IAEA Technical Meeting on the Management of Spent Fuel from High Temperature Reactors
July 11th, 2025

Case Study for the Management of Spent Pebble Fuel

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Introduction

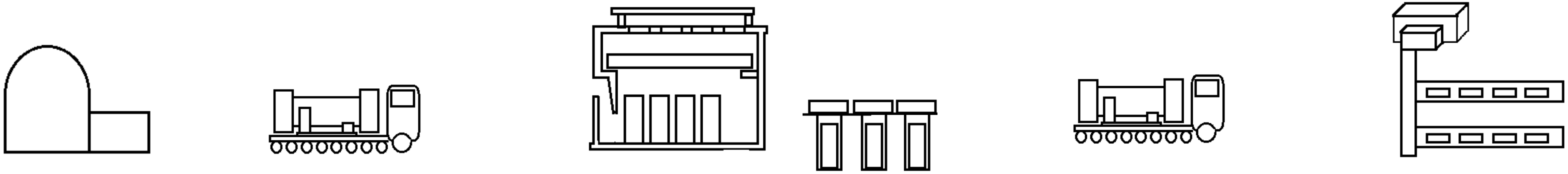
- SMR technology is becoming increasingly important for the future energy supply.
- The technology with high temperature, helium-cooled, graphite moderated, pebble bed reactor (HTGR) is characterized by
  - inherent safety features (no melting of the reactor core) and
  - established experimentally verified
  - and commercial applicable
- An overview of the currently available types of high temperature gas cooled small modular reactor can be found in the
  - IAEA database - Advanced Reactor Information System|Aris - https://iaea.aris.org
  - IAEA publication - SMALL MODULAR REACTOR TECHNOLOGY CATALOGUE, Edition 2024

HTGR – Fuel Management

- As part of the decision-making process the supply and disposal of fuels (HTGR fuel) must be included in addition to the operation of the plant.
- The following phases of the disposal pathways for HTGR fuel are considered:
  - Reactor operation, fuel discharge and fuel storage at the reactor
  - Internal fuel transfer
  - Onsite intermediate storage
  - Fuel handling/treatment after storage
  - Public transport
  - Storage prior final disposal or reprocessing

Schematic Backend Fuel Cycle

Reactor site storage system | Public transport or internal transfer | Storage facility | Public transport | Final disposal repository



Handling and Treatment 1

Handling and Treatment 2

Monitoring Maintenance Repair

Handling and Treatment 3

Handling and Treatment 4

- 2 Options for a disposal unit design
  - ☐ Unshielded, welded canister ☐ Canister loaded into DPC
- 2 Options for location of the storage facility
  - ☐ onsite reactor location ☐ away from reactor, public transport needed
- 3 Options for public transport
  - ☐ on road ☐ on rail ☐ intermodal rail and road
- Options for storage facility concepts depending on selected disposal unit design
  - ☐ inside storage building ☐ outside on storage pad above ground ☐ outside storage pit below ground
  - ☐ vertical ☐ horizontal
- 3 Options for final disposal dependig on geological site selection criteria
  - ☐ crystalline ☐ clay ☐ salt

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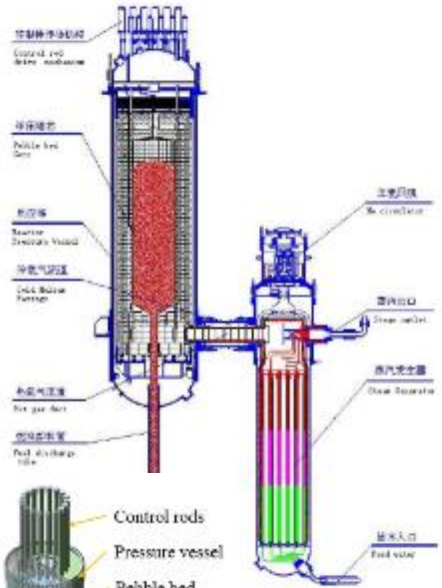
Selected Reactor Types for the Example

- For the comparison following reactor types have been selected
  - **HTR-PM** is a modular High Temperature Gas Cooled Reactor (HTGR) demonstration power plant The current HTR-PM design falls into the category of innovative small sized reactors, featuring 200MW electrical output by two reactor modules.
    - Designer: Institute of Nuclear and New Energy Technology (INET), Tsinghua University of China
    - Status: Operational since 2021 as a unit with 2 modules
  - **Xe-100** is a pebble bed high-temperature gas-cooled reactor with thermal rating of 200 MW, using with pebbles of approximately 15.5 wt% enrichment and achieve a final average burnup of 165 000 MWd/tHM.
    - Designer: X-Energy, USA
    - Status: License Applikation at NRC 2021; Start of construction 2025



Selected Reactor Types for the Example

HTGR-Reactortype		HTR-PM100	XE-100
Thermal power	MWth	250	200
Electrical power	MWel	110	70
No. spheres inside reactor		420,000	223,000
Max. enrichment	wt-%	8,6	15,5
Average discharge burnup	GWd/t	90	168,5
Max. discharge burnup	GWd/t	106	-
Design life reactor	years	40	60
Daily discharge rate of spheres		400	173
No. of spheres per canister	-/day	40,000	6,000
Duration of canister loading sequence	days	100	15
Canister loadings rate	-/year	3.7	10.5
No. canister for design life reactor		appr. 160	appr. 670
No. of canister storage positions		40	632
Service life fuel storage at reactor	years	12	80

- Similar thermal power for both types
- Different fuel management strategies
- XE-100
  - Higher enriched spheres
  - Higher discharge burnup
  - ½ No. of spheres at the core
  - Smaller daily discharge rate
  - Longer design life time
  - Smaller canister capacity
  - Higher loading rate
  - Larger canister storage at reactor, which covers the whole reactor life time
  - Much higher amount of canister for the life time needed

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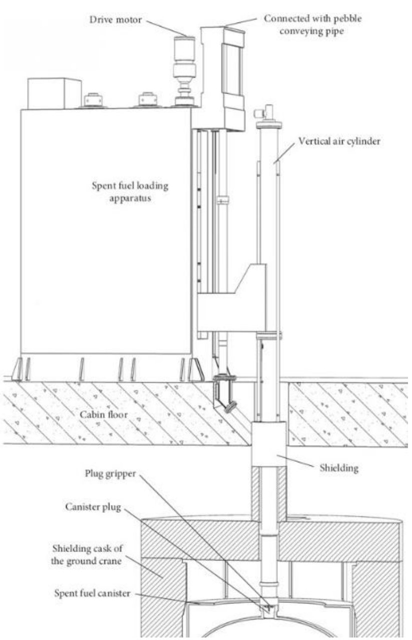
Reactor operation and fuel discharge

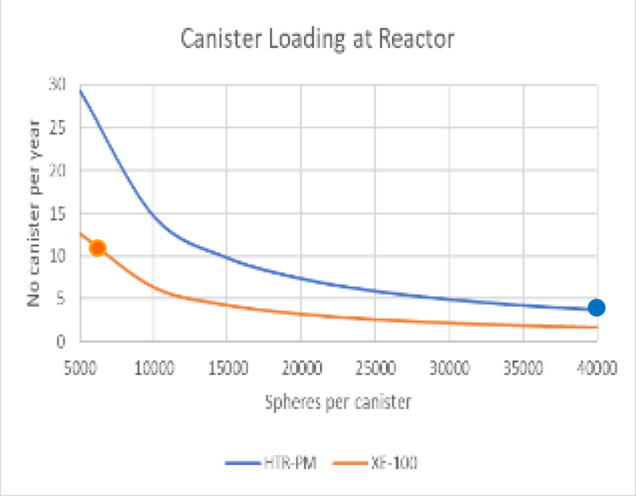
- Key parameters for the disposal planning of HTGR fuel are determined by
  - operating conditions
  - design of the reactor and
  - its infrastructure (fuel handling, fuel storage)
- Spheres have been irradiated with several passes in the reactor, integrity of the spheres is checked at the end of the pass and the burn-up is measured.
- When the final burn-up is reached or defective or broken spheres are detected, they are removed and continuously filled into cylindrical canisters made of thin stainless steel.
- Fully loaded canister is sealed gas-tight with a welded-in lid.
- Remotely transported inside the reactor building to a fuel storage at the reactor.
- Hot canisters are collected in groups, cooled by active ventilation and shielded by thick-walled concrete structures (vault storage).



[Ref.] Science and Technology of Nuclear Installations, Volume 2022, Article ID 1817191
Bin Wu, et al - Design, Experiment and Commissioning of the Spent Fuel Conveying and Loading System of HT-PM

Canister Size

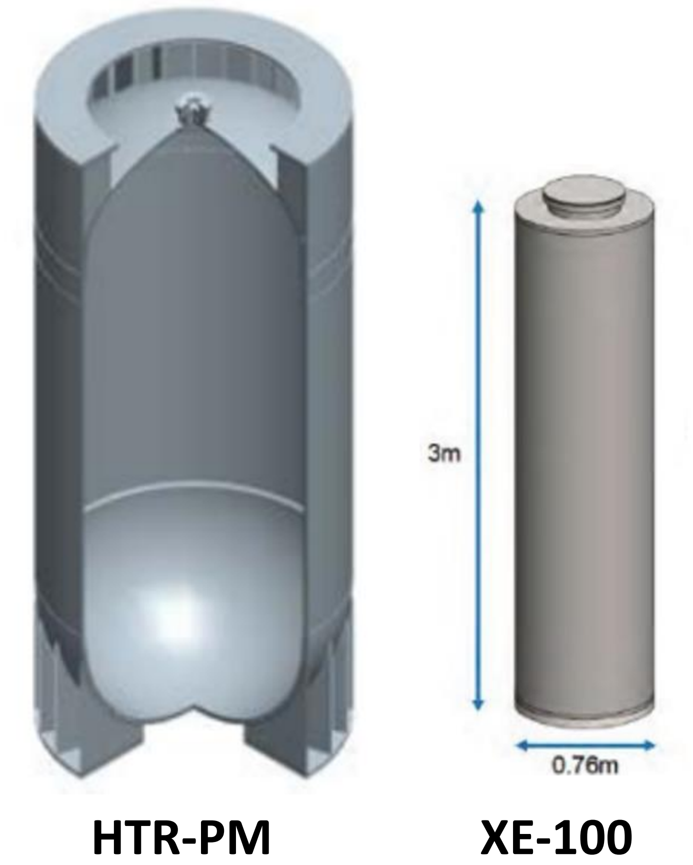
- The main parameters that are determined by the reactor design and must be taken into account when planning the further disposal route are:
- Max. Enrichment and burn-up of the spheres, as well as total number in the reactor
- Size and capacity of spheres in a canister
  - Duration of the canister loading sequence or required number of canisters per year
  - Max. Heat output when fully loaded per canister
- Handling mass and dimensions of the equipment
- Number of storage spaces for canisters in the fuel storage at the reactor



Canister with high capacity

- lower number
- fewer handling operations
- greater dimensions and weights
- higher heat output

Spent Fuel Canister



- Spent fuel canister
  - Canister made of stainless steel
  - Filled with air under normal pressure
  - Welded lid in the center at the top for closure after loading
  - Automatically hoistable and stackable

HTGR-Reactortype		HTR-PM100	XE-100
Sphere capacity		40,000	6,000
Outer diameter	mm	1,780	760
Outer length	mm	4,180	3,000
Canister weight, loaded	kg	10,000	1,800
Mass heavy metall	kg	280	42
Outer canister volume	m^3	10.4	1.36

HTR-PM – Decay Heat of the Spent Fuel Canister

40,000 spheres/canister – 7 g_U/sphere - < 8 % enrichment, 90 GWd/tU

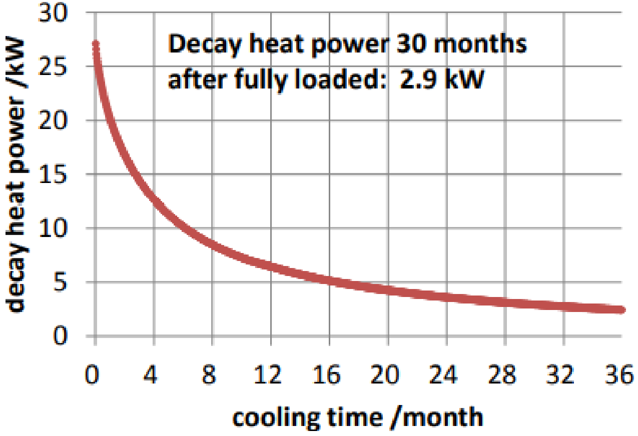


Fig. 5: Spent fuel canister decay heat power in

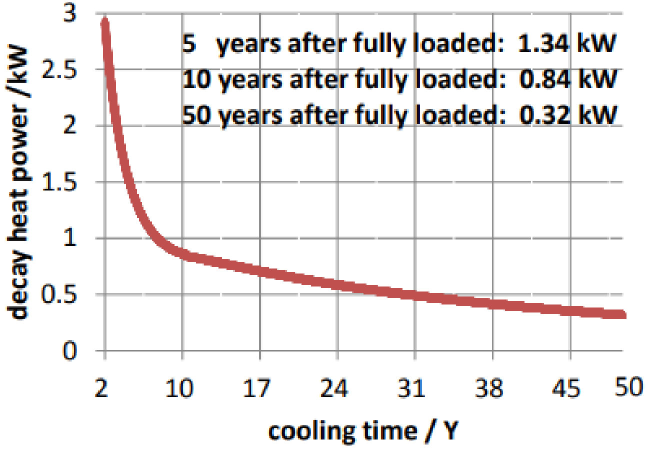


Fig. 6: Spent fuel canister decay heat power in

- High heat load of appr. 28 kW direct after loading needs active cooling measures
- Heat load decrease rapidly, down to 3 kW (10 %) after 30 month
- During longterm storage period between 0.8 and 0.3 kW
- Final Disposal < 0,3 kW/canister, which is low compared to LWR disposal requirement (1.0…2.0 kW)

[Ref.] Proceedings of the HTR 2014, Paper HTR2014-71237
Wang Jinhua, et al Design of the HTR-PM Spent Fuel Storage Facility

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Source terms of a fuel canister

HTGR-Reactortype		HTR-PM100	XE-100
Average discharge burnup	GWd/t	90	168.5
<u>Heat generation per canister</u>			
- Directly after reactor discharge	kW	28.0	Appr. 9.0
- After 30 month	kW	3.0	0.9
- Storage (10…50 years after discharge)	kW	0.8…0.3	0.25…0.1
Final disposal	kW	0.3	0.1
<u>Ratio of produced energy per volume</u>			
Produced energy by spheres within one canister	GWd	25.2	7.08
Produced energy/canister volume	GWd/m^3	2.42	5.2

- For LWR Fuel the ratio of generated energy to canister volume can be determined as 66.5 GWd/m^3
- The disposable volume of HTGR-fuel is 10 to 30 times higher than that of LWR-fuel for the same energy generation.
- The reason for this is that with HTGR-fuel, the graphite moderator encasing the fuel cannot be easily separated.

- Due to low heat load of HTGR fuel
  - long-term interim storage 0.1…0.8 kW
  - final disposal 0.1…0.3 kW

canister can be arranged within a low areal footprint.

- Final disposal of LWR-Fuel the thermal output is 1.0 to 2.0 kW depending on the host rock

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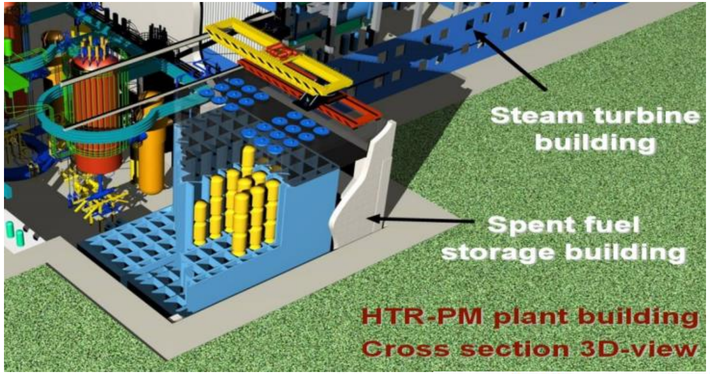
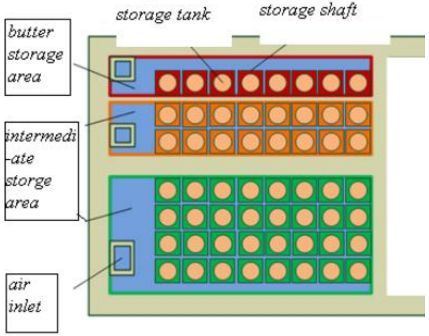
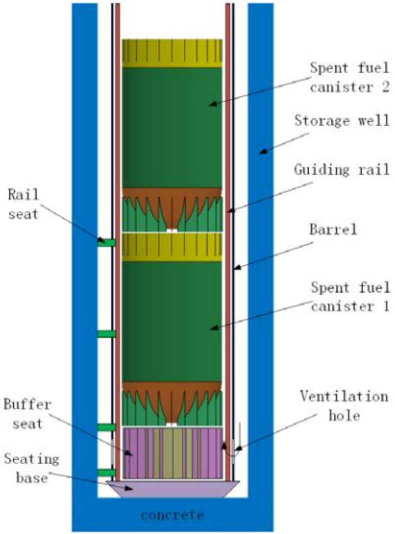
HTR-PM600 – Fuel Storage at the Reactor







- Spent fuel storage building is part of the reactor building for **6 HTR-moduls**
  - 48 spent fuel canister shafts for 5 stacked storage canister each → total of 240 (60/module) canister
  - 3 zones with closed air ventilation (activly working systems) for cooling
  - covers 12 years of plant operation
  - Shielding provided and structural protection by the thick concrete walls of the building, which are part of the reactor building
  - Movement of canister from fuel loading unit to storage with transfer cask
  - Automaticly operated bridge crane for handling of tranfer cask with unshielded canister
  - Interface for loading and handling of transport casks

[Ref.] Science and Technology of Nuclear Installations, Volume 2022, Article ID 1817191
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Internal fuel transfer to onsite storage facility

- If the fuel storage at the reactor cannot accommodate all the canisters produced during the design life, than an internal fuel transfer from the reactor to an onsite intermediate storage is required.
  - HTR-PM: necessary after 10..12 years of start reactor operation
  - XE-100: not necessary during reactor operation
- Safety functions of spheres and canister
  - Activity retention and tightness is ensured by the welded canister
  - Criticality safety must also be maintained by the arrangement of the spheres inside the canister.
  - Due to the outer graphite coating of the spheres, no additional neutron shielding for the transfer cask.
- A transfer cask is required
  - Handling in the reactor and in storage, considering mechanical and thermal accidents
  - Sufficient gamma shielding and heat dissipation.
- A (steel-equivalent) wall thickness of between 250 and 300 mm is required for sufficient shielding of the gamma radiation.
- Depending on the canister size, this results in dimensions and masses for the transfer cask, which must be taken into account for handling, crane capacity and equipment.

Transfer Cask Size

HTGR-Reactortype		HTR-PM100	XE-100
Outer canister diameter	mm	1,780	760
Outer canister length	mm	4,180	3,000
Canister weight, loaded	kg	10,000	1,800
Wall thickness	mm	300	250
Outer transfer unit diameter	mm	2,400	1,300
Outer transfer unit length	mm	4,800	3,600
Transfer unit weight, loaded	kg	90,000	26,000

- Large canister lead to significant higher transfer cask weights
  - Considering limitations for public transport and crane capacity for handling
- The personnel and handling time significantly lower due to the smaller number of units
  - 3-4 per year for large canisters
  - 10-11 per year for small canisters

Onsite intermediate storage

- A range of technologies are available for the storage of canisters, which have also been in use for the storage of LWR-BE for more than 30 years and are currently approved for storage periods of up to 120 years.
- The basic safety requirements in terms of tight containment of the radioactive contents, criticality safety, shielding and heat dissipation are comparable to those for transfer canisters and are defined by international standards.
- However, the boundary conditions for the design and verification of normal operating conditions as well as the assumed accident conditions depend specifically on the location of the storage facility and the selected storage technology.
- A key aspect here is the long-term stability and ageing behavior of the components of the storage system.

Option 1 - Longterm Storage with Concrete Shielding around Canister

(a) Vertical Above Ground
(Maine Yankee, Wiscasset, ME)

(b) Vertical Below Ground
(Humboldt Bay, Eureka, CA)

(c) Horizontal
(Rancho Seco, Herald, CA)

Figure 4-3 Dry Cask Storage Systems (Freeze et al., 2021; Rechard et al., 2015).

Advanced Reactors Spent Fuel and Waste Streams Disposition Strategies

Spent Fuel and Waste Disposition

- Mainly applied as a on-site storage facility
  - Internal movement between reactor and storage facility with transfer cask providing shielding and transshipment abilities
  - Type B(U)F cask for public transport of canister
- Welded canister (one layer) serves for confinement and subcriticality
  - Remark: Service life-time for HTR-PM Storage Canister is 50 years at maritime atmosphaere
- Shielding by additional concrete structures necessary
- Heat removal by passive ambient air ventilation between canister and shielding
- Mobile handling systems for movement and lifting necessary

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology
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June 28, 2023
Milestone No. M2SF-23SN010102015
SAND2023-08602R

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Option 2 - Longterm Storage with Canister loaded in DPC

DPC vertical inside
a storage building
- German storage facilities

DPC vertical outside
on a storage pad
- NNP Surry (USA)

DPC horizontal inside or outside
on a storage pad / Building
- NPP Koeberg (South Africa)

- Applicable for on-site and away from reactor storage facilities,
  because DPC is qualified for public transport and storage as a type B(U)F package
- Welded canister (one layer) serves for confinement and subcriticality
- Monitorable lid system as independent confinement
- Shielding provided by the DPC wall and lids even during transportation
- Heat removal by conduction and passive ambient air ventilation from cask surface
- Robustness against external loads, like airplane crash, explosion etc.
- Shipment from reactor and storage facility possible at any time
- Handling systems for movement and lifting depending on kind of storage
- Maintenance and repair options on storage site possible

Remark: DPC – Dual Purpose Cask for Transport and Storage

Footprint of onsite intermediate storage

HTGR-Reactortype		HTR-PM100	XE-100
No. canister for design life reactor		appr. 160	appr. 670
Outer canister diameter	mm	1,780	760
Outer canister length	mm	4,180	3,000
Footprint for storage of one canister			
- **Vertical storage**	m^2	3,5 x 3,5 – 12,25	2,5 x 2,5 – 6,25
- **Horizontal storage**	m^2	3,5 x 6,0 – 21,0	2,5 x 5,0 – 12,5
Storage area			
- **Vertical storage**	m^2	2,150	4,700
- **Horizontal storage**	m^2	3,700	9,200

- The selection of the technology to be used essentially depends on the specific boundary conditions of the site.
- One advantage of using DPC is that it can be removed directly after storage and that the packaging is robust in the event of an incident
  - external impact such as an airplane crash or terrorist attack

Public Transport

- Canister has to be loaded into a cask qualified as a type B(U)F package, providing
  - Additional shielding
  - Robustness against accidental conditions of transport regarding IAEA safety standards
  - Interfaces for handling during loading and unloading, as well as for the transport equipment
- Transport by road
  - Shipment with heavy load vehicles with individuel transport approval on dedicated roads
    - Limitation of weight of the transport configuration
      legal truck weight < 40 Mg
  - Depending on the local road network and infrastructure
- Transport by rail
  - Shipment with heavy load waggon
  - Depending on the local rail network and infrastructure
    - Current requirement for heavy load waggon: 22 Mg/aixle → 8-10 aixle/waggon

Handling

- Prior and after each internal or public transport
- 2 Options
  - Option 1: Storage of unshielded, welded canister within storage modul
    - Storage on site: loading or unloading of the canister into an **internal transfer cask (multiple use)**
    - Storage away from reactor: loading or unloading of the canister into a **Type B(U)F transport cask (multiple use)**
  - Option 2: Storage of canister loaded into DPC at the reactor
    - Only one loading of the canister into a **Dual Purpose Cask (DPC), also qualified as Type B(U)F transport cask**
- Equipment
  - Handling equiment for closing/opening and leak-tightness testing of the cask
  - Handling equipment and crane for cask lifting and tilting
  - Transport equipment for internal or public transport system
  - Only Option A: Handling equipment for transfer of canister between cask and storage modul
- Radiation Protection (ALARA)
  - Minimization of number of handling/duration and personel dose uptake

Treatment (optional)

- Due to decay of the HTR inventory over time (heat and radiation source) the use of canister with a higher loading capacity is advantageous in order to reduce the number of storage units for the next step of the BEFC
  - Reloading of HTR spheres into a larger canister with higher capacity
  - Necessity depends on the storage duration of HTR spheres at the reactor and the initial canister size
  - Limitation (size and weight) depends on the handling and acceptance criteria at the following steps of the BEFC
- Equipment
  - Shielded facility, which allows opening and closing of canister and dealing with HTR spheres

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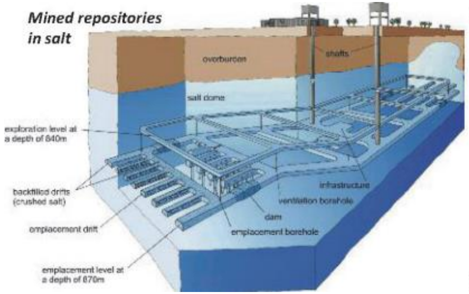
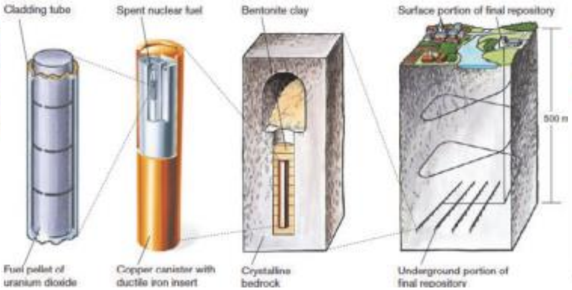
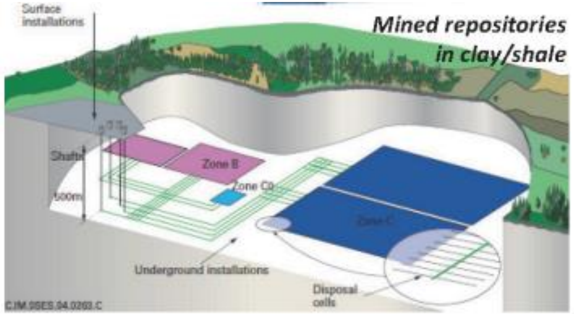
Safety Aspects and Challenges for HTR Fuel

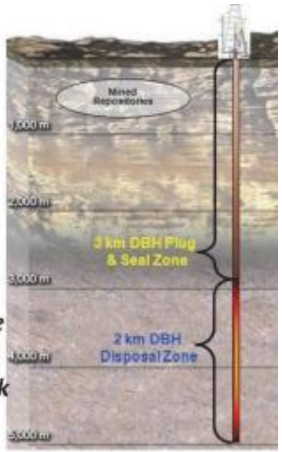
- Significant larger HTR fuel volume compared with LWR fuel
- Significant lower heat generation compared with LWR fuel
- Robust fuel configuration with favorable chemical characteristics for disposal
  - High melting temperature
  - Most fission products remain in the matrix material
- Packaging analysis for HTR fuel
  - No significant issues related to structural performance of canister or DPC
  - Subcriticality of single-canister contents can be maintained under all conditions
    - Limitation of canister diameter has to be respected
  - Thermal and shielding challenges for storage, transport and disposal are less restrictive compared with LWR fuel
    - High heat load directly after discharge, but rapid decrease with time
  - Experience with storage and transportation of HTR fuel exists
    - HTR fuel was included in several concepts for final disposal
- Radiolysis and gas formation out of the fuel during disposal has to be excluded

Options for Final Disposal of HTR Spent Fuel









Advanced Reactors Spent Fuel and Waste Streams Disposition Strategies

Spent Fuel and Waste Disposition

Prepared for US Department of Energy Spent Fuel and Waste Science and Technology

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Table 5-3. Summary of Coated Particle Spent Fuel (from SNL, 2014)

Disposal Concept	Disposal Option Performance	Confidence in Expected Performance Bases	Operational Feasibility	Secondary Waste Generation	Technical Readiness	Safeguards and Security
Salt	✓	✓	✓	✓	✓	✓
Crystalline	✓	✓	✓	✓	✓	✓
Clay/Shale	✓	✓	✓	✓	✓	✓
Deep Borehole	✓ / NA	O / NA	O / ✗	✓ / NA	O / NA	✓ / NA

Note: Split scores indicate that size constraints preclude disposal of some, but not all, waste forms in this group.

Legend: ✓ Strong; O Moderate; ● Weak/Uncertain; ✗ Not Feasible; NA Not analyzed

- HTR fuel retain activity better than LWR fuel
- No need to be treated
- High confidence in disposal performance
- For optimization
  - Repackaging canister
  - Separation of graphit

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Time Schedule for Fuel Management of HTGR-Fuel

- HTR-PM

x0 - start reactor operation
x0 + 3 a - first canister into buffer storage
x0 + 13 a - start operation of onsite storage facility
x0 + 40 a - end of reactor life time
x0 + 45..50 a - last canister into onsite storage facility
x1 - start operation of off-site storage facility at the final disposal site
x1 + 5..10 a - last delivery of fuel from onsite storage facility (end operation of onsite storage facility)
x2 - start operation of conditioning for final disposal

- XE-100

Capacity of the buffer storage at the XE-100 reactor (service life time 80 years > reactor life time 60 years) the onsite storage facility is not necessary

x0 - start reactor operation
x0 + 3 a - first canister into buffer storage at the reactor
x0 + 60 a - end of reactor life time
x0 + 63 a - last canister into buffer storage at the reactor
x1 - start operation of off-site storage facility at the final disposal site (not later than x0 + 70…75 a)
x1 + 5..10 a - last delivery of fuel from buffer storage at the reactor
x0 + 80 a - end of service life of the buffer storage at the reactor
x2 - start operation of conditioning for final disposal

Summary

- Irradiation conditions and reactor infrastructure are different
  - HTR-PM: lower enrichment, burnup-> higher number of spheres; storage capacity at reactor < reactor life time; large canister
  - XE-100: higher enrichment, burnup; storage capacity at reactor > reactor life time → no onsite storage; small canister
- Canister loaded and closed directly after discharge at the reactor are key elements for the disposal path.
  - The size of the canister has a direct influence on the loading capacity, needed number of disposal units, handling dimensions and weights and number of handling activities with related dose uptake
- Canister ensure the main safety functions related to activity retention, sub-criticality
- Disposal units around the canister provide mainly gamma shielding, protection against ambient conditions and robustness for accidental conditions
- The safe and long-term storage and transport of HTGR-spent fuel using canister is a well established disposal pathway,
- Experience of long-term storage over a period of 40 years for spent LWR and as well for HTGR-fuel (457 DPC) using dual purpose casks (DPC) exists in Germany.
- Challenges for storage, transport and disposal of HTGR-fuel are less restrictive compared with LWR fuel
- The disposable volume of HTGR-fuel is 10 to 30 times higher than that of LWR-fuel for the same energy generation.
- The high heat load direct after loading needs active cooling measures at the storage inside the reactor.
- During long-term storage and final disposal the heat load/source term are significant lower compared to LWR fuel
- Depending on the individuell geological boundary conditions the direct final disposal of the DPC is a considerable option.