High Temperature (Gas Cooled) Reactors
IAEA Activities

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Gas-Cooled Reactors Technology
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Contents ...

• Introduction to HTRs

• The Generation–IV goals – why interest in HTR / VHTR
  – Safety characteristics
  – Other goals

• Key technology “pillars” needed for HTGRs near term deployment and IAEA support activities
  – Coated particle fuel
  – Graphite and its behaviour
  – Uncertainties in modelling
  – High temperature materials
  – Safety Design Criteria

• Concluding remarks
HTGR family pedigree

- Gas cooled reactors
  - Helium coolant
  - Coated particle fuel
  - Gas outlet temperature > 700°C
  - Gas outlet temperature > 900°C

- Graphite moderator

- HTGR
  - Thermal spectrum
  - Fast spectrum + no graphite

- VHTR

- GFR
Prismatic (block-type) HTGRs
Pebble type HTGRs

- Spherical graphite fuel element with coated particles
- Possibility of continuous fuel loading / shuffling
- Fuel loaded in cavity to form a pebble bed

Pebble Bed Reactor (PBR)
The coated particle design

Triso fuel triumphs at extreme temperatures up to >1800°C

• The key safety feature:
  – Fission product retention capability of coated particle fuel
  – It contains the vast majority of all fission products even under the most severe postulated accidents
Generations of Nuclear Energy

- **Generation I**
  - Early Prototypes
  - Shippingport
  - Dresden
  - Magnox

- **Generation II**
  - Commercial Power
  - PWRs
  - BWRs
  - CANDU

- **Generation III**
  - Advanced LWRs
  - CANDU 6
  - System 80+
  - AP600

- **Generation III+**
  - Evolutionary Designs
  - ABWR
  - ACR1000
  - AP1000
  - APWR
  - EPR
  - ESBWR

- **Generation IV**
  - Revolutionary Designs
  - Safe
  - Sustainable
  - Economical
  - Proliferation Resistant and Physically Secure

Year Timeline:
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030
Generation IV Goals

- Sustainability
  1. Generate energy sustainably, and promote long-term availability of nuclear fuel
  2. Minimize nuclear waste and reduce the long term stewardship burden
- Safety & Reliability
  3. Excel in safety and reliability
  4. Have a very low likelihood and degree of reactor core damage
  5. Eliminate the need for offsite emergency response
- Economics
  6. Have a life cycle cost advantage over other energy sources
  7. Have a level of financial risk comparable to other energy projects
- Proliferation Resistance & Physical Protection
  8. Be a very unattractive route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism
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Inherent Safety Characteristics

Ceramic coated particle fuel retains radioactive materials up to and above 1800°C
Inherent Safety Characteristics

Heat removed passively without primary coolant – all natural means
Inherent Safety Characteristics

Fuel temperatures remain below design limits during loss-of-cooling events
Inherent Safety Characteristics

Coated particles stable to beyond maximum accident temperatures
Inherent Safety Characteristics

- Containment of Fission Products – Illustration at DLOFC conditions (with a break in the primary system)
Inherent Safety Characteristics

Ceramic fuel retains radioactive materials up to and above 1800°C

Heat removed passively without primary coolant – all natural means

Coated particles stable to beyond maximum accident temperatues

Fuel temperatures remain below design limits during loss-of-cooling events
Significantly improved safety characteristics

- No core meltdown and very low severe core damage frequency by massive air ingress
- Can sustain full load rejection / station blackout conditions
- No need for multiple layers / multiple trains of cooling capabilities
- Simplified designs and few safety related systems

• Passive safety characteristics is achieved through:
  - Low power density (~ 30 times lower than LWRs).
  - Strong negative temperature coefficient means the reactor automatically shuts down without operator interaction.

• Most transients are slow (develop over hours and days)
  - Very large heat capacity (>800 tons of graphite)
  - Maximum fuel temperatures in DLOFC after 24-36 hours
Significantly improved safety characteristics

- Coolant is decoupled from neutronics
- But, water and air ingress needs to be limited

- The intrinsic properties of modular high temperature gas cooled reactors (HTGRs) minimize and, in many cases, eliminate concerns over off-site and on-site power, or need for many safety systems
- BUT, the reactor designer must still assure a safe design – must stay true to the modular HTR safety philosophy
- For licensing it is essential that these safety characteristics must be taken into account
  - have to accept a different approach in fulfilling the fundamental safety requirements to allow commercial competitiveness
- Should be possible to place reactors closer to the heat users
Why HTGRs – other GEN-IV goals

Economics

- Higher (↑20-50%) efficiency in electricity generation than conventional nuclear plants
- Market is growing for smaller reactors
  - Position close to markets or heat users
  - Savings in transmission costs
  - Smaller capital cost (cost of electricity may be higher than large LWRs)
  - Can be deployed in smaller markets / off-grid in isolated locations
- Potential to participate in the complete energy market – huge market potential
HTGR technology addressing the energy challenge

Extended scope of application due to higher temperatures available
Supply of process steam for petro-chemical industry and future hydrogen production
Process heat / co-generation


Near term market potential
North America / USA only:

250-500°C = 75,000MWt
(or 150-300 reactors)
Mostly Petroleum products:

500-700°C = 65,000MWt
(or 130 – 260 reactors)
(Petroleum + Ammonia)

Easily achievable today

Allows flexibility of operation switching between electricity and process heat
Why HTGRs – other GEN-IV goals

Sustainability

- Very adaptive with LEU, MOX, Deep Burn, Thorium
- Several studies performed on U, Pu and Th cycles with high burnup (>200,000 MWd/t).

Proliferation resistance

- offers enhanced non proliferation characteristics with better in-situ utilization of Pu and unfavourable Pu isotopic mix
- Efficiently burns Pu, 20% more efficient that LWRs
High Temperature Gas cooled Reactors

Past Experience | Current test reactors

<table>
<thead>
<tr>
<th>DRAGON</th>
<th>PB-1</th>
<th>AVR</th>
<th>FSR</th>
<th>THTR</th>
<th>HTTR</th>
<th>HTR-10</th>
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- Extensive operating experience
- Mature technology ready for commercial deployment (in next decade) for temperatures up to ~850 °C
- Wealth of know-how available
- Interest from new-comer countries
  - Indonesia (BATAN) experimental power reactor
Newest HTGR designs information

HIGH TEMPERATURE GAS COOLED REACTORS

- HTR-PM (Tsinghua University, China)
- GT-HTR300 (Japan Atomic Energy Agency, Japan)
- GT-MHR (OKBM Afrikantov, Russian Federation)
- MHR-T reactor/Hydrogen production complex (OKBM Afrikantov, Russian Federation)
- MHR-100 (OKBM Afrikantov, Russian Federation)
- PBMR-400 (Pebble Bed Modular Reactor SOC Ltd, South Africa)
- HTMR-100 (STL, South Africa)
- SC-HTGR (AREVA, USA)
- Xe-100 (X-energy, USA)
New deployment of HTGRs – a reality

HTR-PM construction of a commercial demonstration plant

Shidao Bay, Shandong province, China
New deployment of HTGRs – a reality

HTR-PM construction of a commercial demonstration plant
IAEA activities support research, cooperation and information exchange in the technology “pillars” needed for HTGRs for near term deployment
Some pillars related to Technology Development

- Safety
- Coated particle fuel
- Technology and Knowledge (Preservation)
- Materials (high temperatures)
- Economical analysis
- High fidelity analysis and tools
- Co-generation
- Information sharing (stakeholder engagement)
IAEA activities supporting these areas through Member State activities

Nuclear Power Technology Development
http://www.iaea.org/NuclearPower/Technology/

Gas Cooled Reactors
http://www.iaea.org/NuclearPower/GCR/

The HTGR pillars
Coated particle fuel

- Large scale production demonstration with irradiation and accident temperature tests
- IAEA-TECDOC-CD-1674 Advances in High Temperature Gas Cooled Reactor Fuel Technology
- TECDOC: Performance Evaluation of German Mixed Thorium-Uranium and Uranium Oxide TRISO Fuels (In process for publication)
- Re-evaluation of maximum operating temperatures and accident conditions for HTGR fuel and high temperature material performance (new TECDOC)
High fidelity analysis

- Uncertainty in design and safety analysis (CRP)
  - Determine the uncertainty in HTGR calculations at all stages of coupled reactor physics, thermal-hydraulics and depletion calculations
  - Use well defined test cases to propagate uncertainties
  - Develop a methodology but also quantify the most important uncertainties in HTGR design and safety analysis
  - 9 organizations
  - 7 member states
  - Closely follow the OECD LWR Uncertainty Benchmark
  - 3rd RCM to be hosted by INL, USA from 9-12 May 2016
More pillars - HTGRs

- **HTGR Training**
  - IAEA Course on High Temperature Gas Cooled Reactor Technology
  - under development - long term plan and knowledge preservation
  - First course hosted by INET 22 – 26 October 2012, Beijing, China
  - Last course took place from 19-23 Oct 2015 “Training Course on High Temperature Gas Cooled Reactor (HTGR) Technology”, BATAN, Serpong, Indonesia

- Economic Analysis of High Temperature Gas Cooled Reactors and Small and Medium Sized Reactors (25-28 August 2015)

- Technologies to Reduce Waste from Gas Cooled Reactors (Q4 2016)
- Knowledge Preservation of Gas Cooled Reactor Technology (Q4 2016)
  - A HTGR Knowledge Base Portal is also under development
  - Project launched to transfer FZJ knowledge and codes to IAEA for preservation
IAEA Nuclear Graphite Knowledge Base

to support the preservation and sharing of expert knowledge and experience, across the international Graphite Community.

Databases

http://nucleus.iaea.org/sites/graphiteknowledgebase/Pages/home.aspx
Nuclear Graphite KB

• seek to learn from the behaviour of existing graphites how new graphites will behave and how existing graphites will perform at fluences we have not yet reached

• The knowledge base contains two levels of knowledge:
  – General information on the subject of Nuclear Graphite
  – Specialist knowledge, secured for members of the international project
  – All data captured in … Microsoft Excel (>34,000 lines)
  – Links provided to source documents and QA evaluation

• Taxonomy under development and testing of automated tools

• The Nucleus Sharepoint site is hosted and maintained by IAEA

• The 17th International Nuclear Graphite Specialists Meeting is hosted by IAEA (5 – 8 September 2016), Vienna, Austria (www.britishcarbon.org/ingsm)
  – All records of INGSM conferences are available on the KB site
Other activities in HTGRs

- The IAEA support HTGR R&D program in Indonesia and TC missions in support of the MPPR / Experimental Power Reactor project
- 10 MWt pebble bed HTR to be build;
- BATAN completed the concept design and safety case studies in 2015
  - TC missions: Sept 2013, April 2015, Sept 2015
  - DDG NE visit and consultancy meeting August 2014
  - New TC project for 2016 – 2017

Other TECDOC publications:

- Performance Evaluation of German Mixed Thorium-Uranium and Uranium Oxide TRISO Fuels (In process for publication)
- Discussion of Nuclear-Grade Graphite Oxidation in Modular High Temperature Gas-Cooled Reactors (In process for publication)
Ongoing CRP Year 2:
Modular High Temperature Gas-cooled Reactor Safety Design

- A unique safety design and safety criteria approach is needed for modular HTGR
- clarifying the safety approach and safety evaluation criteria
- multiple reactor modules and co-generation considerations
- Launched in December 2014
- 10 member states already participating

- Two publications planned (2017/18):
- NE Series Report: Modular High Temperature Gas-cooled Reactor Safety Design Criteria
- TECDOC: Modular High Temperature Gas-cooled Reactor Safety Design Methodology and Implementation Examples
Ongoing CRP: Year 2
HTGRs applications for energy neutral sustainable comprehensive extraction and mineral products development

First meeting held in November 2015
HTGRs applications for energy neutral sustainable comprehensive extraction and mineral products development

Main field of activity:
• Thermal processing of mineral resources with HTGR process heat .. while extracting impurities (U/Th) … that can fuel the reactor

Overall Expected Outcome
• A future more sustainable co-production option of mineral-U/Th extraction may be developed and commercially explored by member states based on the work
• Techno-economic investigations on the use of HTGRs as heat/electricity supplier for minerals and uranium/thorium recovery from unconventional resources;
  • phosphate rock using the thermal process during phosphate fertilizer production;
  • copper and gold ores during copper and gold mining/extraction;
  • by-products from rare earth elements mining;

Expected Results:
MS have access to a techno-economical study on the viability and application….. this information can be used as one input to decide on possible future deployment of HTGRs for this purpose.
HTGRs – Planned publications

• TECDOC on Role of Nuclear-Grade Graphite in Controlling Oxidation in Modular High Temperature Gas-Cooled Reactors

TECDOC on Improving the Understanding of Irradiation-Creep Behaviour in Nuclear Graphite:
• Part 1: Models and Mechanisms
• Part 2: Recent Developments

• TECDOC on Performance Evaluation of German Mixed Thorium-Uranium and Uranium Oxide TRISO Fuels

• Updated booklet
  • New booklet on Small Modular Reactor Technology Developments to be published (September 2016)
  • To include LWRs, Fast reactors, HTGRs and also MSR (for the first time)
Concluding remarks ...

• Its safety features and high outlet temperature are the strong point in meeting the Gen-IV goals – others mostly also favourable but may need more R&D

• The HTR-PM construction is providing new impetus on HTGR activities

• Also renewed interest from other member states
  – Indonesia planning the experimental power reactor
  – Japan planning hydrogen demonstration and new detailed design of commercial reactor

• Near term deployment
  – cogeneration potential, small grids, safety characteristics
  – Requires demonstrated technology in country of origin

• IAEA continues to support cooperation in GCR and HTGR focussed on key technology areas and knowledge preservation
Thank you!

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http://www.iaea.org/NuclearPower/GCR/
Extra Slides
Global developments and deployment

Japan

• HTTR completed of continuous 50-day high temperature (950°C) operation in March 2010
• Several safety demonstrations done and planned
• Hydrogen production technology: First achievement of continuous H₂ production by IS process in the world
• Design work on Naturally safe and Clean Burn HTGR designs (propose GTHTR 300 series for Middle East)

China:

• HTR-10 completed many safety tests
• HTR-10 upgrade on-going and further safety tests planned
• Construction of HTR-PM started in December 2012
• Helium test loop construction completed for full size testing of main equipment
• Fuel production factory construction started
• First criticality planned for late 2017
Other activities in the world

- **Indonesia**
  - On-going studies on reactor design, coated particle fuel, safety studies and co-generation
  - Small HTGR deployment for the Experimental Power Reactor project announced by government / BATAN

- **Korea (Republic of)**
  - Developing key technologies for HTGRs and focus on hydrogen production
  - Coated particle irradiation in HANARO

- **Russia**
  - GT-MHR project (joined project with USA) – for weapons grade plutonium disposition – Detailed reactor physics analysis
  - Special studies to investigate the potential of industrial nuclear power applications -> options for different industrial technologies
  - ASTRA critical facility
Other activities in the world

- **South Africa**
  - PBMR completed several designs (PBMR-400 with direct cycle).
  - Test facilities constructed (HTF and HTTF)
  - Coated particle fuel successfully manufactured (irradiated as part of the NGNP project)
  - PBMR project stopped in 2010 and is still in care and maintenance
  - Private company STL completed TH-100 concept design (small 100MWth pebble bed reactor)
Other activities in the world

USA (NGNP project)

• Fuel qualification program and heating tests show excellent results
• Fission product retention at up to 1800°C for up to 300 hours
• Graphite materials qualification
• High Temperature Test Facility at Oregon State University about to start testing
  – Depressurized Conduction Cooldown Tests.
  – Pressurized Conduction Cooldown Tests.
  – Normal Operations Tests nearing completion
• Natural Circulation Shutdown Heat Removal Test Facility at ANL
• Licensing Activities with NRC nearing completion with responses to be finalised soon
Other activities in the world

- Activities in EC (including Germany and Netherlands)

- Archer
- INNOGRAPH
  Flammability limits of gases produced during a water ingress accident
- NACOK
- HTR-PL project in Poland
- KüFA
- Heat up to 1800°C for 100’s hours
- IHX
Other activities in the world

• Ukraine
  - possible deployment of HTGRs in the future
    • research related to HTGRs has been revived
    • Ensure that related industrial equipment and technologies are conserved
    - Investigations on graphite, simulated radiation tests using charged particle accelerators, and alternative basic technologies for fuel spheres and coated particles, are performed based on different manufacturing approaches.

• United Kingdom
  - has been running commercial gas cooled reactors for many years
  - only one Magnox reactor presently in operation and with 14 Advanced Gas-Cooled Reactors still in operation and maintaining good efficiency of output over the last few years
  - no plan for any further gas-cooled reactors in the UK
  - designers and contractors continue to play a leading role in international collaborations in the high temperature gas cooled reactor (HTGR) area, along with providing continued support to the remaining operators along with numerous technical universities.

• TWG-members: China, France, Germany, Indonesia, Japan, Korea (Rep. of), Netherlands, Russian Federation, South Africa, Switzerland, Turkey, Ukraine, United Kingdom, United States of America, OECD/NEA, European Commission, Gen-IV.