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Materials Requirements for Nuclear Hydrogen Production Technologies

Satyen Baindur
Ottawa Policy Research Associates, Inc.
http://ottawapolicyresearch.ca

Hydrogen Production

- For Future Transportation Fuel
- For Current Hydrocarbon Refining
- For Other Chemical Industry Applications
- H_2 Production Methods Today:
  - Separation from
    - Hydrides – Hydrocarbons - e.g. steam reforming of methane
    - Hydrides – Water – e.g. electrical hydrolysis (electrolysis)

– Heat or electricity required is produced by burning hydrocarbons

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Hydrogen Production

- Water Splitting – Hydrolysis – emissions-free if:
  - Electricity or Heat used is produced emissions-free
  - Carbon Dioxide sequestration when commercialized – could yield emissions-free H_2
- Current Emissions-free Energy Options:
  - Solar Thermal Hydrolysis or Electrolysis
  - Wind Powered Electrolysis
  - Low Efficiency and/or Intermittency severe constraints.
  - Nuclear – mature technology unhindered by intermittency issues. Nuclear hydrogen production could use excess power available off-peak hours from NPPs.

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Nuclear Hydrogen Production

Nuclear Power Heat (steam) and/or Electricity Enables:

- High Temperature *Thermal* Hydrolysis (thermolysis)
- Thermochemical Hydrolysis
- Electrochemical Processes (including High Temperature Electrolysis, HTE).
- Directed Radiolysis (Hydrogen now produced as waste gas in PWR coolant loop from unintentional radiolysis)

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Nuclear Hydrogen Production II

- Dedicated Nuclear Plant for Hydrogen Generation could supply heat and electricity for one or more of the above processes *simultaneously.*
- Next Generation Nuclear Plants will have higher outlet temperatures; thus greater efficiency, both for nuclear plant and for thermo-chemical and electrolytic processes.
- Fifth Generation Nuclear – Fusion – when commercialized – will enable even higher temperatures and production volumes.

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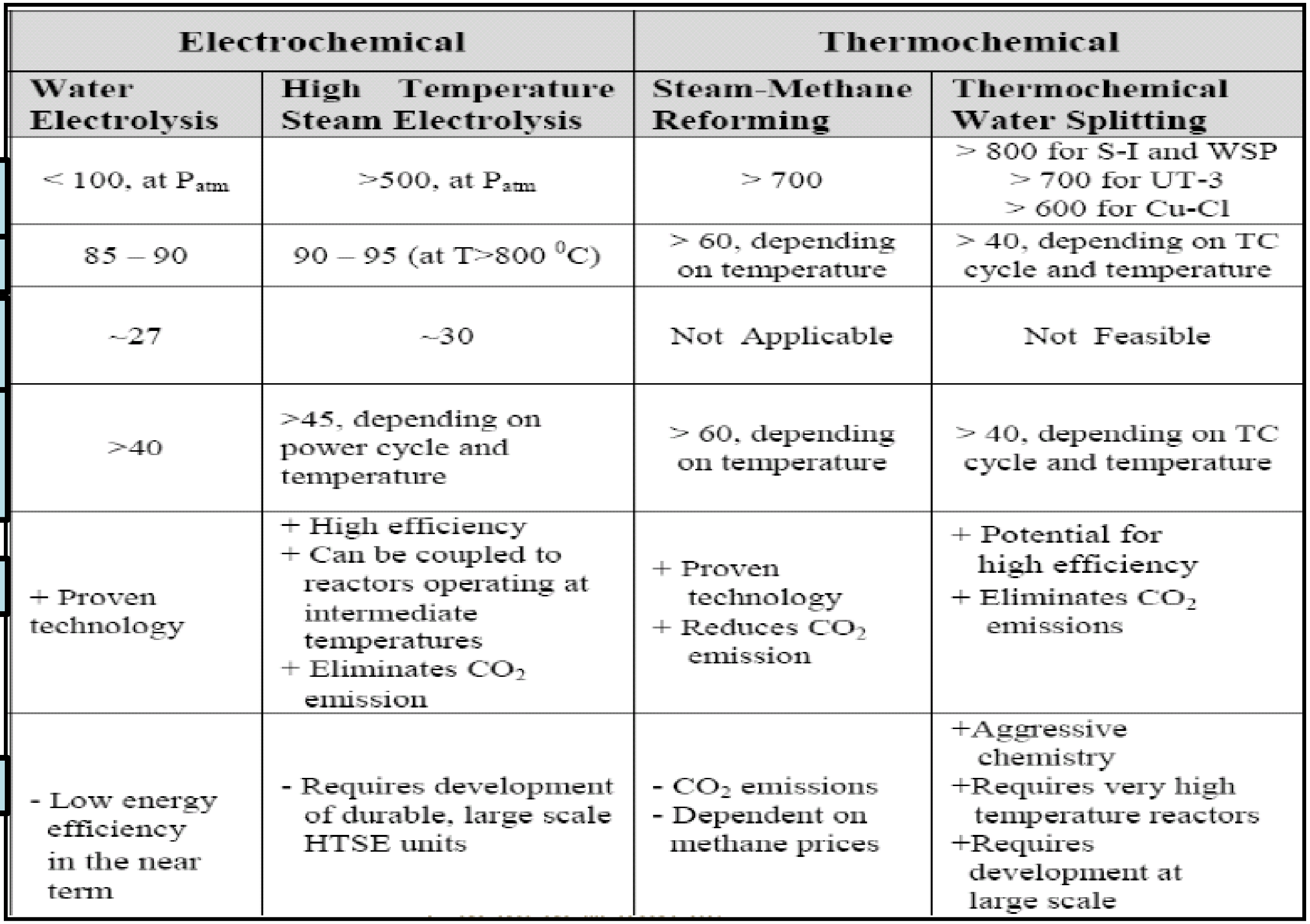
Hydrogen Production Options And Their Operating Requirements



	Electrochemical		Thermochemical	
	Water Electrolysis	High Temperature Steam Electrolysis	Steam-Methane Reforming	Thermochemical Water Splitting
Required Temp (Celsius)	< 100, at P_{atm}	>500, at P_{atm}	> 700	> 800 for S-I and WSP > 700 for UT-3 > 600 for Cu-Cl
Efficiency	85 – 90	90 – 95 (at T>800 ^{0}C)	> 60, depending on temperature	> 40, depending on TC cycle and temperature
Efficiency w/ Light Water Reactor	~27	~30	Not Applicable	Not Feasible
Efficiency w/ Gas-cooled Reactor (GCR)	>40	>45, depending on power cycle and temperature	> 60, depending on temperature	> 40, depending on TC cycle and temperature
Advantages	+ Proven technology	+ High efficiency + Can be coupled to reactors operating at intermediate temperatures + Eliminates CO_2 emission	+ Proven technology + Reduces CO_2 emission	+ Potential for high efficiency + Eliminates CO_2 emissions
Disadvantages	- Low energy efficiency in the near term	- Requires development of durable, large scale HTSE units	- CO_2 emissions - Dependent on methane prices	+Aggressive chemistry +Requires very high temperature reactors +Requires development at large scale

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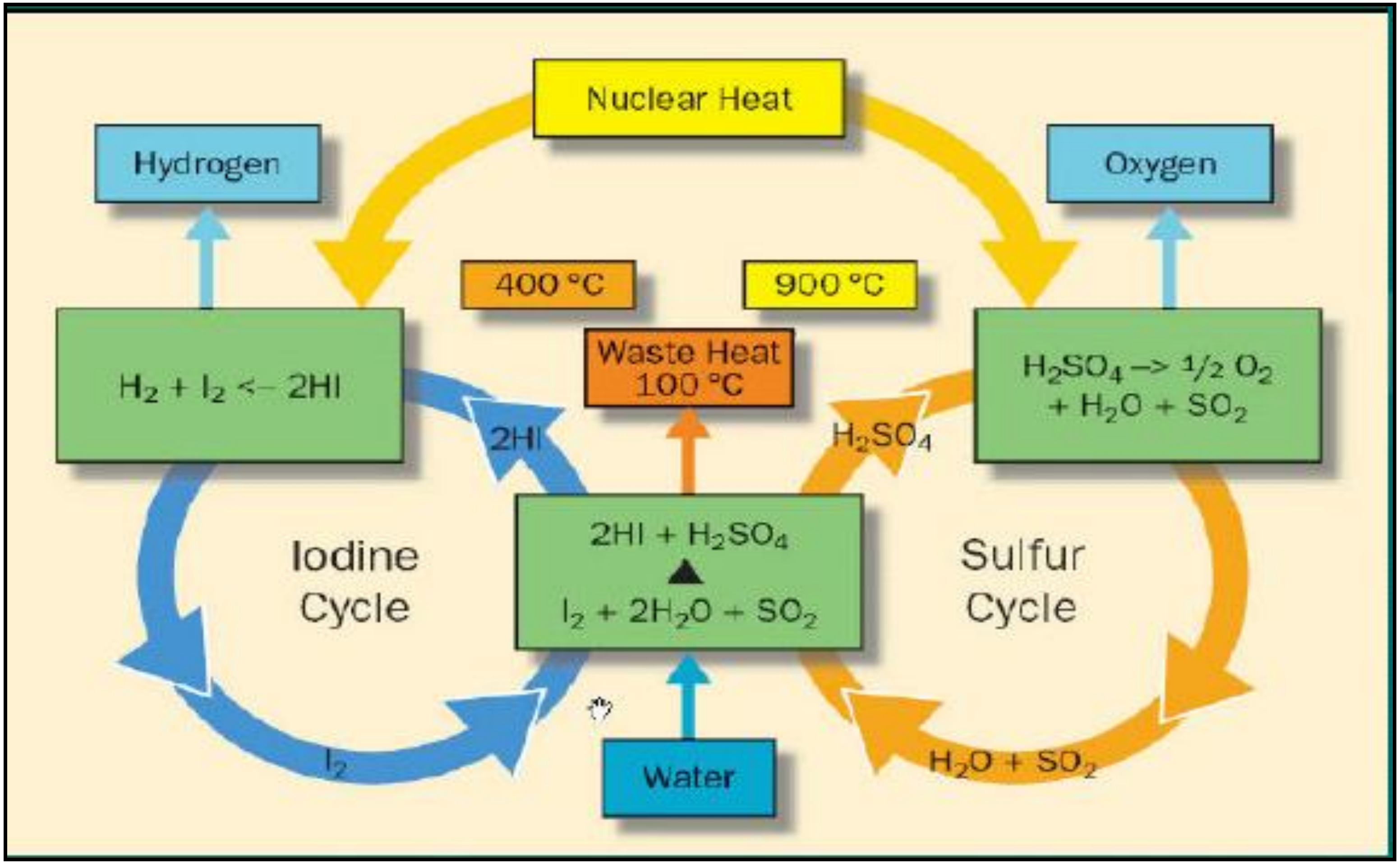
The Sulfur-Iodine (S-I) Thermo-chemical Cycle



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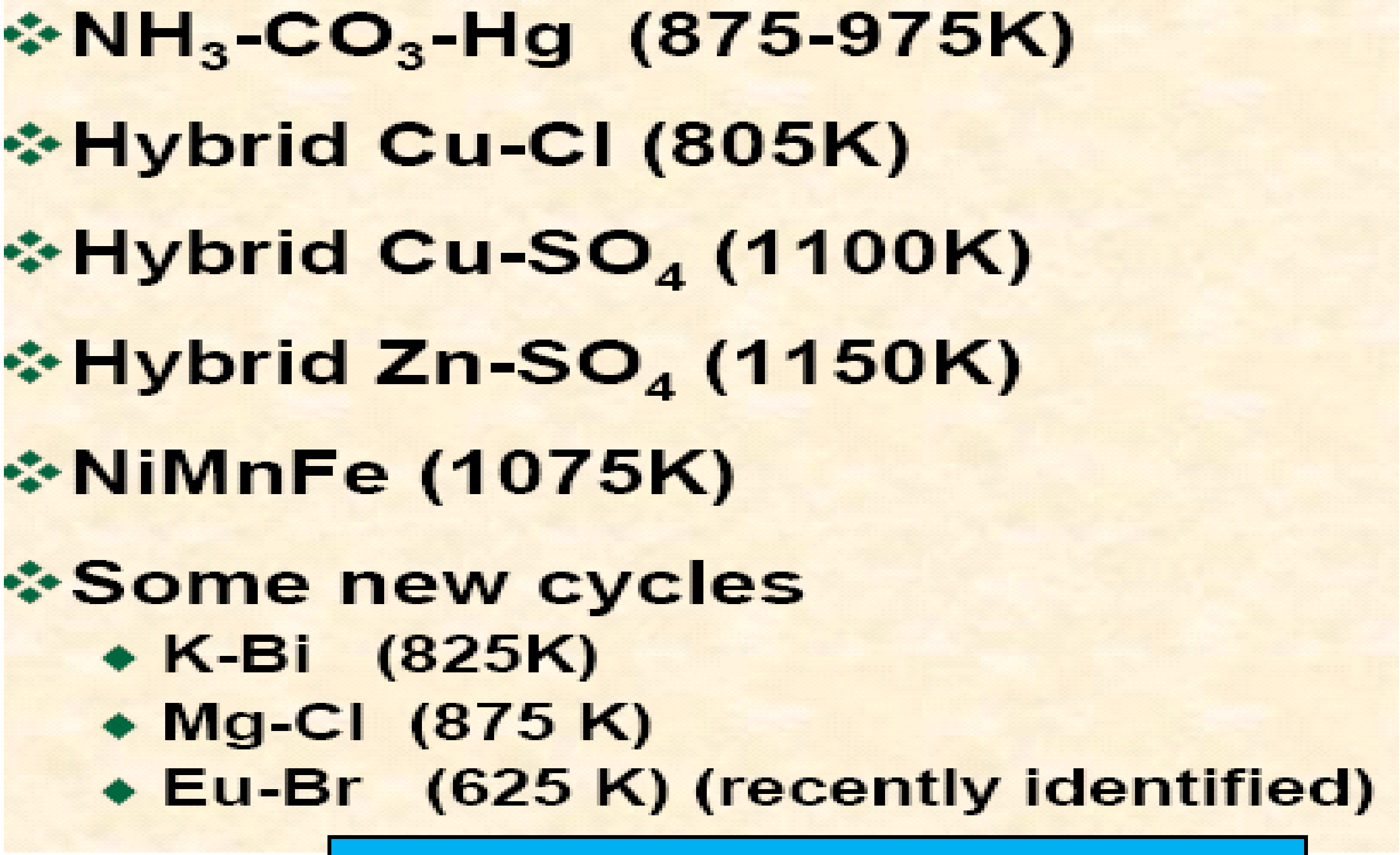
Other Cycles Being Actively Investigated



- NH_3-CO_3-Hg (875-975K)
- Hybrid Cu-Cl (805K)
- Hybrid Cu-SO_4 (1100K)
- Hybrid Zn-SO_4 (1150K)
- NiMnFe (1075K)
- Some new cycles
  - K-Bi (825K)
  - Mg-Cl (875 K)
  - Eu-Br (625 K) (recently identified)

Wilson, Corwin, Sherman, Pickard (2006)

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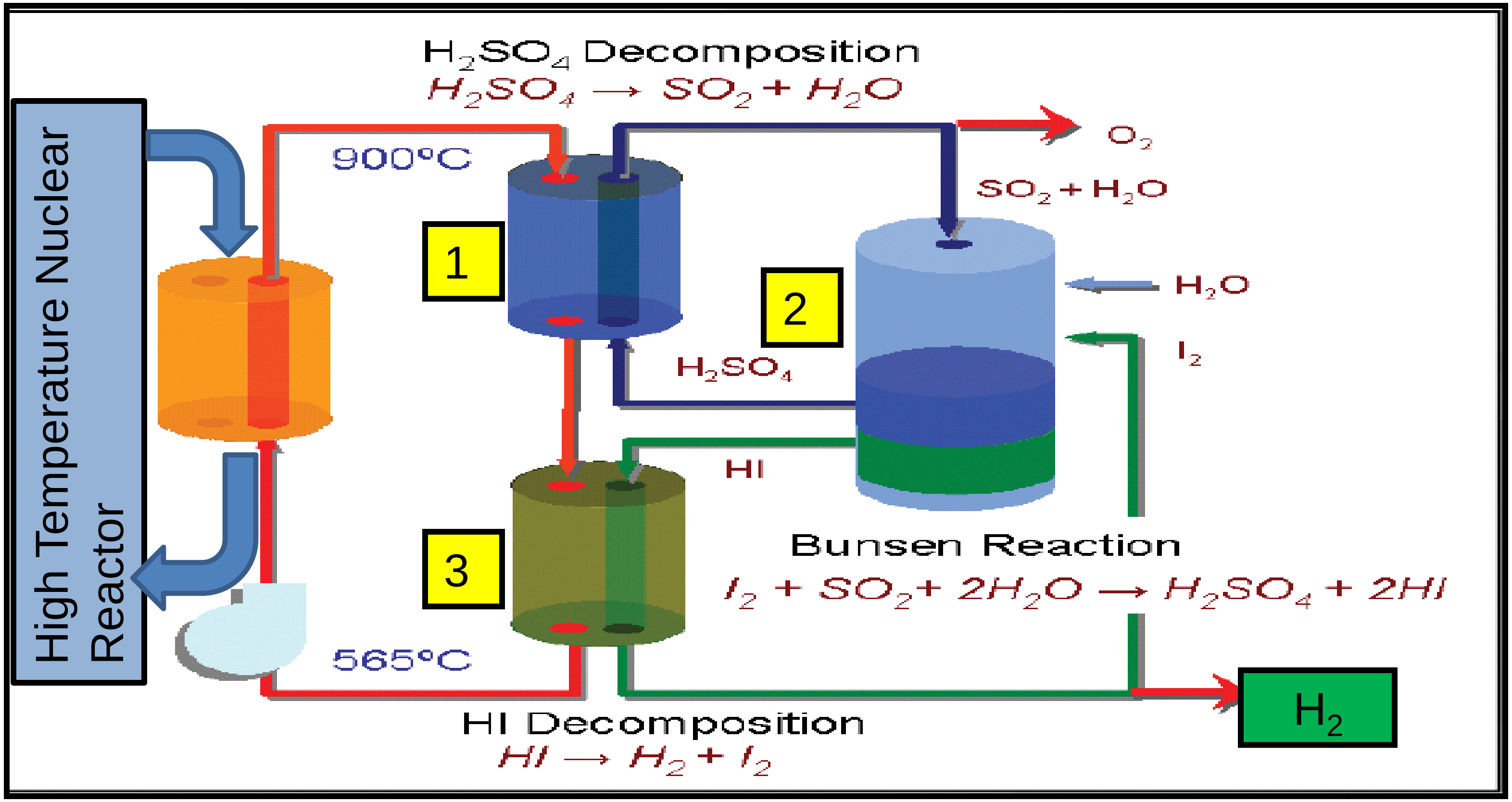
Schematic of the 3 Major Components of a Nuclear Hydrogen Production Facility



Adapted from Wang (2006)

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Basic R&D Issues in High Temp T-C Hydrogen Production Cycles

- Scaling and Efficiency are the Main Issues for thermochemical cycles – bench to pilot plant to industrial scale
- But T-C Cycles Also Present Very Demanding Thermal Management Challenges during Operation.
- Materials Challenges Include:
  - High-temperature Resistance (alloys, ceramics or refractories)
  - Chemical Corrosion Resistance (against acids)
  - Stress Corrosion Resistance (from high Pressure and Temperature conditions)
  - Materials Challenges serious: cause Viability Concerns. (also see Baindur 2007a).

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Candidate Materials for S-I Cycle (Wang 2006)

- Sulfuric Acid Decomposition
  - Outputs Oxygen and Sulfur Dioxide
    - Alloy 800 and Hastelloys for Reaction Vessel and Piping; also Ceramics
- Bunsen Reaction
  - Produces Hydrogen Iodide and Sulfuric Acid
    - Fe-Si Alloys work well as Reaction Vessels and Concentrators;
- Hydrogen Iodide Decomposition
  - Produces and Separates Hydrogen and Iodine
    - Tantalum and Wolfram (Tungsten) Alloys best corrosion resistance
- Extensive Testing of Candidate Materials Required to move beyond Bench Scale

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Heat Exchanger Candidate Materials
(Hechanova UNLV 2005)

- Tensile Property Tests of 3 Nickel-based Alloys: C-22, C-276 and Waspalloy are ongoing at UNLV at (i) Ambient Temperature (ii) 450 C and (iii) 600 C in a nitrogen atmosphere.

- Stress Corrosion Cracking (SCC) for above 3 alloys also measured in 90 C aqueous solution of sulfuric acid and sodium iodide at (i) constant load (ii) slow strain-rate.

- Incoloy-800 also tested for SCC and tensile strength at UNLV

- MIT has tested alloys 800HT and 617 for Heat Exchanger with Catalyst Platinum (Pt) in 2-30 %wt for Sulfuric Acid Decomposition. (Hechanova 2005)

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References

1. Chang, J.,Y-W Kim, K-Y Lee, Y-W Lee, W-J Lee, J-M Noh, M-H Kim, H-S Lim, Y-J Shin, K-K Bae, K-D Jung, *A Study of a Nuclear Hydrogen Production Demonstration Plant,* Nuclear Engineering and Technology, Vol. 39 No. 2, 111-122 (2007).
2. Kim, W. G. et al., *Creep Properties of Hastelloy-X Alloy for the High Temperature Gas Cooled Reactor* Key Engineering Materials, vol. 316-328, pp.477-482 (2006).
3. Baindur, S. *Materials Challenges for the Supercritical Water-cooled Reactor (SCWR)* Canadian Nuclear Society, Saint John New Brunswick, (CNS 2007) June 2007. (Baindur 2007a).
4. Kurata, Y., K. Ikawa and K. Iwamoto, *The effect of heat treatment on density and structure of SiC*, J. Nucl. Mater. 92, 351 (1980).
5. Hechanova, A. *High-Temperature Heat Exchanger Development* Presentation, May 2005.
6. Wilson, D.F., W.R. Corwin, S. Sherman and P. Pickard, *Materials for Nuclear Hydrogen Production Processes,* Presentation to US DOE Hydrogen Program Annual Review, May 2006.
7. Wang, B. *Materials Development Makes Large-Scale Hydrogen Development a Reality,* NHA News, Summer 2006.
8. Roy, A.K., R. Karamcheti, L. Savalia and N. Kothapalli, *Metallurgical Stability and Corrosion Behavior of Structural Materials for Hydrogen Generation*, ASTM Conference, Reno, NV, May 2005.
9. Wong, B., R. Buckingham, L. Brown, B. Russ, G. Besenbruch, A. Kaiparambil, R. Santhanakrishnan and A. Roy, *Construction Materials Development in Sulfur-Iodine Thermochemical Water-Splitting Process for Hydrogen Generation*. AIChE, September 2005, Pittsburgh, PA.

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