Thermochemical Production of Hydrogen from Solar and Nuclear Energy

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Hydrogen production requires energy

NH2

Nuclear Hydrogen

- 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 ➔ Electrolysis
    - Proven technology
    - Overall efficiency ~24% (LWR), ~36% (Hi T Reactors)

      (efficiency of electric power generation x efficiency of electrolysis)
  - Heat ➔ Thermochemical water-splitting
    - Net plant efficiencies of up to ~50%
    - Developing technology
  - Electricity + Heat ➔ High temperature electrolysis or Hybrid cycles

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Thermochemical water-splitting

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- 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

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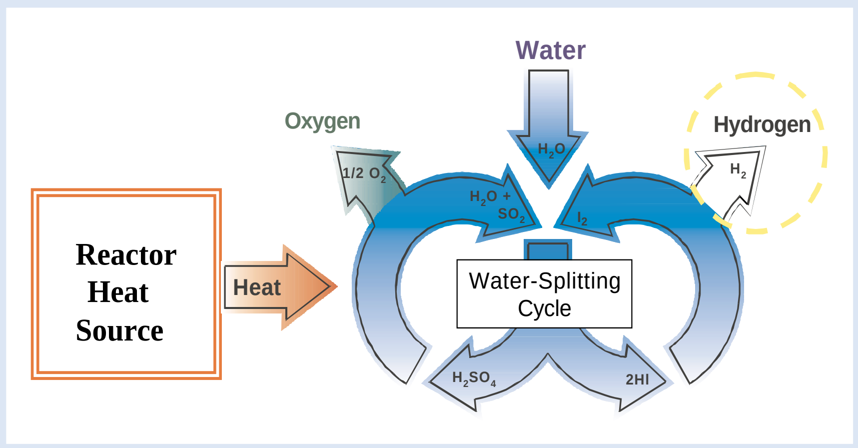
- GA/SNL/UoK reviewed world literature
  - 822 references, 115 unique thermochemical cycles
- Screened these and selected 25 cycles for detailed evaluation
  - Screening: Suitability for coupling to a nuclear heat source
  - Evaluation: Chemical thermodynamics, engineering block flow diagrams
- Identified 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

GENERAL ATOMICS

The S-I cycle is best suited to nuclear production of H_2

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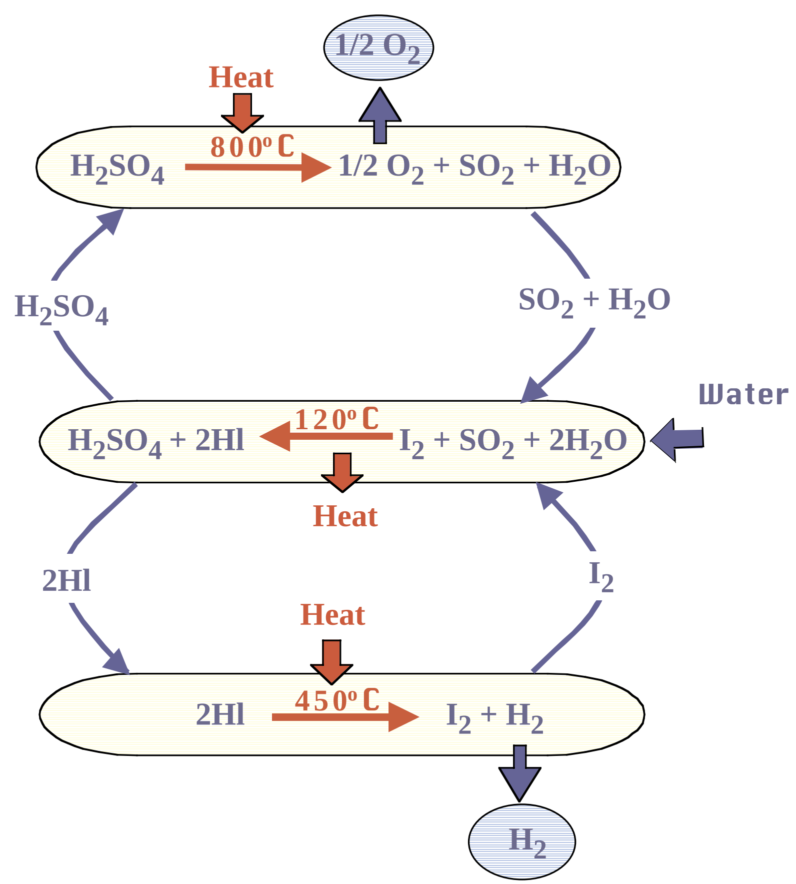
- **Invented at GA in 1970s**
  - Serious investigations for nuclear and solar
  - Chemistry reactions all demonstrated
  - Materials candidates selected and tested
- **Advantages:**
  - All fluid continuous process, chemicals all recycled; no effluents
  - H_2 produced at high pressure – 22 - 84 atm.
  - Highest cited projected efficiency, ~50%
- **Challenges:**
  - Requires high temperature, ≥800°C
  - Must be demonstrated as a closed loop under prototypical conditions

Sulfur-IodineThermochemical Water-Splitting Cycle



GENERAL ATOMICS

The S-I cycle is a thermally-driven chemical process

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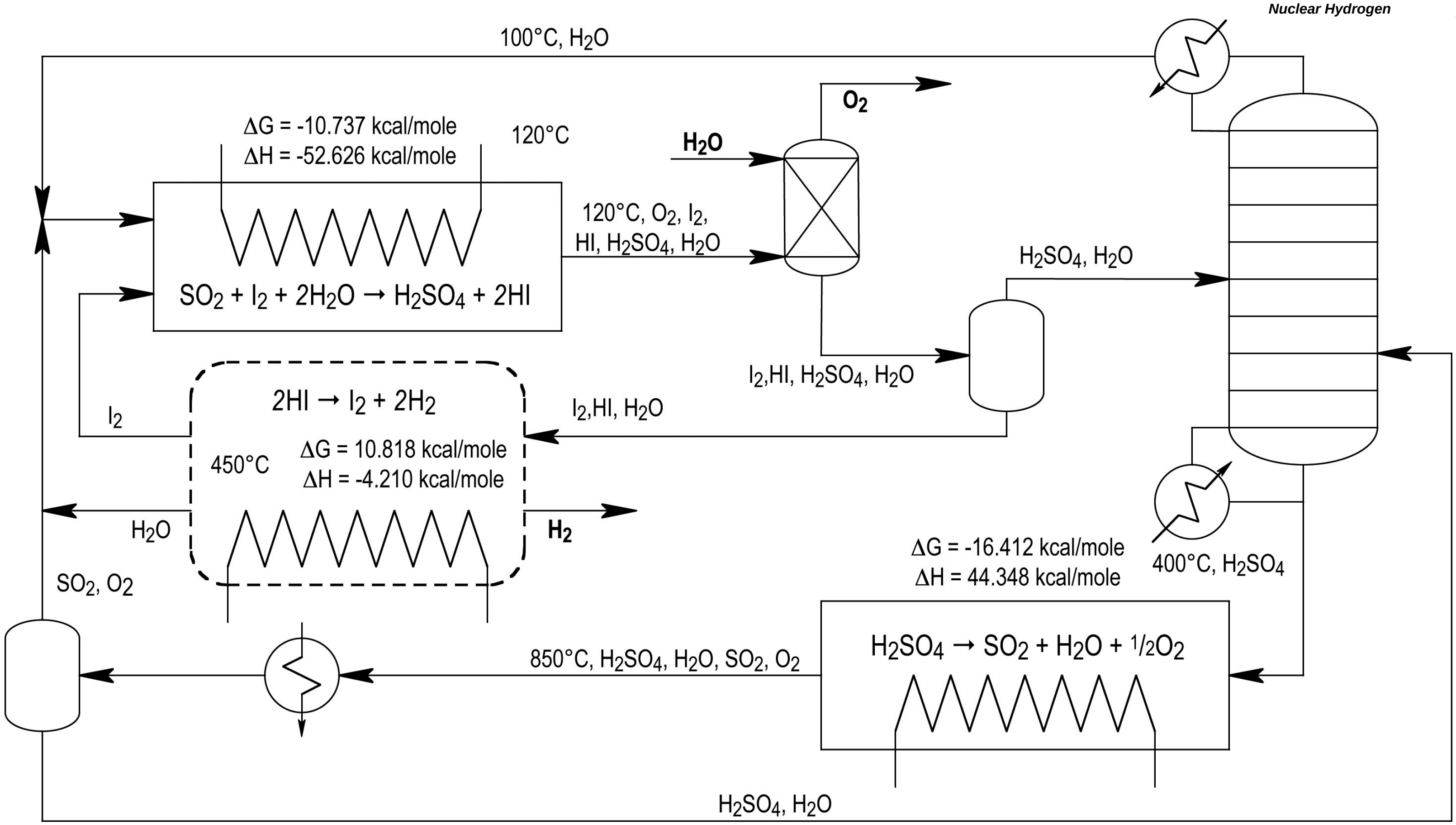

Follows the rules of chemistry and thermodynamics (Carnot)

High predicted efficiency: ~50% at 900°C

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High temperature increases efficiency

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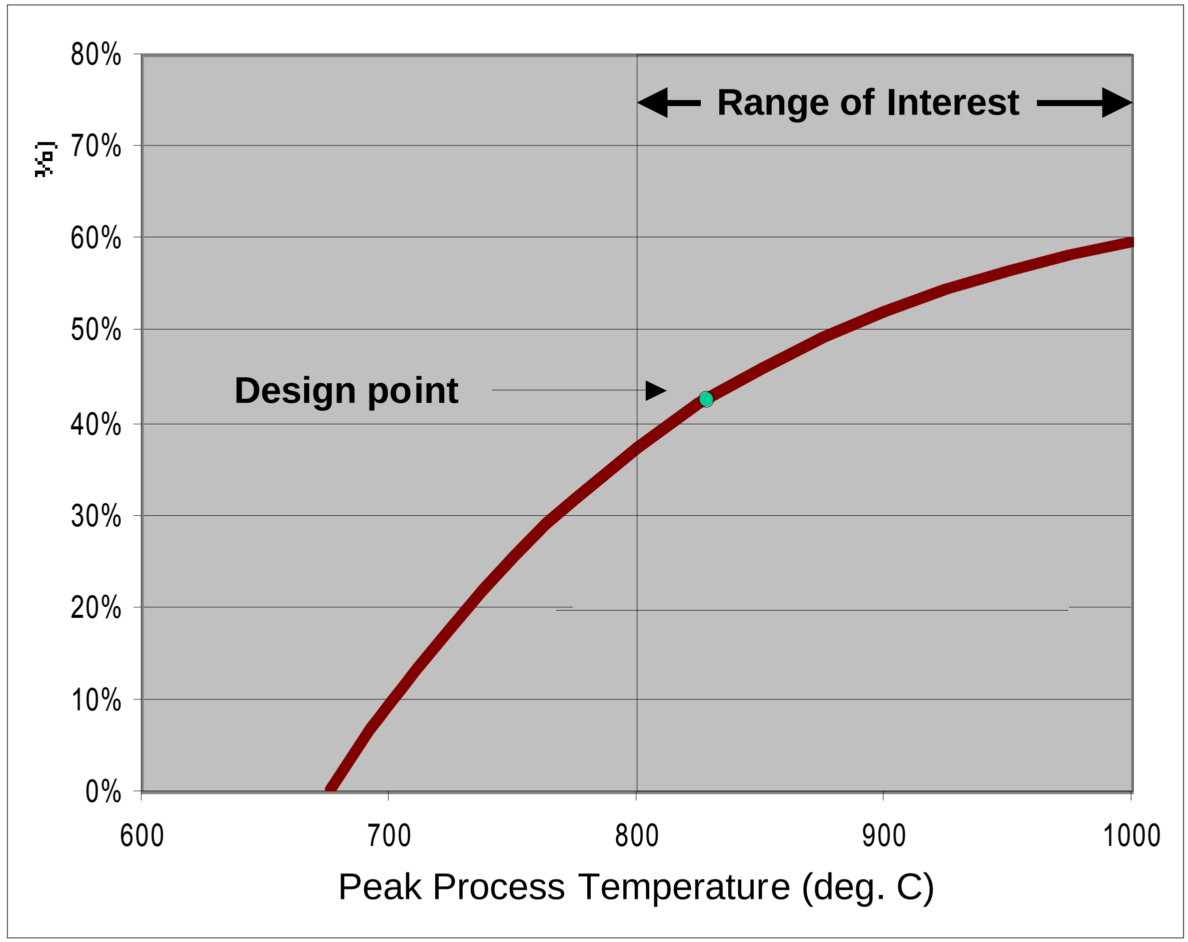
Estimated S-I process thermal-to-hydrogen energy efficiency (HHV)

- Process is coupled to nuclear heat source by an intermediate loop with 2 heat exchangers ~50°C ΔT
- Earlier studies used 827°C, achieved 42% efficiency
- >50% efficiency requires >900°C peak process T
- Reactor outlet T ≥ 950°C desired



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We completed the S-I process design

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- 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
    ($2HI \rightarrow I_2 + H_2$)

600 MWt H_2-MHR Process Parameters		
Material	Flow rate tons/day	Inventory tons
H_2	200	2
H_2O	1,800	40
H_2SO_4	9,800	100
I_2	203,200	2,120

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

Ref. Brown, *et al* AIChE 2003

- 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

GENERAL ATOMICS

SNL evaluated candidate nuclear reactors for thermochemical water-splitting

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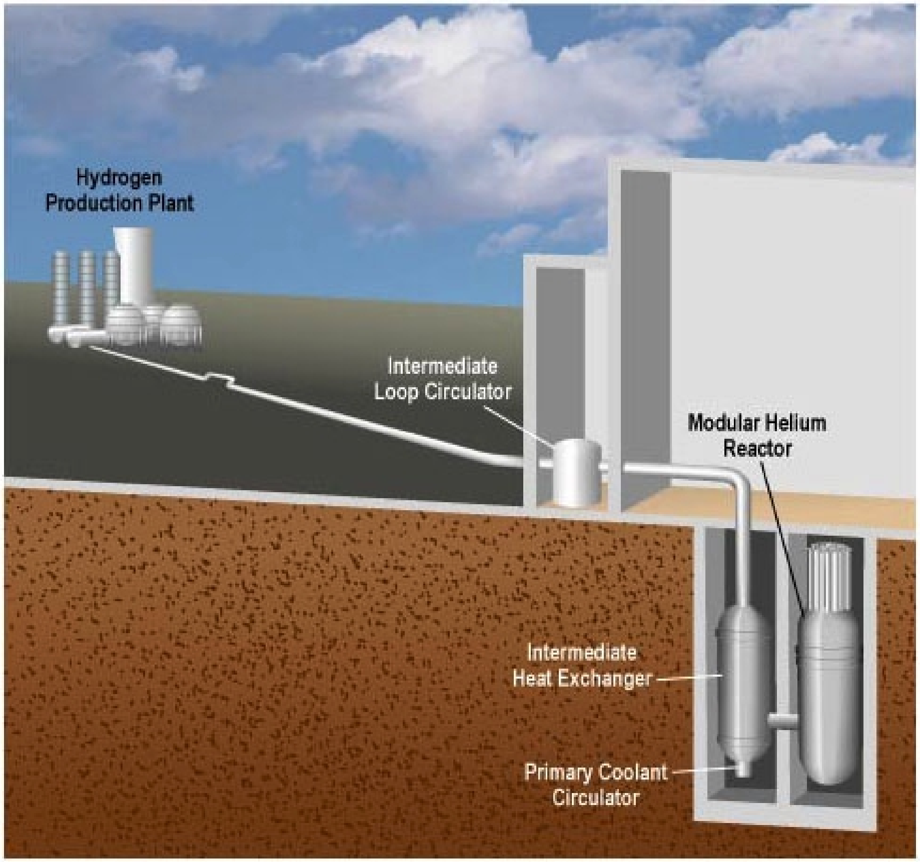
- SNL evaluated 9 categories:
  - PWR, BWR, Organic, Alkali metal, Heavy metal, Gas-cooled, Molten salt, Liquid-core and Gas-core
  - Assessed reactor features, development requirements
- Current commercial reactors are too low temperature
- Helium, heavy metal, molten salt rated well; helium gas-cooled most developed
- Selected Modular Helium Reactor as best suited for thermochemical production of hydrogen



H_2-MHR

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The Modular Helium Reactor solves the problems of first generation reactors

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- 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

GENERAL ATOMICS

Inherent reactor characteristics provide passive safety

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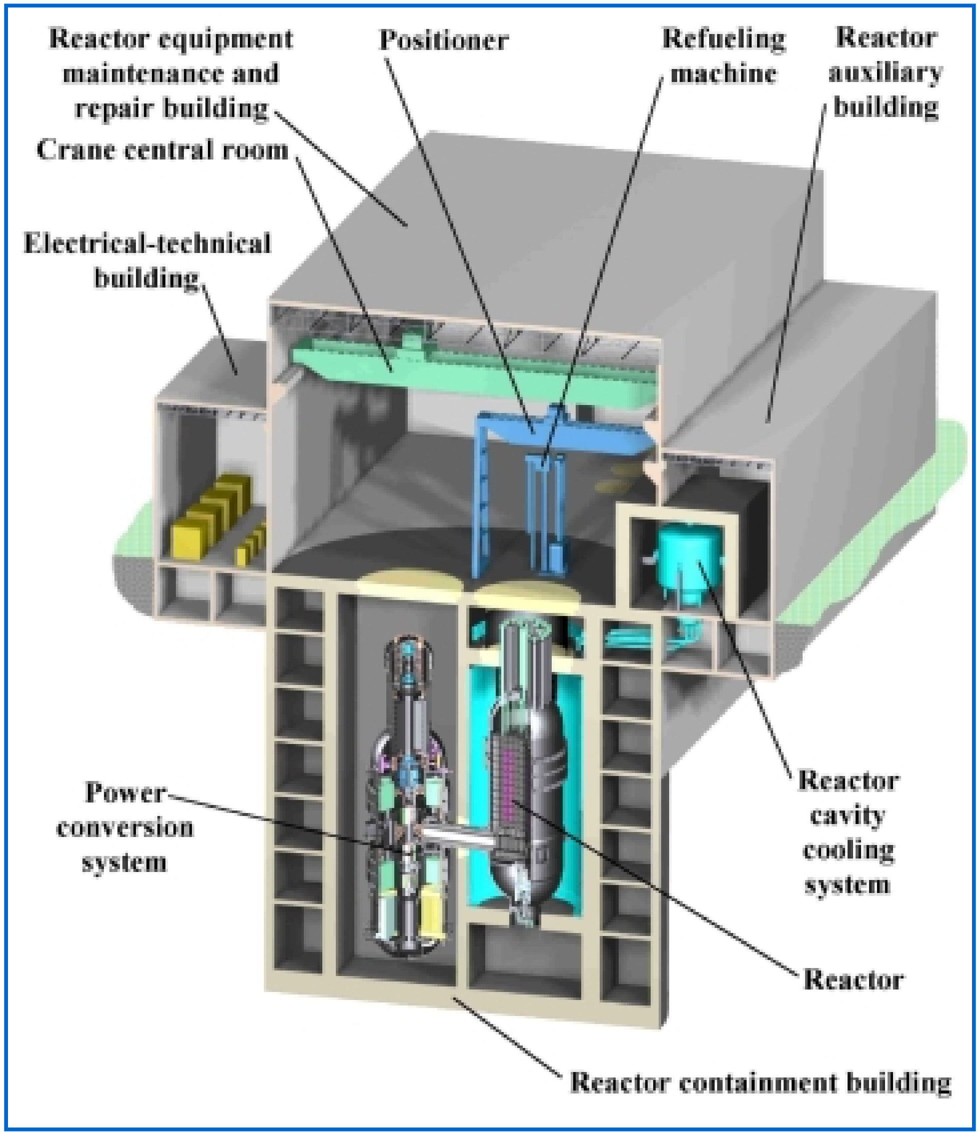

- Helium gas coolant (inert)
- Refractory fuel (high temperature capability)
- Graphite reactor core (high temperature stability)
- Low power density, modular size (slow thermal response)
- Demonstrated technologies from 7 prototypes world-wide over 40 years

. . . EFFICIENT PERFORMANCE WITH PASSIVE SAFETY

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Nuclear-produced H_2 must be economical to compete

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- 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 I_2 inventory

	GT-MHR Electric Plant	MHR Process Heat Plant	VHTR Process Heat Plant	Intermed Loop	S-I Hydrogen Plant + I_2	H2-VHTR H2 Plant
Capital Cost, $/kW_t$	468	326	371	43	297	711
Operating Cost, $/MW_th$	5.0	4.0	4.9	0.1	3.3	8.3

Cost of H_2: $/kg	H2-MHR	H2-VHTR
Public utility	$1.52	$1.42
Regulated utility	$1.69	$1.57
Unregulated utility	$2.01	$1.87

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Nuclear-produced hydrogen will be economic

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- H2-VHTR could produce H_2 at ~$1.40/kg
- Meets steam reformation of natural gas H_2 cost at ~$6.30/MBtu
- $1/MBtu higher natural gas cost or $100/ton CO_2 capture and sequestration cost could each add 20¢/kg of SMR H_2, or $25/ton oxygen sale could subtract 20¢/kg of nuclear H_2
- Nuclear production of H_2 would avoid fossil fuels and CO_2 emissions without economic penalties

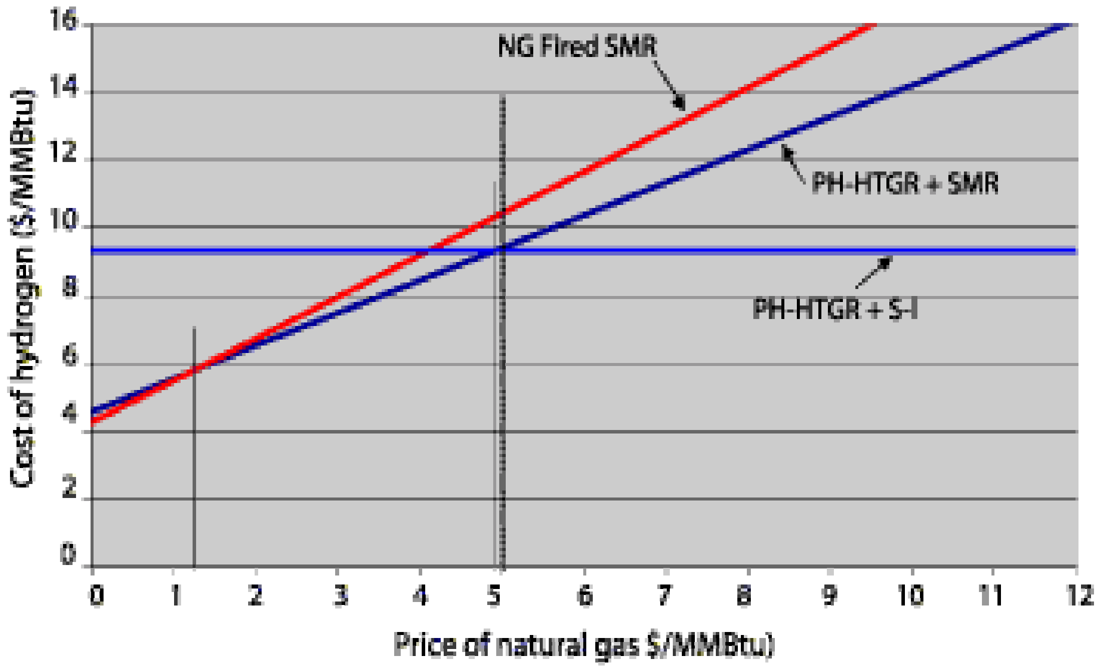

Figure 1 Cost of hydrogen for technology leaders—with CO_2 costs

Figure courtesy of ERRI

.... and CO_2 emission-free

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Nuclear Production of H_2 Appears Attractive

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- A large and growing market for H_2 exists that nuclear energy could serve
  - H_2 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 H_2 from natural gas today if O_2 can be sold
  - Increasing cost of natural gas or CO_2 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...

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- **The first steps have begun:**
  - Demonstrate laboratory scale SI process operation (I-NERI)
  - Conceptual design of H_2-MHR and Intermediate Loop (NERI)
  - Measure needed chemical data (SNL-L, CEA)
  - Tasks could be completed in 3 years
- **Next, build a ~30 MWt Pilot Plant (~10 tons/day of H_2)**
  - Design, build and operate in ~4 years for ~$75-100M
  - Operation with fossil-fueled simulated nuclear heat source
- **Then, build a 600 MWt (200 t/d) H_2- Nuclear Demo Plant**
  - Demonstration of "Nuclear Hydrogen" by ~2015
  - ~$350M + reactor

... but the path forward appears clear

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Solar Production of Hydrogen is an appealing goal

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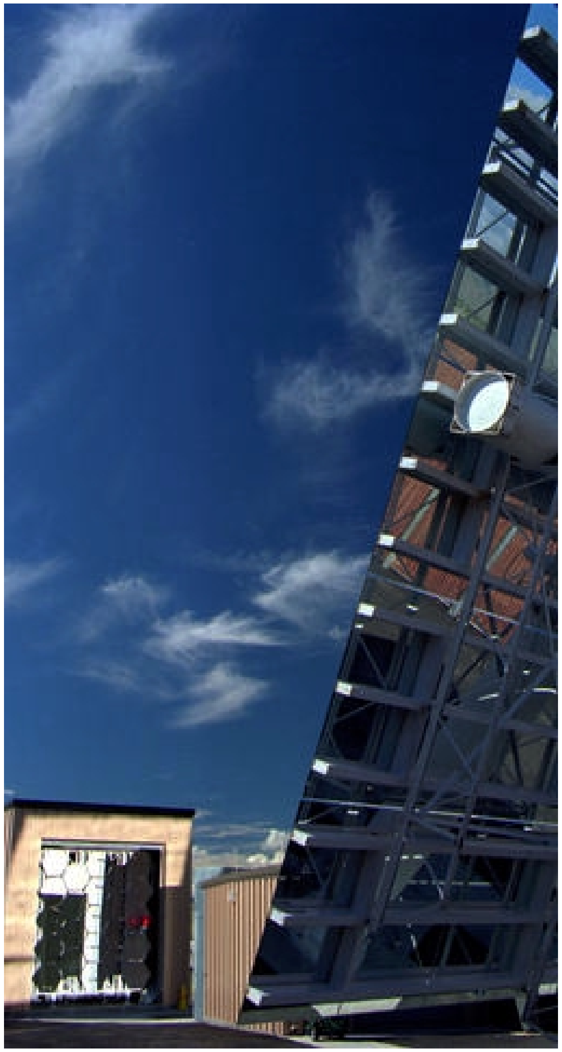
Nuclear Hydrogen

- 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

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Preliminary estimates of Solar thermochemical hydrogen production are encouraging

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- **Start with nuclear-matched S-I cycle coupled to solar receiver**
  - **NREL heliostat/collector: 1 kW/m^2, 51% capture, \$130/m^2, 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/m^2**
  - **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 H_2 efficiency**
  - **Assume same \$/kWt capital cost as S-I**
- **While the assumptions are unproven, the result *is* interesting**

Process	Nuclear S-I	Solar S-I	Solar Hi T S-I	V Hi T Cycle
Temperature ˚C	900	900	1100	2000
Efficiency - Heat to H_2	52%	52%	56%	65%
Hydrogen cost, \$/kg	1.42	3.45	2.50	2.15

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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

SNL Solar Power Tower

Barriers to nuclear thermochemical water-splitting and research opportunities

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- **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 validatiom
  - Measure chemical data
  - Demonstrate process
  - Verify materials

– Study cost/value of CO_2 Cap&Seq
  - Can sustainable sources of H_2 compete? When?

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Barriers to solar thermochemical water-splitting and research opportunities

NH2 Nuclear Hydrogen

- **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 H_2 compete? When?

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Thermochemical Hydrogen Production from Solar and Nuclear Energy

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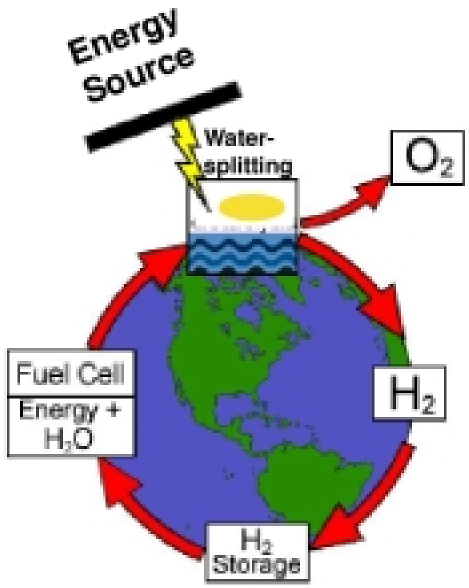

- Thermochemical water-splitting promises efficient hydrogen production from heat
- Requires high temperatures
- For nuclear, the Sulfur-Iodine cycle matched to the Modular Helium Reactor appears attractive and economic
- For solar, process matching and selection is needed
- Thermochemical water-splitting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

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BACKUP VIEWGRAPHS

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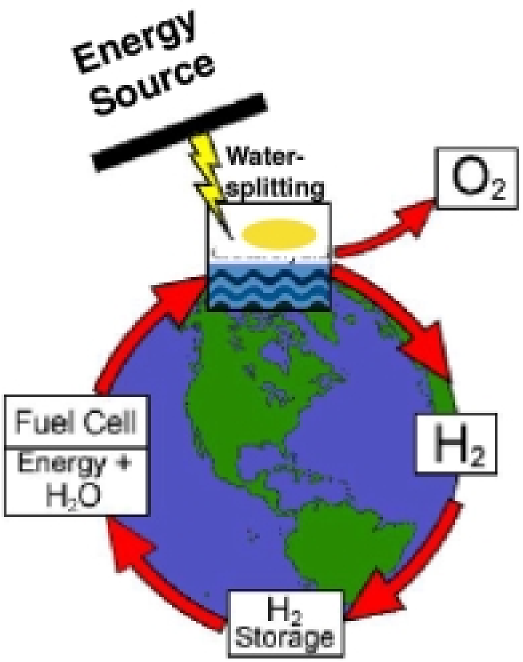
Hydrogen is the Ideal Replacement for Fossil Fuels

- 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



- <u>One issue: where to get the hydrogen</u>?
  - — 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

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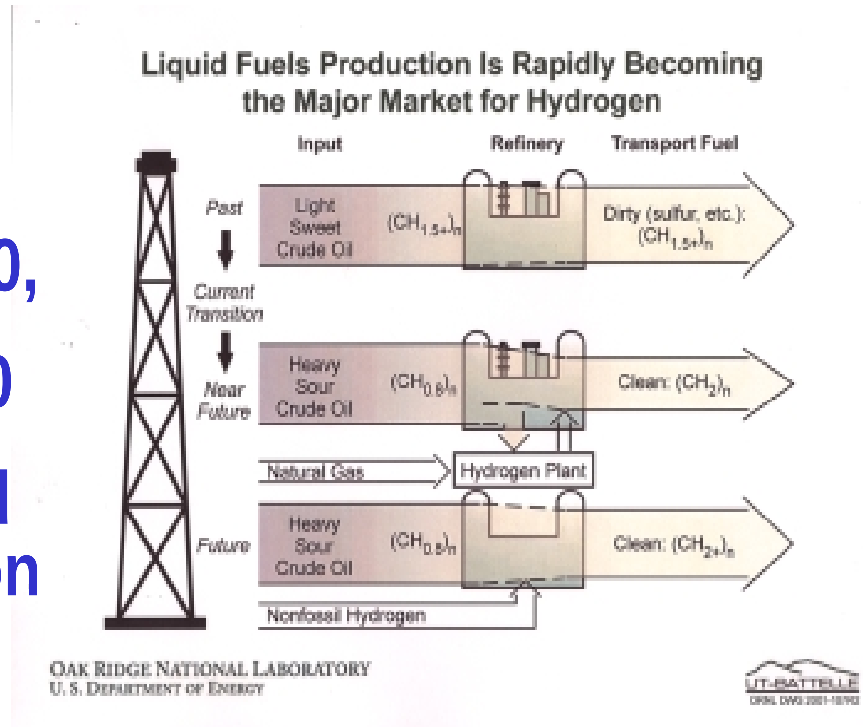
- US use of hydrogen is now 11 million tons/y (48 GWt)
- 95% produced by Steam Reformation of Methane
  - Consumes 5% of our natural gas usage
  - Not CO_2-free: releases 74 M tons of CO_2/y
- Most is used in fertilizer, chemical and oil industries
- ~10%/y growth ➔ X 2 by 2010,
  X 4 by 2020
- Hydrogen Economy will need
  X 18 current for transportation
  X 40 for all non-electric



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Quantifiable screening criteria were developed and applied. . .

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- 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

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The top 25 thermochemical cycles for nuclear energy

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Cycle	Name	T/E*	T °C	Reaction	F†
1	Westinghouse [12]	T	850	$2H_2SO_4(g) \rightarrow 2SO_2(g) + 2H_2O(g) + O_2(g)$	1/
		E	77	$SO_2(g) + 2H_2O(a) \rightarrow H_2SO_4(a) + H_2(g)$	1
2	Ispra Mark 13 [13]	T	850	$2H_2SO_4(g) \rightarrow 2SO_2(g) + 2H_2O(g) + O_2(g)$	1/
		E	77	$2HBr(a) \rightarrow Br_2(a) + H_2(g)$	1
		T	77	$Br_2(l) + SO_2(g) + 2H_2O(l) \rightarrow 2HBr(g) + H_2SO_4(a)$	1
3	UT-3 Univ. of Tokyo [8]	T	600	$2Br_2(g) + 2CaO \rightarrow 2CaBr_2 + O_2(g)$	1/
		T	600	$3FeBr_2 + 4H_2O \rightarrow Fe_3O_4 + 6HBr + H_2(g)$	1
		T	750	$CaBr_2 + H_2O \rightarrow CaO + 2HBr$	1
		T	300	$Fe_3O_4 + 8HBr \rightarrow Br_2 + 3FeBr_2 + 4H_2O$	1
4	Sulfur-Iodine [14]	T	850	$2H_2SO_4(g) \rightarrow 2SO_2(g) + 2H_2O(g) + O_2(g)$	1/
		T	450	$2HI \rightarrow I_2(g) + H_2(g)$	1
		T	120	$I_2 + SO_2(a) + 2H_2O \rightarrow 2HI(a) + H_2SO_4(a)$	1
5	Julich Center EOS [15]	T	800	$2Fe_3O_4 + 6FeSO_4 \rightarrow 6Fe_2O_3 + 6SO_2 + O_2(g)$	1/
		T	700	$3FeO + H_2O \rightarrow Fe_3O_4 + H_2(g)$	1
		T	200	$Fe_2O_3 + SO_2 \rightarrow FeO + FeSO_4$	6
6	Tokyo Inst. Tech. Ferrite [16]	T	1000	$2MnFe_2O_4 + 3Na_2CO_3 + H_2O \rightarrow 2Na_3MnFe_2O_6 + 3CO_2(g) + H_2(g)$	1
		T	600	$4Na_3MnFe_2O_6 + 6CO_2(g) \rightarrow 4MnFe_2O_4 + 6Na_2CO_3 + O_2(g)$	1/
7	Hallett Air Products 1965 [15]	T	800	$2Cl_2(g) + 2H_2O(g) \rightarrow 4HCl(g) + O_2(g)$	1/
		E	25	$2HCl \rightarrow Cl_2(g) + H_2(g)$	1
8	Gaz de France [15]	T	725	$2K + 2KOH \rightarrow 2K_2O + H_2(g)$	1
		T	825	$2K_2O \rightarrow 2K + K_2O_2$	1
		T	125	$2K_2O_2 + 2H_2O \rightarrow 4KOH + O_2(g)$	1/
9	Nickel Ferrite [17]	T	800	$NiMnFe_4O_6 + 2H_2O \rightarrow NiMnFe_4O_8 + 2H_2(g)$	1
		T	800	$NiMnFe_4O_8 \rightarrow NiMnFe_4O_6 + O_2(g)$	1/
10	Aachen Univ Julich 1972 [15]	T	850	$2Cl_2(g) + 2H_2O(g) \rightarrow 4HCl(g) + O_2(g)$	1/
		T	170	$2CrCl_2 + 2HCl \rightarrow 2CrCl_3 + H_2(g)$	1
		T	800	$2CrCl_3 \rightarrow 2CrCl_2 + Cl_2(g)$	1
11	Ispra Mark 1C [13]	T	100	$2CuBr_2 + Ca(OH)_2 \rightarrow 2CuO + 2CaBr_2 + H_2O$	1
		T	900	$4CuO(s) \rightarrow 2Cu_2O(s) + O_2(g)$	1/
		T	730	$CaBr_2 + 2H_2O \rightarrow Ca(OH)_2 + 2HBr$	2
		T	100	$Cu_2O + 4HBr \rightarrow 2CuBr_2 + H_2(g) + H_2O$	1
12	LASL- U [15]	T	25	$3CO_2 + U_3O_8 + H_2O \rightarrow 3UO_2CO_3 + H_2(g)$	1
		T	250	$3UO_2CO_3 \rightarrow 3CO_2(g) + 3UO_3$	1
		T	700	$6UO_3(s) \rightarrow 2U_3O_8(s) + O_2(g)$	1/
13	Ispra Mark 8 [13]	T	700	$3MnCl_2 + 4H_2O \rightarrow Mn_3O_4 + 6HCl + H_2(g)$	1
		T	900	$3MnO_2 \rightarrow Mn_3O_4 + O_2(g)$	1/
		T	100	$4HCl + Mn_3O_4 \rightarrow 2MnCl_2(a) + MnO_2 + 2H_2O$	3/
14	Ispra Mark 6 [13]	T	850	$2Cl_2(g) + 2H_2O(g) \rightarrow 4HCl(g) + O_2(g)$	1/
		T	170	$2CrCl_2 + 2HCl \rightarrow 2CrCl_3 + H_2(g)$	1
		T	700	$2CrCl_3 + 2FeCl_2 \rightarrow 2CrCl_2 + 2FeCl_3$	1
		T	420	$2FeCl_3 \rightarrow Cl_2(g) + 2FeCl_2$	1
15	Ispra Mark 4 [13]	T	850	$2Cl_2(g) + 2H_2O(g) \rightarrow 4HCl(g) + O_2(g)$	1/
		T	100	$2FeCl_2 + 2HCl + S \rightarrow 2FeCl_3 + H_2S$	1
		T	420	$2FeCl_3 \rightarrow Cl_2(g) + 2FeCl_2$	1
		T	800	$H_2S \rightarrow S + H_2(g)$	1
16	Ispra Mark 3 [13]	T	850	$2Cl_2(g) + 2H_2O(g) \rightarrow 4HCl(g) + O_2(g)$	1/
		T	170	$2VOCl_2 + 2HCl \rightarrow 2VOCl_3 + H_2(g)$	1
		T	200	$2VOCl_3 \rightarrow Cl_2(g) + 2VOCl_2$	1
17	Ispra Mark 2 (1972) [13]	T	100	$Na_2O.MnO_2 + H_2O \rightarrow 2NaOH(a) + MnO_2$	2
		T	487	$4MnO_2(s) \rightarrow 2Mn_2O_3(s) + O_2(g)$	1/
		T	800	$Mn_2O_3 + 4NaOH \rightarrow 2Na_2O.MnO_2 + H_2(g) + H_2O$	1
18	Ispra CO/Mn3O4 [18]	T	977	$6Mn_2O_3 \rightarrow 4Mn_3O_4 + O_2(g)$	1/
		T	700	$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g)$	1
		T	700	$CO(g) + 2Mn_3O_4 \rightarrow C + 3Mn_2O_3$	1
19	Ispra Mark 7B [13]	T	1000	$2Fe_2O_3 + 6Cl_2(g) \rightarrow 4FeCl_3 + 3O_2(g)$	3/
		T	420	$2FeCl_3 \rightarrow Cl_2(g) + 2FeCl_2$	3/2
		T	650	$3FeCl_2 + 4H_2O \rightarrow Fe_3O_4 + 6HCl + H_2(g)$	1
		T	350	$4Fe_3O_4 + O_2(g) \rightarrow 6Fe_2O_3$	1/
		T	400	$4HCl + O_2(g) \rightarrow 2Cl_2(g) + 2H_2O$	3/
20	Vanadium Chloride [19]	T	850	$2Cl_2(g) + 2H_2O(g) \rightarrow 4HCl(g) + O_2(g)$	1/
		T	25	$2HCl + 2VCl_2 \rightarrow 2VCl_3 + H_2(g)$	1
		T	700	$2VCl_3 \rightarrow VCl_4 + VCl_2$	2
		T	25	$2VCl_4 \rightarrow Cl_2(g) + 2VCl_3$	1
21	Mark 7A [13]	T	420	$2FeCl_3(l) \rightarrow Cl_2(g) + 2FeCl_2$	3/
		T	650	3FeCl + 4H O(g) → Fe O + 6HCl(g) + H (g)	1
		T	350	$4Fe_3O_4 + O_2(g) \rightarrow 6Fe_2O_3$	1/
		T	1000	$6Cl_2(g) + 2Fe_2O_3 \rightarrow 4FeCl_3(g) + 3O_2(g)$	1/
		T	120	$Fe_2O_3 + 6HCl(a) \rightarrow 2FeCl_3(a) + 3H_2O(l)$	1
22	GA Cycle 23 [20]	T	800	$H_2S(g) \rightarrow S(g) + H_2(g)$	1
		T	850	$2H_2SO_4(g) \rightarrow 2SO_2(g) + 2H_2O(g) + O_2(g)$	1/
		T	700	$3S + 2H_2O(g) \rightarrow 2H_2S(g) + SO_2(g)$	1/
		T	25	$3SO_2(g) + 2H_2O(l) \rightarrow 2H_2SO_4(a) + S$	1/
		T	25	$S(g) + O_2(g) \rightarrow SO_2(g)$	
23	US -Chlorine [15]	T	850	$2Cl_2(g) + 2H_2O(g) \rightarrow 4HCl(g) + O_2(g)$	1/
		T	200	$2CuCl + 2HCl \rightarrow 2CuCl_2 + H_2(g)$	1
		T	500	$2CuCl_2 \rightarrow 2CuCl + Cl_2(g)$	1
24	Ispra Mark 9 [13]	T	420	$2FeCl_3 \rightarrow Cl_2(g) + 2FeCl_2$	3/
		T	150	$3Cl_2(g) + 2Fe_3O_4 + 12HCl \rightarrow 6FeCl_3 + 6H_2O + O_2(g)$	1/2
		T	650	$3FeCl_2 + 4H_2O \rightarrow Fe_3O_4 + 6HCl + H_2(g)$	1
25	Ispra Mark 6C [13]	T	850	$2Cl_2(g) + 2H_2O(g) \rightarrow 4HCl(g) + O_2(g)$	1/
		T	170	$2CrCl_2 + 2HCl \rightarrow 2CrCl_3 + H_2(g)$	1
		T	700	$2CrCl_3 + 2FeCl_2 \rightarrow 2CrCl_2 + 2FeCl_3$	1
		T	500	$2CuCl_2 \rightarrow 2CuCl + Cl_2(g)$	1
		T	300	$CuCl + FeCl_3 \rightarrow CuCl_2 + FeCl_2$	1

*: T = thermochemical, E = electrochemical. †: Multiplier for one mole of H_2O decomposed

GENERAL ATOMICS

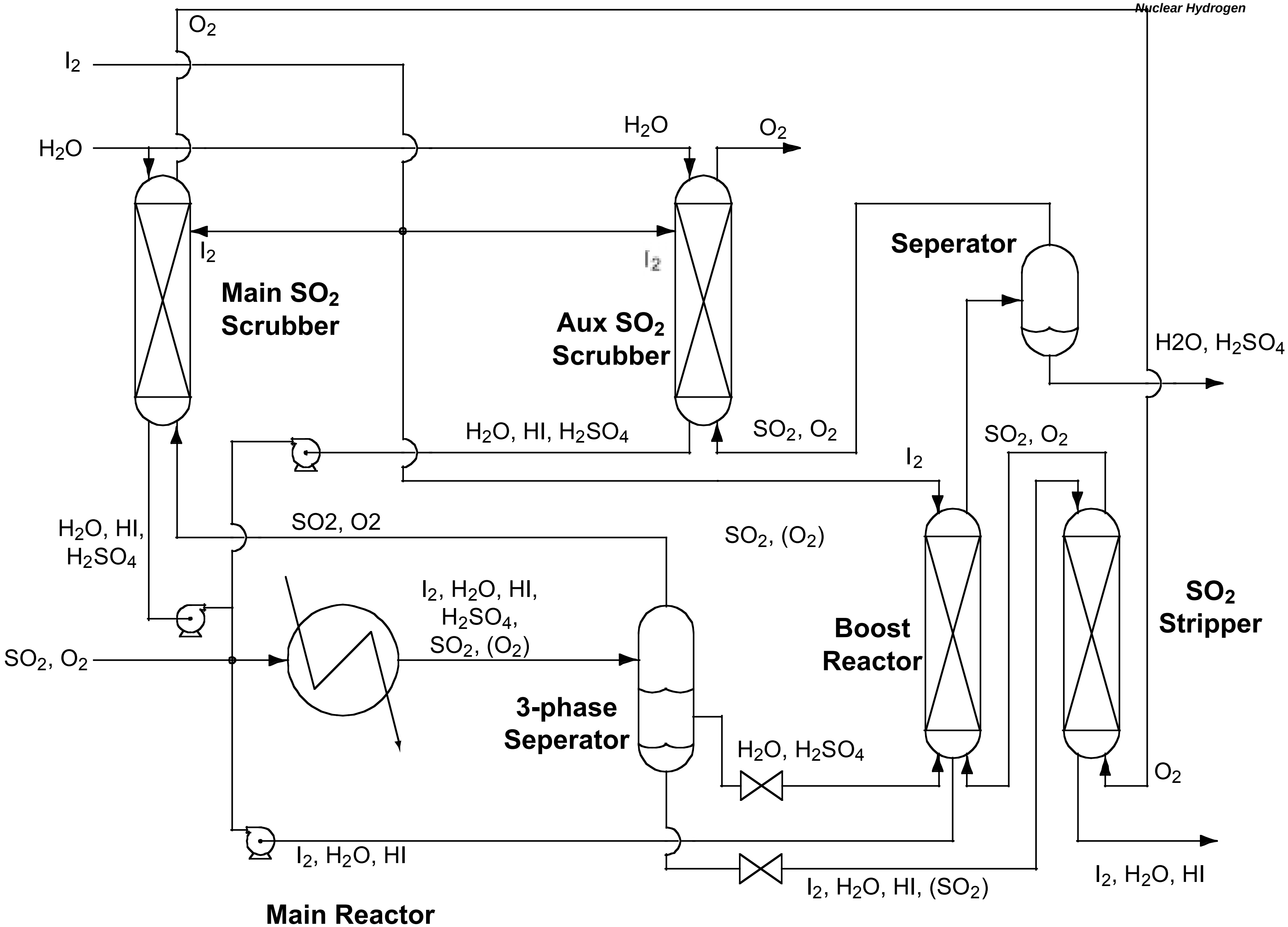
Detailed evaluation criteria were developed and applied

- 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

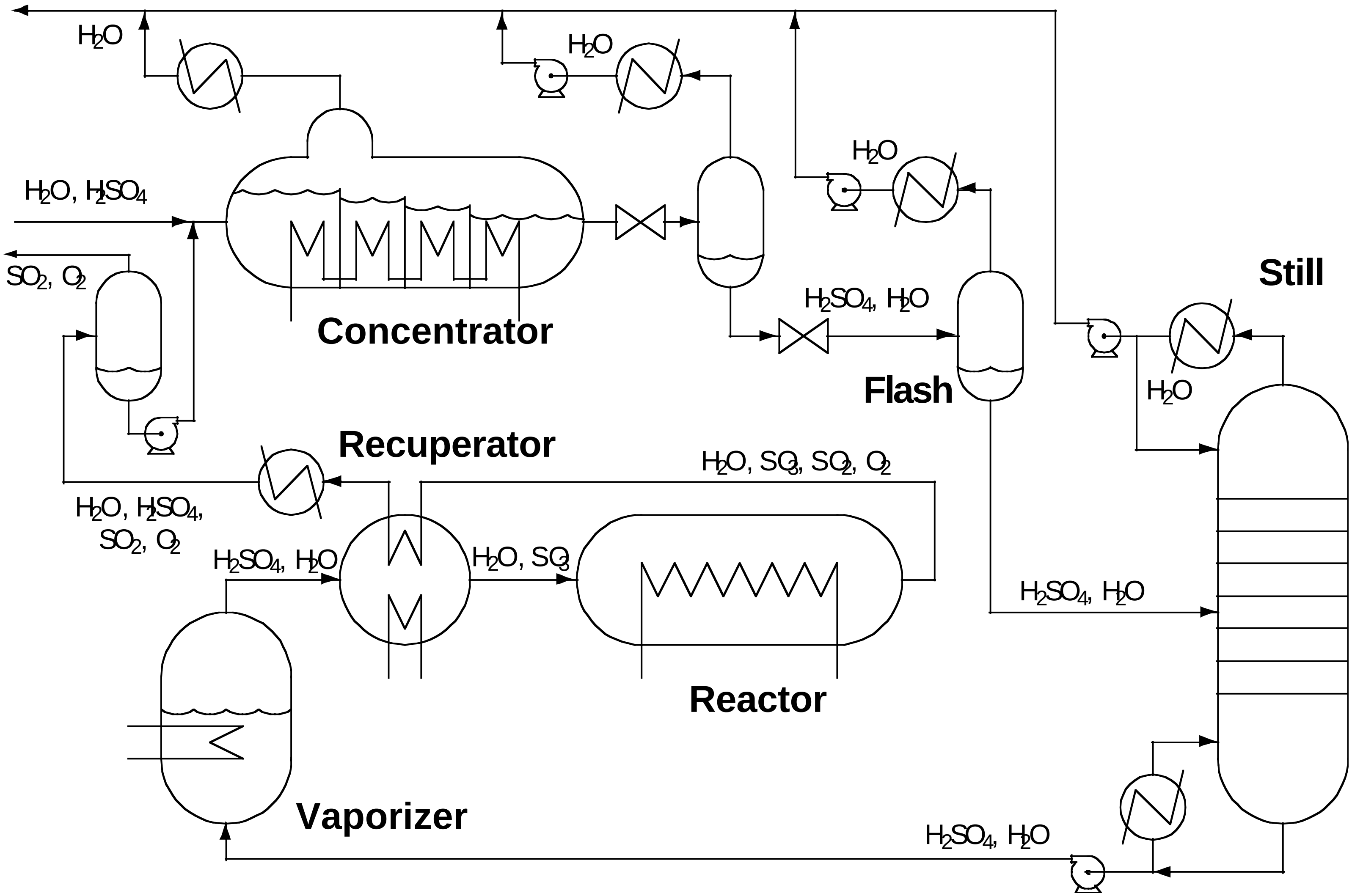
Section 1- Bunsen reaction and Chemical recycle

NH2
Nuclear Hydrogen



GENERAL ATOMICS

Section 2 - Sulfuric acid concentration and decomposition



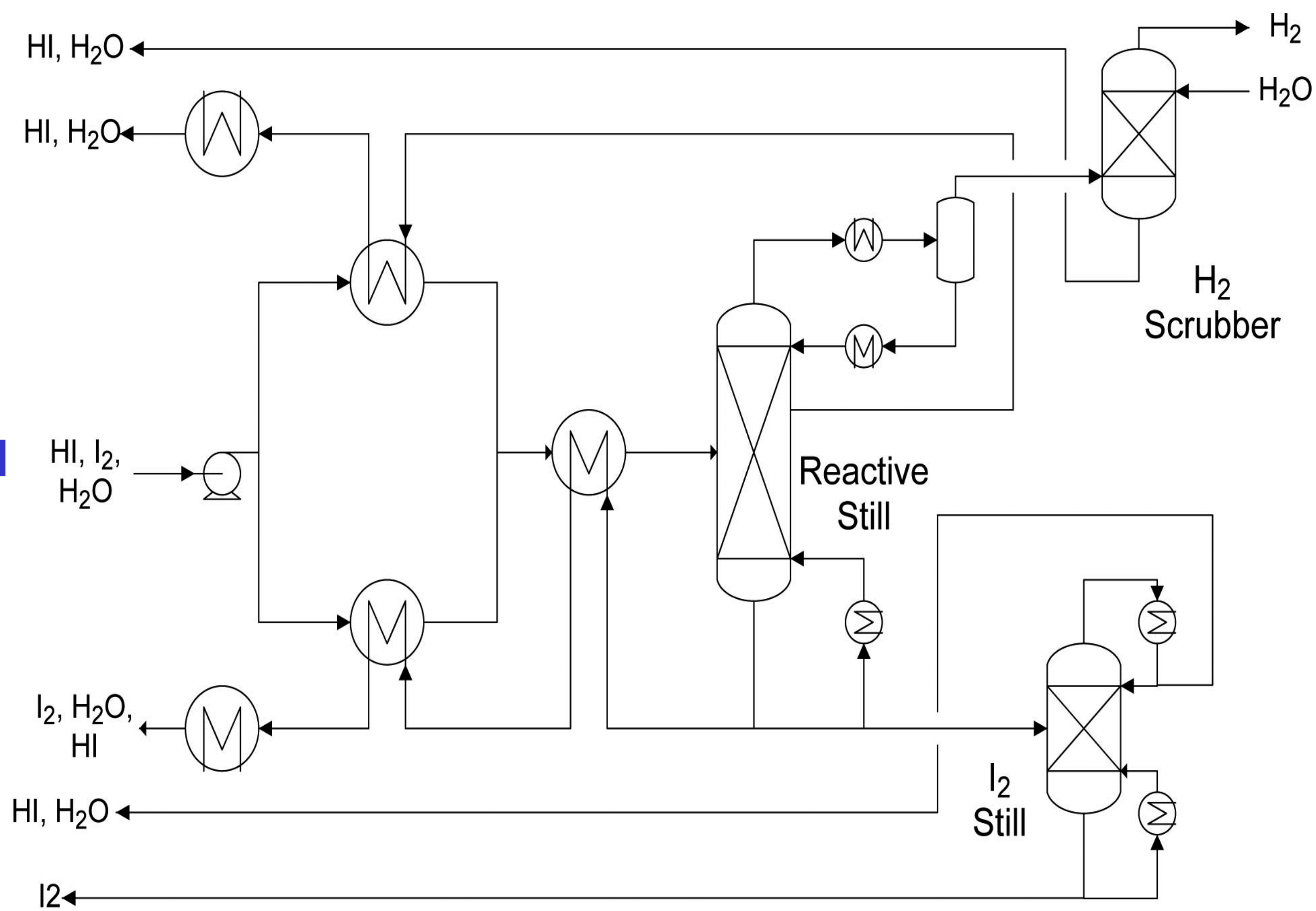
NH2
Nuclear Hydrogen

GENERAL ATOMICS

Section 3 - HI Decomposition - Reactive distillation process

NH2
Nuclear Hydrogen

- 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 H_2O & I_2 per mole HI
- Lower cost with good efficiency
  - 52% at 900°C vs. earlier 47%
  - 23% cost savings
  - 8%with I_2 inventory



GENERAL ATOMICS

The Helium Gas-Cooled Reactor is well-suited for H_2 production

NH2
Nuclear Hydrogen

Assessment of reactor concepts for Sulfur-Iodine thermochemical cycle

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

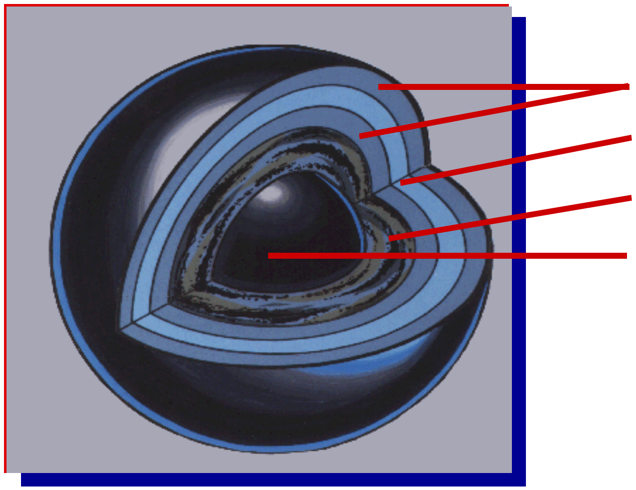
	Materials	Fuel	Component	System	Fab.-Facility	Total
Molten salt	+1	+1	+1	+2	0	+6
Heavy metal	+2	+2	+1	+1	+1	+7

... and needs the least development

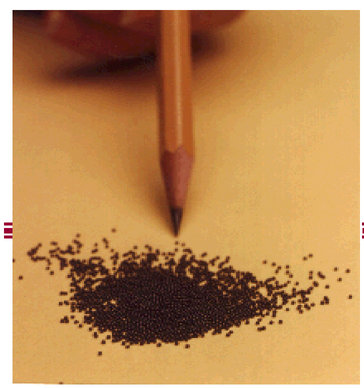
GENERAL ATOMICS

CERAMIC FUEL RETAINS ITS INTEGRITY UNDER SEVERE ACCIDENT CONDITIONS

NH2
Nuclear Hydrogen



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



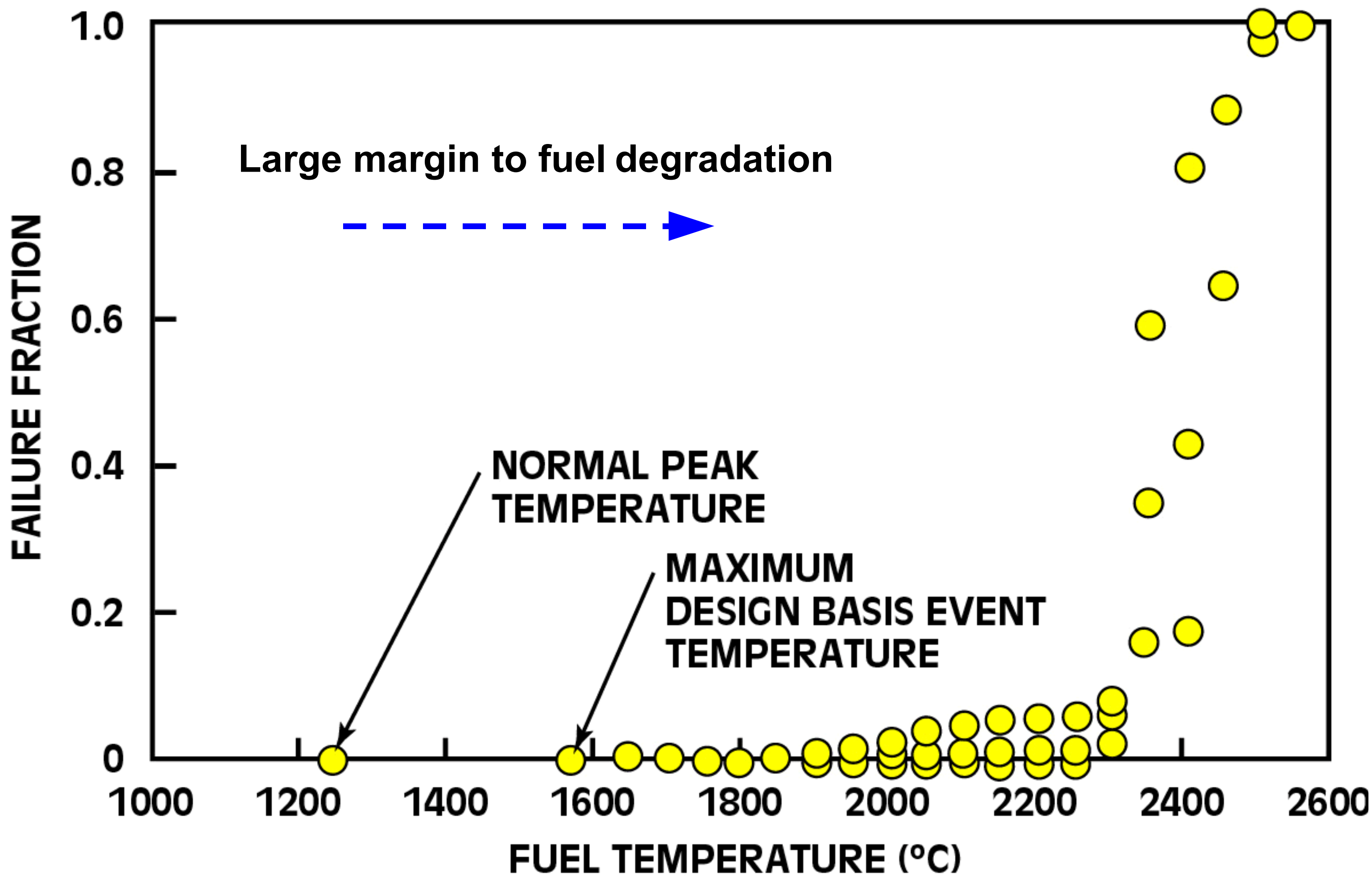
PARTICLES

COMPACTS

FUEL ELEMENTS

GENERAL ATOMICS

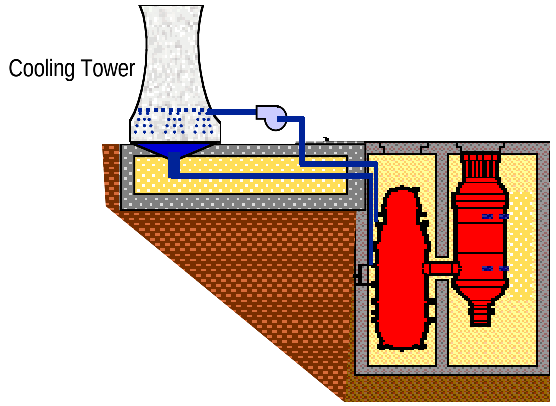
Ceramic Fuel Retains Integrity Beyond Maximum Accident Temperatures



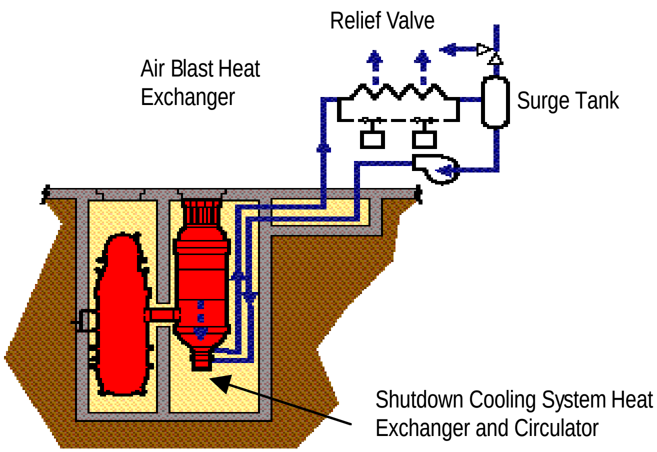
MHR Design has Passively Safe Decay Heat Removal

NH2
Nuclear Hydrogen

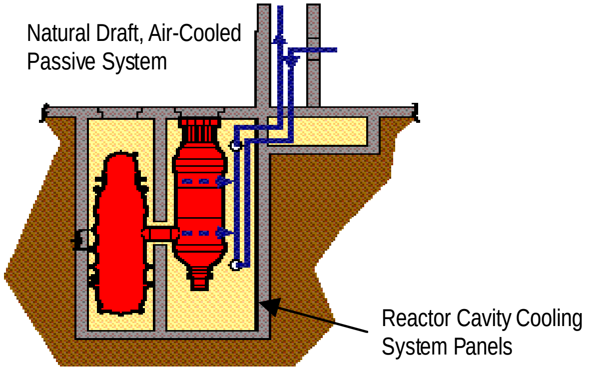
A. Normal - Using Power Conversion System



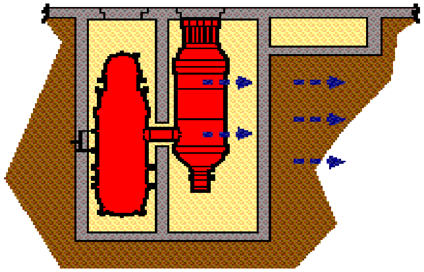
B. Active Shutdown Cooling System



C. Passive Reactor Cavity Cooling System



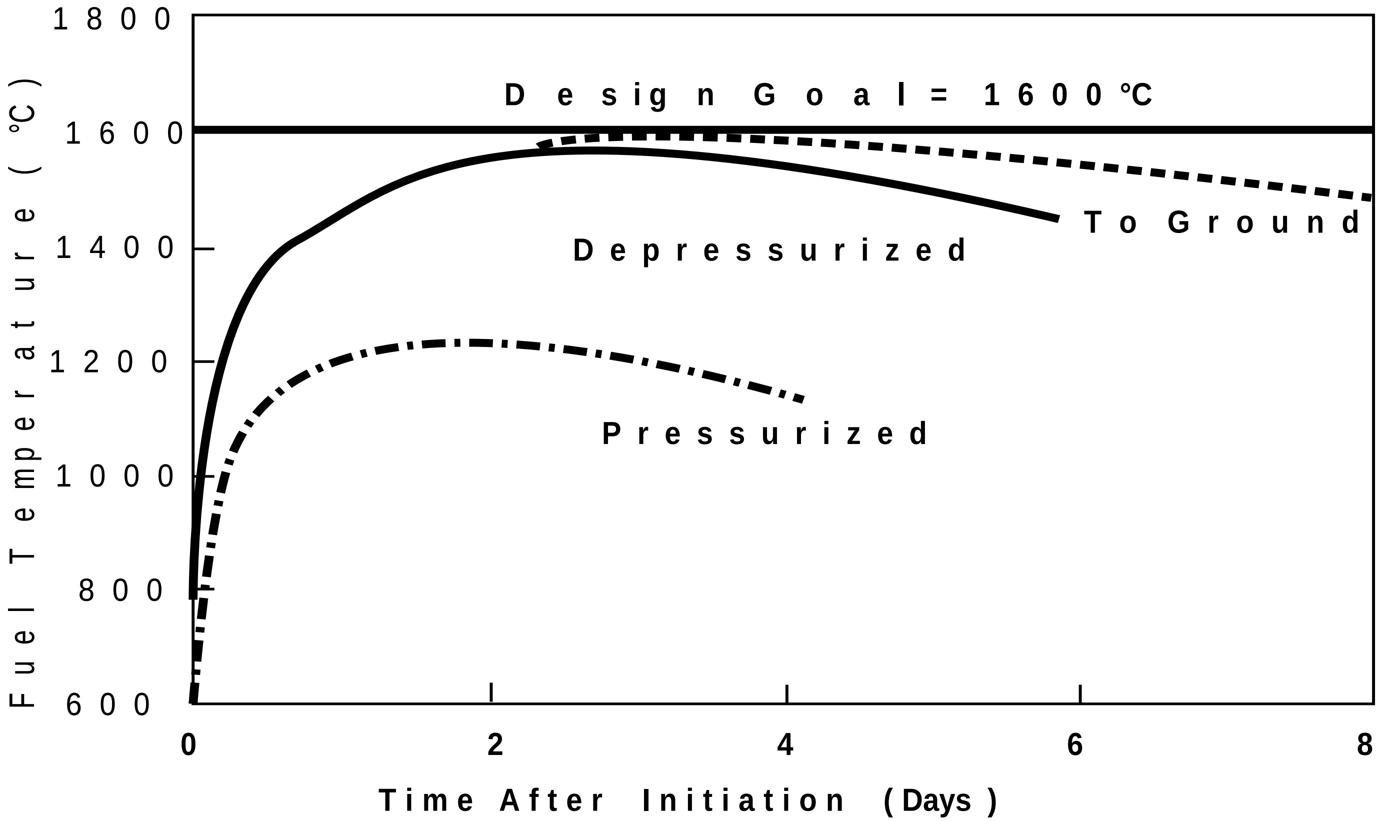
D. Passive Radiation & Conductive Cooling



GENERAL ATOMICS

The MHR is Passively Safe: Fuel temperatures remain below design limits during loss of cooling events

NH2
Nuclear Hydrogen



PASSIVE DESIGN FEATURES ENSURE FUEL REMAINS BELOW 1600°C, PREVENTING RELEASE OF RADIOACTIVITY. ACTIVE SAFETY SYSTEMS NOT NEEDED

GENERAL ATOMICS

Preliminary H_2-MHR Capital Cost Estimates

NH2
Nuclear Hydrogen

Modular Helium Reactor Capital Costs

Estimated "Nth of a kind" costs for 4x600MWt plant

ACCT	DIRECT COSTS	GT-MHR Electric Plant (4x286 MWe) Yr 2002 M$	PH-MHR Process Heat Plant - 850°C (4x600 MWt) Yr 2002 M$	PH-MHR Process Heat Plant - 950°C (4x600 MWt) Yr 2002 M$	Intermediate Loops (2400 MWt) Yr 2002 M$	S-I H2 Plant Hydrogen Plant (2400 MWt) Yr 2002 M$
20	LAND AND LAND RIGHTS	0	0	0		
21	STRUCTURES AND IMPROVEMENTS	132	132	132		
22	REACTOR PLANT EQUIPMENT	443	343	420		
23	TURBINE PLANT EQUIPMENT	91	0	0		
24	ELECTRIC PLANT EQUIPMENT	62	50	50		
25	MISCELLANEOUS PLANT EQUIPMENT	28	28	28		
26	HEAT REJECTION OR S-I SYSTEM	33	0	0		417
	INTERM. LOOP CIRC. & PIPING				73	
2	TOTAL DIRECT COST	789	553	630	73	417
	INDIRECT COSTS					
91	CONSTRUCTION SERVICES	83	58	66	8	44
92	HOME OFFICE ENGR AND SERVICES	25	18	20	2	13
93	FIELD OFFICE ENGR AND SERVICES	28	20	23	3	15
94	OWNER'S COST/ I_2 INVENTORY	138	97	110	13	73 +119
9	TOTAL INDIRECT COSTS	274	192	219	25	145 + 119
	BASE CONSTRUCTION COST	1063	745	850	98	681
	CONTINGENCY	53	37	42	5	33
	TOTAL COST	1116	783	892	103	714
	$ / kW	468/ kWt	326/ kWt	371/ kWt	43 /kWt	297/ kWt

GENERAL ATOMICS

Economic estimates are encouraging

NH2
Nuclear Hydrogen

- **Capital recovery:**
  - IDC (3yrs, 7%), CRF 10.5% (public utility), 90% capacity factor
  - $(711 x 1.116 x 0.105) / 7.9 MW(t)-hr = $10.6/MW(t)-hr
- **Operating cost:**
  - $8.3 / MW(t)-hr
  - Includes nuclear fuel cycle & waste disposal, water and O&M
- **Total cost:**
  - $(10.6 + 8.3) = $18.8/MW(t)-hr.
  - 1 MW(t)-hr = 3600 MJ(t), At 52% heat-to-H_2 that's 1872 MJ(H_2)
  - 1 kg H_2 = 142 MJ. 1872/142 = 13.2 kg/MW(t)-hr
  - $18.8/13.2kg = $1.42/kg of H_2

GENERAL ATOMICS

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 $850/kW$_{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....

NH2

Nuclear Hydrogen

- Radiolysis uses radiation to break chemical bonds
  - $H_2O \rightarrow H_2 + 1/2O_2$
  - $CO_2 \rightarrow CO + 1/2O_2$; $CO + H_2O \rightarrow CO_2 + H_2$
  - 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 ≈ 5%
  - Fraction of fusion energy to medium ≈ 10% (90/10 Xe/H_2O)
  - 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

GENERAL ATOMICS

Thermal processes use fusion for high temperature process heat

NH2

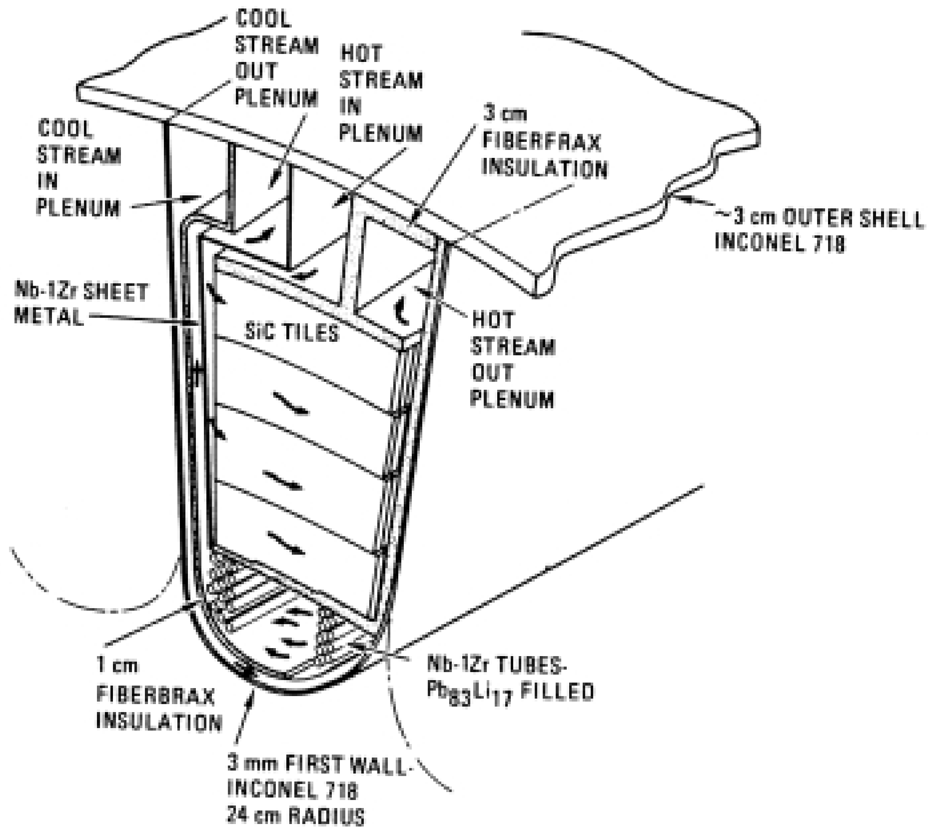
Nuclear Hydrogen

- 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
    - ^6Li + n= T + He, ^7Li + n = T + n' + He; (n, 2n) reactions possible
  - Tritium contamination of product must be avoided
    - Tritium is very mobile, especially at high temperature
    - Clean-up of contaminated H_2 would be impractical
  - Neutron activation can contaminate process fluids

Thermochemical water-splitting uses only heat

NH2
Nuclear Hydrogen

- Single blanket module with two coolant streams
  - High temperature He stream recovers 30% of heat at 1250ºC
  - Tritium breeding zone yields 70% at 450ºC
- Match to Sulfur-Iodine cycle
- Projected efficiency 43% and $1.70 - 2.00/kg H_2
- He flows directly to H_2 process
- Tritium in H_2 below 10CFR20 limits for unrestricted use



GA Utility Synfuel Study, 1983

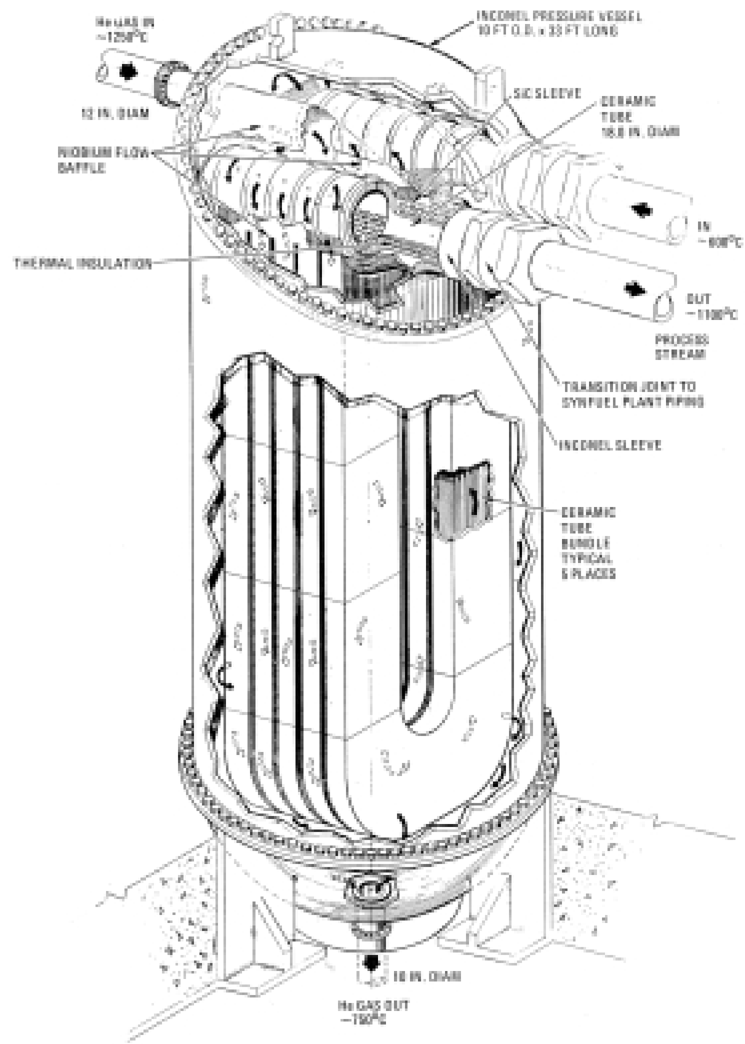
GENERAL ATOMICS

High temperatures require innovative heat transfer loops and heat exchangers

NH2

Nuclear Hydrogen

- 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

GENERAL ATOMICS

Hydrogen production could be a major role for Fusion

NH2

Nuclear Hydrogen

- 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 H_2 will benefit fusion economics
- With development, fusion could help fill the future needs for hydrogen

GENERAL ATOMICS