Applying the IAEA's Geological Disposal Roadmap to SMRs: Addressing Emerging Back-End Challenges

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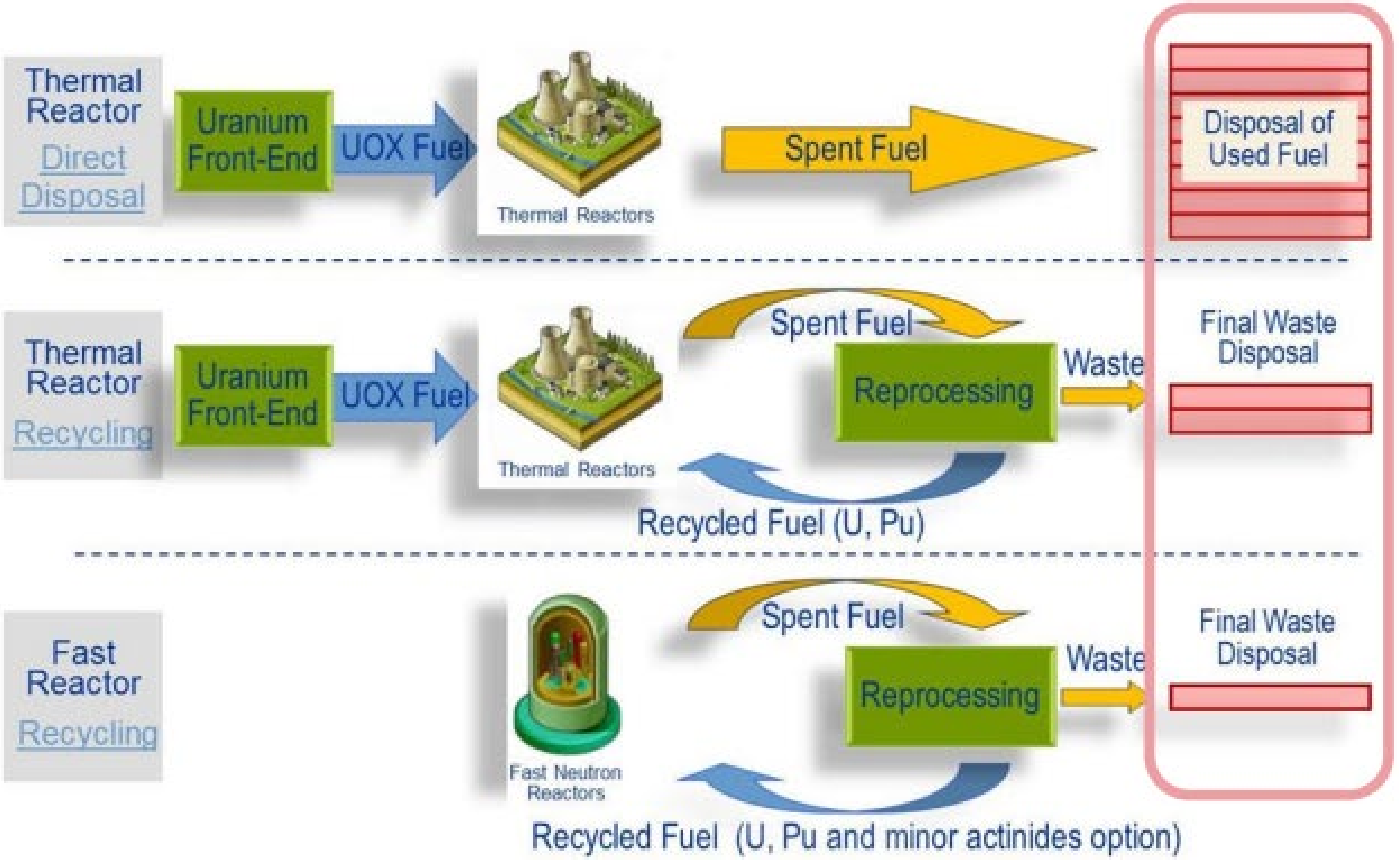
Overview

- For Nuclear power to be sustainable, the nuclear fuel cycle must remain **economically viable and competitive** through the optimization of the use of fissile materials in reactor cores or the **recycling of valuable materials**
- This results in different fuel **cycle options**, some already implemented and others may be deployed in the future
- Potential future synergies between LWR-SMRs and AMRs will bring new spectrum of Nuclear Fuel Cycle Options

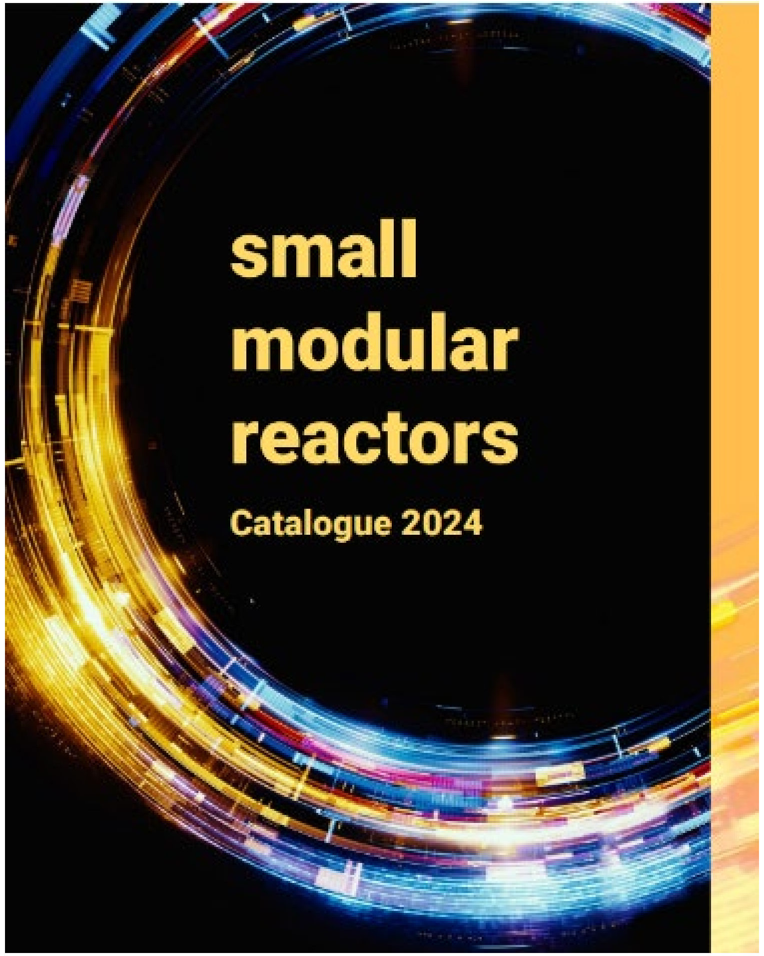


Each Type of Reactor has an Associated Nuclear Fuel Cycle

IAEA SMR Catalogue

CAREM	30	PWR	CNEA	Argentina	Under construction
HAPPY200	200 MWth	PWR	SPIC	China	Detailed Design
i-SMR	170	PWR	KHNP & KAERI	Republic of Korea	Conceptual Design
NuScale Power Module	77	PWR	NuScale Power Inc.	United States of America	Detailed design
NUWARD	170	PWR	EDF, CEA, TA, Naval Group	France	Basic Design
PWR-20	20	PWR	Last Energy	United States of America	Detailed design
RITM-200N	55	PWR	JSC "Afrikantov OKBM"	Russian Federation	Detailed design
SMART	107	PWR	KAERI and K.A.CARE	Republic of Korea, and Saudi Arabia	Detailed design
STAR	10	PTWR	Star Energy	Switzerland	Basic design
Rolls-Royce SMR	470	PWR	Rolls-Royce	United Kingdom	Detailed design
SMR-300	320	PWR	Holtec International	United States of America	Conceptual Design
PART 2: WATER COOLED SMALL MODULAR REACTORS (MARINE BASED)					
ABV-6E	9	Floating PWR	JSC Afrikantov OKBM	Russian Federation	Detailed design
ACP100S	125	Floating PWR	CNNC	China	Basic design
BANDI	60	Floating PWR	KEPCO E&C	Republic of Korea	Conceptual design
KLT-40S	2 × 35	Floating PWR	JSC Afrikantov OKBM	Russian Federation	In Operation
RITM-200M	50	Floating PWR	JSC Afrikantov OKBM	Russian Federation	Detailed design
VBER-300	325	Floating NPP	JSC Afrikantov OKBM	Russian Federation	Detailed design
PART 3: HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
EM2	265	HTGR	General Atomics	United States of America	Conceptual design
FMR	50	HTGR	General Atomics	United States of America	Conceptual design
GTHTR300	300	HTGR	JAEA	Japan	Basic design
GT-MHR	288	HTGR	JSC Afrikantov OKBM	Russian Federation	Basic design
HTGR-POLA	11.5	HTGR	NCBJ	Poland	Basic design
HTMR-100	35	HTGR	STL Nuclear	South Africa	Basic design
HTR-10	2.5	HTGR	INET, Tsinghua University	China	Operational
HTR50S	17.2	HTGR	JAEA	Japan	Conceptual design
HTR-PM	210	HTGR	INET, Tsinghua University	China	In operation
HTTR	30 (t)	HTGR	JAEA	Japan	In operation
MHR-100	87	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual design
MHR-T	205.5	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual design
PeLUIt-40	10	HTGR	BRIN	Indonesia	Conceptual design
Xe-100	82.5	HTGR	X-Energy LLC	United States of America	Basic Design
PART 4: FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
4S	10	LMFR	Toshiba Corporation	Japan	Detailed design
ARC-100	100	Sodium-cooled	ARC Nuclear Canada, Inc.	Canada	Conceptual design
Blue Capsule**	50	Sodium-cooled	Blue capsule technology	France	Conceptual design
BREST-OD-300	300	Lead-cooled	NIKIET	Russian Federation	Under construction
HEXANA	150	Sodium-cooled	Hexana	France	Conceptual design

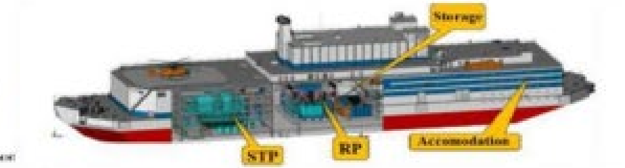
Type of SMR Designs	Number
Land-based water-cooled SMRs	15
Marine-based water-cooled SMRs	6
High Temperature Gas Cooled SMRs (HTGRs)	14
Fast Neutron Spectrum SMRs	10
Molten Salt SMRs (MSRs)	12
Micro-sized SMRs	14



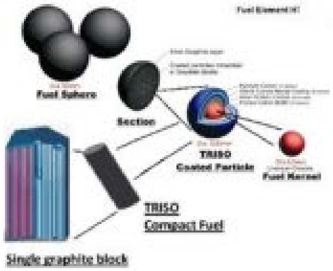
Challenges for spent fuels from different SMR types

Short — Medium — Long Term

- LWR-type SMRs: Enrichment levels of below 5% are similar to conventional PWRs
- LWR-type SMRs: Enrichment levels up to 20% (HALEU)



- HTGR-type SMRs: Pebble Beds/Prismatic



- Advanced Reactors (Fast Neutron SMRs): New fuel types introducing a new spent fuel characteristics/multirecycling processes

- Molten Salt SMRs: Nuclear fuel dissolved in melted chloride/fluoride fuel salts. Recycling of fissile material and managing salt mixtures containing all fission products is a challenge

IAEA FRAMEWORK

- IAEA has produced a set of publications on SMR fuels and back-end management in recent years
- Includes early work on disposal
- Tailoring to diverse SMR designs takes time

Several CRPs underway taking 3-4 years

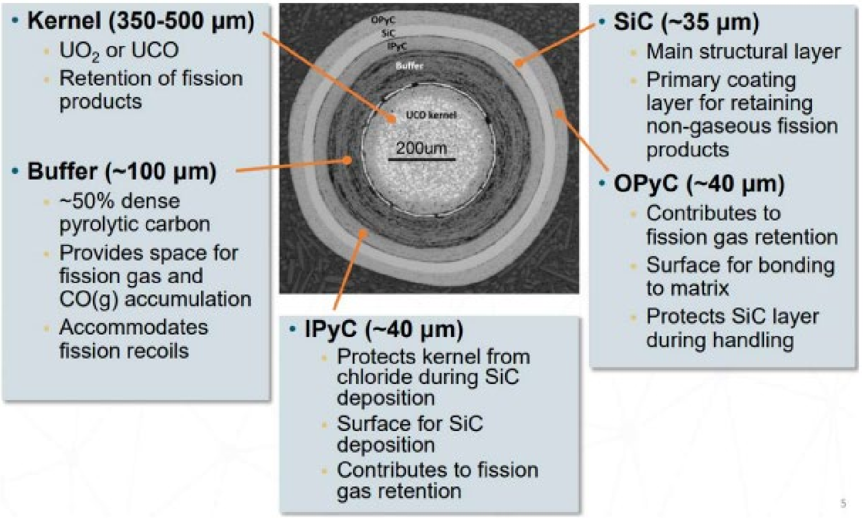
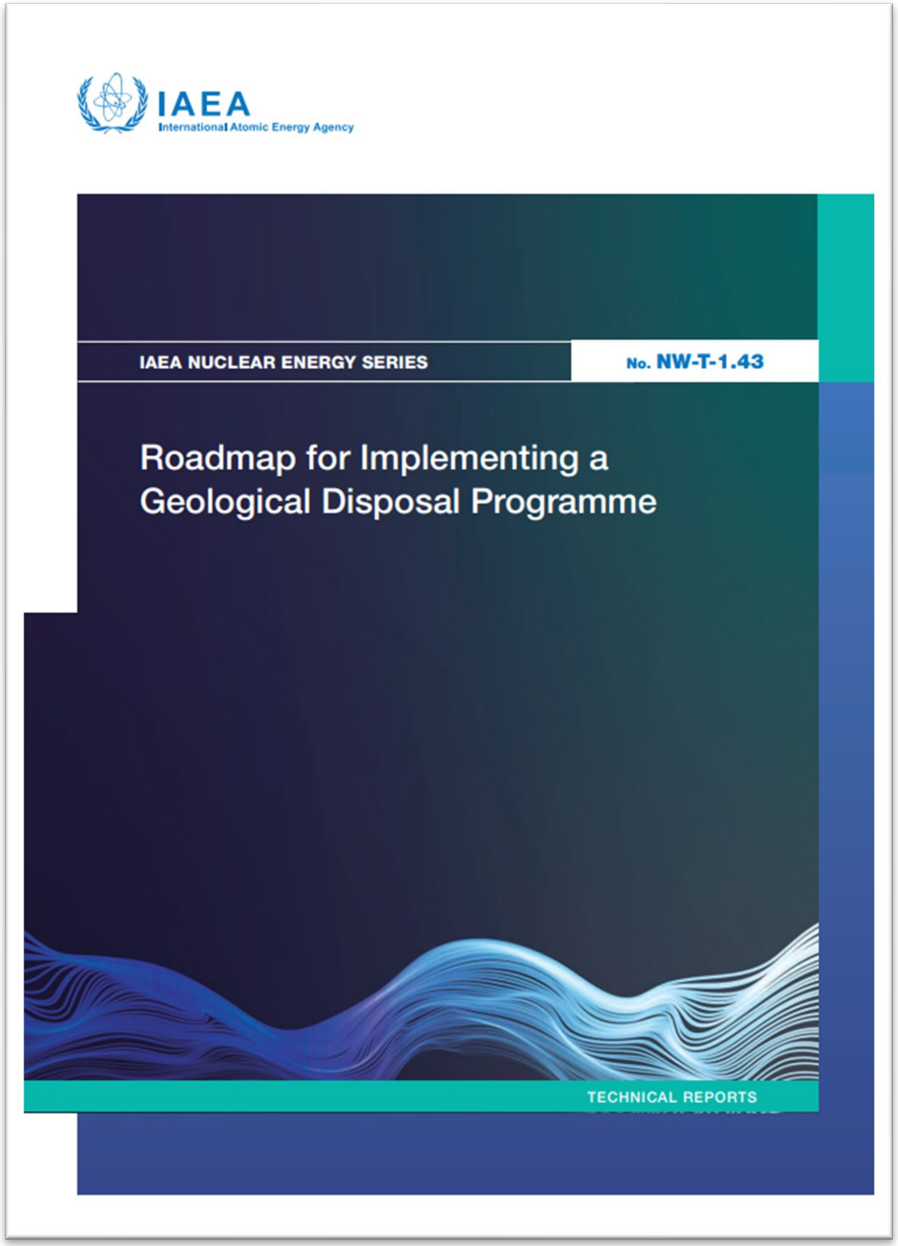


Figure: Cross-sectional view of a TRISO particle fuel with typical dimensions (reproduced from Ref. [6], courtesy of INL). From TECHDOC 2090 (2025)

End point of the fuel cycle

- **Repository design adaptations (thermal load, waste package design)**
- **New waste forms requiring long-term performance assessment**
- **Adapting conditioning and immobilization strategies**
- **Transport & storage interfaces with disposal**

Applying the IAEA DGR Roadmap to new technologies



Historical research and assessments informing current programmes

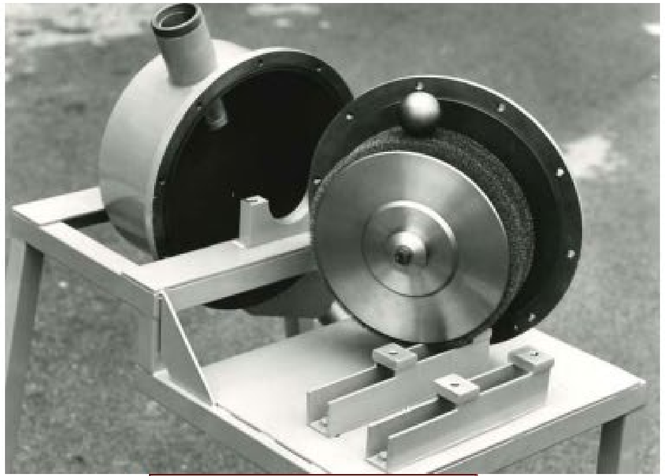
- **Existing research on HALEU, TRISO, and molten salt fuels provides baseline understanding**
- **Some waste forms assessed historically from past advanced reactor programmes**

Table 1.5.1-23. DOE SNF Fuel Group Disposal Analysis Plan (Continued)

Fuel Groups	Fuel Names[a]	Preclosure Releases	Preclosure Criticality[b]	TSPA[c]	Postclosure Criticality
19. Th/U Carbide, TRISO or BISO coated particles in graphite	FSVR [85]	Fuel Groups 1 through 30 are not analyzed for preclosure releases because there are no normal operations or event sequences that result in a release from DOE SNF canisters. An event sequence involving a drop and breach of a DOE standardized canister with DOE SNF is a beyond Category 2 event sequence, so consequence analyses are not required.	Fuel Groups 19, 20, and 21 are analyzed for preclosure criticality safety as part of Criticality Group 6, Section 1.14.	Fuel Groups 1 through 30 are analyzed for postclosure releases based on use of a single surrogate fuel with instantaneous release and a conservative radionuclide inventory distribution. Sections 2.3.7.4.1.1; 2.3.7.4.2.2; and 2.3.7.8.1.	Fuel Groups 19, 20, and 21 are evaluated for criticality potential as part of Criticality Group 6. Section 2.2.1.4.1.3.
	FSVR [86]				
	HTGR (PEACH BOTTOM SCRAP) [935]				
	PEACH BOTTOM UNIT I CORE II (INTACT) [206]				
	PEACH BOTTOM UNIT I CORE II [171]				
20. Th/U Carbide, Mono-pyrolytic carbon coated particles in graphite	GA HTGR FUEL [89]				
	PEACH BOTTOM UNIT I CORE I (PTE-1) [1085]				
	PEACH BOTTOM UNIT I CORE I [169]				
	PEACH BOTTOM UNIT I CORE I [170]				
21. Pu/U Carbide, Non Graphite Clad, Not Sodium Bonded	EBR-II, FFTF and MTR EXPERIMENTS [42]				
	FAST REACTOR FUEL [1029]				
	FFTF CARBIDE FUEL EXPER. [347]				
	FFTF-TFA PINS (AC-3) [1046]				
	FFTF-TFA-ACN-1 RODS [865]				
	FFTF-TFA-FC-1 [325]				

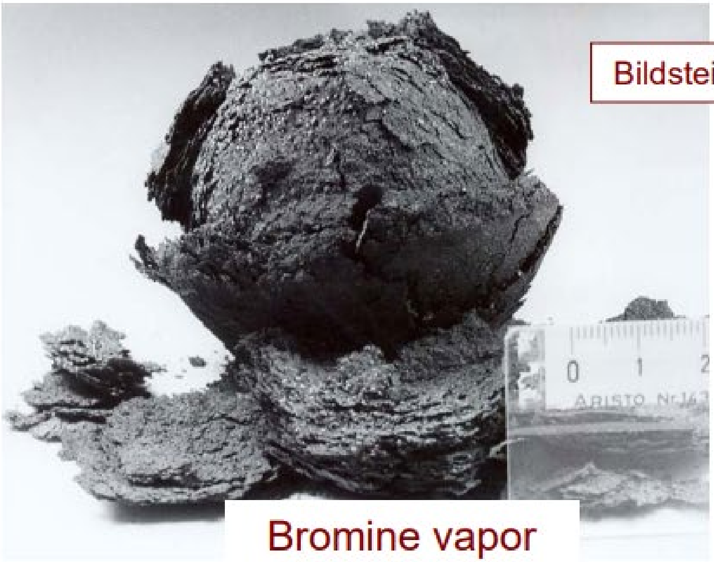
Yucca Mountain repository SAR (2008)

Another example ..



Brushing device

Kronschnabel 1981



Bildstein 1966

Bromine vapor

- Destruction of graphite structure after 1 h exposure
- No attack on coated particles (no intercalation in PyC)

Next steps

- The IAEA Division of Nuclear Fuel Cycle and Waste Technology has launched a Coordinated Research Project (CRP SMR-COGS, T13021)
- Developing a series of roadmaps on different fuel cycle options to support the decision-making process on SMR implementation
- First publication expected in early 2026 (HTR)

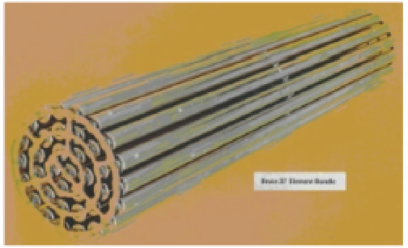


Figure 1: 37-Element CANDU fuel bundle (typical)

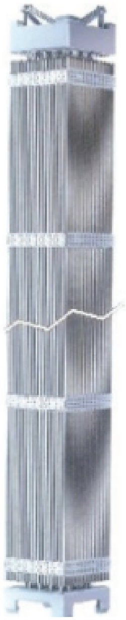


Figure 2: EPR fuel assembly

The CANDU EC-6 fuel bundle is identical to that shown in figure 1 having 37-elements or pins per bundle. This means that the reference CANDU DGR is equally well applicable to the storage of EC-6 fuel. The CANDU fuel bundle is a cylindrical array about 0.010 m in diameter with fuel pins 0.5 m long and weighs about 20 kg. The EPR fuel assembly is square prismatic in shape (17x17 pins in the lattice in a 0.214 m square array) and 4.8 m in length weighing about 180 kg. This difference in shape, size and payload has a marked impact in the design and operations of the repository.

Example of an early assessment of different waste types NWMO (2012)

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Thank you!

Extra slides

DISPOSAL OF HTGR SPENT FUEL

- For HTGR spent fuel, heavy metal mass per volume is ~10 - 20x less than that for typical light-water reactor spent fuel => treat spent fuel to reduce its volume?
- Accordingly, the low heavy metal mass per volume for HTGR spent fuel results in low heat per volume
- Deep geologic repositories designed to date are for typical light-water reactor spent fuel that generates a lot of heat per volume
    - Waste packages are spaced far apart
    - Small percentage of excavated rock is used for emplacement of waste packages (~1% to 5%)
- Analyses currently in progress indicate that disposing of HTGR spent fuel in a repository designed for a low-heat-generating spent fuel would be more cost-effective than disposing of it in a repository designed for a high-heat-generating spent fuel
    - Waste packages could be stacked next to and on top of each other
    - A larger percentage of excavated rock is used for emplacement of waste packages (~25%)
    - Could remove the perceived need to treat the TRISO fuel to reduce its volume