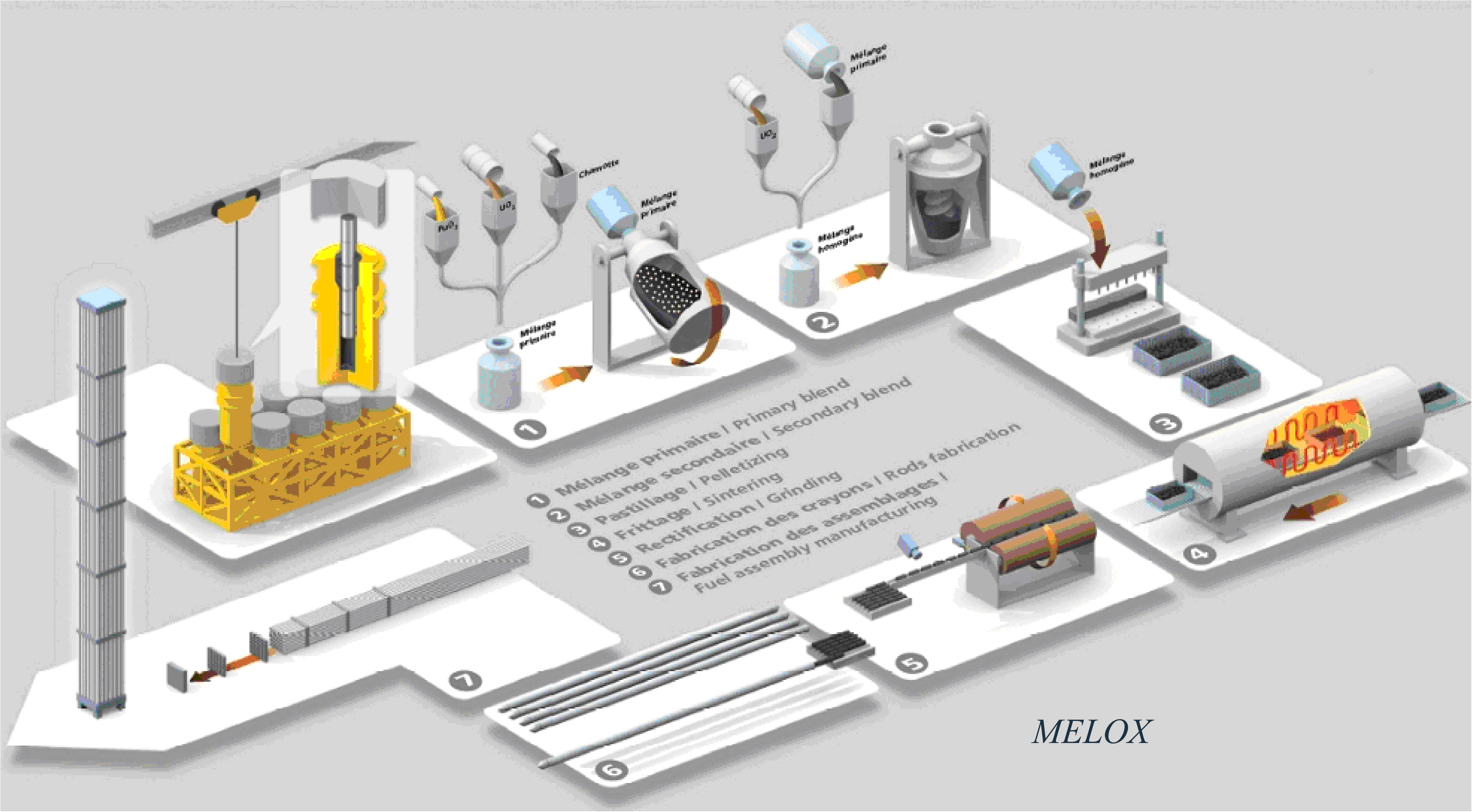
Fission products and minor actinides, by far the most radiotoxic, are vitrified

Structural waste from used fuel assemblies are compacted into steel containers identical to those used for glass. Impact of this compacted waste on possible release of radioelements at a geological disposal facility is negligible.

Most of the technological waste arising from operating the facility is cemented. Most of these concrete packages consist of short-lived, low and intermediate-level waste, which is disposed at the Aube Disposal Center (a surface waste disposal facility).

Recycling – MOX Fuel

RadWasteSummit



04 Standpoint for the Future – New Reprocessing Facilities

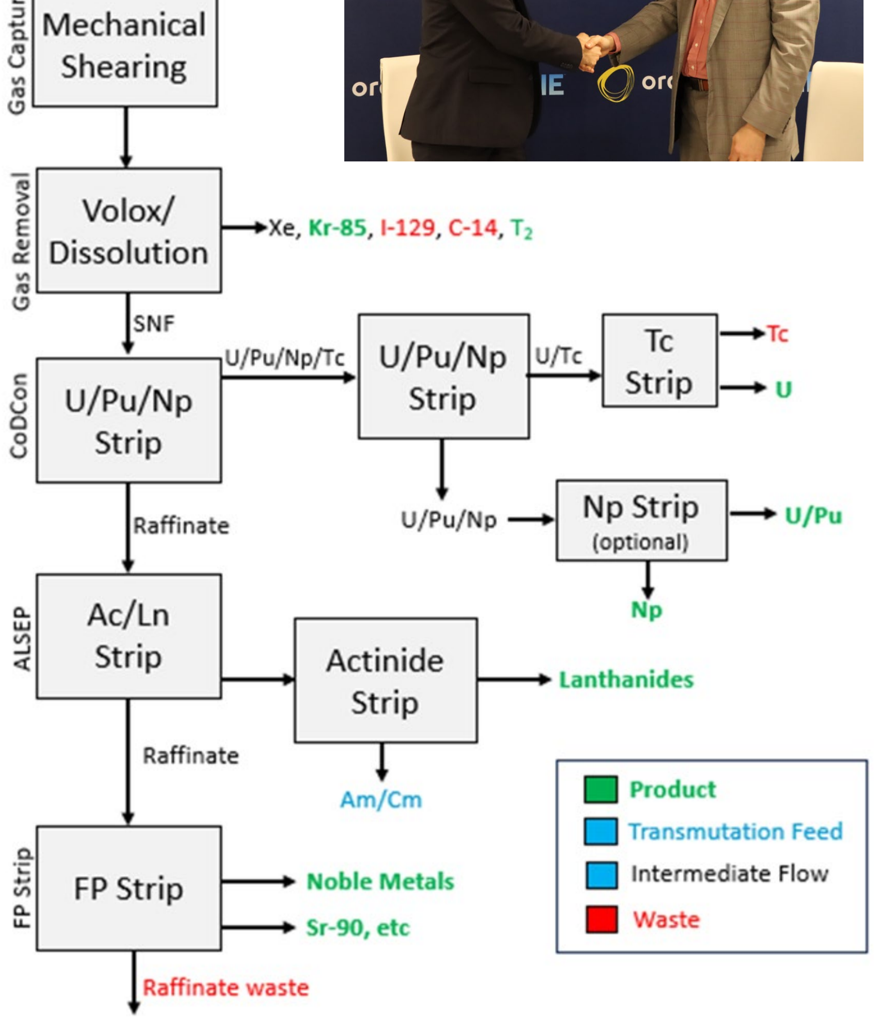
- **Use established technology and lessons-learned**
  - Dissolution rate increase
  - Reduced number of extraction/purification cycles
  - Smaller footprint
  - Solvent and acid recycling
  - Improved safety
- **Use improved monitoring technologies**
  - Online process monitoring & control, reduced laboratory analyzes
  - New non-destructive analysis techniques: CEA, CNRS, and U.S. National Labs
  - Automated MC&A, Criticality controls & safety (collaboration with GE Vernova & Sandia)
- **Benefit from advancement in material science**
  - Corrosion-resistant new materials
  - Concrete additives
  - Reduced maintenance (shearing device blade, centrifugal extractor)
- **Implement process optimization (next slide)**

04 Standpoint for the Future – New Reprocessing Facilities

- **Process optimization**
  - Voloxidation for pre-processing fuel assemblies (collaboration with SHINE)
    - Allows early recovery of tritium* to avoid managing them downstream
  - Co-extraction of U/Pu to create a blended stream:
    - COEX™: Orano/CEA
    - CoDCon: Shine/ANL
  - Advanced Partitioning of FP and MA
    - Separation of minor actinides (ALSEP, SANEX, GANEX, TRUEX) from the waste stream
    - Harvest platinum group metals (Rh, Pd,…) and rare earth elements for sale
    - Looking into Am-241, Kr-85, and Sr-90 as commercial targets
    - Recovery of Am-241 for space activities
  - Improved vitrification: Cold crucible, increase FP content of glass, improve volatile FP management
  - Optimization of off-gases treatment and liquid effluent treatment
  - Reduce HLW volume, raise the portion of LLW suitable for near-surface disposal

04 Orano Supporting SHINE's UNF Recycling Objective

- **SHINE developing a 100 MT/year UNF recycling pilot facility to:**
  - Provide domestic RepU, MOX, and HALEU alternative
  - Reduce UNF volume
  - Create a domestic supply of critical isotopes
- **Leveraging SHINE's unique capabilities**
  - Licensing, construction, and commissioning of 10 CFR Part 50 facility
  - Aqueous uranium handling and safety systems
  - Radionuclide separation and handling
- **Starting with established technologies**
  - Orano to provide experience and knowledge
- **Developing new technologies**



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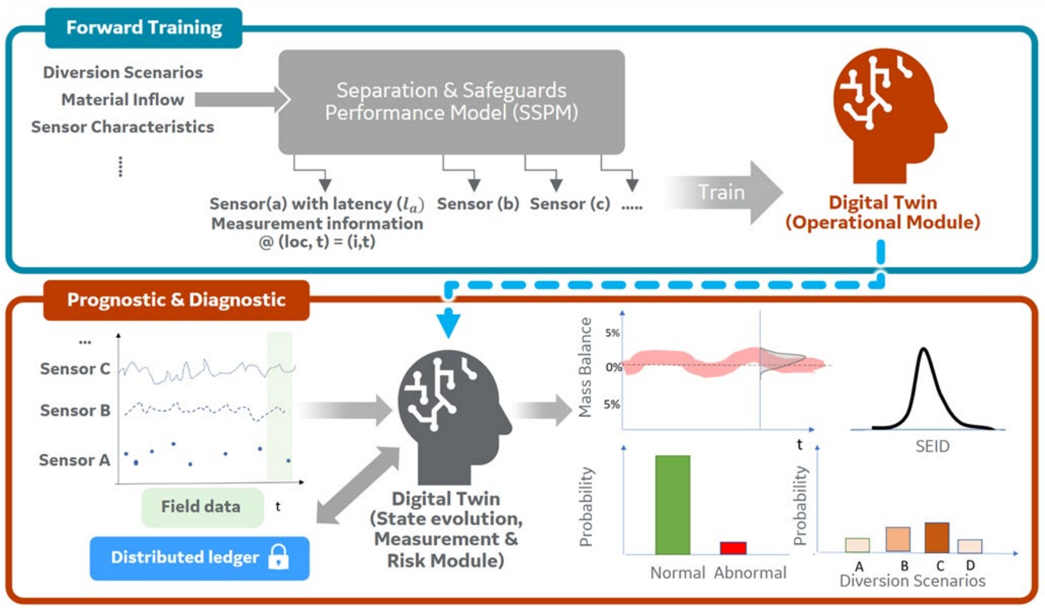
04 Standpoint for the Future – New Reprocessing Facilities

- **Safeguard Modeling** *(example of collaboration with Sandia/GE Vernova)*
  - Maximize the use of new and advanced safeguard approaches, efficient monitoring, and better utilization of technology and data analytics
  - Modeling & simulation can be used to rapidly design and evaluate facility-wide material accounting strategies
  - Identify largest contributions to balance uncertainty
  - Optimize measurement systems
  - Develop cost-effective MC&A strategies



SSPM-L

Separation & Safeguards Performance Model (SSPM)

MAPIT

Material Accountancy Performance Indicator Toolkit (MAPIT)

05 Prospects for the Future – New Reactors

- **Successful new reactors will be, by design, the ones that**
  - are efficient (construction/operation, longer fuel cycle, higher burnup)
  - minimize waste
  - or allow recycling of used nuclear fuel
  - or use reprocessed nuclear material
  - or benefit from a waste disposal plan

- **Many concepts**
  - High-temperature gas-cooled reactor (HTGR)
  - Liquid metal-cooled fast reactors, including sodium-cooled fast reactors, and fluoride salt-cooled reactors
- **Used fuel management**
  - On-site (conditioning, interim storage, shipment off-site)
  - Off-site (direct disposal, consolidated interim storage, recycling)

05 Prospects for the Future – New Fuels

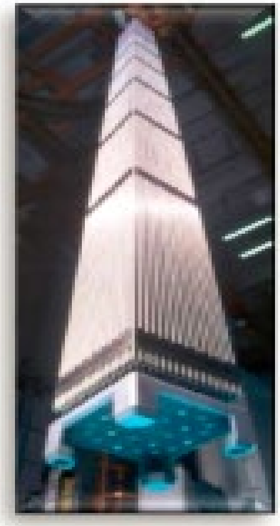
- Oxide/Ceramic fuels
- Metallic fuels
- TRISO fuels
- Liquid Salt fuels

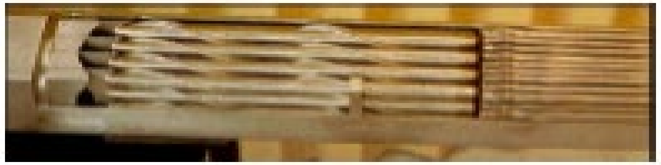
- LEU < 5% enriched U-235
- LEU+ 5% - 10% enriched U-235
- HALEU 10% - 20% enriched U-235
- HEU ≥ 20% enriched U-235
- Mixed U & Pu (oxide, metal, or salt)
- Thorium (oxide, metal, or salt)

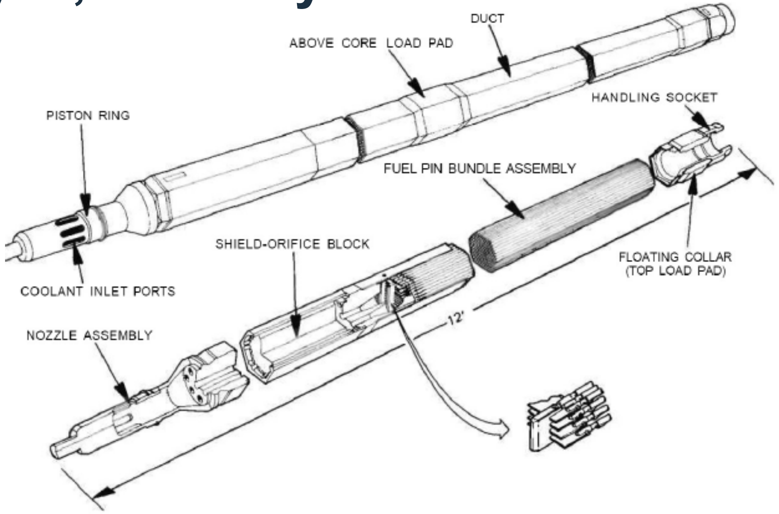
Higher enrichment → more fission products
Higher Burnup → less soluble, more FP, more MA*, altered IC
Cool down period → Less SL-FP, different distribution of FPs
Fuel type → different chemistry, different distribution of FP

05 Oxide/Ceramic Fuels with Cladding

- **Sintered UO_2 or MOX fuel pellets**
  - similar in design to existing LWR oxide fuel pellet
  - but different enrichment level (LEU+)
- **Manufacturing and operating experience**
- **Reprocessing experience at La Hague of UO2 and MOX fuel**
  - LWR UO_2 (46,000 MT) and LWR MOX (73 MT)
  - FBR MOX (Phenix 10 MT at UP2-400; 16 MT at APM)
- **Others: Sellafield, Tokai, Mayak, Trombay …**

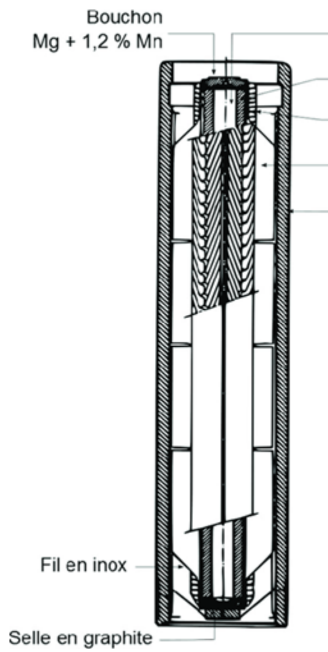


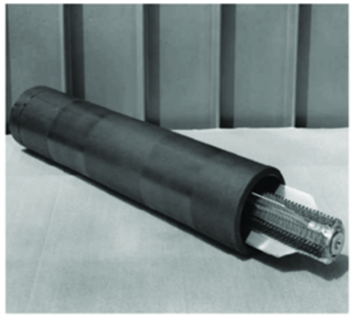




05 Metallic Fuels with Cladding

- **U or U-Zr or U-Pu-Zr alloy rods**
  - Higher thermal conductivity
  - Low heat capacity
  - Higher heavy metal density
  - Superior neutronic characteristics
  - Good stability after irradiation
- **Recycling experience:**
  - Laboratory scale pyro-processing, electrochemical (EBR-II)
  - Industrial scale hydrometallurgy process: UNGG (U-Mo; 28,000 MT), RTR (HE UAl,…; >30 MT)
  - Other industrial scale: Magnox (U-Mg)
- **More challenging for vitrifying FP waste**
- **TerraPower Natrium, ARC Clean Technology ARC-100**

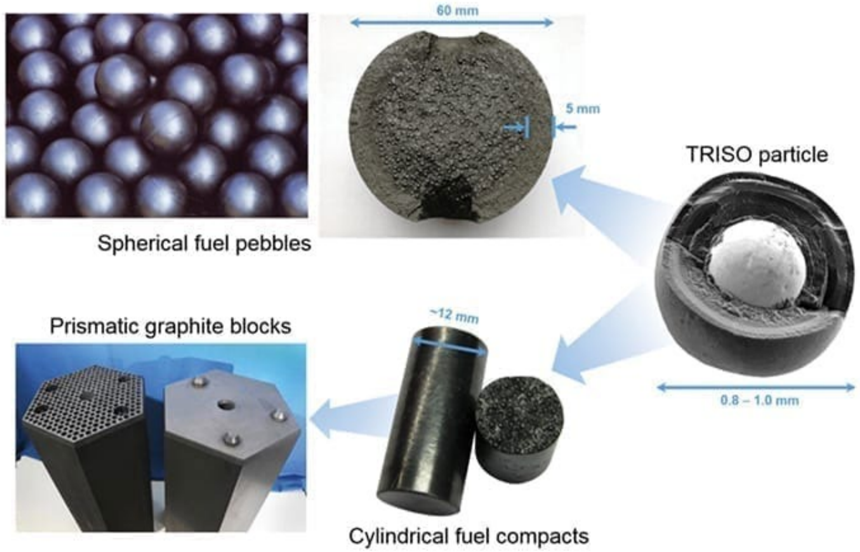




05 TRISO Fuels

- **Fuel kernel**
  - Encapsulated by layers of SiC and carbon-based materials using chemical vapor deposition
  - For use generally in High-Temperature gas reactors (graphite moderator)
  - Prismatic cores and pebble-bed cores
  - Containment of fission products for temperatures up to 1800°C
- **Online refueling**
- **Not designed for reprocessing, but studies exist**
- **X-energy, Kairos Power, Ultrasafe Nuclear, BWXT, Framatome, Westinghouse …**

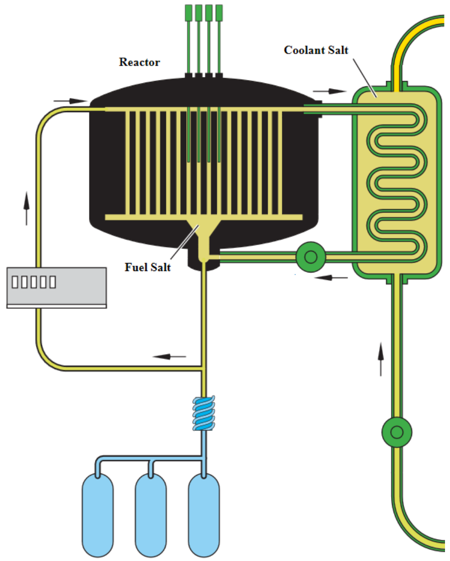
Ultrasafe Nuclear

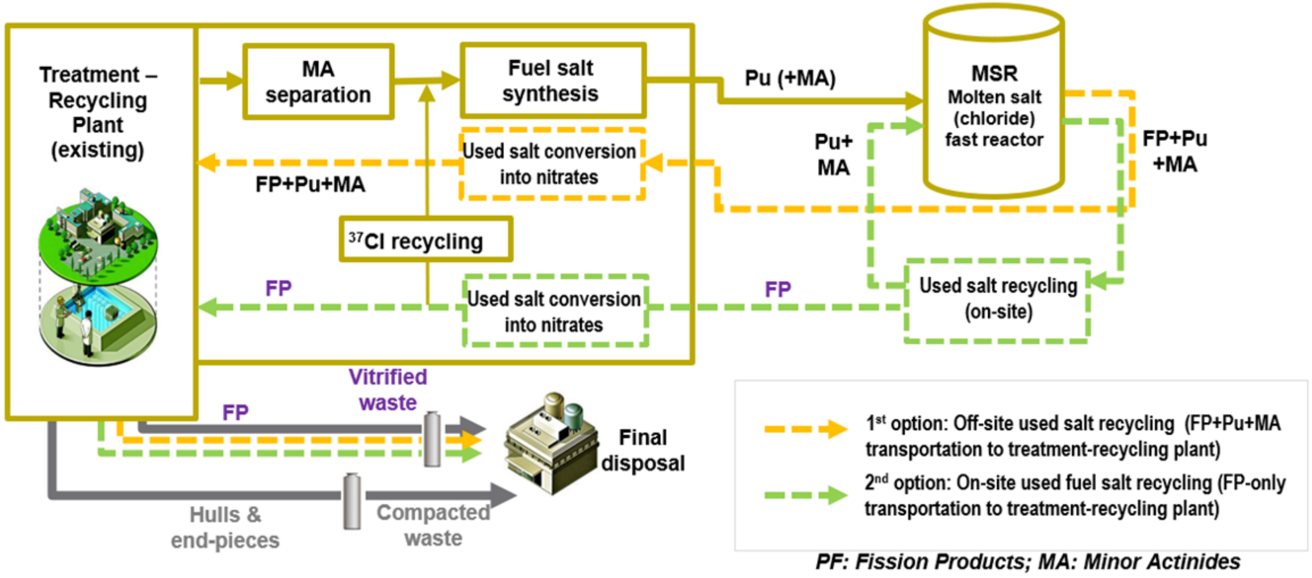


U.S. Department of Energy (DOE) graphic shows different TRi-structural ISOtropic (TRISO) particle fuel forms

05 Liquid Salt Fuels

- **Molten fluoride or chloride salt containing fissile material**
  - No fuel structures
  - Online refueling
  - Same time reprocessing (removal of fission products to avoid buildup) during operation
  - Transmutation & volume reduction
- **Suitable for aqueous processing**
  - Challenges are Chlorides and Fluorides, hence conversion to nitrate salt before reprocessing





06 Conclusion

- **Contrary to the existing reactors, where waste management had to adapt to the fuels produced, successful new generation reactors will be, by design, the ones that benefit from successful used fuel management**
- **When possible, a closed fuel cycle offers many advantages from a sustainability point of view:**
    - Better fuel utilization Recycling of valuable resources
    - Waste minimization (HLW volume and toxicity reduction)
    - Suitable, improved final disposal solutions
- **Many improvements are available, and no challenges cannot be overcome**
- **Multiple reprocessing solutions exist for the new advanced reactors, adapted to their fuel types and especially the ones using oxide and metallic fuels**
- **Through its experience with recycling, wet & dry storage, transportation, and disposal-related activities for LWR and advanced reactor, Orano is well positioned to provide the best solutions for the current and next generation of nuclear fuel cycle and waste management**

Giving nuclear energy its full value

Orano White Papers