History of HTGR

Dominique Hittner
Contents

- Prehistory
- HTGR birth
- First HTGR deployment
- Transition to a new generation of HTGR: new features
- The new generation: modular HTGR
- Summary and conclusion
HTGR

- High Temperature
- Helium cooled
- Graphite moderated
HTGR Family Tree
Prehistory
“Birth of the Atomic Age”

Painting by Gary Sheahan
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1942</td>
<td>First Self-sustained Chain Reaction (E. Fermi)</td>
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<tr>
<td>1943</td>
<td>3,5 MW Graphite-moderated Production Reactor (ORNL)</td>
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<td>1947</td>
<td>Graphite-moderated GCR at Brookhaven</td>
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<tr>
<td>1948</td>
<td>36 MW\textsubscript{th} British Experimental Pile Operation (BEPO)</td>
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<td>1950</td>
<td>160 MW\textsubscript{th} Windscale Plutonium Production Reactors</td>
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<tr>
<td>1951-53</td>
<td>UK studies on CO\textsubscript{2}-cooled MAGNOX Reactors</td>
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<tr>
<td>1956-59</td>
<td>Commissioning of four Calder-Hall Reactors (240 MW\textsubscript{el} total)</td>
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<tr>
<td>1956-68</td>
<td>Air-cooled 1,7 MW\textsubscript{el} G-1 at Marcoule, France</td>
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<tr>
<td>1957</td>
<td>First Commercial GCR in France: 70 MW\textsubscript{el} Chinon A1</td>
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<tr>
<td>1963</td>
<td>30 MW\textsubscript{el} Advanced GCR (AGR) in Windscale (400°C → 600°C)</td>
</tr>
<tr>
<td>1976</td>
<td>First Commercial AGR at Hinkley Point B (625 MW\textsubscript{el} / 41,5 %)</td>
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</table>
Commercial GCR

- Graphite moderated
- \( \text{CO}_2 \) closed cycle inside the concrete reactor vessel limiting temperature (corrosion)
- Steam generators inside the reactor vessel
- Conventional steam conditions (~ 540°C)
- High thermal efficiency (> 40%)
Some Exotic Reactors (1)

3.3 MWth Mobile Low-Power Reactor (ML1), with closed cycle gas turbine – US army, 330 kWe (1962-63)
Some Exotic Reactors (2)

Ultra-High-Temperature Reactor Experience (UHTREX) – ORNL
https://www.osti.gov/servlets/purl/4375338

Thermal Power: 3 MW
Helium Coolant: 3.4 MPa
Temperature $\text{in}^\circ C$: 870
Temperature $\text{out}^\circ C$: 1300
Extruded Fuel with TRISO C.P.
Annular Rotatable Core
On-line Refuelling
Operation: 1966-70
The Invention of HTGR Design

- Mid 1950s: Initial Studies on HTR in UK, US and Germany
- 1960s: Construction & Operation of Prototypes

**Common features**

- Fully Ceramic Core
- Non-Corrosive & Neutronically Inert Helium Coolant
- High Operating Temperatures
- High-Purity Graphite as Moderator and Reflector
- Slow Accident Progression (heat capacity, low power density)
- Self Stabilisation of Nuclear transients (negative temperature coefficient)
The Invention of the Coated Particle Fuel

- First UO$_2$ or UC in ceramic clad: weak fission product (FP) retention
- Invention of Coated Particle in 1957-61 by UKAEA and Battelle
- Kernels made by precipitation from uranyl nitrate in ammonia
- Coatings via pyrolysis of hydro-carbons in fluidized-bed
- Early BISO particles contain buffer & two PyC layers
- TRISO have additional SiC diffusion barrier: FP retention till 1600°C
- Fuel elements
  - Compacts → Blocks → Prismatic core
  - Pebbles → Pebble bed
Two Types of HTGR Fuel Assemblies and Cores

- **Pebble bed core**
- **Compact Block**
- **Block type core**
- **TRISO particle**

- Pebble: 1mm
- Block: 60mm

UO$_2$ or UCO kernel
First HTGR deployment
# Main Features of HTGR Reactors Being Operated

<table>
<thead>
<tr>
<th>Feature</th>
<th>Unit</th>
<th>DRAGON</th>
<th>Peach Bottom</th>
<th>FSV</th>
<th>AVR</th>
<th>THTR</th>
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<tr>
<td>Power (th)</td>
<td>MW</td>
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<td>842</td>
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<td>PCRV</td>
<td>Steel (double)</td>
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<td>Efficiency</td>
<td>%</td>
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<td>BISO</td>
<td>TRISO</td>
<td>BISO/TRISO</td>
<td>BISO</td>
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<td>Enrichment</td>
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<td>HEU</td>
<td>HEU (Pu)</td>
<td>HEU &amp; Th fertile</td>
<td>HEU / LEU</td>
<td>HEU &amp; Th fertile</td>
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<td>Status</td>
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<td>decommissioned</td>
<td>defuelled</td>
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Operating experience (1)

- OECD project in UK
- Good operation during 10 years, but corrosion issues
- Successful demonstration of core heat-up accident (80 days at 1800°C) ⇒ slow fission product release up to $10^{-2}$

**DRAGON test reactor**

Peach Bottom prototype, US, 40 MWe

- U/Th fuel in PyC shell, compacts in 12ft sleeves
- Successful test of Pu-burning (17 g) up to very high Bu
- Availability: 58 (Core 1) - 88% (Core 2)
- Load following demonstrated
- 90 Fuel elements cracked in Core 1, but BISO coated fuel particles exceeded expectations (Core 2)
Operating experience (2)

Fort Saint Vrain prototype, 330 MWe

- Demonstrated TRISO fuel and nuclear physics of block-type core
- Very low collective dose <1 man-rem
- Forgiving operational behaviour

Main issues
- Water cooling pump cavitation ⇒ one year delay
- He circulator and seals leaked bearing water ⇒ many delays
- Reserve shutdown malfunction
- Hot helium bypass and corrosion on control rod drives
- Core fluctuations ⇒ 70% power
- Core support floor liner cooling system leakage

- FSV totally decommissioned in 1997

AVR prototype.
Germany, 15 MWe

- High availability over 21 years of operation to 1988
- Core outlet temperature increased 850°C to 950°C
- Very low personnel doses
- Mass test of HTR fuel
- High Burn-up ~ 20% fima
- Safety demonstrated via passive core cooling
- Survived water ingress accident
- Ceramic structures OK except bottom reflector cracks
- Decommissioning experience
Operating experience (2)

- Commercial project although significant deviations from AVR:
  - inverse helium flow top-to-bottom
  - higher power density. 2 MW/m³ ⇒ 6 MW/m³
  - 42 absorber rods directly driven into the core
  - Pre-stressed Concrete Reactor Pressure Vessel (PCRV)

- Good operational behaviour and low activity in primary circuit, but
  - cracking of pebbles due to many core rod insertions (~ 8000 of 675 000)
  - malfunction of on-load de-fuelling at full power
  - irradiation-induced failure of bolts in hot-gas duct insulation

- Fatal coincidence with Tschernobyl accident and “Transnuclear Scandal”
- Shut-down in Sept. 1989 after 16.410 h operation; availability 61,7 % in 1987
- Fuel Burn-up ~ 100 GWd/t, Reactor now in safe enclosure
Designs of Large block type HTGR in the US

1 Control rod drive & refueling penetrations
2 Circulator
3 Feedwater access shaft
4 Steam generator
5 Liner prestressing system
6 PCRV (pod boiler)
7 Auxiliary circulator
8 PCRV
9 Core
10 Circumferential prestressing system
11 Core auxiliary heat exchanger

1160 MWe

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<tr>
<th>Feature</th>
<th>Unit</th>
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<th>770 MW</th>
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<td>7.05</td>
<td>8.45</td>
<td>9.88</td>
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# Designs of Large block type HTGR in Germany

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<tr>
<th>ACRONYM</th>
<th>Application</th>
<th>Cycle</th>
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<tr>
<td>HTR 1160</td>
<td>EL</td>
<td>SC</td>
<td>HB</td>
<td>700-1540 (el)</td>
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<td>HTR-K</td>
<td>EL</td>
<td>SC</td>
<td>PB-OTTO</td>
<td>1120 (el)</td>
<td>D</td>
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<td>HHT</td>
<td>CHP</td>
<td>DC</td>
<td>HB &amp; PB</td>
<td>1000-1240 (el)</td>
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<td>CHP</td>
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<td>PB-OTTO</td>
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<td>HTR-500</td>
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<td>PB-OTTO</td>
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<td>NHP</td>
<td>IHX, SR</td>
<td>PB-OTTO</td>
<td>3000 (th)</td>
<td>D</td>
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<td>PNP-Demo</td>
<td>NHP</td>
<td>IHX, SR</td>
<td>PB</td>
<td>500 (th)</td>
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<td>HTR-Modul</td>
<td>CHP</td>
<td>SC</td>
<td>PB-MEDUL</td>
<td>200 (th)</td>
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<td>GHR-10</td>
<td>DH</td>
<td>IHX</td>
<td>PB-Batch</td>
<td>10-20 (th)</td>
<td>D, CH</td>
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</table>

HB: Hexagonal Block  
PB: Pebble Bed  
OTTO: Once-through-then-Out  
MEDUL: Multiple-Recycling of pebbles
Transition to a new generation of HTGR: new features
1. Direct helium cycle

1. LP Compressor
2. Intercooler
3. HP Compressor
4. Recuperator
5. Heater
6. HP Turbine
7. LP Turbine
8. Pre-Cooler
8.1 District Heat Removal
9. Gear

EVO simulation of direct cycle plant for cogeneration of district heat and electricity

- 159.6 MW thermal
- Gas-fired heater
- 30 MWel Output
- District Heat
- 750°C / 27 bars

Helium High Temperature Test Facility (HHV) at FZJ
2. Application to Industrial Process Heat

The PNP-500 Project

Steam Methane Reformer Bundle

IHX header

Hot gas valve

KVK Loop
The new generation: modular HTGR
A safety issue and a new technical solution

A problem: the maximum possible temperature of HTGR in case of severe accident increases with the power. How to keep it below the limit of integrity of the fuel?

A solution:
- A fuel that keeps its integrity up to high temperature: the TRISO fuel
- A design that physically prevents the temperature to exceed the fuel integrity limit:
  - Limited power (< ~ 250 MWth for pebble bed and 600 MWth for block type core)
  - A metallic vessel to release heat by radiative heat transfer
The first commercial designs in the 1980s’

**HTR-Module in Germany**
(Siemens / INTERATOM)

- 200 MWth
- Pebble bed design
- Designed with
  - steam generator
  - intermediate heat exchanger
  - steam reformer
2 test reactors at the end of the 90s’

HTR-10, China
Pebble bed, 10 MWth

Still operational

- Under regulatory review after Fukushima accident
- To be coupled with H₂ production plant
### Recent projects (1)

All reactors are following modular design principles.

#### Core Types and Thermodynamic Cycles

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Core Type</th>
<th>Thermodynamic Cycle</th>
<th>Main Applications</th>
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</thead>
<tbody>
<tr>
<td>GT-MHR (GA + Russia)</td>
<td>Prismatic</td>
<td>Direct cycle</td>
<td>Power generation, Burning Pu</td>
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<tr>
<td>SC-MHR (GA)</td>
<td>Prismatic</td>
<td>Steam cycle</td>
<td>Cogeneration of electricity &amp; steam</td>
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<tr>
<td>PBMR (South-Africa)</td>
<td>Pebble bed</td>
<td>Direct/steam cycle</td>
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<tr>
<td>ANTARES (AREVA)</td>
<td>Prismatic</td>
<td>Indirect combined cycle</td>
<td>Cogeneration of electricity &amp; heat</td>
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<tr>
<td>SC-HTGR (AREVA)</td>
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<td>Steam cycle</td>
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<td>GTHTR-300 (JAEA)</td>
<td>Prismatic</td>
<td>Direct cycle</td>
<td>Power generation &amp; H₂ production</td>
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<tr>
<td>HTR-PM (China)</td>
<td>Pebble bed</td>
<td>Steam cycle</td>
<td>Power generation</td>
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</tbody>
</table>

#### Diagrams

- **GT-MHR recuperated direct cycle configuration**
- **SC-MHR steam cycle configuration**
- **ANTARES indirect combined cycle configuration**
Recent projects (2)

ANTARES

GT-MHR

PBMR

GTHTR 300
The NGNP project (1)

- Energy Policy Act of 2005 established Next Generation Nuclear Plant project to build demonstration of HTGR technology by 2021

- Pre-Conceptual Designs by three vendor teams completed in 2007:
  - Westinghouse (PBMR based)
  - General Atomics (MHTGR based)
  - AREVA (SC-HTGR based)

+ Pre-licensing engagement with NRC

- Funding Opportunity Announcement (FOA) issued by the DOE in Sept. 2009 for Phase 1 NGNP conceptual design, cost and schedule estimates, and business plan preparation.
The NGNP project (2)

- FOA awardees announced March 8, 2010: Westinghouse and GA
- Westinghouse withdrew due to the end of PBMR project
- Phase 1 finalised with a project review early 2011
- No Phase 2 launched by the DOE, NGNP activities continued through the NGNP Industry Alliance gathering vendors and end-users.
- The NGNP design programme has been supported by an important R&D programme in US National Labs:
  - Fuel qualification
  - Graphite qualification
  - Testing to support design code validation
Present project: HTR-PM

March 2016

December 2017
New trends

- Micro-reactors for isolated sites and military bases
- In Europe, emphasis on steam supply to steam networks of large industrial sites
Summary and conclusion
Summary

3 phases of HTGR development

- **First Phase** HTGR (DRAGON, Peach Bottom, AVR) proved
  - Basic Concept and Fission Product Retention of CP Fue
  - High availability, low contamination, failure tolerance
  - Capability for high temperature operation ~ 950°

- **Second Phase** HTGR (FSV, THTR) were commercially erected and operated but suffered from prototypical and economic problems. They demonstrated the feasibility of medium-sized cores

- **Third Phase** Modular HTR recur to proven technology:
  - Inherent safety features
  - Simplified systems, series effects in construction
  - Capability for high efficiency power generation / process heat
  - Even two Test Reactors available (HTR-10, HTTR)
Conclusion

- HTGR technology has an extensive base of design, licensing and operating experience with valuable lessons learned

- Prismatic and pebble bed systems share large common base of technology, systems and components

- There is still a large potential for progress:
  - Higher operating temperature
  - Cost reduction
  - Extended market (micro-reactors for isolated sites, industrial heat)