Nuclear-Power Ammonia Production

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Why Nuclear-Powered Ammonia Production?

• Many in the nuclear community are interested in nuclear-powered hydrogen production
  – Interest primarily motivated by talk of a hydrogen economy
  – Focusing on a hydrogen economy makes commercialization dependent on the economics of hydrogen-powered cars

• It would be better to focus on current markets for hydrogen
  – If nuclear-powered is not economical source of hydrogen for current users, it will not be an economical source of transportation fuel

• Ammonia production is the logical place to begin commercializing nuclear-powered hydrogen production
  – Ammonia is the largest consumer of hydrogen in the world

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Topics for Discussion

• Large centralized nuclear-powered ammonia production (2000 tonne / day plants)

• Ammonia production powered by small nuclear reactors (IAEA defines small as <300 MW$_e$)

• Transportable nuclear-powered hydrogen production (if time permits)
Process Design
Major Process Decisions

- **Which process should be used to produce hydrogen?**
  - Water electrolysis (existing technology)
  - Steam electrolysis (developmental)
  - Thermochemical cycles (developmental)
  - Hybrid cycles (developmental)

- **Which process should be used to produce nitrogen?**
  - Cryogen air separation (existing technology)
  - Pressure-swing absorption (existing technology)
  - Burning hydrogen to remove oxygen (existing technology)

- **What type of nuclear power system should be used?**
  - Pressurized water reactor (PWR) (existing technology)
  - Boiling water reactor (BWR) (existing technology)
  - High temperature gas cooled reactor (HTGR) (developmental)
  - Other high temperature reactors (developmental)
Electrolytic Hydrogen Production

- Water electrolysis
  - Commercial technology
  - Produces pure hydrogen
  - Could be operated using existing nuclear reactors

- Steam electrolysis
  - Both Idaho National Laboratory (INL) and the Japanese have developed processes
  - Produces a hydrogen-steam mixture and pure oxygen
  - Efficiencies of 40 - 50% are possible when powered by an high-temperature gas-cooled reactor (HTGR)
The Iodine Sulfate Cycle

**Water Feed**
- $\text{H}_2\text{O} + \text{SO}_2 
- \text{H}_2\text{SO}_4 \rightarrow \text{H}_2\text{O} + \text{SO}_2 + 1/2 \text{O}_2 (850°C)$
- $2 \text{H}_2\text{O} + \text{SO}_2 + \text{I}_2 \rightarrow \text{H}_2\text{SO}_4 + 2 \text{HI} (125°C)$

**Hydrogen Product**
- $2\text{HI} \rightarrow \text{H}_2 + \text{I}_2 (400°C)$

**Heat**
- $\text{H}_2\text{O} \rightarrow \text{H}_2\text{O}$
- $\text{H}_2\text{SO}_4 \rightarrow \text{H}_2\text{O}$
- $\text{HI} \rightarrow \text{HI}$
Thermochemical and Hybrid Cycles

- Theoretical efficiencies of 50% - 65% have been reported in the literature
  - Literature efficiency estimates often neglect the energy consumed by the separation processes
  - Integrated process studies in the literature indicate efficiencies of 40% - 45% are more realistic

- Requires very high temperatures
  - HTGR and molten salt reactors are the only types of nuclear reactors that can supply the required temperatures

- Capital cost of an iodine-sulfate process is about 8 times that of a seam electrolysis process
Choice for Hydrogen Production

- Steam electrolysis is the primary choice for hydrogen production
  - The efficiency is greater than water electrolysis
  - The efficiency is comparable to the practical efficiencies of thermochemical processes if powered by an HTGR
  - Steam electrolysis can be powered by a pressurized water reactor (PWR) or a boiling water reactor (BWR)
  - Capital costs are significantly lower than thermochemical processes

- Water electrolysis evaluated as a possible option
  - Less efficient than steam electrolysis
  - Capital cost are lower than steam electrolysis
  - Proven technology
Nitrogen Production

• Commercial ammonia production requires large volumes of high-purity nitrogen

• Removing oxygen, carbon dioxide, and water are the primary concern
  – Water should be <150 ppm
  – Oxygen and oxygen containing compounds must be <10 ppm
  – Argon does not need to be removed
Nitrogen Plant Selection Based on Purity and Capacity

Figure reproduced from *Kirk-Othmer Encyclopedia of Chemical Technology*
Pressure Swing Adsorption Will Be used for Nitrogen Production

- Pressure swing adsorption (PSA) and cryogenic air separation are appropriate processes for producing large volumes of nitrogen
- PSA produces lower purity nitrogen than cryogenic air separation
  - Removes carbon dioxide, but ...
  - The nitrogen product contains 0.1 - 2% oxygen
- Nitrogen with ppm levels of oxygen can be obtained from PSA by reacting the oxygen with hydrogen
- The energy required for PSA plus the hydrogen for removing the residual oxygen is much less than cryogenic air separation
Choice of Nuclear Power System

• A HTGR with a Brayton cycle is the primary choice for the nuclear power system
  – An HTGR has the highest operating temperatures which favors high cycle efficiencies
  – Brayton cycle is better suited for a HTGR than a Rankine cycle

• A GE Advanced Boiling Water Reactor (ABWR) with a Rankine cycle also evaluated as a possible option
  – Less efficient than an HTGR
  – An example of proven technology
Baseline Process Design: Steam Electrolysis Flowsheet

- **Raw Water Feed**
  - **Water Treatment Plant**
  - **Superheater**
    - **Steam Generator**
    - **Condenser**
      - **Water Separator**
        - **Electrolytic Cell**
          - 80% efficient based on free energy
          - 50% per pass conversion

- **O₂ (g)**
  - From NH₃ Reactor
  - To NH₃ Reactor
  - Return to Reactor
  - **Steam Recycle Compressor**
  - **Wet Hydrogen to DeOxo Reactor**

- **H₂O (g)**
  - From NH₃ Reactor
  - To NH₃ Reactor
  - Return to Reactor
  - **Steam Recycle Compressor**
  - **Wet Hydrogen to DeOxo Reactor**

- **H₂O (L)**

- **H₂O (g)**
  - From NH₃ Reactor
  - To NH₃ Reactor
  - Return to Reactor
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  - From NH₃ Reactor
  - To NH₃ Reactor
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  - **Wet Hydrogen to DeOxo Reactor**
Baseline Process Design: Pressure Swing Adsorption Flowsheet

Air

Air Compressor

C.W

After Cooler

Water Separator

Filter

Air Receiver

Adsorber Beds

N₂, O₂, Ar, CO₂, H₂O

Drier Beds

Absorber beds remove CO₂

De-oxo reactor reduces O₂ to 5 ppm

Drier Bed

Drier Surge Tank

Dry Reactant Gas

Nitrogen Surge Tank

H₂, N₂, Ar, O₂, H₂O (g)

De-Oxo Reactor

Wet Hydrogen From Electrolysis

H₂O (L)

Drier Receiver

H₂O (g)
Baseline Process Design: Ammonia Process Flowsheet

- Reactant Gas Compressor
- H₂, N₂, Ar, H₂O, O₂
- Multiple intercoolers used for compressor
- Ammonia Reactor
  - 200 atm
  - 20% NH₃ in exit
- Use NH₃ refrigeration
- Dissolved argon prevents excessive accumulation

Dry Reactant Gas

Reactant Gas

C.W

De-Oxo Reactor

H₂, N₂, NH₃, Ar, H₂O, O₂

Primary Condenser

Flash Drum

Refrigerated Condenser

Intermediate Condenser

C.W

Degassing Drum

Liquid NH₃

Liquid Ammonia Product

Superheater

Primary Condenser

Intermediate Condenser

Refrigerated Condenser

Flash Drum

Purge Gas

Dry Reactant Gas
Baseline Process Design: Fully Integrate Brayton Cycle

- **Primary Loop Working Fluid:** Helium
- **Primary Loop Pressure:** ~70 atm
- **Secondary Loop Working Fluid:** Helium
- **Secondary Loop High Pressure:** ~70 atm
- **Secondary Loop Low Pressure:** ~20 atm

Diagram showing the process design with
- **HTGR**
- **Primary Loop Compressor**
- **Intermediate Heat Exchanger**
- **Driver for Primary Loop Compressor**
- **Refrigerator**
- **Cooler**
- **Secondary Loop Compressor**
- **Driver for Secondary Loop Compressor**
- **Drivers for Other Process Compressors**
- **Driver for DC Electric Generator**
- **Driver for NH₃ Plant Compressor**
- **Process Heat**
- **Driver for Other Process Compressors**
- **Interstage Cooler**
- **Drives for Other Process Compressors**
Large Centralized Production
Energy Consumption for HTGR-Powered Ammonia Process with Steam Electrolysis

- Nuclear Reactor
  - Electricity: 84%
  - Compressors: 10%
  - Process Heat: 6%
# Performance and Costs of Large Nuclear-Powered Ammonia Plants

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Hydrogen Process</th>
<th>Efficiency (MJ fuel* / MJ&lt;sub&gt;T&lt;/sub&gt;)</th>
<th>Capital Investment (million $)</th>
<th>Production Cost ($/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTGR with heat integration</td>
<td>Steam Electrolysis</td>
<td>0.48</td>
<td>1440</td>
<td>172</td>
</tr>
<tr>
<td>HTGR with no heat integration</td>
<td>Steam Electrolysis</td>
<td>0.41</td>
<td>1570</td>
<td>189</td>
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<tr>
<td>HTGR</td>
<td>Water Electrolysis</td>
<td>0.37</td>
<td>1590</td>
<td>187</td>
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<tr>
<td>ABWR with heat integration</td>
<td>Steam Electrolysis</td>
<td>0.29</td>
<td>1540</td>
<td>196</td>
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<tr>
<td>ABWR</td>
<td>Water Electrolysis</td>
<td>0.23</td>
<td>1680</td>
<td>200</td>
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</tbody>
</table>

* Fuel value based on higher heating value
Cost Breakdown for HTGR-Powered Steam-Electrolysis Plant

Capital Costs
- Nuclear Power Plant 81%
- Ammonia Plant 19%

Operating Costs
- Nuclear Heat 40%
- Feeds and Catalysts 2%
- Labor and Supervision 2%
- Other 14%
- Depreciation 42%
Depreciation is the Largest Component of Operating Costs for a Nuclear-Powered Ammonia Plant

HTGR-Powered Plant
- Feeds and Catalysts: 2%
- Labor and Supervision: 2%
- Nuclear Heat: 40%
- Other: 14%
- Depreciation: 42%

Steam Reforming Plant
- Feeds and Catalysts: 2%
- Labor and Supervision: 1%
- Other: 26%
- Natural Gas: 67%
- Depreciation: 5%
Lessons for Study of Large Nuclear-Powered Ammonia Plants

- Efficiency is not the most important factor affecting the economic viability of a nuclear-powered ammonia plant
  - Efficiency varied by a factor of 2 for cases studied
  - Capital investment and operating costs only varied by 16%

- None of the options considered in this study was clearly superior to the others
  - Accuracy of the estimates is ±30%
  - Capital costs of steam electrolysis and water electrolysis differ by <10%
  - Capital costs of an HTGR and a ABWR differ by <10%
Small Modular Reactors
The US Department of Energy’s Global Nuclear Energy Partnership (GNEP)

- The goal of GNEP is to expand the worldwide use of economical, environmentally responsible nuclear energy to meeting growing electricity demand while virtually eliminating the risk of nuclear material misuse.

- An important element of the GNEP program is grid-appropriate reactors:
  - Small, proliferation-resistant reactors suitable for developing countries
  - Built in standardized modules that generate 50 - 300 MW_e
  - Feature fully passive safety systems
  - Simple to operate
  - Highly secure
The International Reactor - Safe and Secure (IRIS) is an Example of a Grid-Appropriate Reactor

IRIS is a Westinghouse-designed PWR that generates up to 335 MWₐ
### Other Modular Reactor Designs

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Manufacturer Country</th>
<th>Type</th>
<th>Power (MW&lt;sub&gt;e&lt;/sub&gt;)</th>
<th>Efficiency (%)</th>
<th>Temperature (°C)</th>
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</thead>
<tbody>
<tr>
<td>IRIS</td>
<td>Westinghouse USA</td>
<td>PWR</td>
<td>50 - 335</td>
<td>33.5</td>
<td>328</td>
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<tr>
<td>MSBWR</td>
<td>GE USA</td>
<td>BWR</td>
<td>50 &amp; 200</td>
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<td>-</td>
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<tr>
<td>GT - MHTR</td>
<td>General Atomics USA</td>
<td>HTGR</td>
<td>285</td>
<td>-</td>
<td>-</td>
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<tr>
<td>VBER-150</td>
<td>Russia</td>
<td>PWR</td>
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<td>31.5</td>
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<td>CAREM</td>
<td>CNEA &amp; INVAP Argentina</td>
<td>PWR</td>
<td>27</td>
<td>27.0</td>
<td>-</td>
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<tr>
<td>SMART</td>
<td>South Korea</td>
<td>PWR</td>
<td>100</td>
<td>30.3</td>
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<tr>
<td>MRX</td>
<td>JAERI Japan</td>
<td>PWR</td>
<td>50 -300</td>
<td>-</td>
<td>-</td>
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<tr>
<td>GTHTR</td>
<td>JAERI Japan</td>
<td>HTGR</td>
<td>300</td>
<td>47.0</td>
<td>850</td>
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<tr>
<td>HTGR-PM</td>
<td>Chincerely China</td>
<td>Pebble Bed Reactor</td>
<td>195</td>
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<tr>
<td>NP-300</td>
<td>Techocatome France</td>
<td>PWR</td>
<td>100 -300</td>
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Performance and Costs of Nuclear-Powered Ammonia Plants

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Production (tonne NH$_3$/day)</th>
<th>Efficiency (MJ fuel* / MJ$_T$)</th>
<th>Capital Investment (million $)</th>
<th>Production Cost ($/tonne)</th>
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<tbody>
<tr>
<td>IRIS</td>
<td>1120</td>
<td>0.29</td>
<td>580</td>
<td>201</td>
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<tr>
<td>GTHTR</td>
<td>1080</td>
<td>0.42</td>
<td>700</td>
<td>227</td>
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<tr>
<td>HTGR</td>
<td>2100</td>
<td>0.48</td>
<td>1440</td>
<td>172</td>
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<tr>
<td>ABWR</td>
<td>2100</td>
<td>0.29</td>
<td>1540</td>
<td>196</td>
</tr>
</tbody>
</table>

* Fuel value based on higher heating value
Comparison of Alternatives
Alternatives to be Considered

- **Nuclear options**
  - Large HTGR with steam electrolysis
  - ABWR with steam electrolysis
  - IRIS with steam electrolysis
  - GTHTR with steam electrolysis

- **Non-nuclear options**
  - Steam reforming natural gas with and without carbons sequestration and a natural gas price of $7.25 / MMBTU
  - Partial oxidation of coal with and without carbons sequestration and a coal price of $35 / short ton
  - Wind-powered plant based on water electrolysis
Comparison of Alternatives

<table>
<thead>
<tr>
<th>Process</th>
<th>Production (tonne NH₃/day)</th>
<th>Efficiency (MJ fuel* / MJₚ)</th>
<th>Capital Investment (million $)</th>
<th>Production Cost ($/tonne)</th>
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<td>Historic Average</td>
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<td>165</td>
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<tr>
<td>HTGR</td>
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<td>48.3</td>
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<td>172</td>
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<td>ABWR</td>
<td>2100</td>
<td>29.4</td>
<td>1540</td>
<td>196</td>
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<tr>
<td>IRIS</td>
<td>1120</td>
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<td>201</td>
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<tr>
<td>Coal</td>
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<td>870</td>
<td>218</td>
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<tr>
<td>GTHTR</td>
<td>1080</td>
<td>41.5</td>
<td>700</td>
<td>227</td>
</tr>
<tr>
<td>Coal w/sequestration</td>
<td>2100</td>
<td>39.5</td>
<td>1000</td>
<td>291</td>
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<tr>
<td>Wind</td>
<td>2100</td>
<td>-</td>
<td>4000</td>
<td>321</td>
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<tr>
<td>Natural Gas</td>
<td>2100</td>
<td>79.0</td>
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<td>331</td>
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<tr>
<td>June 2006 Price</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>340</td>
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<tr>
<td>Natural gas w/ Sequestration</td>
<td>2100</td>
<td>76.4</td>
<td>420</td>
<td>356</td>
</tr>
</tbody>
</table>

* Fuel value based on higher heating value
Observations

• Nuclear-powered ammonia production has the lowest operating costs
  – 10 - 20% less than partial oxidation of coal
  – 40 - 50% less than steam reforming methane

• Nuclear-powered ammonia production has the highest capital costs
  – 65 - 75% more than partial oxidation of coal
  – 400 - 430% more than steam reforming methane

• Efficiency is not a good indicator of operating costs or capital costs
  – Efficiency of ABWR plant 60% less than HTGR plant
  – Capital investment for ABWR plant only 7% greater
  – Production costs for ABWR plant only 14% greater
Before Tax Return on Investment Assuming an Ammonia Price of $340 / tonne

Return on Investment (%)
Ammonia Price Needed to Earn a 20% ROI Before Taxes

$500/tonne

Ammonia Price ($ / tonne)

- Taxes on Profit
- After Tax Profit
- Depreciation
- Other Fixed Cost
- Variable Costs

HTGR  ABWR  IRIS  Coal  MHGR  Coal w/o CO2  Wind  N.G.  N.G. w/o CO2
Observations

• At $340 / tonne, an ammonia plant is not an attractive investment

• An IRIS-powered plant may be the best method of producing ammonia without carbon dioxide emissions
  – Highest rate of return at current ammonia prices
  – Price to earn 20% ROI is comparable to natural gas with carbon sequestration
  – ROI is not sensitive to fluctuations in natural gas and ammonia prices
  – Does not required exotic technologies

• Capital investment, not efficiency, is the most important factor governing the economics of nuclear-powered ammonia production
Summary and Conclusions

- The main advantages of nuclear-powered ammonia production are
  - Uses readily available raw materials (air and water)
  - Low, stable operating costs
  - No carbon dioxide production

- High capital costs are the major disadvantage of nuclear-powered ammonia production

- Smaller, standardized modular reactors could reduce capital costs
  - Reduce construct cost and time
  - Reduce licensing cost and time
Transportable Ammonia Production
Ammonia is a Possible Petroleum-Free Military Fuel

- **Advantages**
  - Readily available world-wide
  - Can be produced from a variety of raw materials
  - Can be used in a variety of power systems (diesel, turbines, fuel cells)
  - Could be produced in or near the theater of operations from air and water

- **Disadvantages**
  - More difficult to handle and transport than hydrocarbon fuels
  - Not a good fuel for aircraft
Some Considerations When Producing Ammonia in the Theater of Operation

- Would like to maximize production, so yield is a more important consideration than capital cost
- Would like to maximize flexibility
  - Obtain power from local electrical grid if available
  - Use transportable nuclear reactor if local power unreliable
- Need a transportable ammonia plant and reactor
- Would like to simplify set-up and operations
Configuration for a Transportable Nuclear-Powered Ammonia Plant

- The proposed ammonia plant is electric powered and uses steam electrolysis to produce hydrogen
  - Can be powered by a nuclear reactor or the local electrical grid
  - Simplifies the interface between the reactor and ammonia plant
  - Steam electrolysis plant consumes ~20% less power than a water electrolysis plant

- The ammonia plant will be powered by a small 10-MWt gas-cooled reactor
  - A pebble-bed reactor is the most likely choice
  - Power generated a a Brayton cycle or Stirling cycle
### Efficiencies of a Small Ammonia Plant Powered by a 10 MW<sub>t</sub> Reactor

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Reactor Outlet Temperature (°C)</th>
<th>Production Rate (tonne/day)</th>
<th>Efficiency (MJ&lt;sub&gt;fuel&lt;/sub&gt; / MJ&lt;sub&gt;t&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pebble Bed</td>
<td>950</td>
<td>16</td>
<td>0.42</td>
</tr>
<tr>
<td>Pebble Bed</td>
<td>850</td>
<td>15</td>
<td>0.39</td>
</tr>
<tr>
<td>PWR</td>
<td>328</td>
<td>11</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Skid Mounted Sections of a Small Ammonia Plant Commercially Available

- Commercially available equipment
  - Electric-powered boilers
  - PSA nitrogen plants
  - Ammonia refrigeration
  - Compressor

- Other equipment expected to be small
  - Electrolyzers
  - Ammonia reactors

Small PSA nitrogen plant

Likely scale of electrolyzers
The TRISO Fuel Particles Used in a Pebble Bed Reactor Are the Primary Barriers to the Release of Radioactive Materials

Will withstand a loss-of-coolant accident without melting

Will withstand air ingress without burning
A Proposed Pebble Bed Reactor Design

Reactor Unit

Helium Flowpath
Reactor Shielding Provided by an Earthen Barrier

Nuclear Reactor

Ammonia Plant