High Temperature Gas-cooled Reactor: History

Advanced Reactor Technologies

Idaho National Laboratory

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ADVANCED REACTOR TECHNOLOGIES

Overview

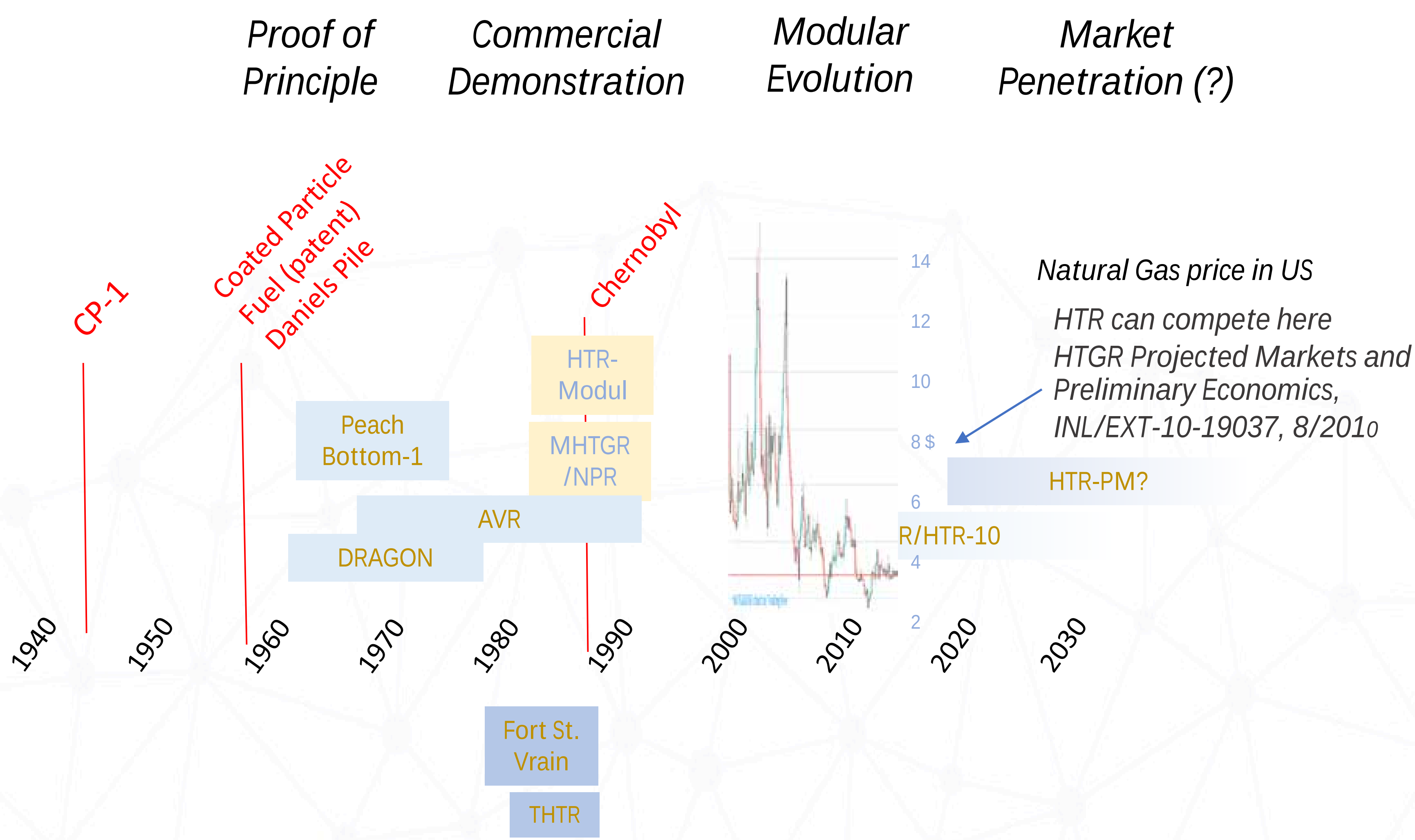
- Early and related concepts
- First Generation US and German plants
- Modular High Temperature Gas-cooled Reactors (mHTGR*)

** In these presentations, **M**HTGR refers to a specific design developed by General Atomics*

Visitor Entrance to THTR300 (European Institute for Climate and Energy website)

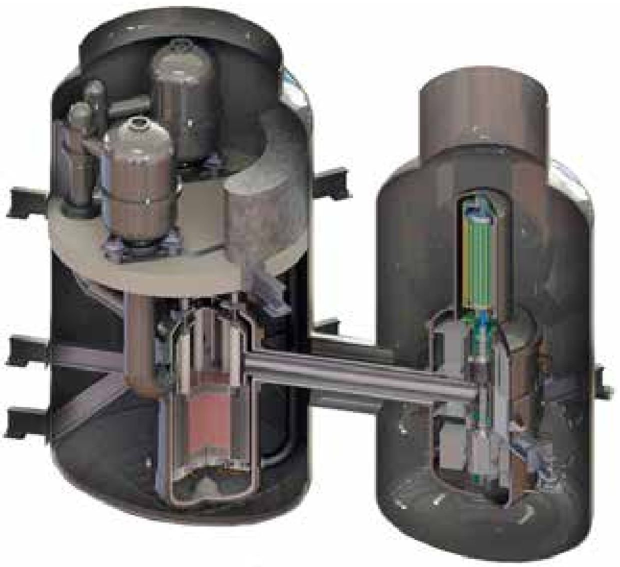
The Training Course delivered to the NRC in 2010 was spread over a few more days and was prepared and delivered by experienced vendors (see Suggested Reading List). You are encouraged to review that course material for specific design details and the view from a vendor perspective.

Timeline of HTGR Development

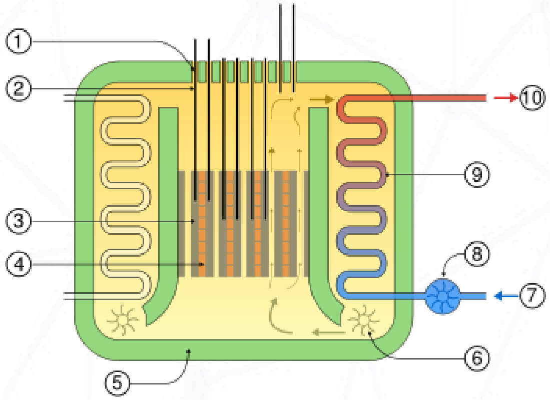


Related Concepts

- British Advanced Gas-cooled Reactor (AGR)
  - CO_2-cooled, 600°C outlet
  - UO_2 rods in SSTL clad
- Very High Temperature Reactor (VHTR)
  - Really hot HTGR (>850-1000°C)
- Advanced High-Temperature Reactor (AHTR) or PB-FHR (Kairos)
  - Molten salt instead of He
- Gas-cooled Fast Reactor (GFR)
  - Fast spectrum (no graphite)
  - UC fuel



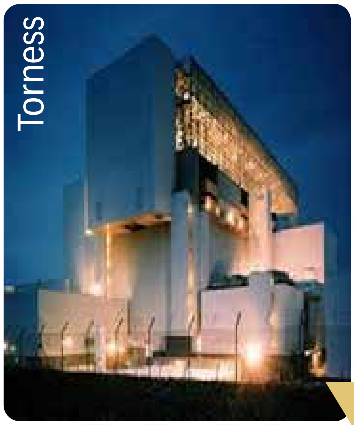
General Atomics EM2 GFR concept

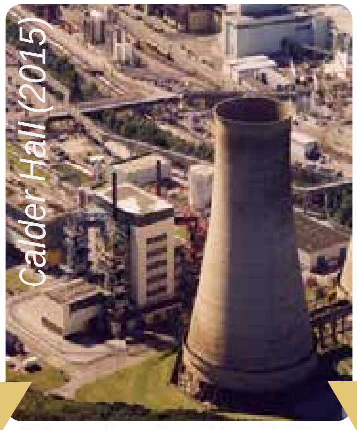


Torness AGR (Scotland)

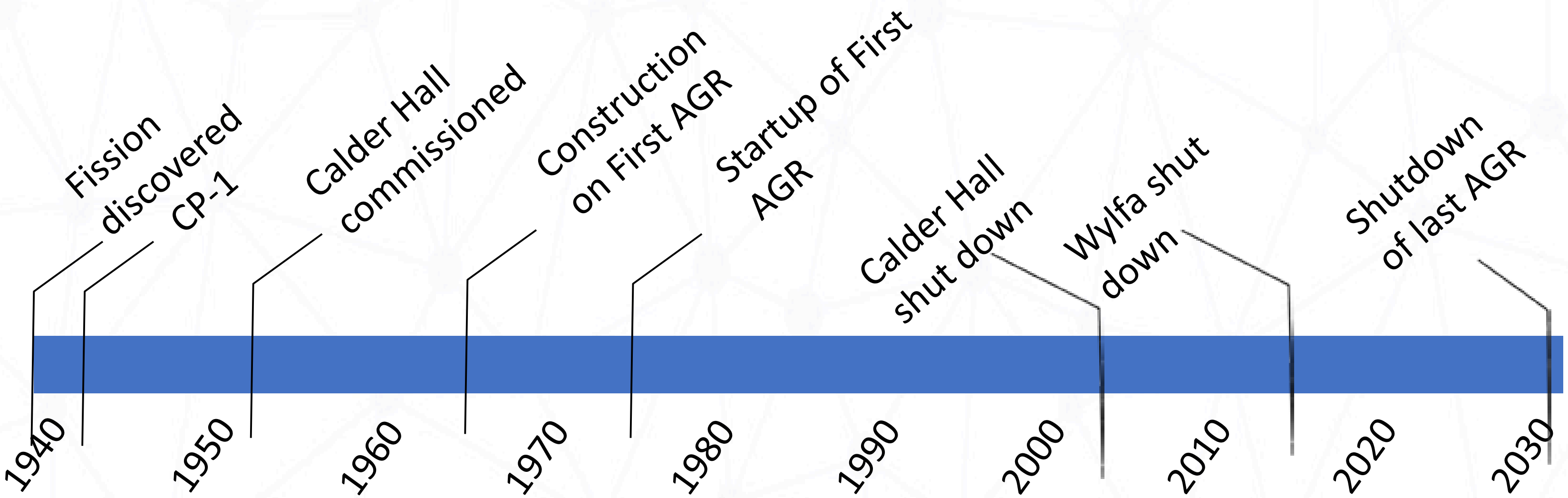
Prologue – Graphite-moderated, Gas-cooled Reactors (US/UK/France)

- CP-1 (air-cooled)
- Production/Power Reactors



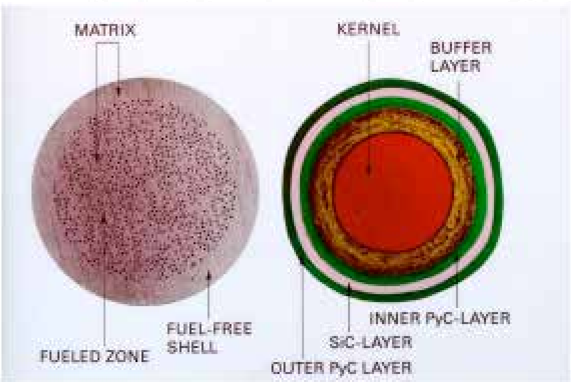


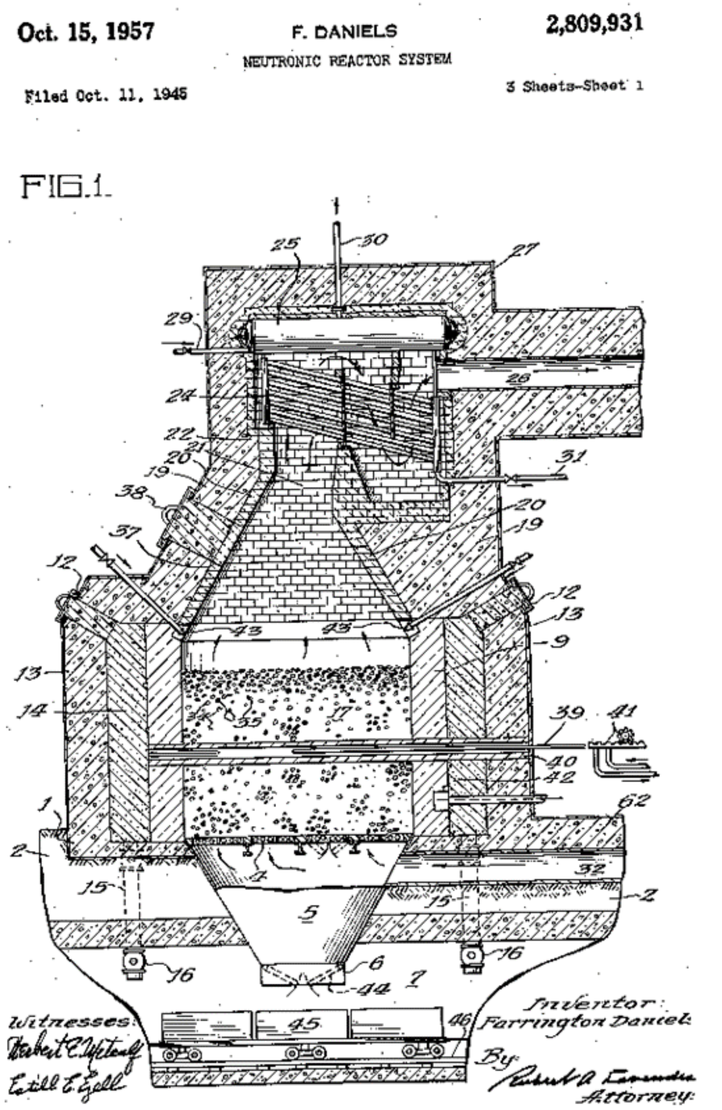
- CO_2 cooled
  - MAGNOX (UK), UNGG(Fr)
  - AGR (UO_2 pellets in SS, <650°C CO_2, concrete RPV, reasonable performance after a rocky start)



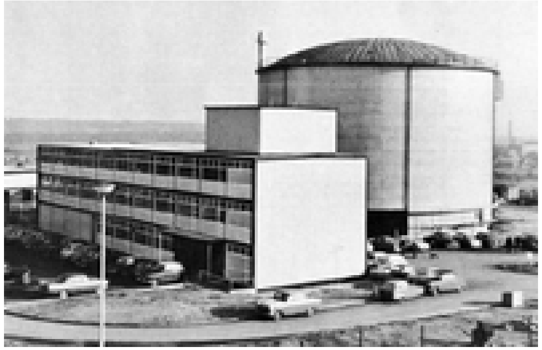
HTR Conceived

- Daniels Power Pile (1945)
  - F. Daniels (ORNL)
  - Graphite or BeO moderated
  - He cooled, 1350°F/732°C outlet
  - IHX and closed cycle Brayton
  - UC_2 or UO_2 in cladding
- Actual Experimental reactors followed
  - GCRE, ML-1, EGCR
- Final Puzzle Piece…Coated Fuel Particle
  - UKAEA, Battelle idea (~1957)
  - Superior retention of fission products at elevated temperatures (esp. in the TRISO version)

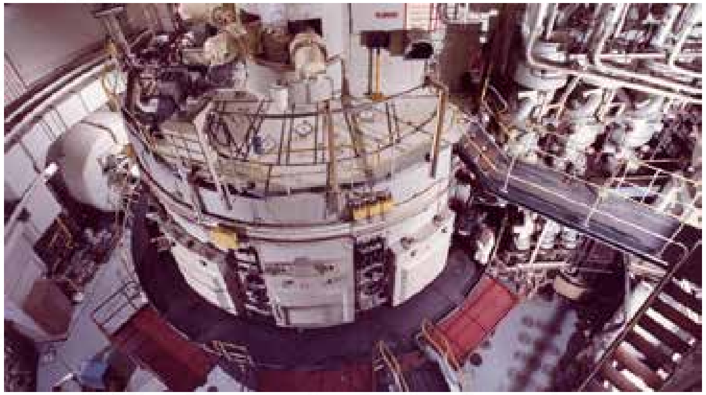


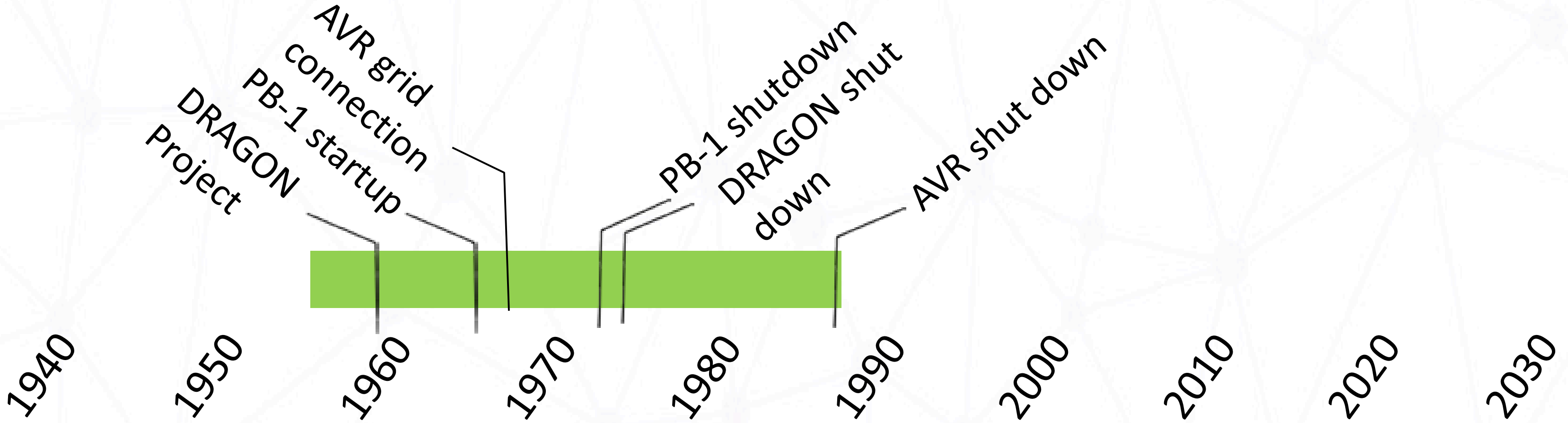


Phase 1 – Proof of Concept – DRAGON



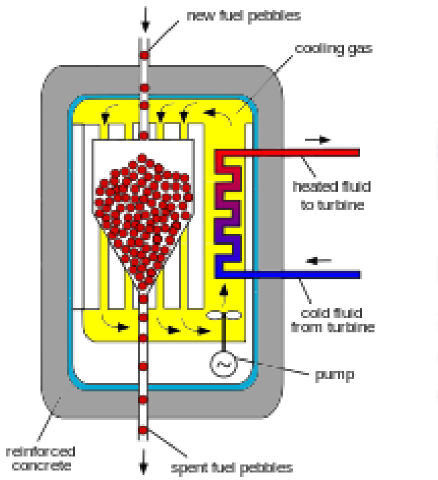
- Built in the UK under a OECD/Euratom sponsorship
- Particle fuel and material testing
- Engineering challenges encountered and resolved
  - Control rod bowing
  - Replacement of inner reflector blocks
  - IHX and pipe corrosion

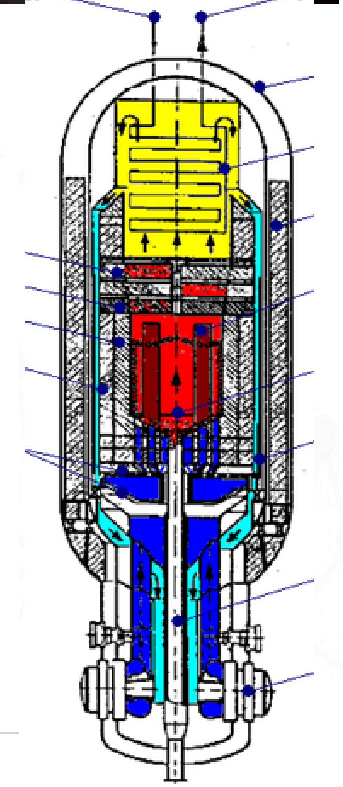




Arbeitsgemeinschaft VersuchsReaktor (AVR) (Germany)

- Pebble Bed reactor conceived by R. Schulten
- Arbeitsgemeinschaft VersuchsReaktor – 40 MWt/15 MWe prototype PBR for testing systems and fuels (BISO/TRISO)
- He-cooled up to 950°C at the outlet
- Only One (1!) operator needed for reactor/primary circuit operation
- Shutdown achieved by stopping forced circulation (rods inserted after cooldown)
- Growing pains
  - Leaky shield led to steam generator (SG) contamination
  - 1978 SG leak dumped 27 m^3 of water into the core while shut down (dried out and restarted)
  - Unpredicted high core temperatures

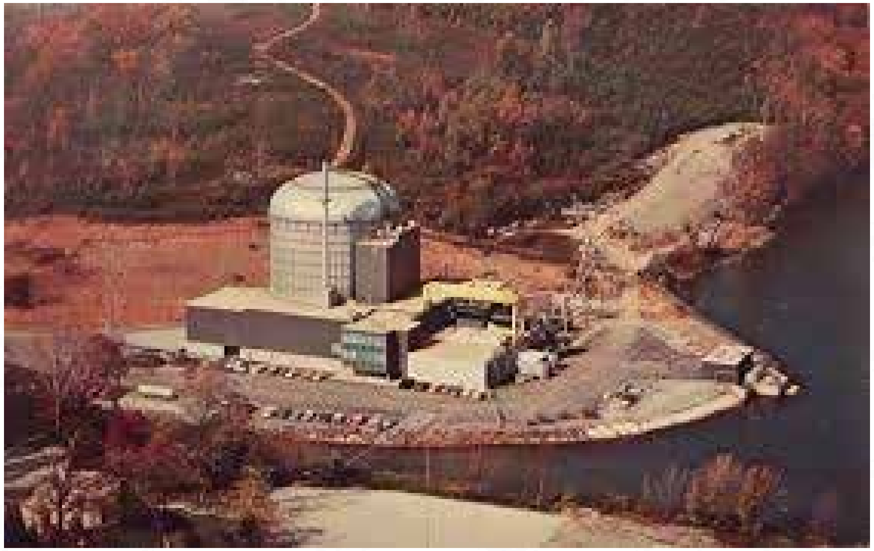


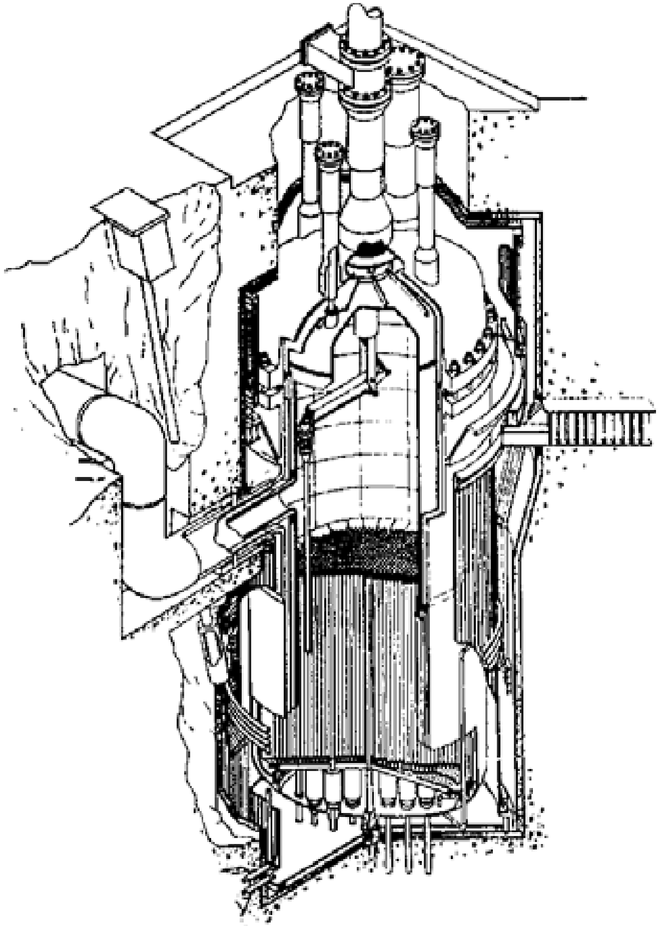


Despite some bad publicity (Moorman, 2008), AVR is considered an HTR success story (Kuppers, 2014).

Peach Bottom 1

- 115 MWt/40 MWe designed by General Atomics with support from the AEC and 57 utilities
- Prismatic – BISO coated fuel particles (cfp) in compacts/blocks
- 85% availability, load following, low operator doses
- Growing pains – Some cracking of blocks in the first core





Kingrey, K., “Fuel Summary for Peach Bottom Unit 1 High Temperature Gas-Cooled Reactor Cores 1 and 2”, INEEL/EXT-03-00103, April 2003.

Phase 2 – Commercial Demo – Fort St. Vrain

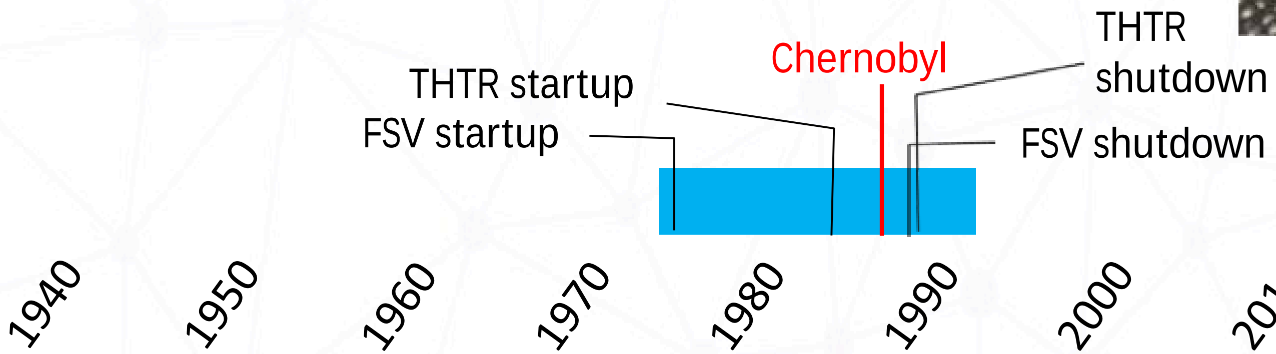
- 842 MWt/330MWe General Atomics design built with support form 57 utilities
- HEU/Th coated fuel particles in compacts/blocks
- Pre-stressed concrete Pressure Vessel (PV)
- Very low worker doses
- Growing pains resulted in low availability
  - Core flexing à coolant oscillations (restraints recommended)
  - Leaky water-lubed gas circulators led to large ingress event
  - Core thermal fluctuations (Xe)
  - Reserve shutdown malfunction, hot He bypass on CR drives

Despite these engineering issues, modern HTGR technology was demonstrated.

Shenoy, History and Evolution - Module 2A -HTGR Technology Course for the Nuclear Regulatory Commission, 2010.

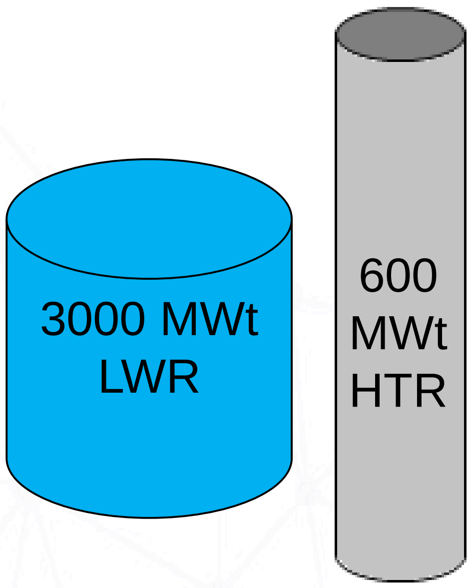
Thorium High-temperature Nuclear Reactor

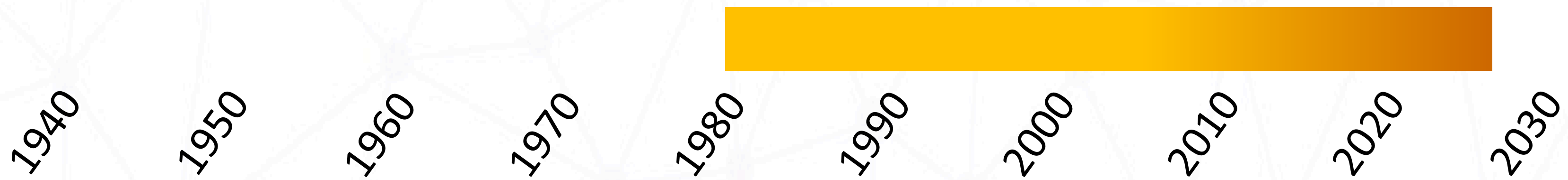
- 750 MWt/300 Mwe German Design
- HEU/Th cfp in pebbles
- Prestressed concrete PV
- Dry cooling
- Growing pains
    - Broken pebbles (shutdown rod insertion)
    - He upflow hindered pebble discharge
    - Bolt heads detached from hot duct assembly



Phase 3 – Small and Modular (mHTGR)

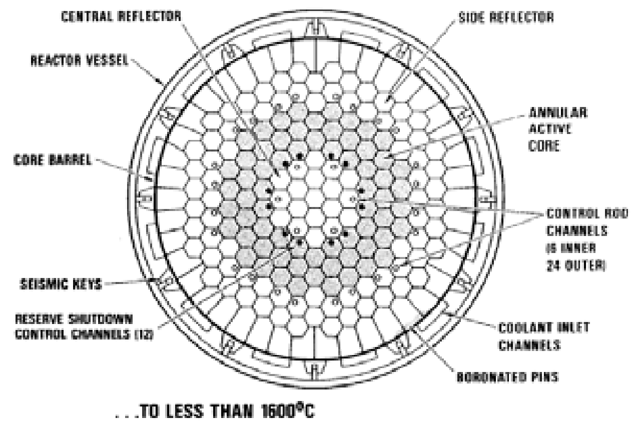
- Larger HTRs were envisioned after FSV and THTR
  - Low power density meant that the vessel would be huge
  - Active decay heat removal required
- Modular
  - Multiple modules with staggered deployment
  - Passive heat removal (high aspect ratio)

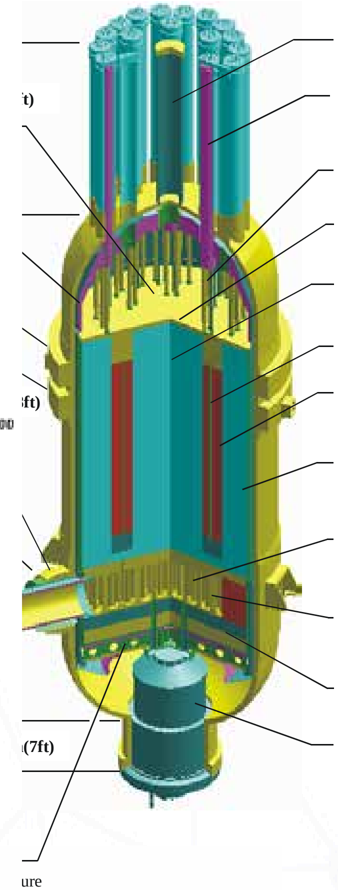


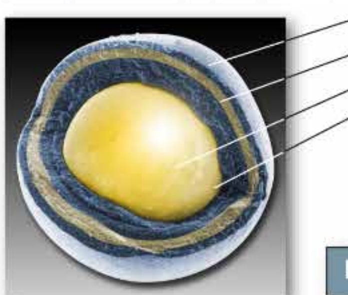


Modular High Temperature Gas-Cooled Reactor (MHTGR)

- General Atomics (GA) design, coalition of industrial interests
- 350 MWt prismatic (annular core) in a steel RPV
- Draft Pre-Application SER issued by NRC in 1989, revised and re-issued in 1995
- The basis for subsequent modular prismatic reactor designs such as the New Production Reactor, GT-MHR, Deep Burn MHR, AREVA SC-HTGR



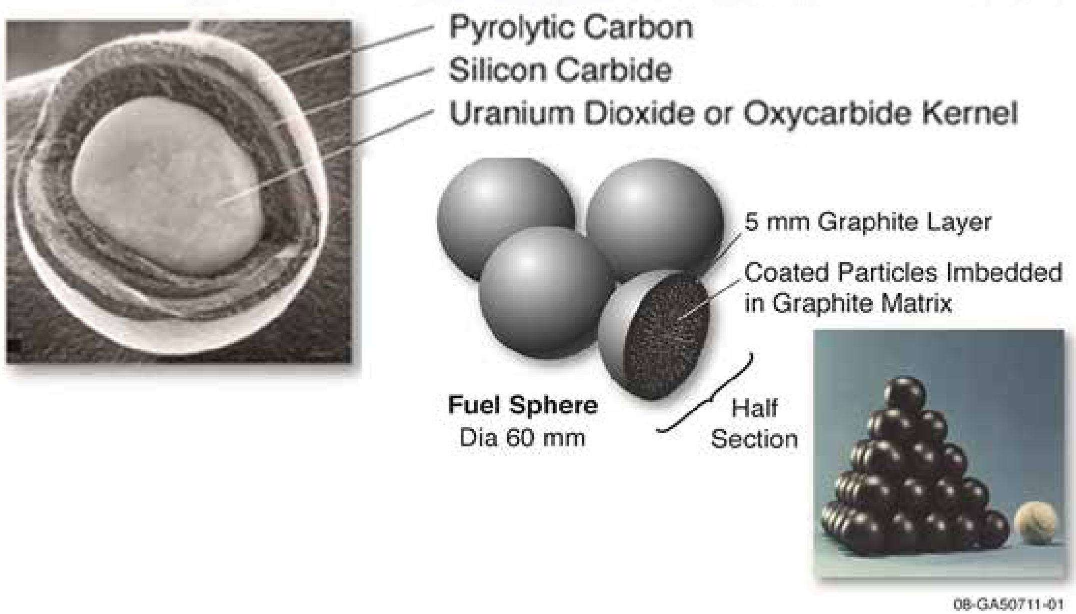


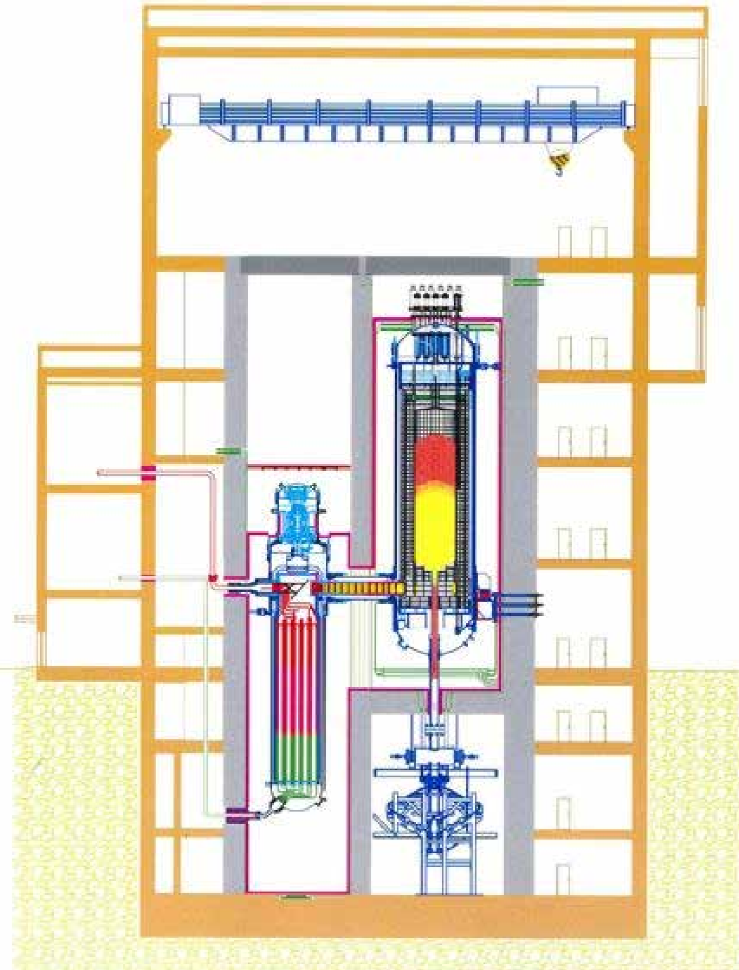


TRISO-coated fuel particles (left) are formed into fuel compacts (center) and inserted into graphite fuel elements (right) for the prismatic reactor

HTR Modul

- KWU/Siemens-Interatom
- 200 MWt pebble bed with online recirculating fuel (high burnup)
- Design submitted to German Licensing Authority in the late 1980's
- The basis for subsequent modular PBR designs like the PBMR and HTR-PM



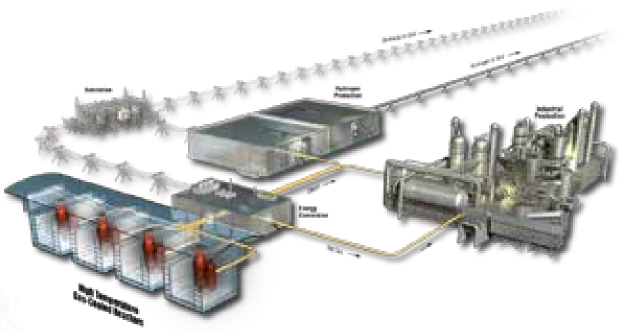


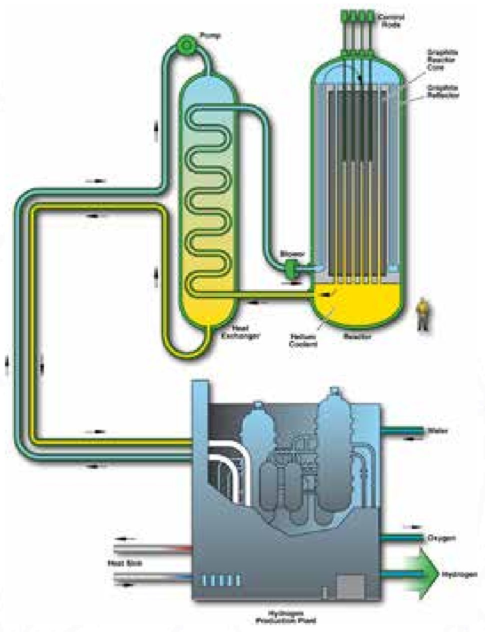
Lessons Learned

- HTR Potential was recognized very early
  - Accident tolerant fuel (TRISO)
  - Process heat applications
  - Modularity
- Problems (engineering) were typical of FOAK efforts – not generally inherent to the technology
  - Poor fuel performance in NPR, MHTGR
- Sensitive to the market, and politics
- NRC draft SER
  - Event selection was ok; TRISO fuel was problematic
- NGNP
  - (AGR) TRISO Fuel is ok; event selection needs work (current License Modernization Project is addressing this issue)

Phase 4 – Energy Security and Flexibility (CO_2-free)

- Government-sponsored R&D
  - US (NGNP/ART) – EPACT 2005, fuel and material qualification, etc.
  - Japan (JAEA) – technology development since the 1980s, HTTR, gas turbine and H_2 technology
  - China (INET) – keeps it simple (200 MWt PBR), 2-unit demo under construction and a '6-pack' looking for a site
  - Generation IV International Forum VHTR
- Industrial Interest
  - NGNP (GA, AREVA/Framatome, Westinghouse/PBMR)
  - X-energy, BWXT(fuel),
  - vSMR – StarCore, U-Battery, UltraSafe Nuclear, HolosGen, BWXT, X-Energy





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1940 1950 1960 1970 1980 1990 2000 2010 2020 2030

International Efforts

South Africa

- In ~1998 the PBMR company tried to pick up where HTR Modul left off. Ran out of Government support in 2010. Almost $1B spent
- Some very nice test facilities constructed

He Test Facility Pelindaba

Japan

- Steady prismatic HTR technology development since the 1980's
- Nice 30 MWt engineering-scale reactor (to be connected to a gas turbine and H_2 plant)
- 50, 300, and 600 MWt commercial designs
- Working on gas turbine and H_2 technology

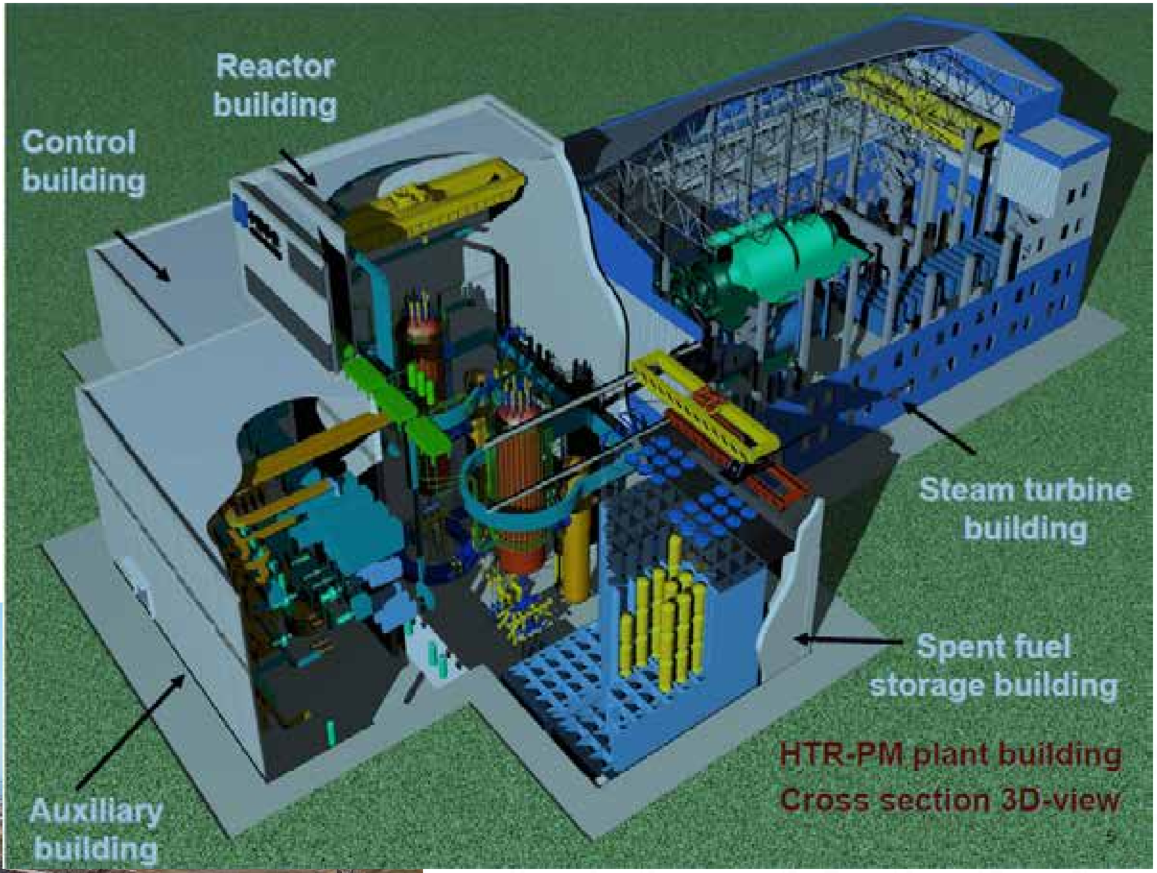
HTTR (Japan: 1999-)

China

- 10 MWt engineering scale reactor
- 2 unit HTR-PM DPP to go critical in 2019
- Impressive engineering test facilities

HTR-10 (China: 2000-)

HTR-PM under Construction in Weihai, China



Overview of HTGR Projects in China, Technical Meeting on Knowledge Preservation for Gas Cooled Reactor Technology and Experimental Facilities, Vienna, Austria, 2018.

Suggested Reading List

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