Facilitating SMR fuel fabrication from HALEU UF_6

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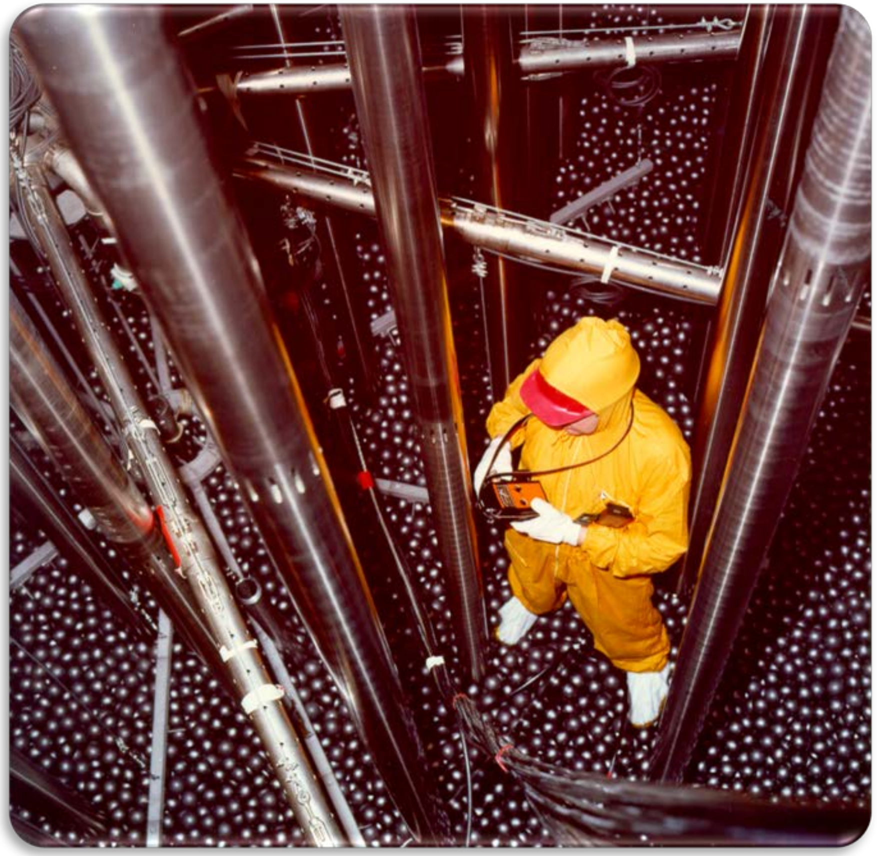
Overview

1. NUKEM's fuel production history
2. Major SMR concepts and their fuel
3. SMR fuels from HALEU UF_6 deconversion
4. Metallic uranium vs. HTR TRISO fuel production route
5. High temperature Small Modular Reactors (HT-SMRs)



THTR-300, Hamm-Uentrop

1. NUKEM's Fuel Production History: UO_2 and U metal

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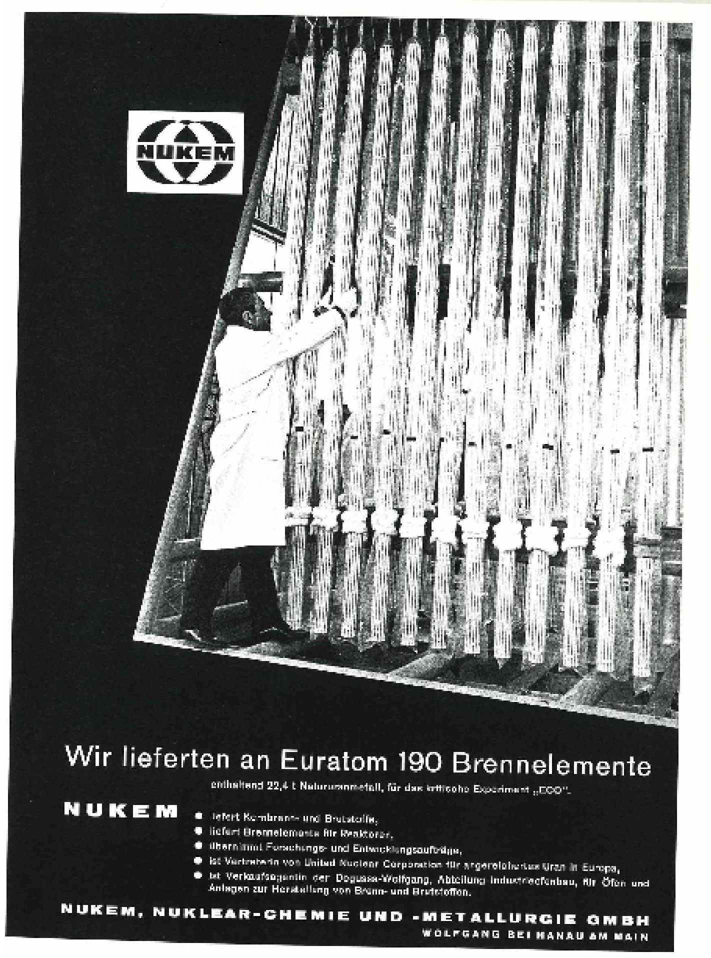
- **NUKEM / Siemens Fuel plant** (RBU, Reaktor Brennelement Union) in Hanau Wolfgang (Germany)
  - 1950's: Fuel assemblies from **U-metal**, FR2 (Karlsruhe), ECO (ISPRA)
  - 1960's: **UAl_x in Al**, up to 93% U-235 (HEU), FA for material test reactors (MTR)
  - 1970's: **AUC pilot plant**, 93% U-235 (HEU), for Oxide based (UO_2) FA, production route for all German power reactors

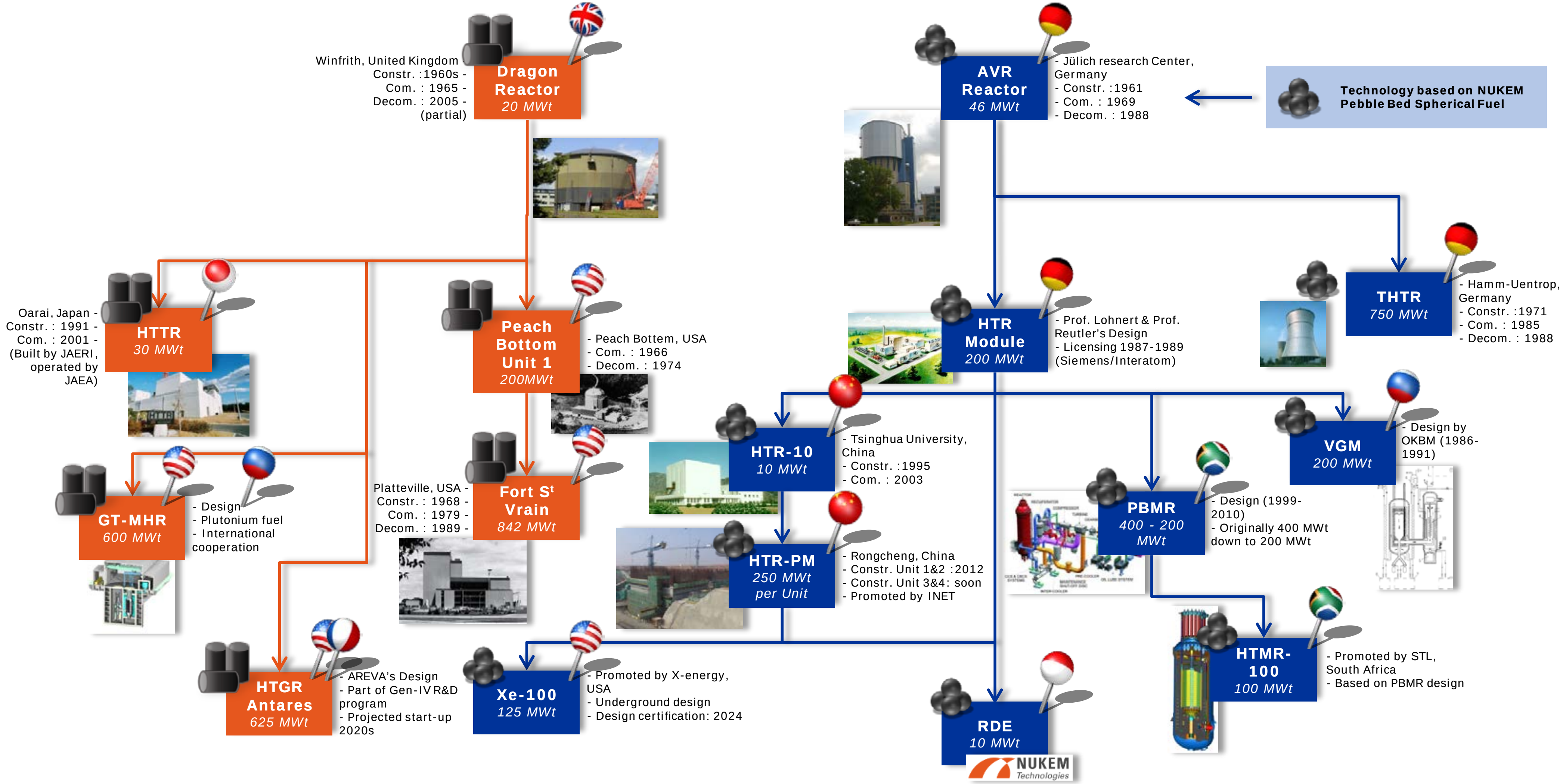
- 1980's-2000's: **AUC / U metal plant** (BATAN, Indonesia)
  - for MTR by Siemens
  - HALEU, up to 20% U-235
  - Rework/recycling included



1. NUKEM's Fuel Production History: HTR fuel

- 1960's: **German HTR program**
  - NUKEM's responsibility: Fuel specifications, Fuel element design and manufacturing process
- 1970's: **HTR fuel plant** (HOBEG) in Hanau (Germany)
  - 250 000 Fuel Spheres for experimental AVR, Jülich
  - 1 000 000 Fuel Spheres for THTR-300, Hamm-Uentrop
- 2000's: **PBMR** Project in South Africa (PBMR Pty. Lt.)
  - Basic, Detail And Procurement Design
  - Unfortunately stopped during procurement phase due to financial reasons
- 2010's: **Laboratory-scale** facilities
  - Indonesia
  - South Korea

1. The Spherical HTR Fuel Element



2. Major SMR concepts and their fuel

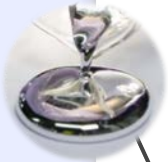
Liquid-metal cooled SMR

Fuel
- U metal alloy
- MOX (low fissile)
  - ➢ Pu and DU

Neutrons fast (mainly)

Coolant Na, Hg, Pb, Sn, …

Example Sodium-cooled fast reactor (SFR)



Water-cooled SMR

Fuel
- UO_2 pellets
- MOX (high fissile)

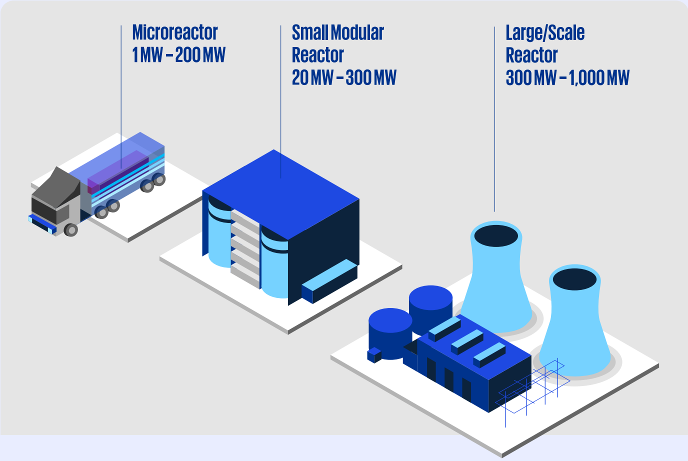
Neutrons thermal

Coolant Light water

Example Pressurized water reactor (PWR)

Small Modular Reactors (SMR)

IAEA definition:
Advanced reactor ***up to 300 MW_e per module***



Molten-salt SMR

Fuel
- UF_4 in molten salt
- also, with Pu (or Th)

Neutrons fast or thermal

Coolant Molten salt (F, Li, Be, Cl)

Example Molten salt fast reactor (MSFR)

Gas-cooled SMR

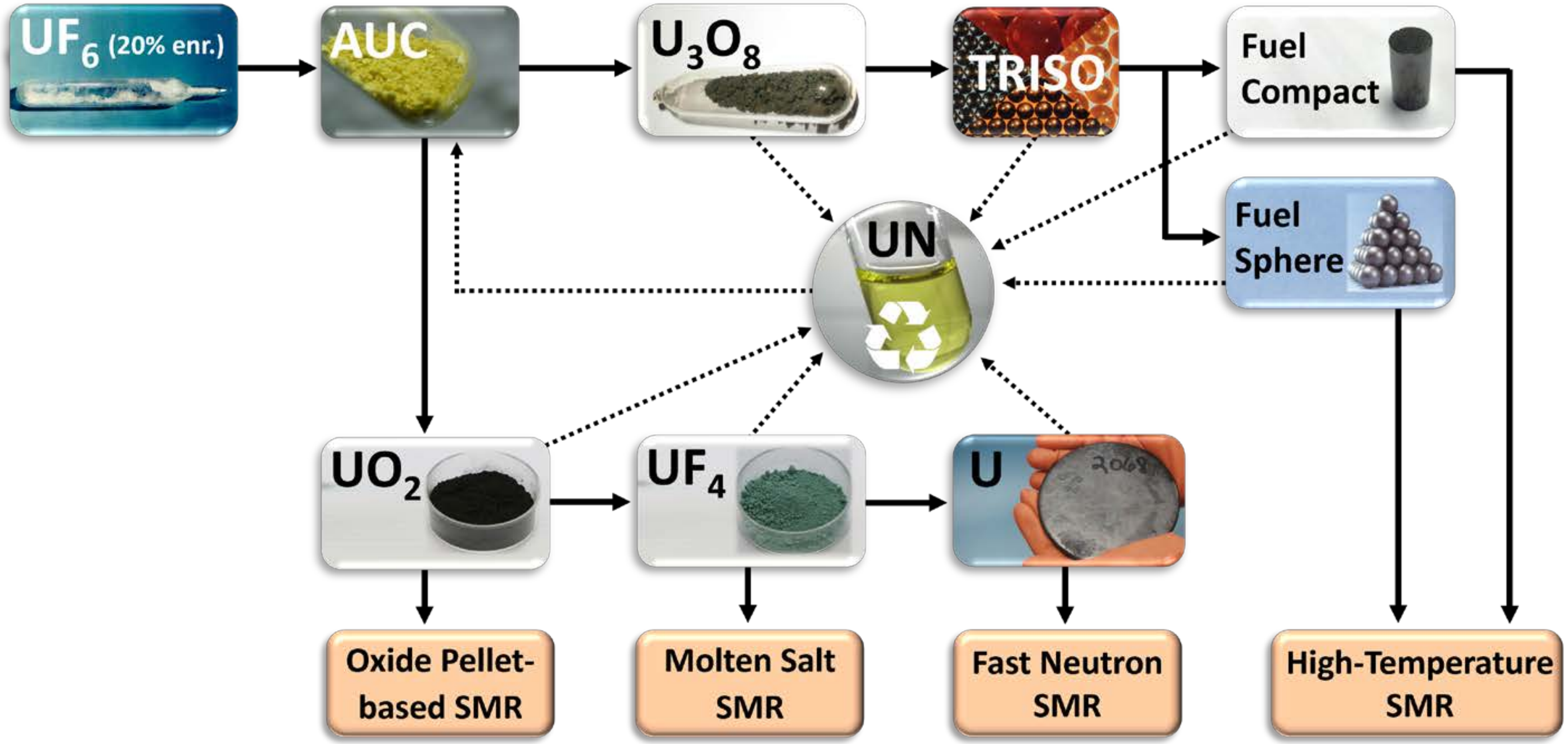
Fuel UO_2 TRISO particles

Neutrons thermal

Coolant He

Example High temperature gas-cooled reactor (**HTGR**)

3. SMR fuels from HALEU UF_6 deconversion



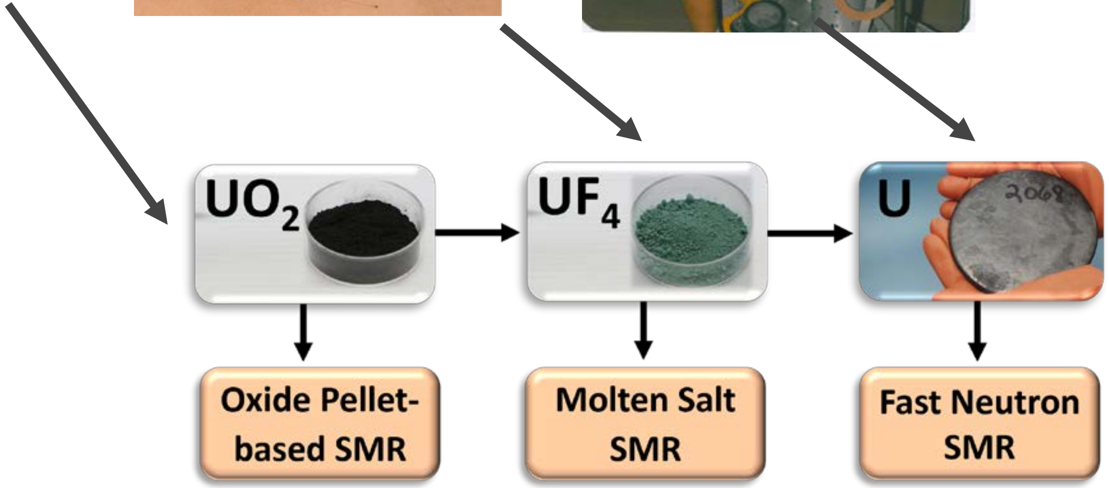
4. Metallic Uranium Fuel Production Route

U metal production

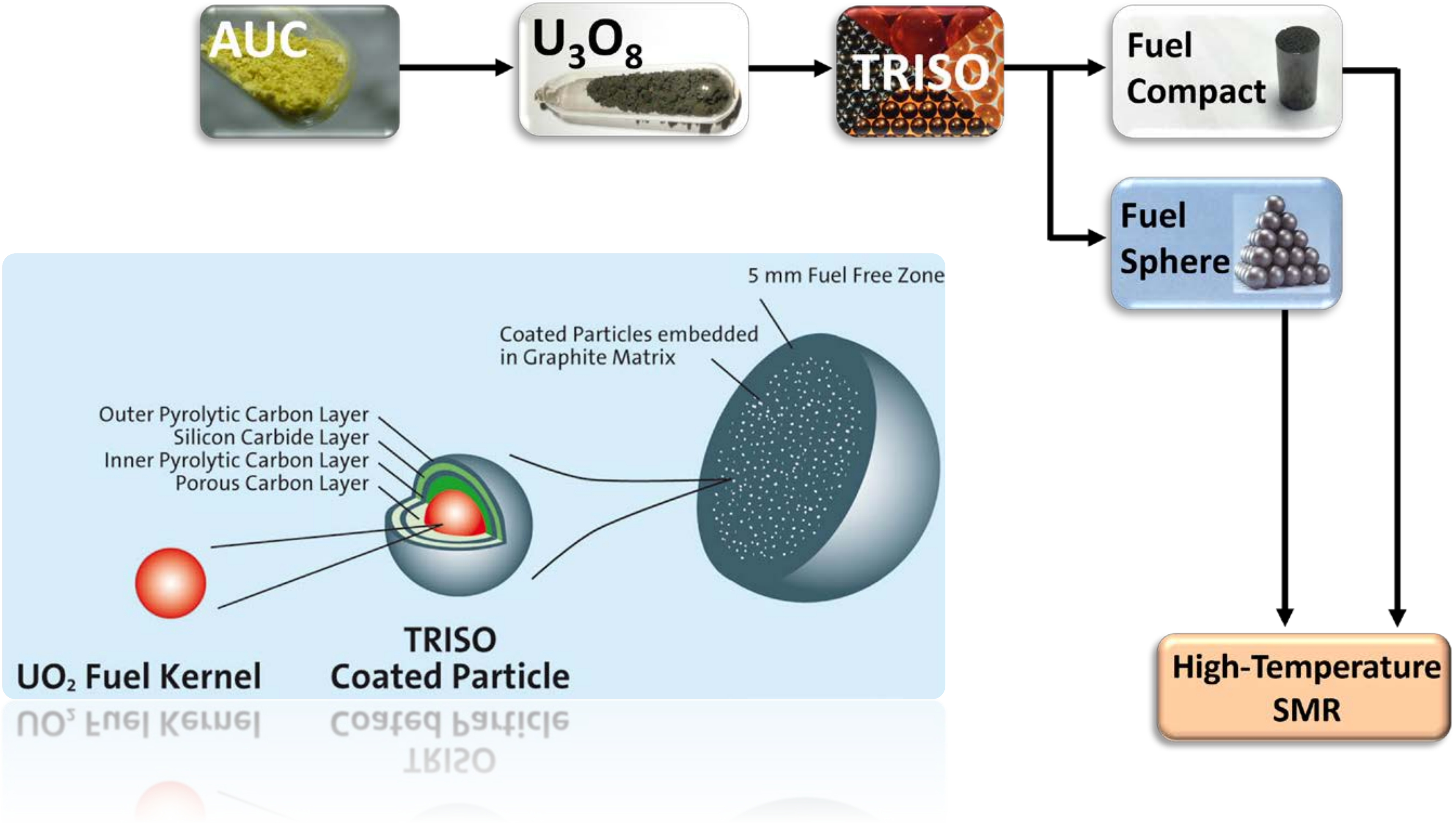
1. UF_6 + $(H_2O/CO_2/NH_3)$ → AUC + (NH_4F)
2. AUC + (H_2) → UO_2 + $(NH_3/CO_2/H_2O)$
3. UO_2 + 4HF → UF_4 + $(4H_2O)$
4. UF_4 + 2Ca → U + $(2CaF_2)$

Calciothermic reduction (4.)

- Inside graphite crucible
- Filled with UF_4/Ca mixture (5 kg U)
- Heating up to ignition
- Regulus with more than 90% yield
- Scrap recycled via recovery

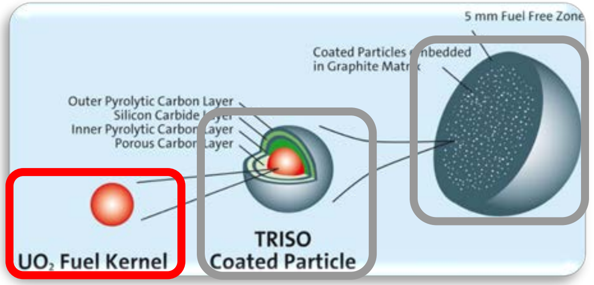


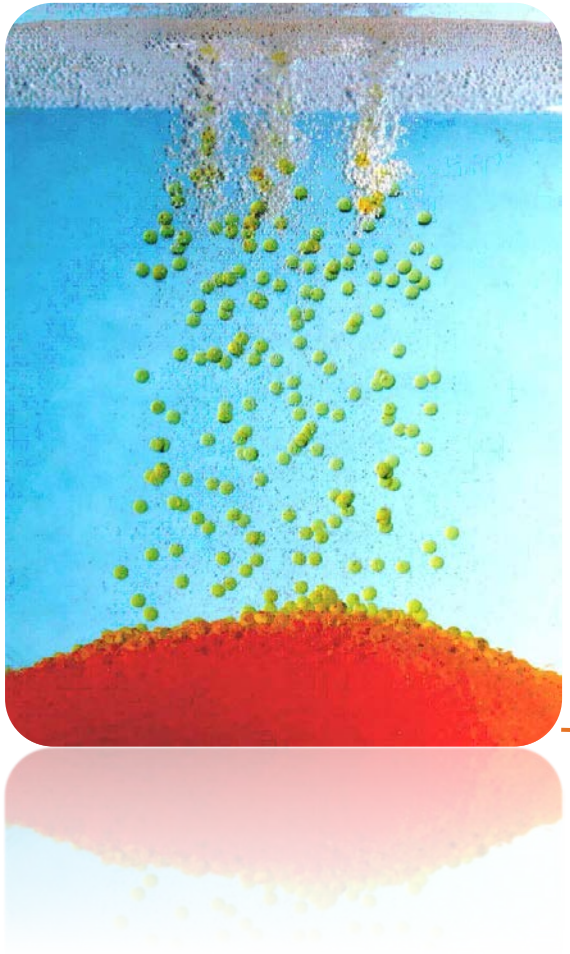
4. HTR TRISO Fuel Production Route

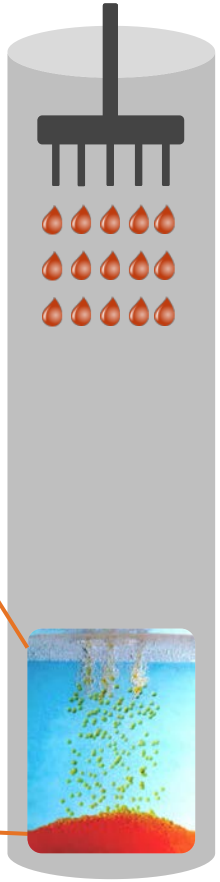


4. HTR Fuel Production – Kernels

- Kernel Casting
  - Drip casting of Kernels
  - ADU Precipitation from Uranyl nitrate and additives
  - UO_2 or UCO-based

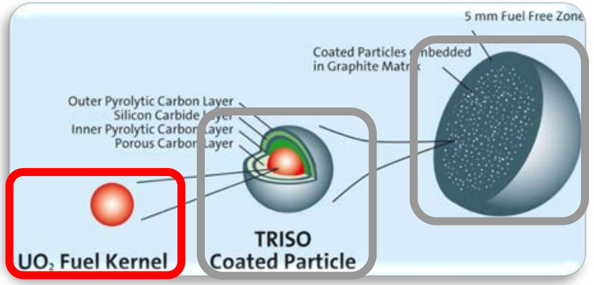




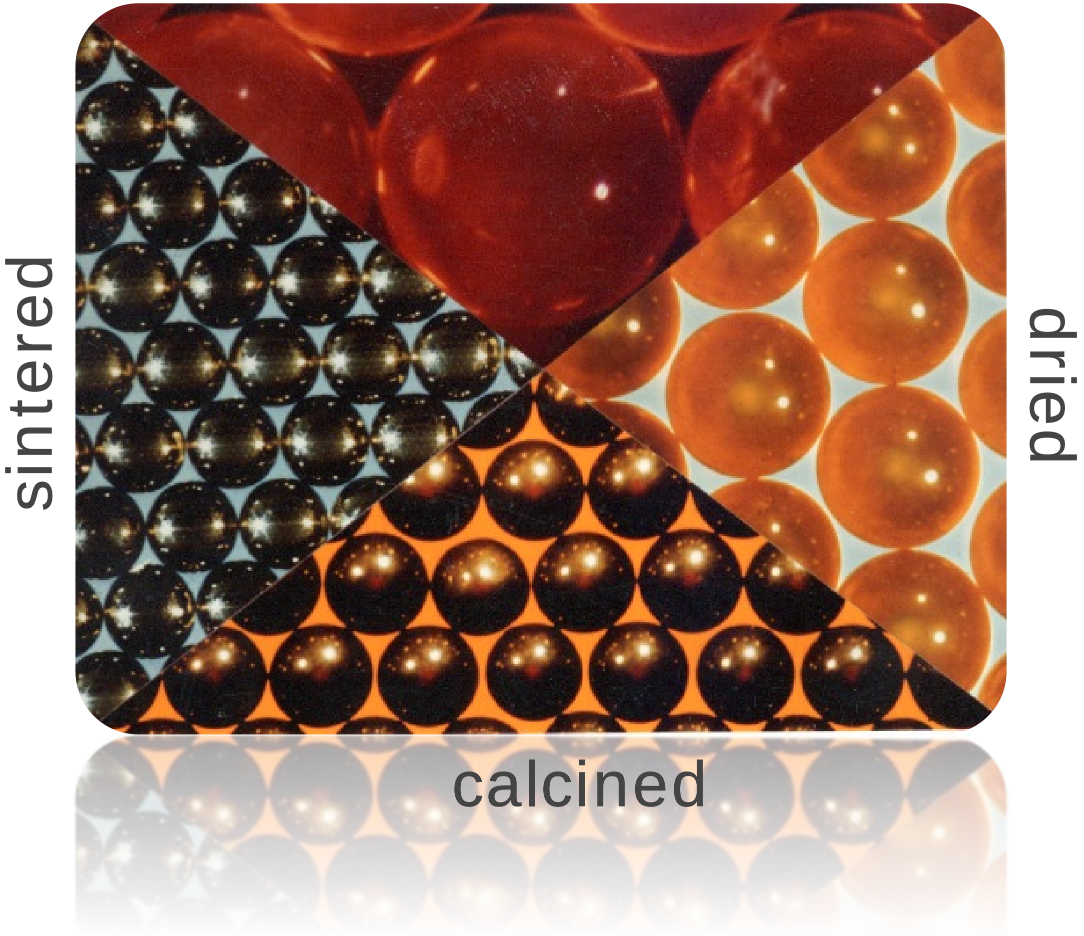


4. HTR Fuel Production – Kernels

- Kernel Casting
- Ageing, Washing, Drying (AWD)
- Calcining
- Sintering
- Sieving, Sorting, Sampling and Portioning (SSSP)

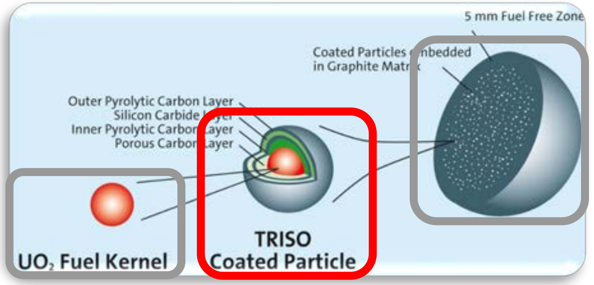


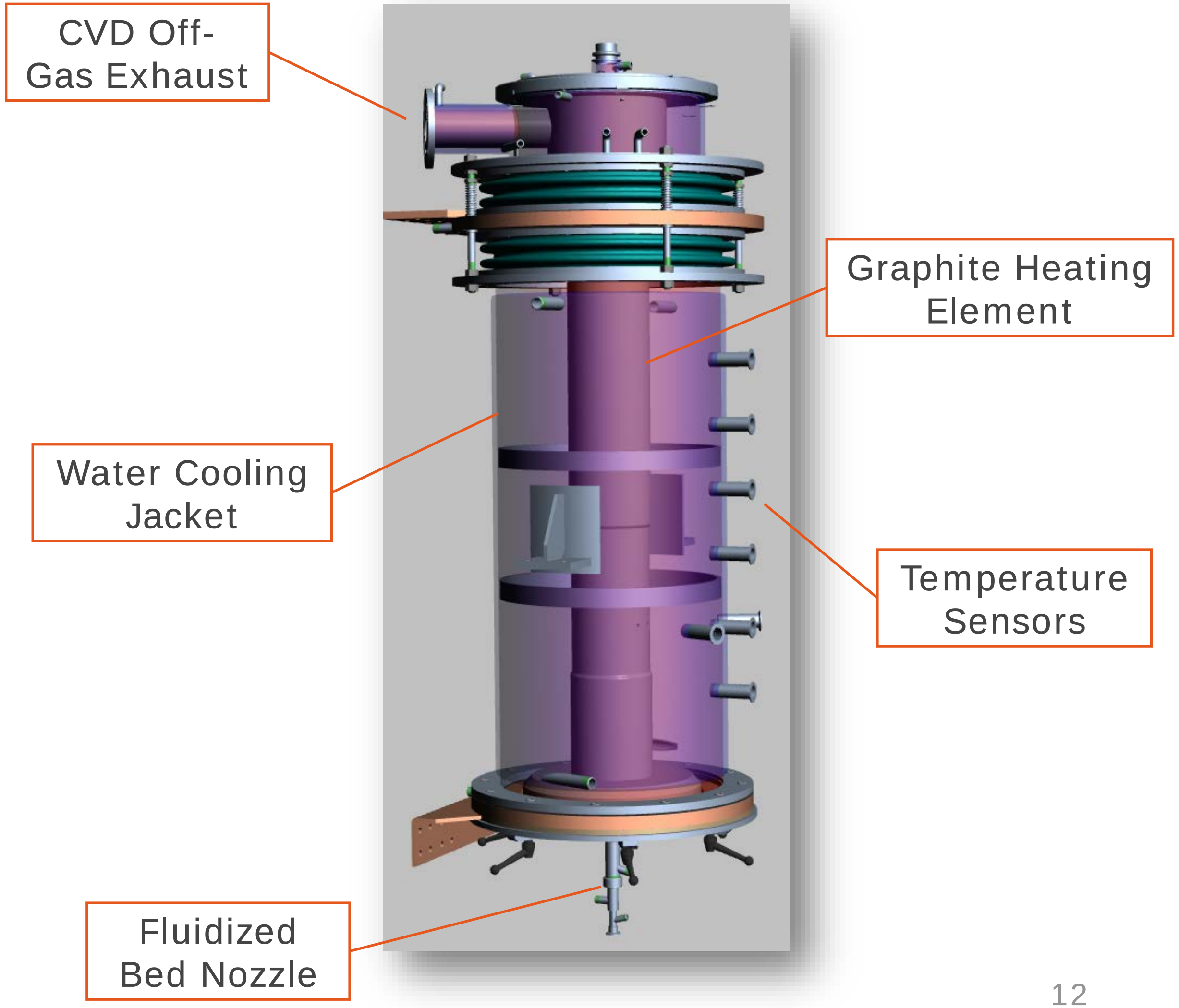
vibro-dropped



4. HTR Fuel Production – Coating Facility

- NUKEM Coater
- Key equipment to achieve **standard quality** fuel
- Chemical Vapor Deposition (CVD) Coating with Acetylene, Propylene and MTS
- Sieving, Sorting, Sampling and Portioning (SSSP)

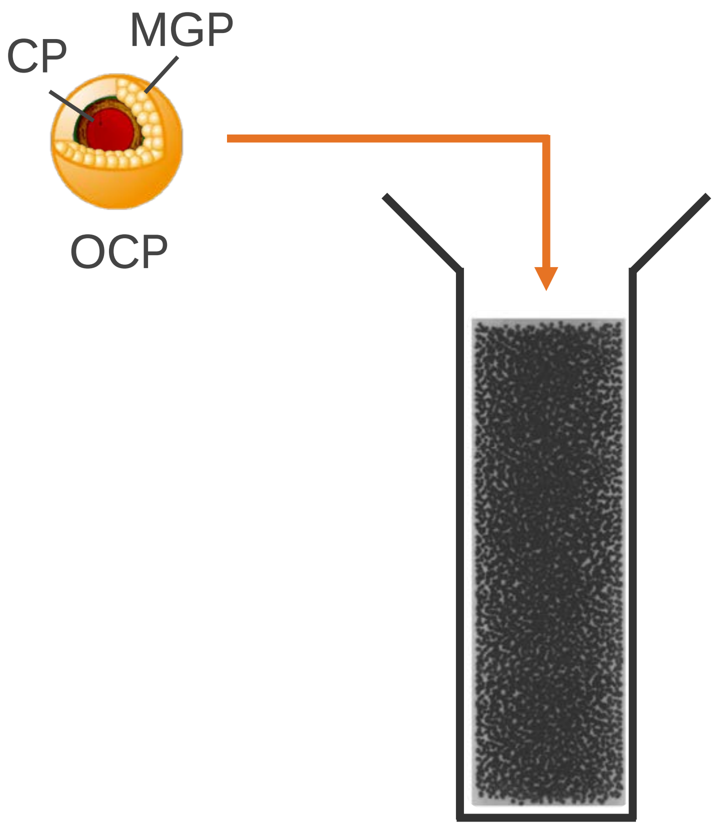




4. HTR Fuel Production – Fuel Facility

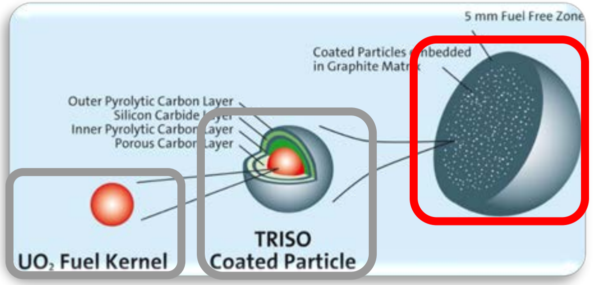
- Fuel Compact or Fuel Sphere **Pressing**
- OCPs are filled into pressing moulds

Fuel Compacts



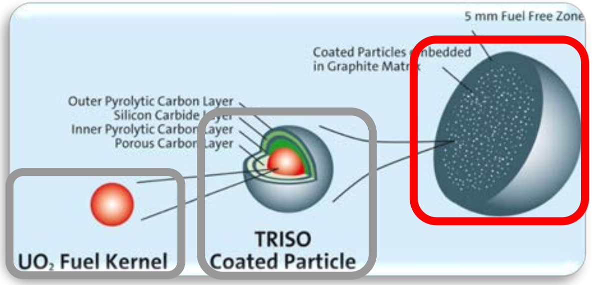
Fuel Spheres

Fuel Sphere Pressing Line,
(NUKEM HOBEG, Hanau, Germany)



4. HTR Fuel Production – Fuel Facility

- Carbonizing (800 °C)
- Annealing (1900 °C)
- Final Quality Control



Fuel Spheres

Fuel Sphere Pressing Line
(NUKEM HOBEG, Hanau, Germany)

4. HTR Fuel Plant - Uranium Recovery

U_3O_8 → Dissolution in HNO_3 → $UO_2(NO_3)_2$ + C → Particle Filtering → Clean $UO_2(NO_3)_2$ → Precipitation NH_4OH/H_2O_2 and Filtration → ADU / UP → Calcining → NG U_3O_8

Dirty U_3O_8

$UO_2(NO_3)_2$ (aq.)

Carbon particles

Add H_2O_2

Wet $UO_4 \cdot H_2O$ precipitate

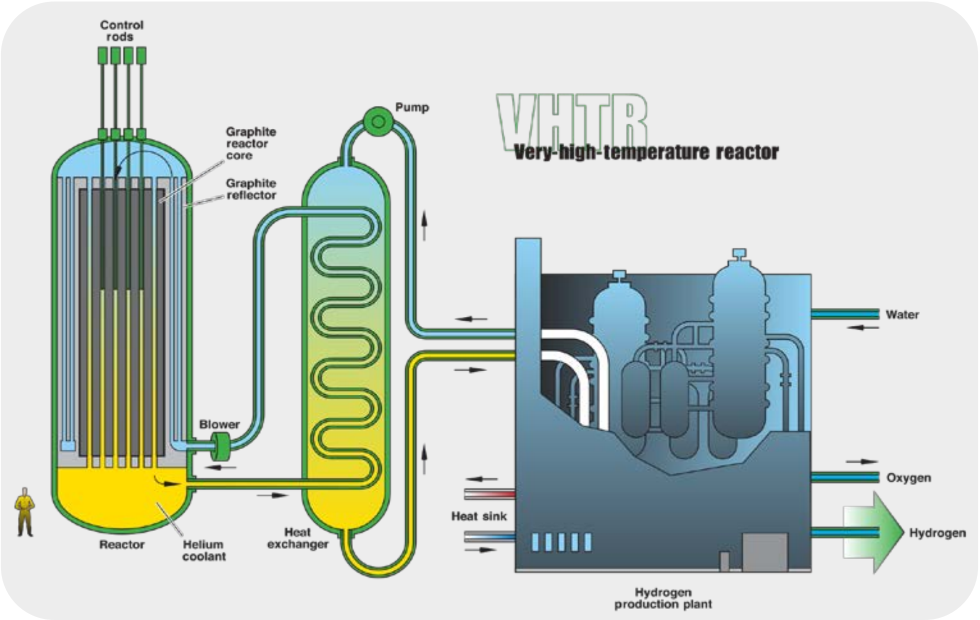
Clean U_3O_8

Source: Leiem, wikipedia.org, CC BY-SA 3.0

Source: Chemolunatic, wikipedia.org, CC BY-SA 4.0; woelen.homescience.net

5. High temperature SMRs

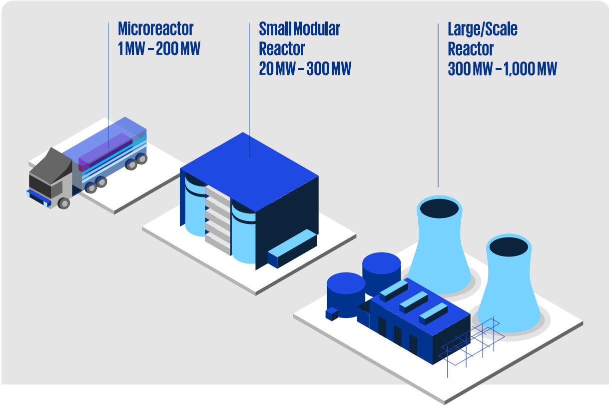
- Nearly all reactor designs (established to Gen IV) can be designed as SMR
- Common HTR concepts:
  - High-temperature gas-cooled reactor (HTR), outlet: 750 °C
  - Very-High-Temperature Reactor (VHTR), outlet: 1000 °C
- Advantages of **high temperatures**:
  - Replacing fossil fuel generated process heat
  - e.g., synchronous electricity and hydrogen production via high-temperature water electrolysis
  - High thermal conversion efficiency



Source: Wikipedia, https://en.wikipedia.org/wiki/High-temperature_gas_reactor#/media/File:Very_High_Temperature_Reactor.svg

5. High temperature SMRs

- **Advantages** of the **SMR concept**:
  - Less fissile material increases **safety**
  - **Standardisation** of components
  - Design **integration** to reduce complexity
  - **Flexible** application in industrial cluster areas: less grid restrictions



- **Inherent safety** features of the **HTR concept**:
  - **Retention** of fission products (TRISO fuel)
  - Core **meltdown impossible**: heat can always passively dissipate even without an active helium cooling circuit
  - Small core **power density** (compared to PWR)
  - Large **heat capacity** and temperature stability of graphite-based reactor cores

Questions?

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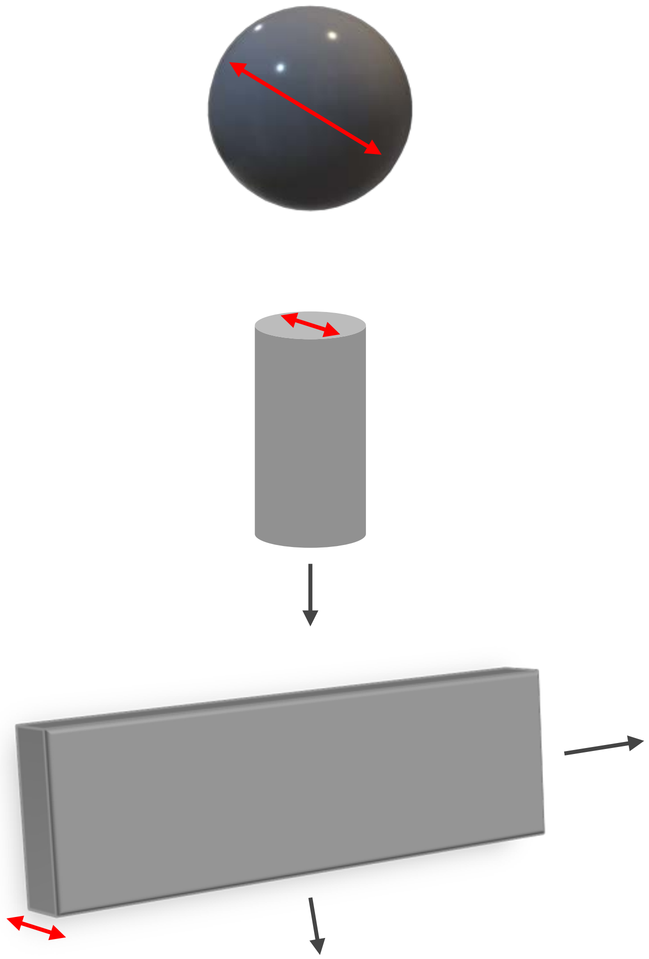
Criticality Safety - Practice

- Safe Mass principle is avoided wherever feasible

Slab Tank

Tube Array Tank

Criticality Safety - Principles



- Safe Mass
- Safe Volume
- Safe Cylinder Diameter
- Safe Slab Thickness

- <u>Assumptions:</u>
  - ➢ Optimal moderation
  - ➢ Worst-case reflection