Advanced nuclear reactors: what about the back-end?

Focus on Treatment and Reprocessing/Recycling aspects

Renaud Liberge, Arnaud Gay, Sven Bader

Technical Meeting on Back End of the Fuel Cycle Considerations for Small Modular Reactors

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Overview of presentation

1. Introduction
2. Advanced Reactor Fuel Types
3. Generic Fuel Cycle Approach
4. Treatment and Reprocessing/Recycling
5. Takeaways

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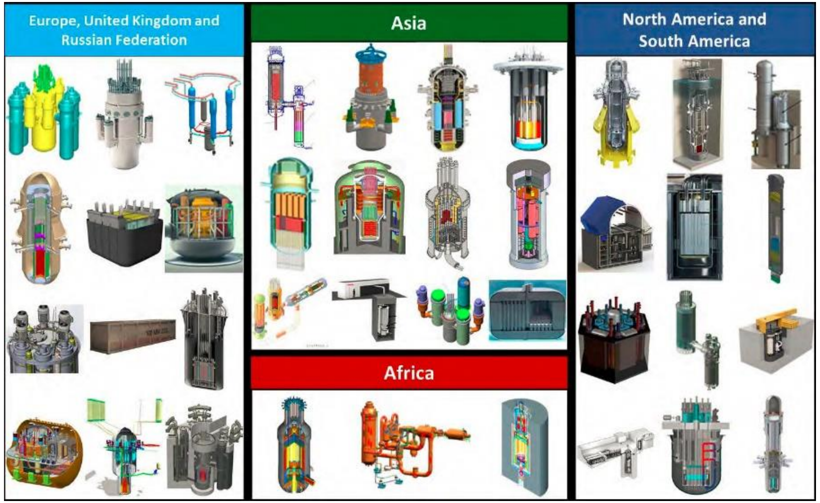
1. Introduction

SMR HTR LFR

iPWR SFR MSR

- **Nuclear is essential in the fight against climate change**
- **More than 70 concepts of Advanced Reactors (AR)**
- **Safe, flexible, reliable and competitive sources of power**



Source: Advances in SMR Technology Developments; A Supplement to IAEA Advanced Reactors Information System (ARIS) – 2020 edition

➔ ***But sustainability will be achieved only if solutions for Spent/Used nuclear fuels exist***

2. Advanced Reactor Fuel Types

Back-end management of Advanced Reactors can be approached through their fuel types

- Oxide/ceramic fuels with cladding
- TRISO fuels
- Metallic 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)

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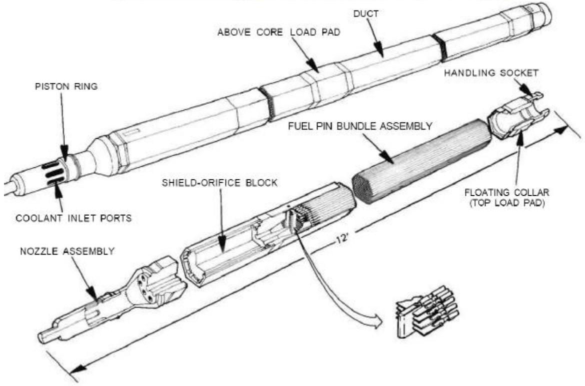
2. Advanced Reactor Fuel Types

Oxide/ceramic fuels with cladding

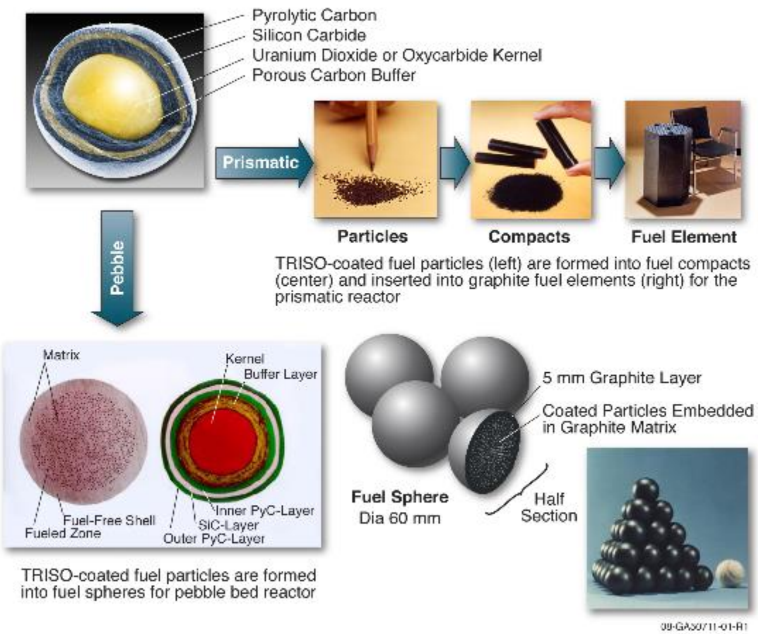
- **Sintered pellet UO_2 or MOX fuel similar in design to an existing-LWR oxide fuel pellet**
- **Fission gas plenum (often helium filled when manufactured)**
- **Extensive operating, manufacturing, and irradiation experience with UO_2 and MOX fuel**
- **Extensive recycling experience of UO_2 and some experience with MOX**
- **On-site/off-site treatment not necessary**
- **Conditioning of SNF necessary in case of Direct Disposal**



2. Advanced Reactor Fuel Types

TRISO fuels

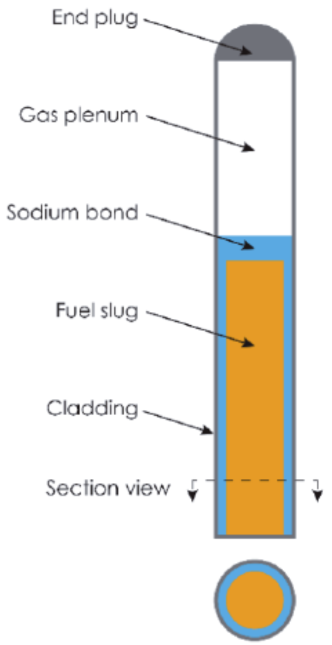
- **Fuel kernel encapsulated by four layers of SiC and carbon-based materials**
- **Arranged in prismatic blocks of graphite or in billiard ball-sized pebbles of graphite**
- **For use in either high-temperature gas or molten salt-cooled reactors, with high burn-up potential**
- **Containment of fission products remain in TRISO particles for temperatures up to 1600°C**
- **No successful recycling efforts demonstrated <u>yet</u> and will have high waste-to-fuel ratio**
- **Residual salt removal may be necessary for MSR fuels**
- **Treatment of fuel to remove/reduce graphite content potentially needed for storage and for disposal**



2. Advanced Reactor Fuel Types

Metallic fuels

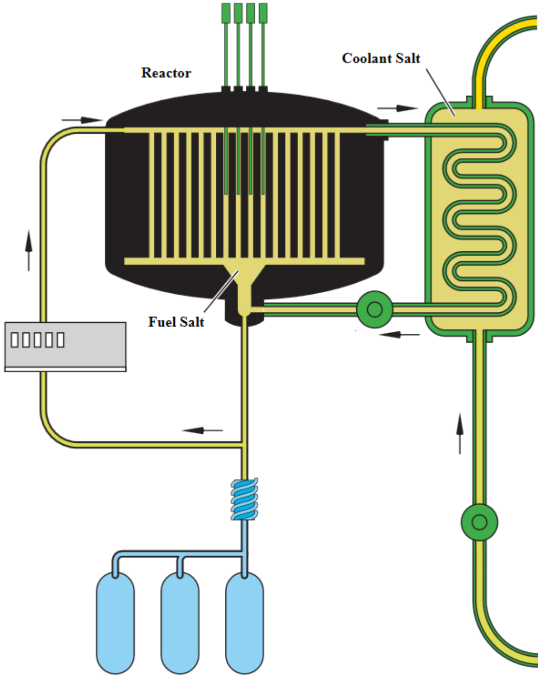
- U-Zr or U-Pu-Zr alloy rods (good irradiation stability)
- Sodium-filled gap between the fuel and cladding (keep fuel temperatures low)
- Large fission gas plenum (argon filled when manufactured, accommodate high gas release)
- Injection cast as cylindrical slugs placed inside the cladding or advanced alloy cladding tubes
- Some recycling experience (pyro-processing / electrochemical and aqueous polishing process)
- Removal of any sodium present on the fuel may be needed for storage
- Sodium bonded fuel will require treatment prior to disposal



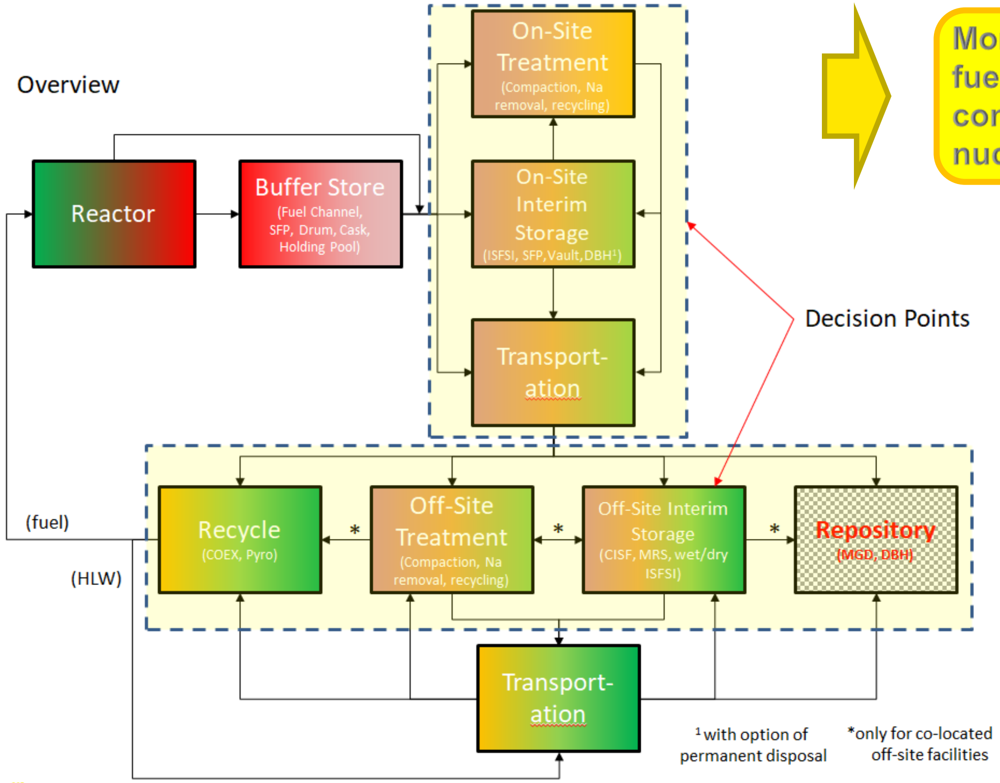
2. Advanced Reactor Fuel Types

Liquid salt fuels

- **Molten fluoride or chloride salt containing fissile material**
- **No fuel structures like cladding, fuel ducts, grid spacers, etc.**
- **Liquid fuel allows for online fueling during operation and real time conditioning/recycling/ waste processing (removal of fission products). It opens the door to:**
  - **Transmutation of actinides and minor actinides in reactor**
  - **Significant overall UNF volume reduction**
- **Conditioning of fuel (polishing and stabilization) is necessary to avoid fission product buildup in reactor**
- **Conversion to an acceptable waste form for disposal likely required**



3. Generic Fuel Cycle Approach



More than 600 possible scenarios for backend fuel cycle management depending on specific context and specific choices for a given nuclear system.

Common "bricks"

- Interim storage(s),
- Transportation,
- **Treatment (on-site, off-site),**
- **Reprocessing/recycling,**
- Repository

4. Treatment and Reprocessing/Recycling

Fuel Type	First Option	Second Option
Oxide/Ceramic	Aqueous Reprocessing & Recycling - Demonstrated mature process	Electrochemical/Pyro-Processing Recycle - Demonstrated at lab-scale - Maturation of final waste forms needed
Metallic	Electrochemical/Pyro-Processing Recycle - Demonstrated process in need of industrialization - Maturation of final waste forms needed	Aqueous Reprocessing & Recycling - Demonstrated process (with UNGG)
TRISO	Conditioning - Remove/reduce graphite in preparation for direct disposal	Aqueous Polishing Recycle - Challenge to remove SiC & PyC layers - Lab-scale demo to be performed first
Liquid	Aqueous Reprocessing & Recycling - Performed on-line for fuel salt	Electrochemical/Pyro-Processing Recycle - Potentially performed for bled off wastes

4. Treatment and Reprocessing/Recycling

Hydrometallurgy: a broad range of fuels already reprocessed at La Hague Plants

Fuel type	Quantities treated at La Hague	Time period
UNGG (Natural Uranium Graphite Gas Reactor)	4,900 tHM	1966 - 1990
PWR (UO_2)	33,650 tHM	1977 - now
BWR (UO_2)	3,800 tHM	1976 - 2010
LWR (MOX)	73 tHM	1992 - 2008
LWR (RepU)	24 tHM	2006 - 2020
FNR	10 tHM	1979 - 1984
RTR (UAl, U_3Si_2)	3,100 fuel assemblies	2005 - now





4. Treatment and Reprocessing/Recycling

TRISO fuels: lots of studies/tests to separate graphite

Main requirements:

- **No TRISO particles with the graphite**
- **Integrity of TRISO particles maintained**
- **Deal with ^{14}C release**

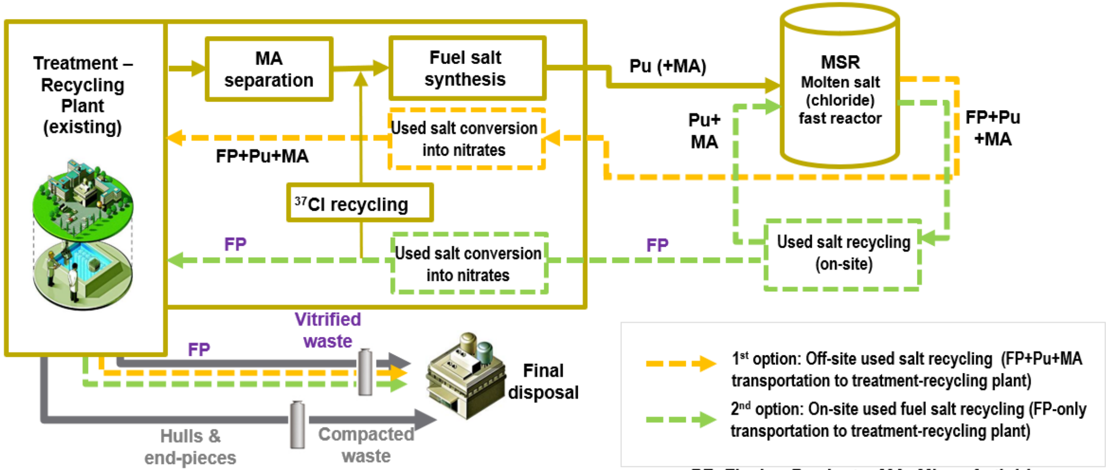
Method	Description
Graphite burning	Graphite (and outer layer of PyC) can be burned at high temperature under oxidizing atmosphere
Other thermal treatment	Thermal shock by submitting the fuel element to sudden temperature variation
Mechanical grinding / crushing	Use of mechanical grinder / crusher or HP waterjet
Ultrasonic methods	Use of sonic waves under water to create erosion of the graphite by cavitation
Pulsed currents	Use high-voltage micro pulses to shatter the graphite
Exfoliation	Creating a graphite intercalated compounds (GIC) that will lead to complete exfoliation of the graphite

4. Treatment and Reprocessing/Recycling

Liquid fuel in Molten Salt Reactors

➔ Possible synergy with MSR actinide converter and treatment-recycling plant

- **Salt-type fuels are suitable for hydro-processing (for chloride-type fuels)**
- **Pyro-processing is also an option (necessary for fluoride-type fuels)**
- **Possibility to efficiently burn actinides**
- **Opens the door to reduce drastically the long-term radiotoxicity and lifespan of HL waste (that will only contain fission products)**



PF: Fission Products; MA: Minor Actinides

5. Takeaways

- **Advanced Nuclear Reactors will offer promising solutions for low-carbon, safe, reliable and affordable power generation**
- **Designing the backend of the fuel cycle from the beginning as a system is essential**
- **When possible, closed fuel cycle offers many advantages from a sustainability point of view (waste minimization, preservation of resources, reuse of valuable materials, optimization of final disposal)**
- **Orano is willing to support the sustainable deployment of the next generation of Advanced Reactors fuel cycle systems and the implementation of efficient solutions for backend management**

Thank you for your attention!

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Giving nuclear energy its full value