Technical Meeting on the Management of Spent Fuel from High Temperature Reactors

IAEA, Vienna – July 9th, 2025

Operational Experience in Germany for Managing Spent Pebble Fuels

05.07.2025 V1.1

The Classic Role of GNS in Germany

Responsibility of the Utilities

Preussen Elektra

RWE

EnBW

VATTENFALL

GNS

Spent Fuel and HLW

We take care of...

(i.e. Competence and Responsibility of GNS)

Operational and Decommissioning Waste (LLW/ILW)

Interim Storage HLW/SF

Repository HLW/SF

Responsibility of the Federal Republic of Germany

BGZ Gesellschaft für Zwischenlagerung mbH

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

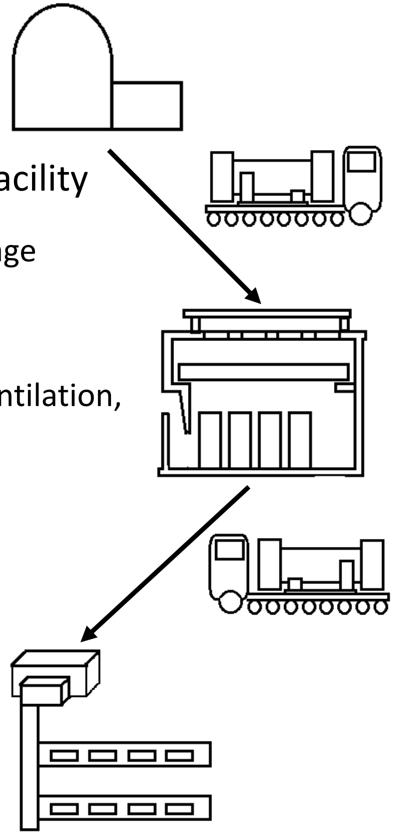
Interim Storage ILW/LLW

Repository Konrad

Backend Fuel Cycle Strategy in Germany

- **Disposal Path – Direct disposal of SNF and HTGR-Fuel**
  - Decay storage inside the reactor pool
  - Transfer of fuel to a on-site storage facility **or** public transport to off-site storage facility
    - Dual purpose cask (DPC) licensed for longterm storage and as Typ B(U)F transport package
  - Longterm storage of SNF and HTGR-Fuel at the storage facility
    - Storage building with maintenance area, crane, additional shielding, passive thermal ventilation, structural protection
  - Public Transport of fuel to the final disposal repository
    - Already loaded DPC cask will be used for shipment after storage
  - Final disposal of fuel
    - LWR: Transshipment from DPC into final disposal casks
    - HTGR: Direct disposal of DPC (former concept for host rock: salt)

→ **Currently applied disposal path in Germany**



GNS Casks Worldwide

GNS already has developed and manufactured more than 2000 casks for High Level Waste and Spent Fuel.

Loaded and in interim storage:	**2030**
▪ Germany	1473
▪ Lithuania (Ignalina)	308
▪ Czech Republic (Dukovany, Temelin)	151
▪ USA (e.g. Surry)	35
▪ Switzerland	32
▪ Bulgaria (Kozloduy)	19
▪ Belgium	8
▪ South Africa	4

Additional casks delivered to:

- Finland, France, Netherlands, Russia, Korea

as of 06/2024






Short History of Pebble-Bed Reactors in Germany (1)

The AVR Reactor in Jülich

- AVR: 15 MW_E
- 288 k fuel assemblies with various types of fuel

- 1960 Start of construction of AVR
- 1966 First criticality of AVR
- 1967 Start of power operation
- 1988 Final shutdown of AVR
- 1994 Licensing for safe enclosure
- 2009 Licensing for dismantling

- 1993-2009 Defueling into 152 CASTOR® THTR/AVR casks and storage in on-site storage facility.

- Originaly planned reprocessing facility „JUPITER“ never went into hot operation.

GNS

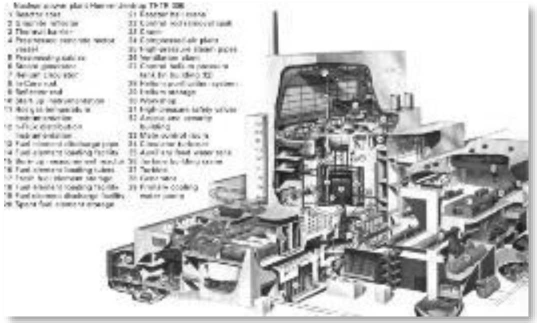
Short History of Pebble-Bed Reactors in Germany (2)

The THTR-300 Reactor in Hamm

- THTR: 300 MW_E
- 660 k fuel assemblies in total, only one type of fuel

- 1971 Start of construction of THTR
- 1983 First criticality of THTR
- 1985 Start of power operation
- 1989 Final shutdown of THTR
- 1997 Licensing for safe enclosure
- Safe Inclusion of reactor
- 2030 Start of decomissioning reactor

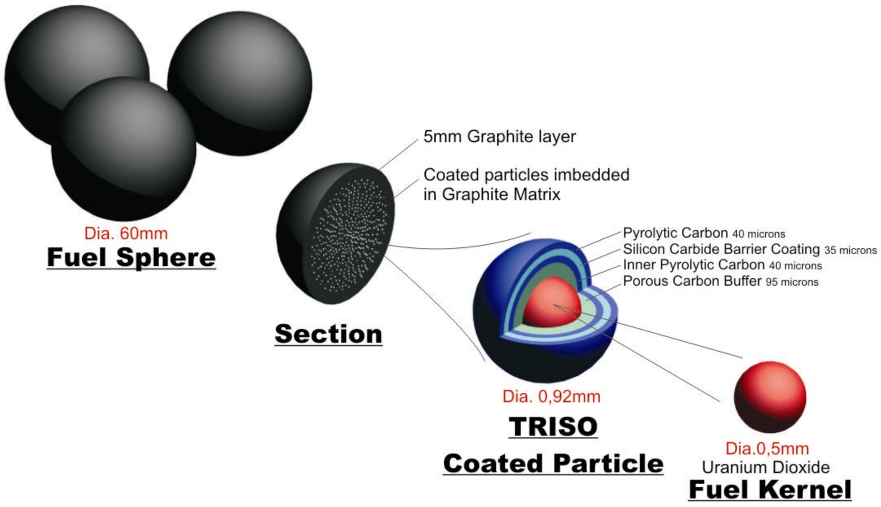
- 1993-1995 Defueling into 305 CASTOR® THTR/AVR casks and transport to centralized interim storage facility Ahaus (today operated by BGZ).



GNS

Fuel Types of Pebble-Bed Reactors in Germany

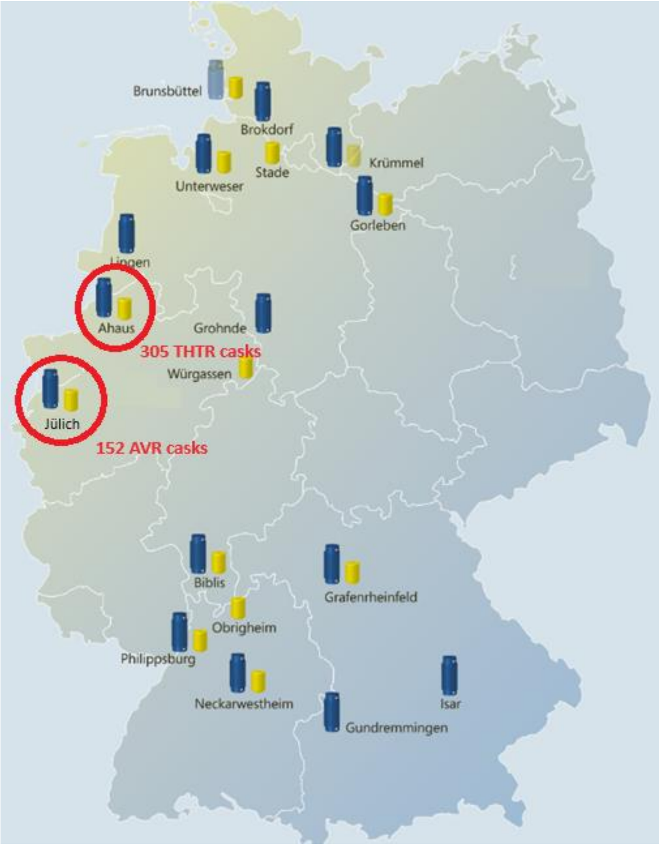
- Fuel Types AVR
  - $(U, Th)C_2$ - BISO
  - $(U, Th)O_2$ - BISO
  - UO_2 - BISO / TRISO
  - ThO_2 - BISO / TRISO
  - UC_2 - TRISO
  - UCO - TRISO
- Fuel Types THTR
  - $(U, Th)O_2$ – BISO
- HEU and LEU fuel used for reactor operations



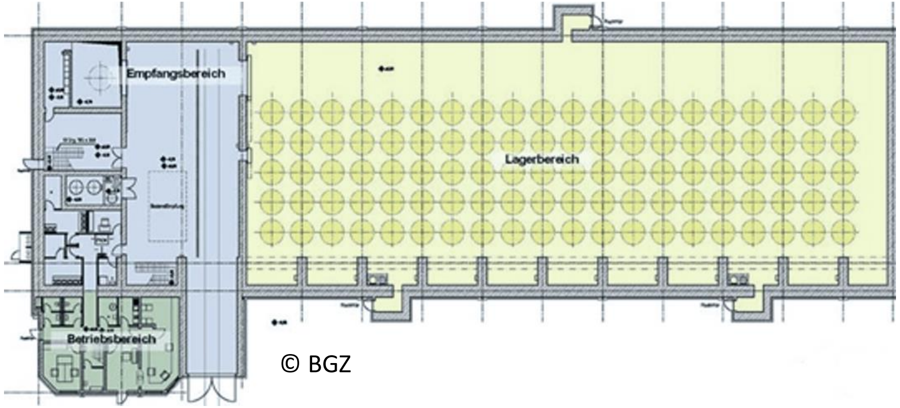
BISO – Bistructural Isotropic w/o the Silicon Carbide Barrier Coating
TRISO – Tristructural Isotropic

- For THTR the planned burnup of > 100 GWD/t was not reached due to short reactor operations
  - Major issue: Large number of broken/damaged fuel pebbles during reactor operations
  - Clamped control rods bars and damaged retaining bolts

Storage Facilities in Germany

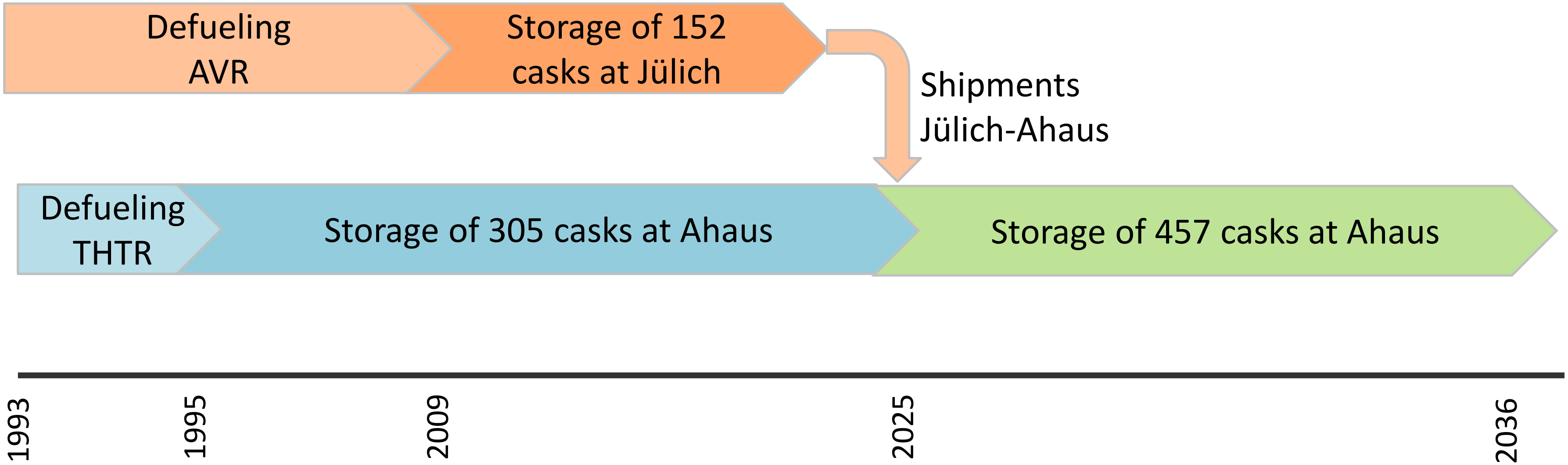


- Longterm storage of HTGR-Fuel
  - Storage building
    - additional shielding
    - passive thermal ventilation
    - structural protection
  - Entrance and maintenance area
  - Heavy weight crane for cask handling

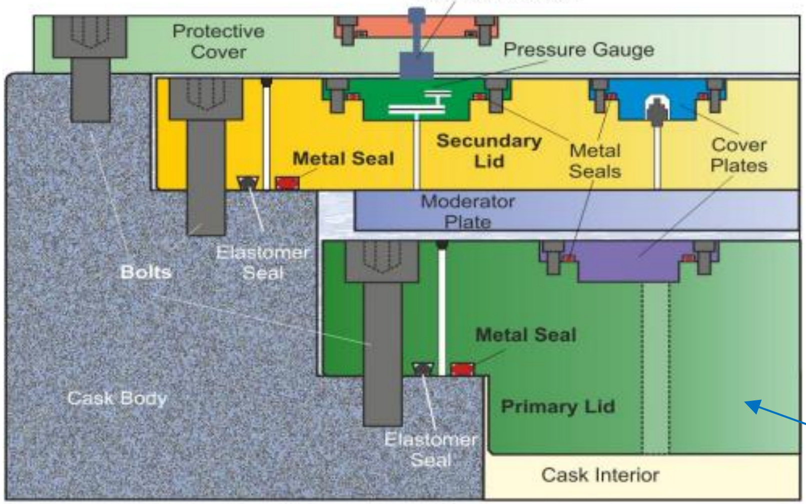


GNS

Time line – Storage of HTGR Fuel in Germany

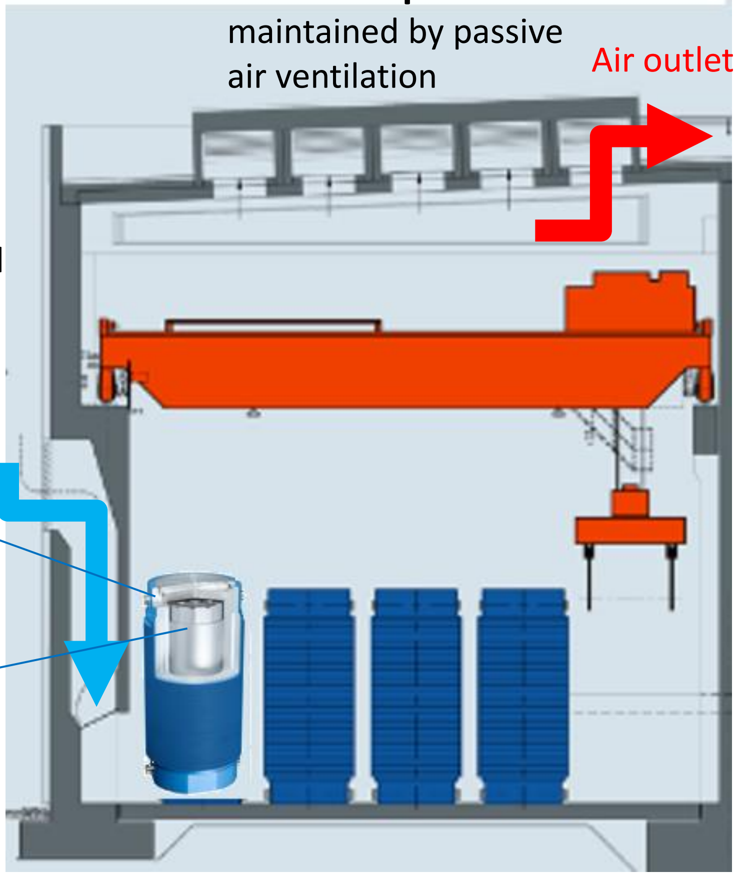


Safety Functions of an Interim Storage Facility and DPC



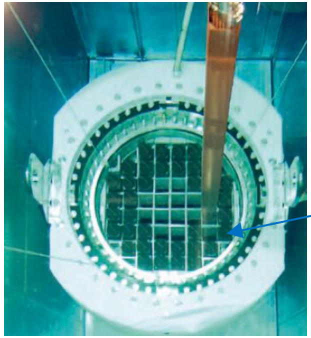
Heat Dissipation
maintained by passive air ventilation

Safe Enclosure
maintained by bolted double lid system and metallic seals and pressure monitoring



Radiation Shielding
provided by cask and storage building

Sub-criticality
guaranteed by the cask basket



GNS

Design Principles of the DPC

- CASTOR® casks are Dual Purpose Casks (DPCs)
  - transportation as Type B(U)F package according to IAEA safety regulations
  - longterm storage of the dry inventory without any additional equipment to maintain the safety under normal and accidental conditions (aircraft or missile impact)
- Safe enclosure is guarenteed by a double lid system, metallic gaskets and monitored with a pressure switsch
- Gamma shielding is provided by the thickness of the cask wall made of ductile cast iron and the cask lids made of stainless steel
- Heat transfer is achieved mainly by conduction through the cask components and minimised gaps, as well as by enlargement of the outer surface with fins

Additionally for LWR-Fuel

- Subcriticality is mainly maintained by the arrangement of the inventory (LWR) inside a robust basket structure consisting of boronated material, which is placed in the inner cavity of the cask
- For neutron shielding polyethylen rods and plates are placed inside the wall

→ Safety functions are achieved exclusively through passive design features and physical properties

The CASTOR® Concept

CASTOR® casks fulfil all protection objectives during transport and dry interim storage

- Monolithic cask body (ductile cast iron)
- Bolted double barrier lid system (forged steel) tightened with metallic seals
- Lid system permanently monitored during interim storage

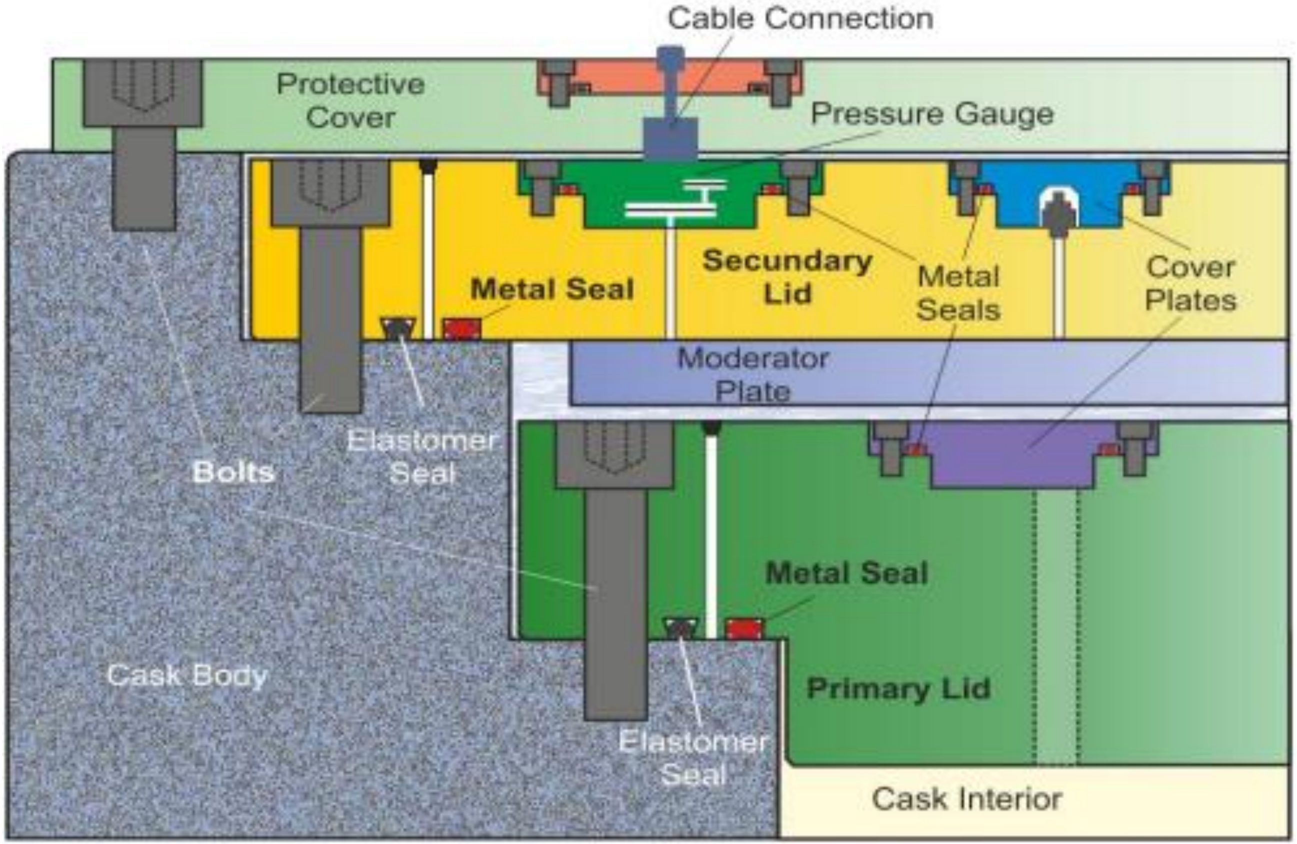
Additionally for LWR Fuel

- Polyethylene rods inside the cask wall and PE plates at both ends
- Radial cooling fins machined into the cask wall enlarge the surface of the cask
- Robust basket design guarantee sub-criticality under standard and accident conditions

→ These uniform features of the CASTOR® concept facilitate the evaluation for extended storage and transfer of experience

GNS

Double Lid System of CASTOR® Designs



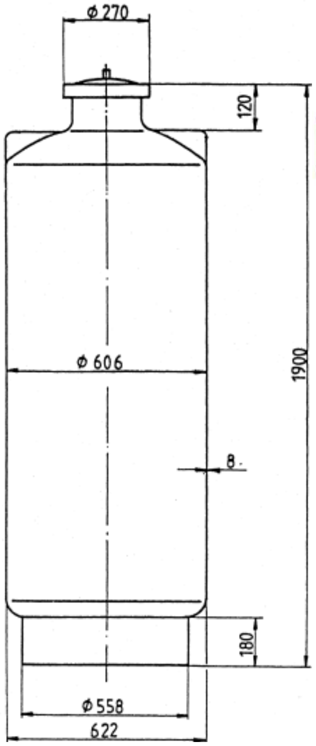
Safe Enclosure is the main protective challenge for long-term storage of HTR-Fuel

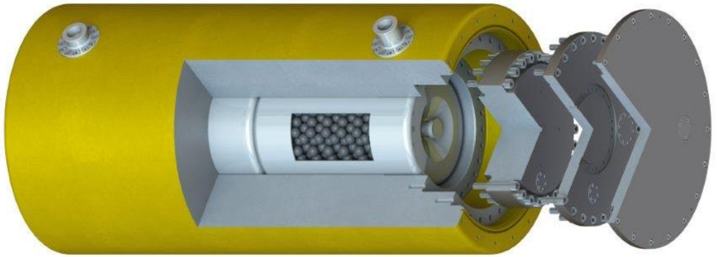
It is maintained by

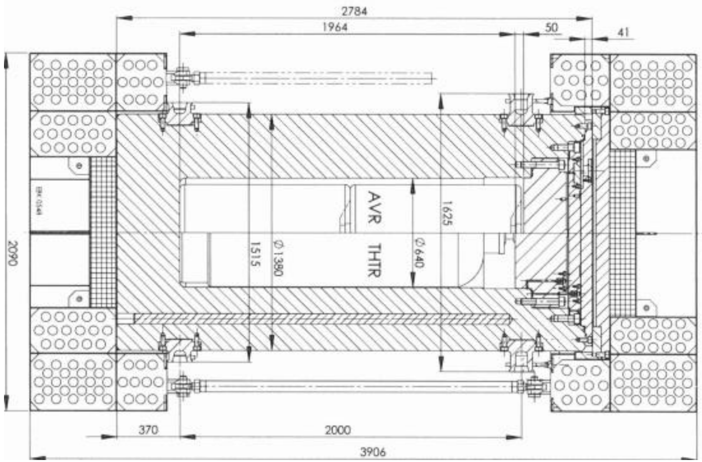
- bolted double lid system
- metallic seals and
- pressure monitoring

CASTOR® THTR/AVR – Dimensions and Weights

- THTR-Canister: 1.96 m x Ø 0.60 m
  - Containing 2110 THTR-Pebbles
- Cavity dimensions: 2.0 m x Ø 0.64 m
- Outer dimensions:
  - Storage 2.8 m x Ø 1.38 m
  - Transport 3.9 m x Ø 2.09 m
- Mass:
  - Canister 320 kg / 380 kg
  - Empty 25,280 kg
  - Storage 26,100 kg
  - Transport 32,100 kg







IMPACT OF AN EXPLODING LPG RAIL TANK CAR ONTO A CASTOR SPENT FUEL CASK

. View of the test facility. (a) Before the test. (b) After the propane rail tank explosion

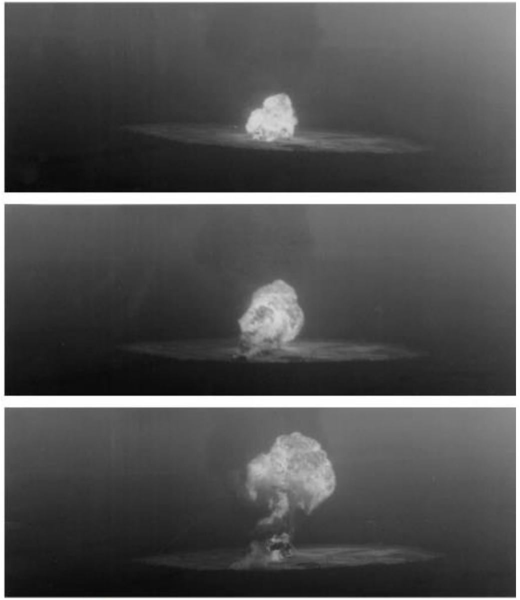


Figure 7. BLEVE, expanding fireball, photographs taken from a helicopter.

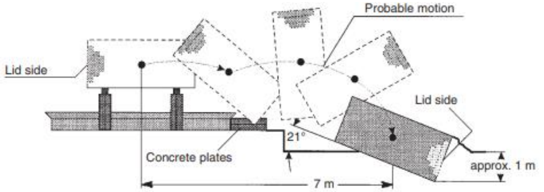
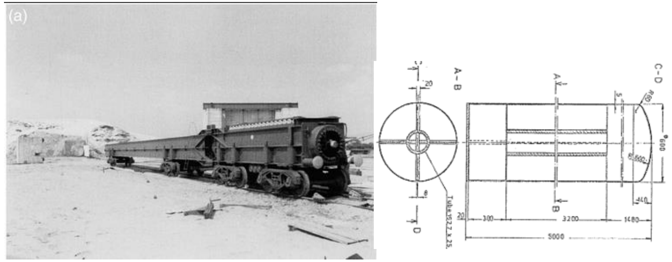


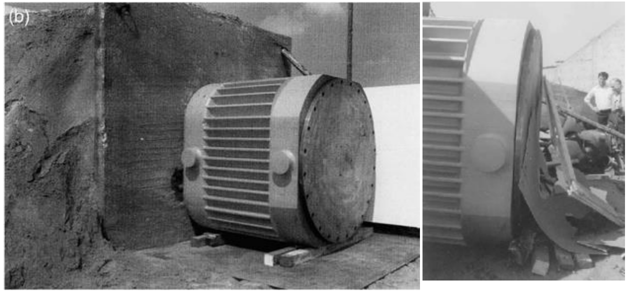
Figure 13. Movement of the CASTOR cask after the impact of the propane rail tank explosion.

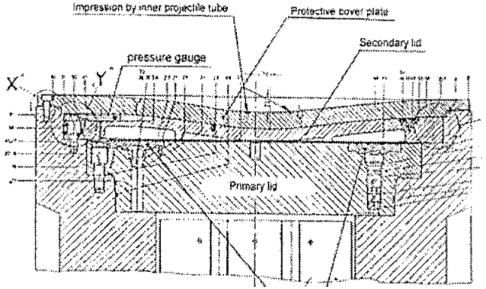
- On 27 April 1999 a fire test was performed with a 45 m3 rail tank car partially filled with 10 m3 pressurised liquid propane.
- A CASTOR THTR/AVR spent fuel transport cask was positioned beside the propane tank as to suffer maximum damage from any explosion.
- About 17 min after fire ignition the propane tank ruptured.
- This resulted in a BLEVE with an expanding fireball, heat radiation, explosion overpressure, and tank fragments projected towards the cask.
- This imposed severe mechanical and thermal impacts directly onto the CASTOR cask , moving it 7 m from its original position. This involved rotation of the cask with the lid end travelling 10 m before it crashed into the ground.
- Post-test investigations of the CASTOR cask demonstrated that no loss of leaktightness or containment and shielding integrity occurred.

https://tes.bam.de/TES/Content/DE/Downloads/radioaktive-stoffe/rmtp1999104231.pdf?__blob=publicationFile
https://www.gns.de/en/casks-containers-equipment/safety/explosion-test-with-rail-tank-car/

Robustness against Airplane Crash







- Airplane crash test simulations with military aircraft (Phantom type) are part of the licensing requirements for both casks and storage facilities.
- Between 1970 and 1980 a number of tests on storage casks were carried out at the Meppen military facility in Germany. A one-third scale model of a GNS cask was used to simulate the impact of a turbine shaft of a military aircraft using a hollow-tube projectile.
- Two different impact orientations were used:
  - perpendicular to upright cask body (lateral impact) and
  - perpendicular to center of lid system.
- The projectile completely disintegrated in the test, but the cask sustained only minor damage.

National Academies of Sciences, Engineering, and Medicine. 2006. Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report. Washington, DC: The National Academies Press. https://doi.org/10.17226/11263

https://www.researchgate.net/profile/Bernhard-Droste/publication/284139368_Spent_Fuel_Transport_and_Storage_Casks_under_Extreme_Accidents/links/564c467408ae020ae9f8c43f/Spent-Fuel-Transport-and-Storage-Casks-under-Extreme-Accidents.pdf

Storage Experience in General

- First CASTOR® loaded in 1983 (Switzerland) and is still stored at the ZWILAG storage facility
- By June 2024 a total of 2030 DPC with GNS-design stored worldwide
  - Suitability for interim storage confirmed
  - Long-term operational experience established
  - 457 casks with HTR fuel at the Facilities Ahaus an Jülich
- Majority of DPC are based on the CASTOR® design concept
  - Bolted cask made of Ductile Cast Iron and closed with a monitored double lid system
  - Current annual cask loading frequency: 60 casks/year
  - As of 06/2024 appr. 1473 CASTOR® DPC stored in Germany

→ Four decades of operational experience with loaded CASTOR® casks

GNS

Storage of CASTOR® THTR/AVR loaded with HTR-Fuel

- Dual Purpose Casks (DPC) for transport and storage
  - THTR: One Canister with 2110 intact pebbles
    One Canister with broken pebbles/fragments
  - AVR: 2 Canister with 1900 pebbles
- Casks were loaded in hot cells
- First license granted in 1990
- Start of dry storage in 1993 after the first cask loadings
- 305 casks with THTR fuel at storage facility Ahaus
  152 casks with AVR fuel at storage facility Jülich
- Low heat load below 200 W/cask
- Cask are double stacked and stored in narrow space
- Continuous 24/7 pressure monitoring during 30 years of storage
- Maintenance free storage

Transport after Long-Term Interim Storage

- After 2013 three options for further storage of the AVR fuel have been discussed:

  A. Transport of casks to SRNL for reprocessing of the fuel

  → *Successful 10CFR71 Licensing of CASTOR® THTR/AVR casks with DOE and NRC*

  B. Transport to Ahaus Centralized Storage Facility

  → *Currently planned for 2025*

  → *Periodic Inspection of casks and partly replacement of trunnions.*

  C. New Storage Facility in Jülich

Long-Term Storage and Final Disposal

Aging effects of fuel

- No corrosion effects expected for the fuel
- Emission of fission products over time are negligible.
- No further embrittlement during storage
- Mechanical stability not affected over time
- No further aging effects known

Final disposal (Reference Concept 1999)

- Final disposal of THTR and AVR fuel **without reprocessing**
- Repository within host rock: salt considered
- **Direct disposal** of HTR-fuel inside DPC CASTOR® THTR/AVR

Figure - THTR reactor core with controll rod bars

GNS

Summary & Outlook

- The safe and long-term storage and transport of spent fuel using dual purpose casks (DPC) is a well established disposal pathway, which is applied in Germany since nearly 40 years for spent LWR and as well for HTGR-fuel (457 DPC).
- This operational experience demonstrates the feasibility and reliability of the BEFC for spent HTGR-fuel and may help future owner/operator of new SMR designs.
- Depending on the individuell geological boundary conditions the direct final disposal of the DPC is a considerable option.

Excellence for Nuclear.