Pebble Bed Modular Reactor: Technology & Project Overview

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Contents

- Background to High Temperature Reactors
  - Basic technology
  - Early prototypes
- South African Interest
- The PBMR Project
  - Overview of PBMR design and technology
  - Commercial and economic issues
  - Applications for HTRs
  - Future prospects
Different types of reactors: UK experience

- Sodium-cooled fast reactors:
  - DFR
  - PFR

- Gas-cooled reactors:
  - Magnox

- Water-cooled reactors:
  - SGHWR
  - Sizewell B PWR

- Present: Westinghouse
What are High Temperature Reactors?

First proposed by UKAEA’s Harwell Laboratory in early 1950s

Typical characteristics:
- Graphite moderated
- Helium cooled
- Refractory fuel and core materials
- High gas outlet temperatures: $\geq 700^\circ$C

Two major design variants:
- Prismatic (or ‘block’) core
- Pebble-bed core
Why are HTRs of interest?

- Low core power density, inert single-phase coolant, highly self-limiting nuclear feedback characteristics: very high levels of safety.

- High gas temperatures provide good thermal efficiency and allow use of direct-cycle gas turbines.

- High temperatures offer several alternative (non-electricity) applications, e.g. manufacture of hydrogen.
Blocks versus Pebbles

Prismatic (block) core

Pebble-bed core
<table>
<thead>
<tr>
<th>Pebble-Bed</th>
<th>Prismatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-line refuelling</td>
<td>Batch refuelling</td>
</tr>
<tr>
<td>No large excess reactivity</td>
<td>Burnable absorbers required</td>
</tr>
<tr>
<td>Fuel can be drained from core</td>
<td>No uncertainty in fuel position</td>
</tr>
<tr>
<td>No kernel migration</td>
<td>Individual identification of fuel</td>
</tr>
<tr>
<td>Good geometric stability</td>
<td>Fuel is load-bearing and may distort</td>
</tr>
<tr>
<td>Rapid discharge of defective fuel</td>
<td>Reduced possibility of handling damage</td>
</tr>
<tr>
<td>Control rods in reflector</td>
<td>In-core control rods</td>
</tr>
</tbody>
</table>
Experimental HTRs

- First operational HTR was the DRAGON
  - OECD DRAGON project began in 1959
  - 20 MWt reactor operated at Winfrith from 1966-1976
  - prismatic core design (block fuel)
  - 750°C helium outlet temperature
  - coated particle concept developed at Harwell / RAeE
- Dragon was followed by Peach Bottom, USA (67-74)
- AVR at Jülich, Germany (‘68-’89) - the first pebble-bed design

⇒ All experimental reactors showed remarkably good performance (AVR ran for 21 years!)
Early commercial prototypes

Fort St Vrain (Colorado, USA)
- 330 MWe station designed by General Atomics
- prismatic core (block fuel) with secondary steam-circuit
- operated intermittently from 1979 - 1989
- many technical difficulties (leakage from water-lubricated bearings, high helium bypass flows...)

THTR (Uentrop-Schmehausen, Germany)
- 300 MWe HTR designed by HRB (ABB-Reaktor)
- pebble-bed design, with secondary steam-circuit
- operated from 1985-89
- some operating problems
- closed for political and economic reasons (post-Chernobyl era, dominance of light-water reactors)
Why did the early HTRs not succeed?

Experimental reactors worked exceptionally well, but ...

- Prototype systems suffered from technical difficulties (especially Fort St Vrain)
- Large core structures required costly on-site construction
- No single dominant design
- Dominant position of Light Water Reactors based on US designs
- Adverse public opinion in Germany post-Chernobyl
South African interest in HTRs ....
World electricity prices

World Electricity Prices
1 January 2000

Industrial rates based on 2.5MW @ 40% load factor
Distribution of current capacity in southern Africa

- Capacity dominated by large coal-fired stations close to pit heads
- Poor quality coal
- High costs of coal transportation
- Limited transmission system / high transmission losses
- Need to serve remote communities
ESKOM installed capacity vs. demand

![Graph showing ESKOM installed capacity vs. demand](Image)
Eskom requirements for new capacity

Comprehensive review of options conducted in early 1990s

- Competitive Economics (with Eskom coal stations)
- Distributed Generation (away from coal fields - small units)
- Short Lead Times (reduce risk / capacity mismatch)
- Load/Frequency Following (increased domestic loads)
- Reduced Environmental Impact (low/no emissions)

Review parameters favoured nuclear plant, but required:

- Economic performance
- Demonstrated Technology
- “Walk Away” Safety
<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sent-out power</td>
<td>150-200 MWe per module</td>
</tr>
<tr>
<td>Continuous stable power range</td>
<td>15-100%</td>
</tr>
<tr>
<td>Ramp rate (0-100%)</td>
<td>10%/min</td>
</tr>
<tr>
<td>Load Rejection w/o trip</td>
<td>100%</td>
</tr>
<tr>
<td>Cost Target</td>
<td>$1000 / kWe</td>
</tr>
<tr>
<td>Construction Target</td>
<td>24 months</td>
</tr>
<tr>
<td>General Overhauls</td>
<td>30 days per 6 years</td>
</tr>
<tr>
<td>Emergency Planning Zone</td>
<td>&lt; 400 meters</td>
</tr>
<tr>
<td>Plant Operating Life Time</td>
<td>40 years +</td>
</tr>
<tr>
<td>Design Aircraft Impact (to survive)</td>
<td>Boeing 747 / 777</td>
</tr>
<tr>
<td>Seismic requirement</td>
<td>0.4 g</td>
</tr>
</tbody>
</table>
Why the Pebble Bed reactor?

- Need for low fuel costs / avoidance of fuel transport favoured nuclear
- Current generation light-water reactors too large for SA grid (typically > 1000MWe), and seen as too expensive
- Small, modular reactor with passive safety seemed ideal → HTRs
- Pebble-bed technology selected because:
  - seen as most technically-successful HTR design
  - excellent and consistent performance from NUKEM fuel
  - modular designs in existence (from ABB and Siemens)
  - remaining expertise in German engineering and research facilities
Key strategies for the PBMR

- **Standardisation**
  - Minimise engineering cost for multi-region implementation
  - Establish common international licensing ‘norms’

- **Small size**
  - Shorten construction period (repetition in \( \leq 6 \) months)
  - Maximise learning curve benefits
  - Facilitate inherent safety features (passive heat removal etc.)

- **Simplification**
  - Facilitate inherent safety
  - Simplify operation and maintenance
ESKOM’s way forward

- Establish a separate design team (~100 personnel) as a subdivision of ESKOM Enterprises
- Conduct an initial feasibility study for ESKOM review and as a basis for discussions with potential investors
- Promote the concept within RSA and seek (informal) Government backing
- Seek international investment partners, ideally with relevant nuclear and generation experience
- Establish a project aimed at construction of a demonstration plant in South Africa
The PBMR Project
Co-operation agreement signed between ESKOM, BNFL, EXELON, and IDC for a Detailed Feasibility Study (2000-2002)
10% is reserved for an Economic Empowerment Entity - currently held by ESKOM
PBMR project structure

- Design integration team based in Centurion, near Pretoria (including key personnel seconded from investors)
- Large design packages sub-contracted to major suppliers, e.g.
  - Mitsubishi Heavy Industries for turbines and generator
  - Westinghouse Reaktor (former ABB) for safety and control systems
- Fuel manufacturing technology team from Nuclear Energy Commission of South Africa (NECSA), based at Pelindaba
Project staff resources

- PBMR (including BNFL secondees) 280
- Sargent & Lundy / Murray & Roberts 40
- IST Nuclear 60
- MHI / Nukem / SGL / Westinghouse ... 90
- Eskom client office 30

Total ~ 500

Total man-hours to date ~ 2,750,000
Total costs to date ~$150M
(~ $350M US equivalent)
Project status

- Significant design enhancements over past 18 months to improve economics and reduce risk
- Design has converged to a more commercially viable plant from standpoint of economics, licensing and maintainability
- Detailed Feasibility phase and Business Plan completed: investors willing in principle to proceed (negotiations ongoing)
- South African Government review underway now to recommend best project configuration. Many options being studied, including:
  - appropriate for ESKOM to remain as both “producer” and customer?
  - conduct RSA investment through NECSA?
- South African government appears committed to the project: announcement expected in the next few months
Commercial / economic issues
(BNFL perspective)
Rationale for BNFL interest in PBMR

- BNFL Group front-end services are provided by Westinghouse
- Currently supporting new build programmes in Japan and South Korea, based on large PWR systems
- Recognition that light water reactor technology is mature, and alternative technologies may offer advantages
- Recognition that large monolithic plants are not well suited to all markets
Electricity supply industry: a new outlook

- Long-term centralised planning of electricity supply has been replaced in many countries by **short-term market-driven** decisions

- **De-regulation** of the electricity supply industry has led to increased producer risk (no guaranteed market), and a collapse in unit prices

- Large, capital-intensive projects are difficult to sustain for independent generators needing to raise private capital (at least in Western markets)

- Generators driven towards small, step-wise increases in capacity to minimise capital-at-risk and time interval between investment and income
Key economic targets for new build

- First ‘demonstration’ unit will **not** be economically competitive because of ‘one-off’ First-of-a-Kind costs
- Must be able to show that series build can compete with lowest cost alternatives in potential markets
- Typical targets for N\textsuperscript{th}-of-a-Kind plants:
  - capital cost of around $1000 \text{ per kWe}
  - production costs of around 3\text{¢ per kW·h}

Projected costs for PBMR series build are consistent with these targets
BNFL portfolio of advanced nuclear systems

- BNFL Group reactor system portfolio covers a range of deployment time scales and system technologies

- AP600
  - Ready for deployment now.

- AP1000
  - Commercial deployment from 2010

- PBMR
  - Deployment from 2020

- IRIS (integral PWR)

- Fast Reactors (2050?)

- No R&D required

- R&D required

- GFR
PBMR Technology & Safety Approach
PBMR Technology

- PBMR is a small (nominal 400 MWt) modular pebble bed HTR
  - helium cooled, graphite moderated
  - direct cycle gas turbine - no secondary steam circuit
  - refractory core materials removes possibility of core melt accidents
  - high outlet temperature: 900°C
    - good thermal efficiency (~ 42%)
    - flexibility for alternative applications
  - high fuel average burnup (~ 80 GWd/tU initially, higher later)
  - very high degree of inherent safety

- Design based on ABB-THTR and HTR-100, and Siemens MODUL

- Direct cycle technology introduced by PBMR
Comparison with previous HTR designs

<table>
<thead>
<tr>
<th></th>
<th>Dragon</th>
<th>Peach Bottom</th>
<th>AVR</th>
<th>Fort St. Vrain</th>
<th>THTR</th>
<th>HTR-Modul</th>
<th>PBMR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Country</strong></td>
<td>UK</td>
<td>USA</td>
<td>Germany</td>
<td>USA</td>
<td>Germany</td>
<td>Germany</td>
<td>RSA</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>Prismatic</td>
<td>Prismatic</td>
<td>Pebble</td>
<td>Prismatic</td>
<td>Pebble</td>
<td>Pebble</td>
<td>Pebble</td>
</tr>
<tr>
<td><strong>Power (MWt)</strong></td>
<td>20</td>
<td>115</td>
<td>46</td>
<td>842</td>
<td>750</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td><strong>Power Density (MW/m³)</strong></td>
<td>14</td>
<td>8.3</td>
<td>2.5</td>
<td>6.3</td>
<td>6.0</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Gas Pressure (MPa)</strong></td>
<td>2.0</td>
<td>2.4</td>
<td>1.1</td>
<td>4.8</td>
<td>4.0</td>
<td>6.0</td>
<td>9.0</td>
</tr>
<tr>
<td><strong>Core Inlet Temp. (°C)</strong></td>
<td>350</td>
<td>340</td>
<td>270</td>
<td>405</td>
<td>250</td>
<td>250</td>
<td>537</td>
</tr>
<tr>
<td><strong>Core Outlet Temp. (°C)</strong></td>
<td>750</td>
<td>725</td>
<td>950</td>
<td>785</td>
<td>750</td>
<td>700</td>
<td>900</td>
</tr>
<tr>
<td><strong>Turbines</strong></td>
<td>none</td>
<td>steam</td>
<td>steam</td>
<td>steam</td>
<td>steam</td>
<td>steam</td>
<td>Gas</td>
</tr>
<tr>
<td><strong>RPV</strong></td>
<td>steel</td>
<td>steel</td>
<td>steel</td>
<td>concrete</td>
<td>concrete</td>
<td>steel</td>
<td>Steel</td>
</tr>
</tbody>
</table>

**Country:** UK, USA, Germany, USA, Germany, Germany, RSA


**Fuel:** Prismatic, Prismatic, Pebble, Prismatic, Pebble, Pebble, Pebble

**Power (MWt):** 20, 115, 46, 842, 750, 200, 400

**Power Density (MW/m³):** 14, 8.3, 2.5, 6.3, 6.0, 3.0, 4.0

**Gas Pressure (MPa):** 2.0, 2.4, 1.1, 4.8, 4.0, 6.0, 9.0

**Core Inlet Temp. (°C):** 350, 340, 270, 405, 250, 250, 537

**Core Outlet Temp. (°C):** 750, 725, 950, 785, 750, 700, 900

**Turbines:** none, steam, steam, steam, steam, steam, Gas

**RPV:** steel, steel, steel, concrete, concrete, steel, Steel
PBMR fuel design

Fuel Sphere

Dia. 60mm

Half Section

5mm Graphite layer

Coated particles imbedded in Graphite Matrix

Pyrolytic Carbon 40/1000mm
Silicon Carbite Barrier Coating 35/1000mm
Inner Pyrolytic Carbon 40/1000mm
Porous Carbon Buffer 95/1000mm

Dia. 0.92mm

Coated Particle

Dia. 0.5mm

Uranium Dioxide

Fuel
Fuel Performance

Fuel Temperatures [°C]

Failure Fraction
PBMR: circuit schematic
Loss of Coolant Event

265 MW PBMR Ref. Core: Temperature Distribution during a DLOFC
PBMR plant layout
Module building

Depressurization shaft

Outside barrier against externally generated pressure & impact loads

Reactor Cavity provides shielding to personnel & acts as a barrier against internally generated missiles

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height total</td>
<td>62.9 m</td>
</tr>
<tr>
<td>Height above ground</td>
<td>40.9 m</td>
</tr>
<tr>
<td>Depth below ground</td>
<td>22 m</td>
</tr>
<tr>
<td>Width</td>
<td>37.0 m</td>
</tr>
<tr>
<td>Length</td>
<td>66.1 m</td>
</tr>
<tr>
<td>Levels (floors)</td>
<td>11</td>
</tr>
<tr>
<td>Material</td>
<td>40 MPa concrete</td>
</tr>
<tr>
<td>Seismic acceleration</td>
<td>0.4 g Horizontal</td>
</tr>
</tbody>
</table>

Aircraft crash:
- (a) < 2.7 ton - no penetration;
- (b) Limiting case (777):
  predicted to penetrate outside barrier but not reactor cavity:
  nuclear safety not compromised

BNFL

Westinghouse
PBMR multi-module site
PWR and PBMR power station footprints

Typical PWR
1400 MWe

PBMR
1320 MWe
Power Plant
Summary of PBMR advantages

• **Safety**
  - can withstand very high temperatures (1600°C) without core or fuel degradation
  - strongly negative reactivity temperature coeff.

• **Economics**
  - elimination of secondary circuit, fewer safety grade components, and modular design/factory-fabricated units all reduce capital cost
  - generating costs competitive with CCGT

• **Proliferation resistance**
  - highly stable fuel form - very difficult to recover fissile material
  - fuel is very well suited to long-term storage/direct disposal in sub-surface vaults

• **Flexibility**
  - small, modular units (400 MWt / 170 MWe)
  - suitable for electricity production and high temperature process heat
PBMR Technology Development Status
Key developments over last 18 months

- Power turbine-generator
- Reactor core structures
- System integration
- Operation and maintenance
- Constructability
- Licensing (both in South Africa and Overseas)
- Materials properties (especially graphite)
Current status of technology issues: turbo-machinery

- Original submerged generator replaced with an external generator with a shaft seal - eliminates carbon dust problems and simplifies maintenance.

- Replacement of electromagnetic ‘catcher’ bearings with standard oil-lubricated thrust bearings: reduced technology risk and allows multiple rundown capability.

### TOTAL SHAFT LENGTH
20.1 m / 88 t
AND MASS

### GENERATOR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant</td>
<td>Air</td>
</tr>
<tr>
<td>Height (Inlet to Top)</td>
<td>17.2 m</td>
</tr>
<tr>
<td>Mass</td>
<td>326 t</td>
</tr>
<tr>
<td>Power output (50 Hz)</td>
<td>180 MW, 11kV</td>
</tr>
</tbody>
</table>

### TURBINE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>Helium</td>
</tr>
<tr>
<td>Height (Inlet to Outlet)</td>
<td>4.4 m</td>
</tr>
<tr>
<td>Tip Dia. (typical)</td>
<td>2.1 m</td>
</tr>
<tr>
<td>Mass</td>
<td>338 t</td>
</tr>
<tr>
<td>Speed</td>
<td>3000 rpm</td>
</tr>
<tr>
<td>Stages</td>
<td>10</td>
</tr>
<tr>
<td>Efficiency</td>
<td>93.5%</td>
</tr>
<tr>
<td>Mass flow</td>
<td>194 kg/s</td>
</tr>
</tbody>
</table>
Current status of technology issues: reactor core structures

- Original design for core internal structures considered to require significant re-design
- PBMR Co undertaking re-design, assisted by consultants and Westinghouse Reaktor
- Key changes:
  - solid central reflector
  - increased size to accommodate new reference power level: 3.7 m ID x 10 m effective height
  - replaceable inner reflector
  - austenitic SS core barrel
  - CFC straps for core restraint
  - inlet plenum located in core support structure
Testing programme

- Code Validation
  - Critical Core Test Facility: ASTRA (Moscow)
  - Micro Turbine Model: Potchefstroom University
- Equipment Test Rigs: IST (and Gamma-Metrics)
- Fuel Manufacturing Equipment: NECSA (Pelindaba)
- Helium Test Loop: NECSA
- Fuel Qualification and Testing
  - First core: NIKIET (Russia)
  - Longer-term: SAFARI (Pelindaba)
PBMR micro-model at Potchefstroom University

Operation of the PBMR micro-model has demonstrated the stable operating characteristics and control system for a 3-shaft Brayton cycle

Heater section

Turbo-machinery Section
Scheduled Test

- **Pressure Range**: 3.2MPa to 9.5MPa
- **Main Loop Temperature Range**: up to 660°C**
- **Maximum Flow**: 2.47kg/s @ 9.5MPa
- **Target level of purification**: >99.997% pure He

**Temperatures up to 1100°C are generated within test sections**
Fuel manufacturing labs at Palindaba

Kernel Casting  
Particle Coating  
Pebble Pressing
Other Systems and Components Testing

- Fuel Handling System
- T/G Dry Gas Seal
- Gas Valve Actuation
- Turbo Machinery
- Heat Transfer
- Air Ingress
Status of licensing in South Africa

- Agreed licensing process, scope of submittals and schedule
- Agreed list of key licensing issues and strategy to address
- Safety Analysis Report Rev 1 submitted to NNR on 5 December 2001
- Formal questions from NNR on SAR Rev 1 issued and all responses submitted to NNR in November 2002
- Environmental Impact Assessment (EIA) Record of Decision (RoD) issued mid-2003 - positive outcome
- NNR Summary Progress Report on PBMR Licensing Process issued March 2003
- SAR Rev 2 submittal issued at the end of 2003
US Licensing Status

- NRC agreement on proposed approach
- Phase 1 of the Regulatory Guidance Review completed
- Fuel Test and Qualifications program progressed
- US Licensability Assessment completed
- Pre-application activities by Exelon documented; ready for reactivation
- Multiple Module Reactor Issues responded to by NRC
- Non-LWR issues and workshops continuing
- NRC Pre-application review to start in 2004
- Start of Design Certification planned for 2006; completion after startup of the Demonstration reactor
Future Developments
Impact of burnup/enrichment and U-loading per fuel sphere on fuel cost per MW.h

- 9 gms/FS
- 12 gm/FS
- 16 gm/FS
- 20 gm/FS

(8.3%) (~17%)
Future development path

Current Technology Regime

PBMR Demonstration Plant

400 MWt 900°C

- Safety Case
- IHX Hydrogen Process
- Codes and Standards (60 y)

Technology Threshold

400 MWt 1000°C

- Reactor Outlet Pipe Liner
- Turbine Blade/Disc Material Development
- Material and Component Qualification
- Codes and Standards (60 y)

400 MWt 1200°C

- Fuel
- Control Rods
- Graphite Lifetime
- RPV and Core Barrel Material

>500 MWt >1200°C

Future Technology Regime

- Fuel
- Graphite Lifetime
- Optimization of Commercial Margins
Future Prospects: Alternative Applications
Alternative applications

Although modular HTRs offer good prospects for electricity generation, their high temperatures allow alternative and/or complimentary applications:

- Heat applications
  - Hydrogen production
  - Industrial process heat
  - District heating
- Management of nuclear materials (e.g. Pu)
# Heat applications & temperatures

<table>
<thead>
<tr>
<th>Application</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>200</td>
</tr>
<tr>
<td>Cement</td>
<td>320</td>
</tr>
<tr>
<td>Iron manufacture</td>
<td>direct reduction</td>
</tr>
<tr>
<td>Electricity generation (Gas turbine)</td>
<td></td>
</tr>
<tr>
<td>Gasification of coal</td>
<td></td>
</tr>
<tr>
<td>Hydrogen (IS process)</td>
<td>(900°C)</td>
</tr>
<tr>
<td>Hydrogen (Steam reforming)</td>
<td>(320°C)</td>
</tr>
<tr>
<td>Styrene, Ethylene</td>
<td></td>
</tr>
<tr>
<td>Town gas</td>
<td></td>
</tr>
<tr>
<td>Oil desulphurisation</td>
<td></td>
</tr>
<tr>
<td>Wood pulp</td>
<td></td>
</tr>
<tr>
<td>Urea synthesis</td>
<td></td>
</tr>
<tr>
<td>Desalination, District heating</td>
<td></td>
</tr>
<tr>
<td>Very High Temperature Reactor</td>
<td>1500°C</td>
</tr>
<tr>
<td>HTR (PBMR)</td>
<td>900°C</td>
</tr>
<tr>
<td>AGR</td>
<td>650°C</td>
</tr>
<tr>
<td>LMFBR</td>
<td>550°C</td>
</tr>
<tr>
<td>LWR</td>
<td>320°C</td>
</tr>
<tr>
<td><strong>Nuclear Heat</strong></td>
<td></td>
</tr>
</tbody>
</table>
Hydrogen overview

Hydrogen has several advantages as an energy carrier:

- It can release energy with minimal pollution: the only by-product of combustion is water.
- It can produce both heat and electricity (in fuel cells).
- It can transfer more energy per unit mass than fossil fuels.
- It is readily transported by pipelines, and can be converted to forms suitable for storage.
- Nuclear power offers the almost unique position of large-scale, reliable hydrogen production with near-zero emissions.
Applications for hydrogen

- Current world production: 50 million tonnes / annum: forecast to grow at 5-10% /year
- Current major use is in ammonia production
- Largest rate of growth in consumption is in the oil industry (cracking and pre-treating of reformer feeds)
- Estimated that in 10-20 years, energy used to produce hydrogen in the US may exceed current nuclear energy production
Current and future production routes

CO₂ from process and heat source

Fossil-fired steam reformation of methane (97%)
Electrolysis (3%)

Steam reformation with nuclear heat (reduced CO₂ emissions)

High temperature electrolysis (zero emissions with nuclear)

Thermo-chemical water splitting (zero emissions with nuclear)
Hydrogen production by electrolysis

- Currently produces around 3% of annual consumption
- High cost due to electrical demand; used only for high purity $\text{H}_2$
- Suitable for over-night production using low-cost base-load nuclear electricity
- AECL have investigated siting of reactors close to US border:
  - sale of electricity to USA during the day
  - hydrogen production by electrolysis at off-peak hours
- High temperature electrolysis could significantly improve efficiency, but R&D required
Hydrogen production by steam reformation

- Most hydrogen is currently produced by steam reforming of methane (using heat from fossil fuels)
- Requires heat at >750°C (typically around 900 °C)
- Produces CO₂ as a by-product
- JAERI propose a demonstration of nuclear steam reforming circa 2008
Replaces thermal decomposition of water (requiring > 3000ºC) with several partial reactions

Iodine-Sulphur (I-S) process:

- **H₂ production by thermo-chemical water splitting**
Japanese prototype I-S plant

- JAERI investigating the I-S process for emissions-free hydrogen production using nuclear heat
Hydrogen production compatible with nuclear

- Near-zero emissions technology; remote siting of production facility
- Storage allows de-coupling between production and use, allowing dual-purpose stations: electricity and hydrogen production

\[
2H_2O \rightarrow 2H_2 + O_2
\]
A future for nuclear hydrogen production?

- Nuclear offers:
  - a near-zero emissions option
  - demonstrated and established technology
  - near-term demonstration of direct coupling with H\textsubscript{2} production

- Nuclear should not be the only solution (others include solar & biological processes) but is likely to be an important contributor

- Temperatures available from current reactors (predominantly light-water) limit production method to electrolysis

- High temperature gas-cooled modular reactors (e.g. PBMR) offer a safe, flexible, and economic future energy source
Summary

- Market conditions appear to favour small, flexible, modular units.
- Detailed Feasibility Study indicates a technically achievable project: technical development of the PBMR has progressed well, and the system shows good potential to operate with very high levels of safety, and to support a range of applications.
- Business Case suggests the PBMR will be able to meet the challenging capital and production cost targets required by the investors.
- BNFL (and the other investors) intend to continue with the project, subject to satisfactory negotiations and Govt Approval.
- Meanwhile, discussions are ongoing with other investors who have expressed an interest in joining the Project.