Thermochemical Production of Hydrogen from Solar and Nuclear Energy

Presentation to the Stanford Global Climate and Energy Project

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Hydrogen production requires energy

- Hydrogen is an energy carrier, not an energy source; its production requires energy
- A Hydrogen Economy only makes sense if hydrogen is produced with sustainable, non-fossil, non-greenhouse gas energy
  - Solar and Nuclear (fission and in the long term fusion)
- Hydrogen can be produced from water using thermal energy
  - Electric power generation $\rightarrow$ Electrolysis
    - Proven technology
    - Overall efficiency $\approx 24\%$ (LWR), $\approx 36\%$ (Hi T Reactors)
    - (efficiency of electric power generation $\times$ efficiency of electrolysis)
  - Heat $\rightarrow$ Thermochemical water-splitting
    - Net plant efficiencies of up to $\approx 50\%$
    - Developing technology
  - Electricity + Heat $\rightarrow$ High temperature electrolysis or Hybrid cycles
Thermochemical water-splitting

- A set of coupled, thermally-driven chemical reactions that sum to the decomposition of water into $H_2$ and $O_2$
  - All reagents returned within the cycle and recycled
  - Only high temperature heat and water are input, only low temperature heat, $H_2$ and $O_2$ are output
- High efficiency is possible – at high temperature
- A developing technology
  - Explored extensively in the 1970s
  - Numerous possible cycles identified and explored
  - Never commercialized
DOE NERI project evaluated thermochemical cycles

- GA/SNL/UoK reviewed world literature
  - 822 references, 115 unique thermochemical cycles
- Screened these and selected 25 cycles for detailed evaluation
  - Screening: Suitability for coupling to a nuclear heat source
  - Evaluation: Chemical thermodynamics, engineering block flow diagrams
- Identified the Sulfur-Iodine (S-I) as best suited for hydrogen production from a nuclear heat source
  - Higher efficiency, easier handling
  - France, Japan have also selected the S-I cycle (or “I-S cycle”)

Ref.: Brown, et al, AIChE 2002
The S-I cycle is best suited to nuclear production of H₂

- Invented at GA in 1970s
  - Serious investigations for nuclear and solar
  - Chemistry reactions all demonstrated
  - Materials candidates selected and tested

- Advantages:
  - All fluid continuous process, chemicals all recycled; no effluents
  - H₂ produced at high pressure – 22 - 84 atm.
  - Highest cited projected efficiency, ~50%

- Challenges:
  - Requires high temperature, ≥800°C
  - Must be demonstrated as a closed loop under prototypical conditions
The S-I cycle is a thermally-driven chemical process

Follows the rules of chemistry and thermodynamics (Carnot)
High predicted efficiency: ~50% at 900°C
High temperature increases efficiency

Estimated S-I process thermal-to-hydrogen energy efficiency (HHV)

- Process is coupled to nuclear heat source by an intermediate loop with 2 heat exchangers \(\sim 50^\circ C \Delta T\)
- Earlier studies used \(827^\circ C\), achieved 42% efficiency
- >50% efficiency requires >900\(^\circ\)C peak process T
- Reactor outlet T \(\geq 950^\circ C\) desired
We completed the S-I process design

- Used chemical process design code Aspen Plus
- Designed the three main chemical process systems
  - Prime or Bunsen reaction
    \[ 2H_2O + SO_2 + I_2 \rightarrow H_2SO_4 + 2HI \]
  - Sulfuric acid decomposition
    \[ 2H_2SO_4 \rightarrow 2SO_2 + 2H_2O + O_2 \]
  - Hydrogen iodide decomposition
    \[ 2HI \rightarrow I_2 + H_2 \]

- We estimate high efficiency (52% at 900°C) and reasonable cost (~$250/kWt)
  - Benefit of high reactor outlet temperature important

- Experimental verification is needed
  - HI, H_2O, I_2 Vapor-Liquid Equilibrium data needed
  - Confirmation of HI Reactive Distillation analysis important, may allow further cost savings


### 600 MWt H_2-MHR Process Parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>Flow rate tons/day</th>
<th>Inventory tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>H_2</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>H_2O</td>
<td>1,800</td>
<td>40</td>
</tr>
<tr>
<td>H_2SO_4</td>
<td>9,800</td>
<td>100</td>
</tr>
<tr>
<td>I_2</td>
<td>203,200</td>
<td>2,120</td>
</tr>
</tbody>
</table>

SNL evaluated candidate nuclear reactors for thermochemical water-splitting

- SNL evaluated 9 categories:
  - PWR, BWR, Organic, Alkali metal, Heavy metal, Gas-cooled, Molten salt, Liquid-core and Gas-core
  - Assessed reactor features, development requirements

- Current commercial reactors are too low temperature

- Helium, heavy metal, molten salt rated well; helium gas-cooled most developed

- Selected Modular Helium Reactor as best suited for thermochemical production of hydrogen

H₂-MHR
The Modular Helium Reactor solves the problems of first generation reactors

- High temperature all-ceramic fuel is passively safe
- Allows high coolant temperatures – 850 - 950°C
- Coupled to gas turbine at 850°C: GT-MHR, 48% efficiency
- Coupled to S-I water-splitting at 950°C: Hydrogen at 52% efficiency
- Reduces cost and minimizes waste
- Proliferation resistant

. . . . Opens a new opportunity for nuclear power
Inherent reactor characteristics provide passive safety

- Helium gas coolant (inert)
- Refractory fuel (high temperature capability)
- Graphite reactor core (high temperature stability)
- Low power density, modular size (slow thermal response)
- Demonstrated technologies from 7 prototypes world-wide over 40 years

. . . EFFICIENT PERFORMANCE WITH PASSIVE SAFETY
Nuclear-produced H₂ must be economical to compete

- Start with GT-MHR cost estimates
  - Subtract cost of gas turbine system and generator
  - Add estimate of “VHTR” cost premium for 950°C – +23%
  - Add cost of circulators, heat exchangers, intermediate loop, hydrogen plant and I₂ inventory

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost, $/kWt</td>
<td>468</td>
<td>326</td>
<td>371</td>
<td>43</td>
<td>297</td>
<td>711</td>
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<tr>
<td>Operating Cost, $/MW,h</td>
<td>5.0</td>
<td>4.0</td>
<td>4.9</td>
<td>0.1</td>
<td>3.3</td>
<td>8.3</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost of H₂: $/kg</th>
<th>H2-MHR</th>
<th>H2-VHTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public utility</td>
<td>$1.52</td>
<td>$1.42</td>
</tr>
<tr>
<td>Regulated utility</td>
<td>$1.69</td>
<td>$1.57</td>
</tr>
<tr>
<td>Unregulated utility</td>
<td>$2.01</td>
<td>$1.87</td>
</tr>
</tbody>
</table>
Nuclear-produced hydrogen will be economic

- H2-VHTR could produce H₂ at ~$1.40/kg
- Meets steam reformation of natural gas H₂ cost at ~$6.30/MBtu
- $1/MBtu higher natural gas cost or $100/ton CO₂ capture and sequestration cost could each add 20¢/kg of SMR H₂, or $25/ton oxygen sale could subtract 20¢/kg of nuclear H₂
- Nuclear production of H₂ would avoid fossil fuels and CO₂ emissions without economic penalties

Figure 1 Cost of hydrogen for technology leaders—with CO₂ costs

Figure courtesy of ERRI

.... and CO₂ emission-free
Nuclear Production of H₂ Appears Attractive

• A large and growing market for H₂ exists that nuclear energy could serve
  – H₂ for oil refineries is the likely first market and can provide a bridge to the future Hydrogen Economy

• The Modular Helium Reactor coupled to the Sulfur-Iodine water-splitting cycle is an attractive system:
  – High efficiency, reasonable cost, passive safety

• Estimated costs of ~$1.40/kg could compete with H₂ from natural gas today if O₂ can be sold
  – Increasing cost of natural gas or CO₂ costs will give nuclear increasing cost advantage

Nuclear production of hydrogen can be the enabling technology for the Hydrogen Economy
Effort will be needed to achieve economic hydrogen from nuclear energy...

- **The first steps have begun:**
  - Demonstrate laboratory scale SI process operation (I-NERI)
  - Conceptual design of \( \text{H}_2 \)-MHR and Intermediate Loop (NERI)
  - Measure needed chemical data (SNL-L, CEA)
  - Tasks could be completed in 3 years

- **Next, build a \( \sim 30 \) MWt Pilot Plant (\( \sim 10 \) tons/day of \( \text{H}_2 \))**
  - Design, build and operate in \( \sim 4 \) years for \( \sim 75-100M \)
  - Operation with fossil-fueled simulated nuclear heat source

- **Then, build a 600 MWt (200 t/d) \( \text{H}_2 \)- Nuclear Demo Plant**
  - Demonstration of “Nuclear Hydrogen” by \( \sim 2015 \)
  - \( \sim 350M + \) reactor

... but the path forward appears clear
Solar Production of Hydrogen is an appealing goal

- **Solar receivers can deliver high temperature**
  - NREL/U.Colorado demonstrated 51% collection efficiency at 2000°C in the process fluid for thermal cracking of methane

- **Solar diurnal cycle is a real limitation**
  - ~ 8 hours of useful energy per day
  - 8/24 = 33% duty cycle
  - Capital equipment only earning revenue 1/3 of time
  - Hydrogen unit cost increased 3 x

- **Solar can deliver higher temperatures than nuclear** – can we use it effectively to off-set the low duty cycle?

Photos of NREL Solar Furnace
Preliminary estimates of Solar thermochemical hydrogen production are encouraging

- **Start with nuclear-matched S-I cycle coupled to solar receiver**
  - NREL heliostat/collector: 1 kW/m², 51% capture, $130/m², 8 hr/day
  - Lower capital cost than nuclear, but low duty cycle hurts

- **Increase temperature to maximum S-I can use – 1100°C**
  - NREL advanced heliostat/collector: $75/m²
  - Better – but doesn’t use the full temperature potential of solar

- **Assume hypothetical thermochemical cycle at 2000°C**
  - Assume same 79% of Carnot efficiency as S-I → 65% heat to H₂ efficiency
  - Assume same $/kWt capital cost as S-I

- **While the assumptions are unproven, the result is interesting**

<table>
<thead>
<tr>
<th>Process</th>
<th>Nuclear S-I</th>
<th>Solar S-I</th>
<th>Solar Hi T S-I</th>
<th>V Hi T Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature °C</td>
<td>900</td>
<td>900</td>
<td>1100</td>
<td>2000</td>
</tr>
<tr>
<td>Efficiency - Heat to H₂</td>
<td>52%</td>
<td>52%</td>
<td>56%</td>
<td>65%</td>
</tr>
<tr>
<td>Hydrogen cost, $/kg</td>
<td>1.42</td>
<td>3.45</td>
<td>2.50</td>
<td>2.15</td>
</tr>
</tbody>
</table>
Evaluation of solar water-splitting is needed

- We have proposed to do serious investigation of solar thermochemical cycles
  - Update and search our database for cycles well-suited to solar:
    - Develop solar screening criteria
    - Higher temperature cycles possible for higher efficiency
    - Match receiver characteristics to chemical reactions
    - Search for diurnal accommodation to improve capital utilization
  - Do conceptual designs for interesting cycles and systems
  - Build and test prototype solar receivers/chemical reactors
- We are hopeful of DOE support starting in FY’03
Barriers to nuclear thermochemical water-splitting and research opportunities

**BARRIERS**

**Reactor**
- Public antipathy to nuclear energy
- Development and demonstration of MHR is needed
  - Demonstrate cost and performance
  - Mitigate investment risk

**S-I Process**
- Demonstration of S-I cycle
  - Demonstrate cost and performance

**System economics**
- Fossil fuels with no environmental costs dominate the market

**OPPORTUNITIES**

- Study of public perceptions and public education
- Development and demonstration
  - Fuel fabrication and testing
  - Detailed reactor design
  - Construction of a Demo plant

- S-I Process validation
  - Measure chemical data
  - Demonstrate process
  - Verify materials

- Study cost/value of CO₂ Cap&Seq
  - Can sustainable sources of H₂ compete? When?
Barriers to solar thermochemical water-splitting and research opportunities

**BARRIERS**

**Solar collector**
- Need low cost & high efficiency
  - High collection efficiency
  - High energy retention
  - Low maintenance, high reliability

**Process**
- Need solar-matched process
  - High temperature/efficiency
  - Match to solar receiver geometry?
  - Diurnal accommodation
  - Demonstrate cost and performance

**System economics**
- Economics of high temperature solar are challenging

**OPPORTUNITIES**

- Develop efficient, effective collectors
  - Selective filters, tailored emissivities
  - “Smart” systems for alignment
  - Value engineering of system

- Process selection and validation
  - Identify and select solar-matched cycle
  - Measure chemical data
  - Demonstrate process
  - Verify materials

- Study system economics
  - Can renewable sources of H₂ compete?
    When?

GENERAL ATOMICS
Thermochemical Hydrogen Production from Solar and Nuclear Energy

- Thermochemical water-splitting promises efficient hydrogen production from heat.
- Requires high temperatures.
- For nuclear, the Sulfur-Iodine cycle matched to the Modular Helium Reactor appears attractive and economic.
- For solar, process matching and selection is needed.
- Thermochemical water-splitting is developmental – opportunities for R&D are ample.
- Thermochemical production of hydrogen can be part of a sustainable energy future.
Hydrogen is the Ideal Replacement for Fossil Fuels

• Hydrogen can reduce CO$_2$ emissions and dependence on fossil fuels
  — No greenhouse gases. Hydrogen produces only water as the “waste product”
  — In a fuel cell, hydrogen can get twice the efficiency as a gasoline engine

• Hydrogen is ready to be a viable option
  — Research base available from DOE/EERE program for hydrogen use, storage and distribution

• One issue: where to get the hydrogen?
  — Hydrogen is an energy carrier, not an energy source
  — Most hydrogen chemically bound as water, carbohydrates or hydrocarbons
  — Energy is required to separate H from oxygen or carbon
The Hydrogen Economy will need a lot of hydrogen

- **US use of hydrogen is now 11 million tons/y (48 GWt)**
- **95% produced by Steam Reformation of Methane**
  - Consumes 5% of our natural gas usage
  - Not CO$_2$-free: releases 74 M tons of CO$_2$/y
- **Most is used in fertilizer, chemical and oil industries**
- **~10%/y growth → X 2 by 2010, X 4 by 2020**
- **Hydrogen Economy will need X 18 current for transportation X 40 for all non-electric**
Quantifiable screening criteria were developed and applied. . .

- Each cycle was given a numerical score based on
  - Number of chemical reactions
  - Number of chemical separations required
  - Number of elements
  - Elemental abundance of least abundant element
  - Relative corrosiveness of process solutions
  - Degree to which process is continuous and flow of solids is minimized
  - Degree to which maximum process temperature is appropriate to advanced high temperature nuclear reactor
  - Number of published references to the cycle
  - Degree to which the cycle has been demonstrated
  - Degree to which good efficiency and cost data are available

- Go-No go criteria were applied
  - Environmental Health and Safety – Mercury cycles eliminated
  - Excessive maximum temperature – Cycles above 1600°C eliminated
  - Thermodynamically unfavorable – $\Delta G/RT > 50$ kcal/mole

... reducing the number of cycles to 25
<table>
<thead>
<tr>
<th>Cycle Name</th>
<th>T/E</th>
<th>T °C</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westinghouse [12]</td>
<td>T</td>
<td>850</td>
<td>2H₂SO₄(g) → 2SO₂(g) + 2H₂O(g) + O₂(g) × 1</td>
</tr>
<tr>
<td>Ispra Mark 13 [13]</td>
<td>E</td>
<td>77</td>
<td>2H₂SO₄(g) + 2H₂O(a) → H₂SO₄(a) + H₂(g) × 1</td>
</tr>
<tr>
<td>UT-3 Univ. of Tokyo [8]</td>
<td>T</td>
<td>600</td>
<td>2FeCl₂ + 2HCl + S → 2FeCl₃ + Cl₂(g) + 2HCl(g) × 1</td>
</tr>
<tr>
<td>Sulfur-Iodine [14]</td>
<td>T</td>
<td>850</td>
<td>2H₂SO₄(g) → 2SO₂(g) + 2H₂O(g) + O₂(g) × 1</td>
</tr>
<tr>
<td>Julich Center EOS [15]</td>
<td>T</td>
<td>800</td>
<td>2Fe₂O₃ → 4FeCl₂ + 4HCl + O₂(g) × 2</td>
</tr>
<tr>
<td>Tokyo Inst. Tech. Ferrite [16]</td>
<td>T</td>
<td>1000</td>
<td>2Na₂Fe₂O₄ + 3Na₂CO₃ + H₂O → 2Na₂Fe₂O₄ + 3CO₂(g) + H₂(g) × 1</td>
</tr>
<tr>
<td>Hallé Air Products 1965 [15]</td>
<td>T</td>
<td>800</td>
<td>2CO₂(g) + 2H₂O(g) → 4HCl(g) + O₂(g) × 2</td>
</tr>
<tr>
<td>Gaz de France [15]</td>
<td>E</td>
<td>25</td>
<td>2HCl → Cl₂(g) + H₂(g) × 1</td>
</tr>
<tr>
<td>Nickel Ferrite [17]</td>
<td>T</td>
<td>800</td>
<td>Na₂MnFe₂O₄ → Na₂MnFe₂O₄ + 2H₂(g) × 1</td>
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<tr>
<td>Aachen Univ. 1972 [15]</td>
<td>T</td>
<td>850</td>
<td>2Cl₂(g) + 2H₂O(g) → 4HCl(g) + O₂(g) × 1</td>
</tr>
<tr>
<td>Ispra Mark 1C [13]</td>
<td>T</td>
<td>1000</td>
<td>2FeCl₃ + 3FeCl₂ + 3H₂O → 2FeCl₃ + 3H₂(g) × 1</td>
</tr>
<tr>
<td>LASL- U [15]</td>
<td>T</td>
<td>25</td>
<td>3CO₂ + 3H₂O → 3CO₂(g) + 3H₂(g) × 1</td>
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<tr>
<td>Ispra Mark 8 [13]</td>
<td>T</td>
<td>700</td>
<td>3MnCl₂ + 3H₂O → Mn₂O₃ + 6Cl₂(g) × 1</td>
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<tr>
<td>Ispra Mark 6 [13]</td>
<td>T</td>
<td>850</td>
<td>2Cl₂(g) + 2H₂O(g) → 4HCl(g) + O₂(g) × 1</td>
</tr>
<tr>
<td>Ispra Mark 4 [13]</td>
<td>T</td>
<td>850</td>
<td>2H₂O(g) → 4HCl(g) + O₂(g) × 1</td>
</tr>
<tr>
<td>Ispra Mark 3 [13]</td>
<td>T</td>
<td>850</td>
<td>2Cl₂(g) + 2H₂O(g) → 4HCl(g) + O₂(g) × 1</td>
</tr>
</tbody>
</table>
Detailed evaluation criteria were developed and applied

- Thermodynamic calculations were made for each chemical reaction
  - Cycles were eliminated if any reaction had a large positive Gibbs free energy that could not be performed electrochemically nor shifted by pressure or concentration
- Preliminary block flow diagrams were prepared for each cycle
  - Cycles were eliminated that required the flow of solids
  - Cycles were eliminated due to excess complexity
  - Cycles were eliminated which are not well matched to the characteristics of a high temperature reactor
- Hybrid cycles were eliminated due to scalability concerns
  - Hybrid cycles are inherently limited in size
  - All previous cost comparisons of hybrid and pure thermochemical cycles have indicated higher cost for hybrid cycles

The Sulfur-Iodine cycle was selected
Section 1 - Bunsen reaction and Chemical recycle

NH2

Main Reactor

Aux SO2 Scrubber

Main SO2 Scrubber

Boost Reactor

Separator

SO2 Stripper

I2, O2

I2

H2O

H2O, HI, H2SO4

SO2, O2

I2, H2O, HI, H2SO4, SO2, (O2)

I2, H2O, HI

H2O, H2SO4

I2, H2O, HI

3-phase Separator

H2O, H2SO4

O2
Section 2 - Sulfuric acid concentration and decomposition
Section 3 - HI Decomposition - Reactive distillation process

- Univ. of Aachen suggested for cost savings
- Use U. Aachen analysis
- High recycle to Section 1
  ~ 5 to 1 recycle of HI
  ~ 4-5 moles H₂O & I₂ per mole HI
- Lower cost with good efficiency
  52% at 900°C vs. earlier 47%
  23% cost savings
  8% with I₂ inventory
The Helium Gas-Cooled Reactor is well-suited for H₂ production

Assessment of reactor concepts for Sulfur-Iodine thermochemical cycle

<table>
<thead>
<tr>
<th>Coolant</th>
<th>Gas</th>
<th>Salt</th>
<th>Heavy Metal</th>
<th>Alkali Metal</th>
<th>Molten Core</th>
<th>PWR</th>
<th>BWR</th>
<th>Organic</th>
<th>Gas Core</th>
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<tr>
<td>1. Materials compatibility</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>B</td>
<td></td>
<td>F</td>
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<td>2. Coolant stability</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td></td>
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<td>F</td>
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<td>3. Operating pressure</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>F</td>
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<td>4. Nuclear issues</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
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<td>5. Feasibility-development</td>
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<td>B</td>
<td>B</td>
<td>C</td>
<td>C</td>
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<td>1. Safety</td>
<td>B</td>
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<td>B</td>
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<td>2. Operations</td>
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<td>3. Capital costs</td>
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<td>C</td>
<td>C</td>
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<td>4. Intermediate loop compatibility</td>
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<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td></td>
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<td>5. Other merits and issues</td>
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<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
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<td></td>
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</table>

Unweighted mean score (A=4.0) 3.67 3.30 3.33 2.87 2.80 N/A N/A N/A N/A

Development cost trends relative to GCRs

<table>
<thead>
<tr>
<th></th>
<th>Materials</th>
<th>Fuel</th>
<th>Component</th>
<th>System</th>
<th>Fab.-Facility</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molten salt</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+2</td>
<td>0</td>
<td>+6</td>
</tr>
<tr>
<td>Heavy metal</td>
<td>+2</td>
<td>+2</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+7</td>
</tr>
</tbody>
</table>

... and needs the least development
CERAMIC FUEL RETAINS ITS INTEGRITY UNDER SEVERE ACCIDENT CONDITIONS

TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).

PARTICLES  COMPACTS  FUEL ELEMENTS

Pyrolytic Carbon
Silicon Carbide
Porous Carbon Buffer
Uranium Oxycarbide
Ceramic Fuel Retains Integrity Beyond Maximum Accident Temperatures

Large margin to fuel degradation

NORMAL PEAK TEMPERATURE

MAXIMUM DESIGN BASIS EVENT TEMPERATURE

FUEL TEMPERATURE (°C)

FAILURE FRACTION
MHR Design has Passively Safe Decay Heat Removal

A. Normal - Using Power Conversion System

B. Active Shutdown Cooling System

C. Passive Reactor Cavity Cooling System

D. Passive Radiation & Conductive Cooling
The MHR is Passively Safe: Fuel temperatures remain below design limits during loss of cooling events.

Design Goal = 1600°C

PASSIVE DESIGN FEATURES ENSURE FUEL REMAINS BELOW 1600°C, PREVENTING RELEASE OF RADIOACTIVITY. ACTIVE SAFETY SYSTEMS NOT NEEDED
# Preliminary H₂-MHR Capital Cost Estimates

## Modular Helium Reactor Capital Costs

Estimated “Nth of a kind” costs for 4x600MWe plant

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$ / kW: 468/kWt, 326/kWt, 371/kWt, 43/kWt, 297/kWt

**GENERAL ATOMICS**
Economic estimates are encouraging

- **Capital recovery:**
  - IDC (3yrs, 7%), CRF 10.5% (public utility), 90% capacity factor
  - \( \frac{(711 \times 1.116 \times 0.105)}{7.9 \text{ MW(t)-hr}} = \$10.6/\text{MW(t)-hr} \)

- **Operating cost:**
  - \$8.3 / \text{MW(t)-hr}
  - Includes nuclear fuel cycle & waste disposal, water and O&M

- **Total cost:**
  - \( \frac{(10.6 + 8.3)}{13.2 \text{ kg}} = \$1.42/\text{kg of H}_2 \)
The Fusion Applications study found products well-suited to fusion

- Electricity
- Fissile fuel and tritium*
- Radioisotopes (esp. Co$^{60}$)*
- Fission waste burning*
- Synthetic fuels (hydrogen)
- District and process heat*
- Rare metals*
- Space propulsion

*: Most require co-generation of electricity
A significant potential market for synfuels from fusion was projected

- In developed countries, 30% of energy use is to generate electricity. 70% goes for transport and industrial needs.

- Gas Research Institute in 1972 projected the potential by 2000 for:
  - 1000 fusion plants to replace natural gas with hydrogen
  - 2000 fusion plants to replace fossil fuels for non-electric use

- The economics were challenging however:
  - Oil cost $20/bbl, fusion heat source cost estimate $850/kW\text{th}
  - With 50% heat-to-hydrogen efficiency, fusion would be cheaper than oil at $50/bbl...

The dream didn’t come true — but the market is still there!
Direct processes appear interesting....

- **Radiolysis uses radiation to break chemical bonds**
  - \( \text{H}_2\text{O} \rightarrow \text{H}_2 + 1/2\text{O}_2 \)
  - \( \text{CO}_2 \rightarrow \text{CO} + 1/2\text{O}_2; \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \)
  - Recombination, competing reactions, low densities limit fraction of energy captured to <10%

- **Thermal spike chemistry uses neutron knock-on atoms to produce transient microscopic high temperature zones for non-equilibrium chemistry (2-5 eV, \(10^{-10}\) s)**
  - Need N~20-100 medium for energy transfer \(\approx 5\%\)
  - Fraction of fusion energy to medium \(\approx 10\%\) (90/10 Xe/\(\text{H}_2\text{O}\))
  - Total yield < 1%

- **Neutron activation and tritium are serious concerns**

- Ref: “Study of Chemical Production Utilizing Fusion Neutrons” GA–A15371, 1979

.... but are limited to fractional utilization with significant complications
Thermal processes use fusion for high temperature process heat

• 80% of fusion energy is carried by 14 MeV neutrons

• Neutrons can penetrate cooled structure, deposit heat in insulated interior high temperature zone
  – Extreme temperatures possible in principle

• Fusion neutrons also create challenges:
  – Neutrons are needed for tritium production
    • $^6\text{Li} + n = T + \text{He}$, $^7\text{Li} + n = T + n' + \text{He}$; (n, 2n) reactions possible
  – Tritium contamination of product must be avoided
    • Tritium is very mobile, especially at high temperature
    • Clean-up of contaminated H₂ would be impractical
  – Neutron activation can contaminate process fluids
Thermochemical water-splitting uses only heat

- Single blanket module with two coolant streams
  - High temperature He stream recovers 30% of heat at 1250°C
  - Tritium breeding zone yields 70% at 450°C
- Match to Sulfur-Iodine cycle
- Projected efficiency 43% and $1.70 - 2.00/kg H₂
- He flows directly to H₂ process
- Tritium in H₂ below 10CFR20 limits for unrestricted use

GA Utility Synfuel Study, 1983
High temperatures require innovative heat transfer loops and heat exchangers

- Extreme temperatures and aggressive process fluids require ceramic components
- Conceptual design studies indicate the technologies are challenging but not impossible.
- Process fluids do not see fusion neutrons — no activation concerns
- Two coolant streams needed
  - Tritium permeation must cross breeder tubes to low temperature loop to high temperature loop to process loop to contaminate product
- Slip-stream processing, natural barriers and SiC excellent tritium barrier limit release to 2.1 Ci/d, below 10CFR20 limits for unrestricted use

GA Utility Synfuel Study, 1983
Hydrogen production could be a major role for Fusion

- Direct processes (radiolysis) appear limited to fractional topping cycles, add significant complication
- Thermal processes — high temperature electrolysis, thermochemical water-splitting — are similar to fission application, will benefit from that development
- Fusion can potentially provide higher temperatures, but has additional requirements and concerns
  - Tritium production impacts the fraction of heat delivered at high temperature — net thermochemical efficiencies <50%
  - Tritium control will have strict limits, will require innovative technology and design choices
- High value of H₂ will benefit fusion economics
- With development, fusion could help fill the future needs for hydrogen