HIGH EFFICIENCY GENERATION OF HYDROGEN FUELS USING NUCLEAR ENERGY

A Nuclear Energy Research Initiative (NERI) Project
for the U.S. Department of Energy
by

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summarized by
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for the
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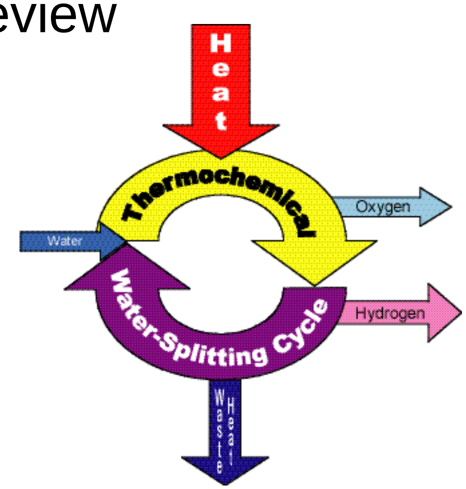


The Hydrogen Economy will require clean energy

- Hydrogen is an energy carrier, not an energy source
- A Hydrogen Economy only makes sense if hydrogen is produced with non-fossil, non-greenhouse gas energy
- Our options for clean energy are very limited
  - Nuclear (Fission, Fusion)
  - Solar (Solar thermal, Photovoltaic)
  - Renewables (Hydropower, Geothermal, Wind, Biomass)

Nuclear power can provide that energy

How can we get hydrogen from nuclear energy?

- **Electric power generation – Electrolysis**
  - **Overall efficiency approximately 25-30%**
    (efficiency of electric power generation x efficiency of electrolysis)
  - **Higher temperature reactors can lead to higher efficiency, ~35-40%**
- **Heat – Thermochemical water-splitting**
  - **A thermochemical water-splitting cycle is a set of chemical reactions that sum to the decomposition of water into hydrogen and oxygen**
  - **Energy is input via endothermic high temperature chemical reactions, rejected via exothermic low temperature chemical reactions**
  - **Splits water at moderate temperatures (~700-900°C vs ~5,000°C for thermolysis)**
  - **Plant efficiencies of ~50%**
- **Electricity/Heat – High temperature electrolysis or Hybrid thermochemical water-splitting**
  - **Efficiencies of ~40%**

The choice will depend on overall economics

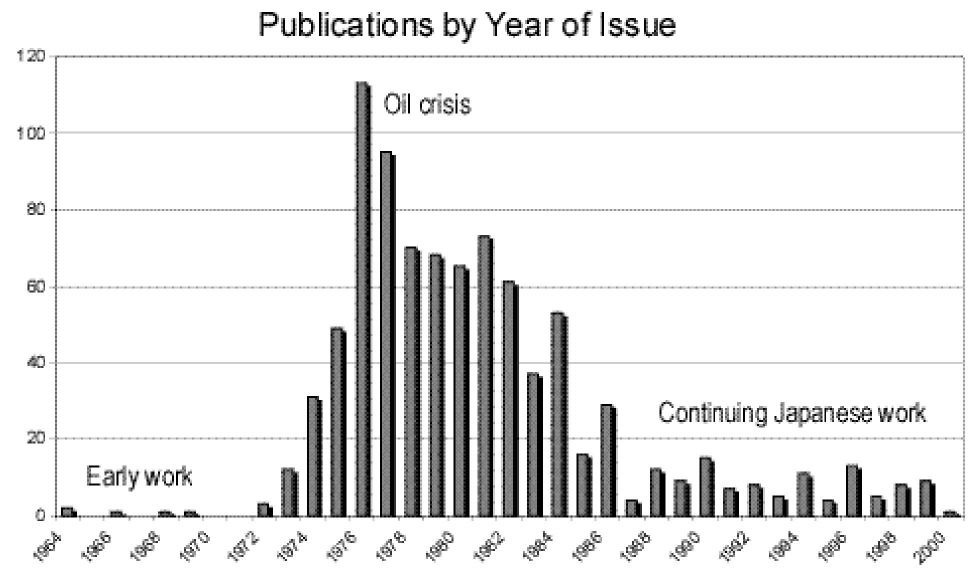
NERI is searching for an economical path to hydrogen production with nuclear power

- **Objective of our Project: "Define an economically feasible concept for the production of hydrogen, by nuclear means, using an advanced high temperature nuclear reactor as the energy source."**

- **Tasks for 3 year, $1.6M study: Team: SNL, UoK, GA**
  - **Carry out extensive literature review to identify candidate thermochemical water-splitting cycles (All)**
  - **Develop and apply screening criteria to identify most promising cycles and to select one for detailed analysis (All)**
  - **Evaluate candidate nuclear reactors, select most promising options and select one for use in the chemical cycle analysis (SNL)**
  - **Develop detailed chemical flowsheet for selected process and determine projected process efficiency (UoK, GA)**
  - **Estimate the size and cost of the process equipment (All)**

Literature survey located 822 references and 115 cycles

- Literature database will be available on the Internet
- Go-No go feasibility and ES&H criteria were applied
- Quantifiable screening criteria were developed and each cycle was given a numerical score

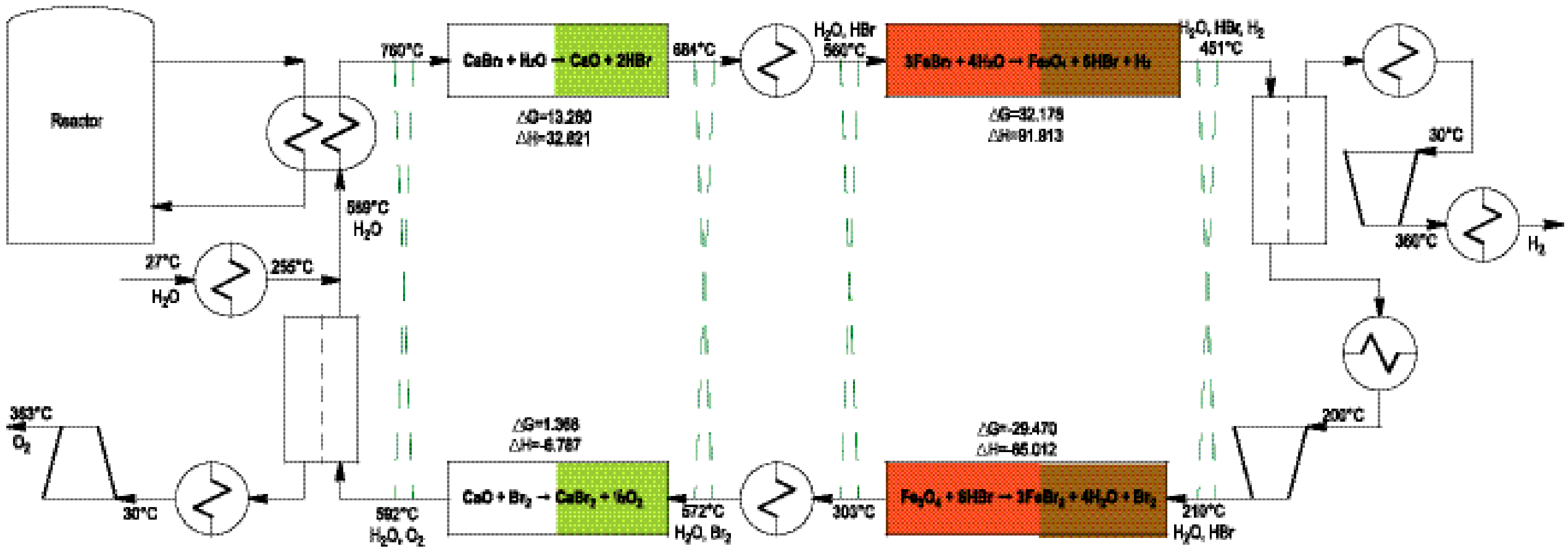


Screening reducing the number of cycles to 25

- Detailed investigations were made of each cycle
  - Thermodynamic calculations
  - Preliminary block flow diagrams
- Two cycles stood out as well-suited for coupling to nuclear energy: Adiabatic UT-3 cycle and Sulfur-Iodine cycle

Detailed evaluation yielded 2 cycles

The adiabatic UT-3 process is conceptually simple. . .



- **Invented at Univ. of Tokyo, being pursued in Japan, SI cycle is backup**
  - **Chemistry demonstrated in pilot plant**
  - **Requires 760°C, 40% efficiency predicted, 45-49% with high T co-generation**
- **Four gas solid reactions in stationary beds ($CaBr_2$↔CaO, $FeBr_2$↔Fe_3O_4)**
- **Challenges:**
  - **H_2 and O_2 removed via membranes – possible scale-up difficulties**
  - **H_2 and O_2 produced at subatmospheric pressures, must be compressed**
  - **Lower efficiency and possible solid attrition in non-steady state operation**
  - **Limited potential for improvement – already at melting point of $CaBr_2$**

. . . but requires development

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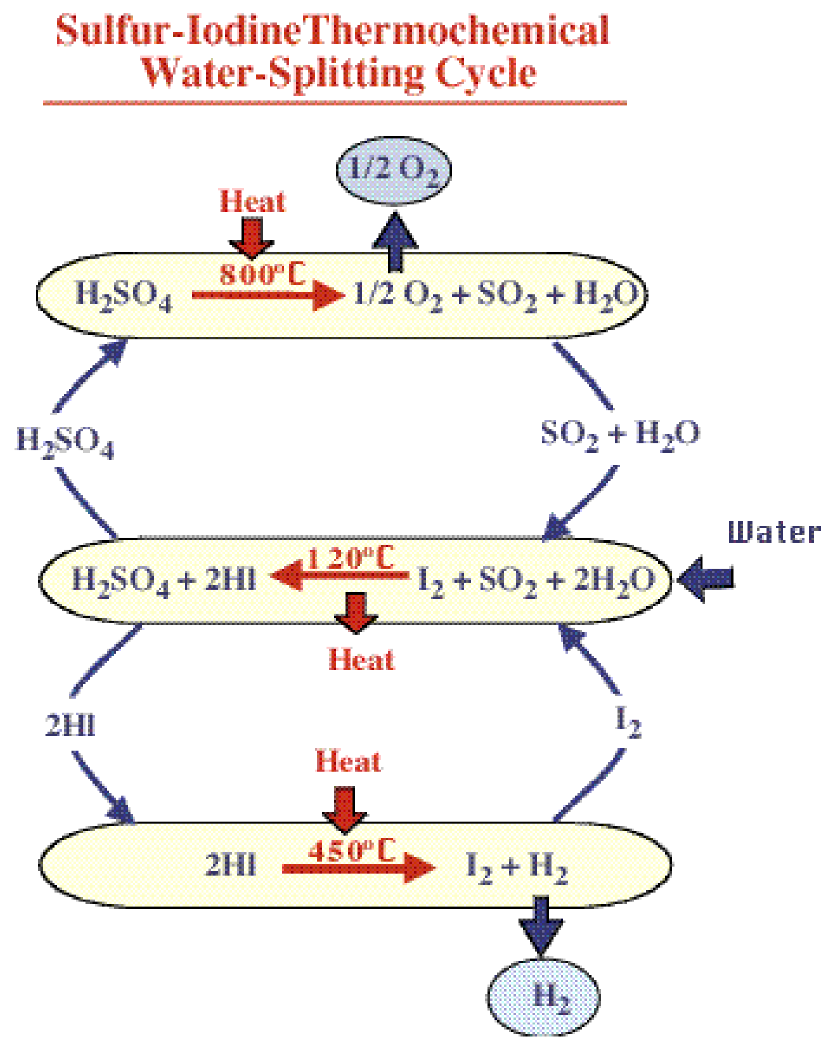
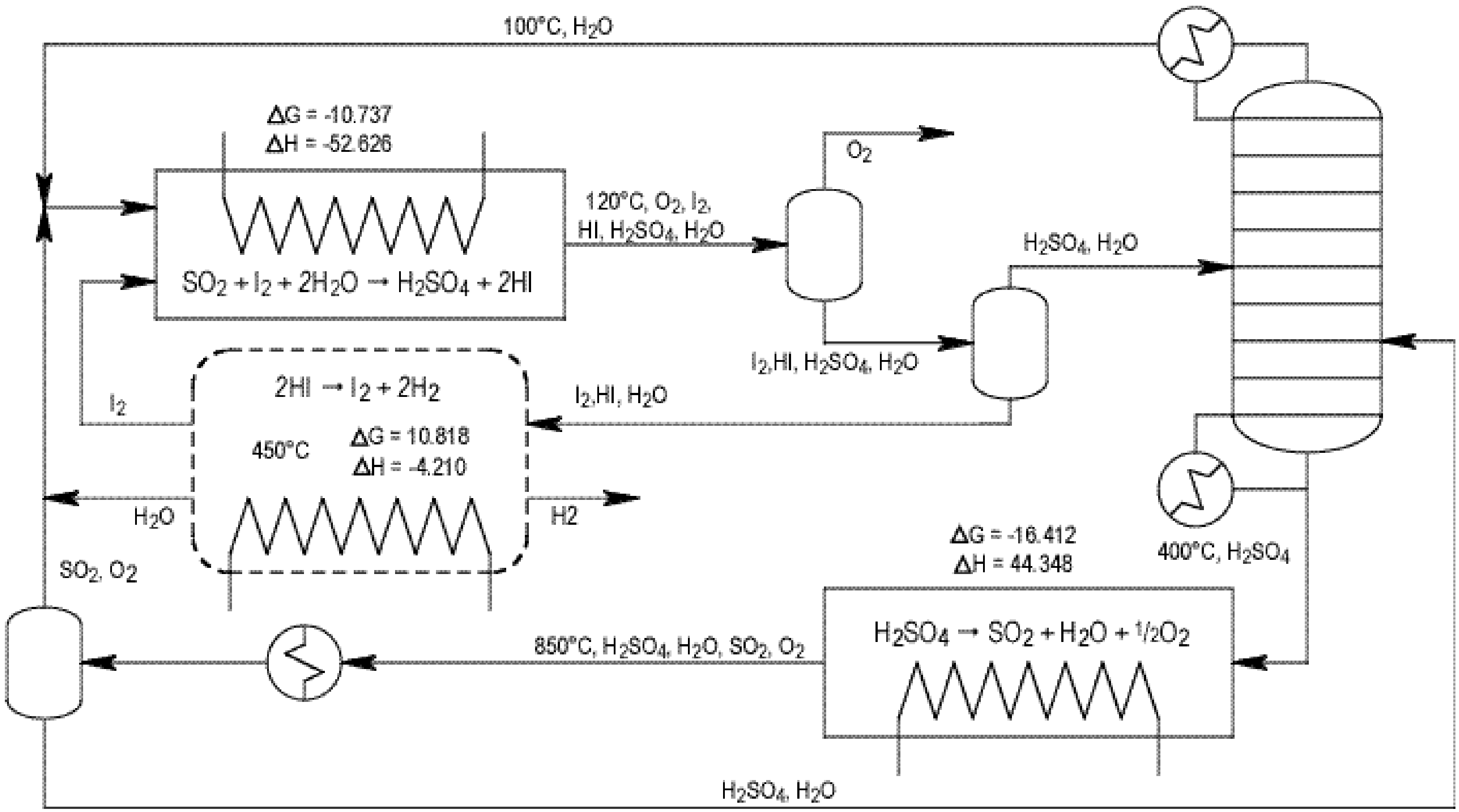
The Sulfur-Iodine cycle is an all-liquid/gas process. . .

- **Invented at GA in 1970s**
  - **Serious laboratory investigations done for nuclear and solar**
- **Advantages:**
  - **All fluid continuous process, chemicals all recycled; no effluents**
  - **Chemistry reactions all demonstrated**
  - **Highest efficiency quoted for any water-splitting process, 52%**
  - **Improvements have been identified for still higher efficiency, lower cost**
- **Challenges:**
  - **Requires high temperature, ≥800°C**
  - **Must be demonstrated as an integrated closed loop cycle**
  - **Process cost and economics must be verified**
- **The S-I cycle could make H_2 at 45-55% efficiency and co-produce H_2 and electricity at over 60%**



. . . and has the potential to produce low cost hydrogen

The Sulfur-Iodine cycle . . .



. . . is an all fluid process and was chosen for our work

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SNL evaluated candidate reactors

- **Considered 9 categories of reactors:**
  - **Pressurized water-cooled, Boiling water-cooled, Organic-cooled, Alkali metal-cooled, Heavy metal-cooled, Gas-cooled, Molten salt-cooled, Liquid-core and Gas-core**
- **Assessed reactor features for interface with SI cycle against 5 requirements and 5 criteria, and considered relative development requirements**
- **Three reactor types are suitable for thermochemical hydrogen production**
  - **Helium Gas Cooled Reactor**
    - **Superior – Demonstrated temperature capability**
  - **Heavy Metal Cooled Reactor (Lead-Bismuth)**
    - **Probably adequate with sufficient development**
  - **Molten Salt Cooled Reactor**
    - **Probably adequate with sufficient development**

… and recommended helium gas-cooled reactors

The flowsheet design of the SI process will be completed in July '02

- **Used chemical process design code Aspen Plus**
- **Evaluated available thermodynamic data, evaluated and improved thermodynamic models, contacting US and foreign researchers interested in thermochemical hydrogen production**
- **Designed the three main chemical process systems**
  - **Prime reaction ($2H_2O + SO_2 + I_2 \rightarrow H_2SO_4 + 2HI$)**
  - **Sulfuric acid concentration and decomposition ($2H_2SO_4 \rightarrow 2SO_2 + 2H_2O + O_2$)**
  - **Hydrogen iodide concentration and decomposition ($2HI \rightarrow I_2 + H_2$)**
- **Additional chemical data will improve efficiency and cost**
  - **Sulfuric acid thermodynamics at high concentrations**
  - **Iodine systems equilibrium thermodynamics**
  - **Better data will allow a more efficient design**

Additional experimental data — chemical properties and integrated loop operation —required before construction

The Modular Helium Reactor solves the problems of first generation reactors

- High temperature ceramic fuel is passively safe
- Allows high coolant temperatures - 850 - 950ºC
- Coupled to gas turbine: GT-MHR, 48% efficiency
- Coupled to water-splitting cycle: Hydrogen at 50%
- Reduces cost and minimizes waste
- Proliferation resistant due to hard neutron spectrum

. . . Opens a new opportunity for nuclear power

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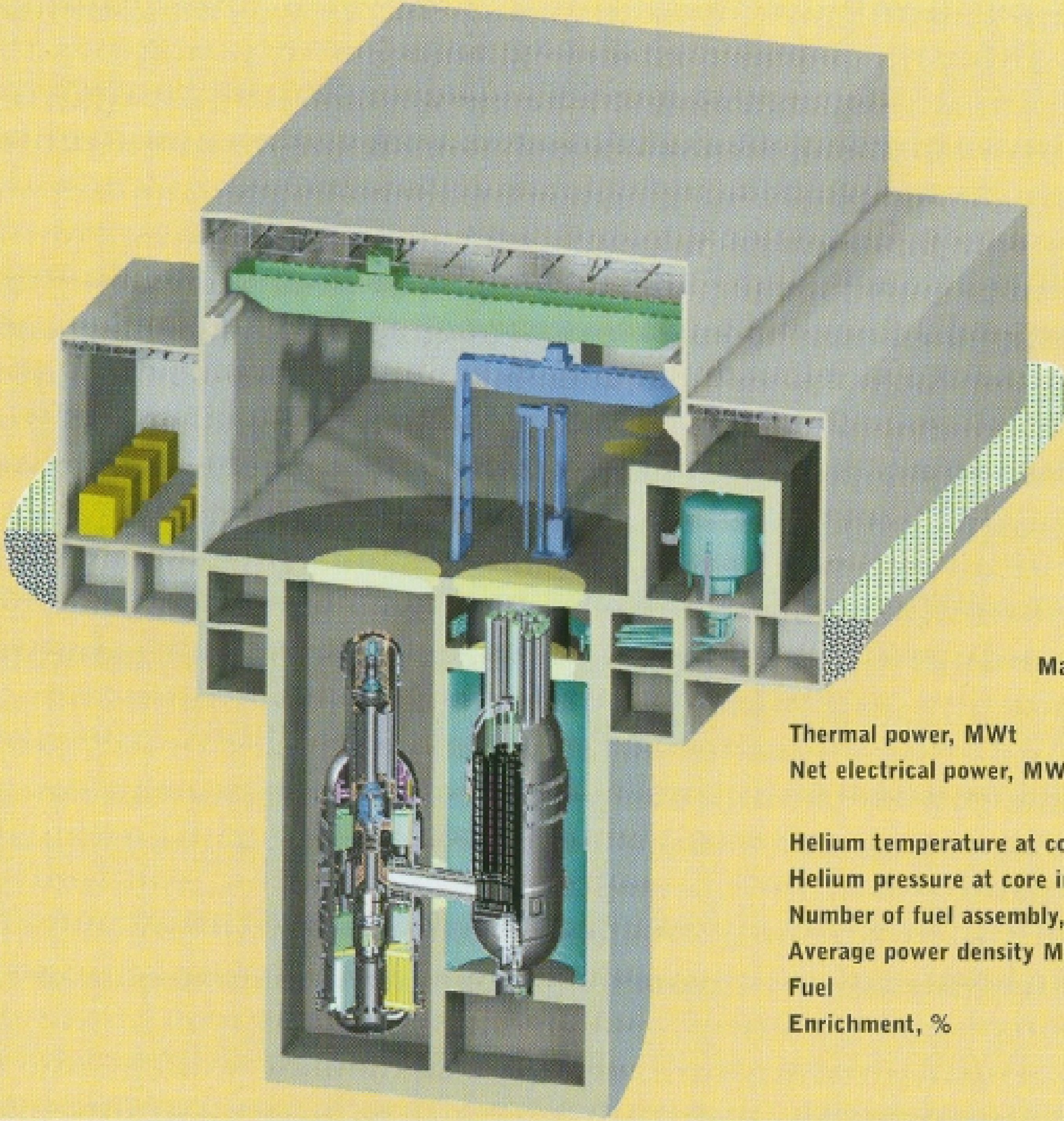

GT-MHR module arrangement

Main technical data

Thermal power, MWt	600
Net electrical power, MWe	280
Helium temperature at core inlet/outlet, °C	488/850
Helium pressure at core inlet, MPa	7,15
Number of fuel assembly, columns	102
Average power density MWt/m^3	6,5
Fuel	UO_2
Enrichment, %	20

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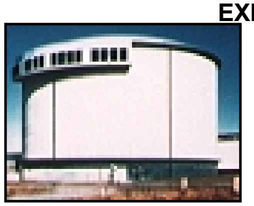
MHR builds on 40 years of progress

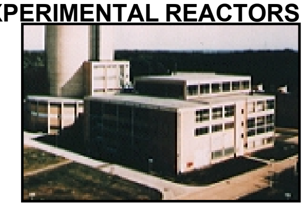
This is the foundation for today's opportunity.

EXPERIMENTAL REACTORS

DEMONSTRATION OF BASIC HTGR TECHNOLOGY

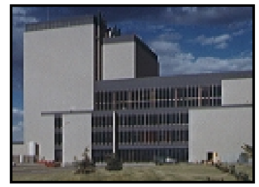


DRAGON (U.K.) 1963 - 76

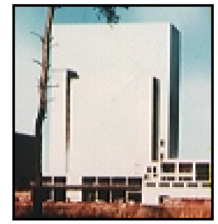


AVR (FRG) 1967 - 1988

PEACH BOTTOM 1 (U.S.A.) 1967 - 1974



FORT ST. VRAIN (U.S.A.) 1976 - 1989



THTR (FRG) 1986 - 1989

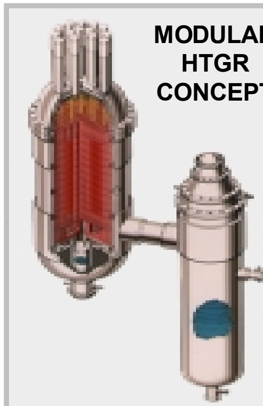
HTTR (Japan) 2000 - on

LARGE HTGR PLANTS

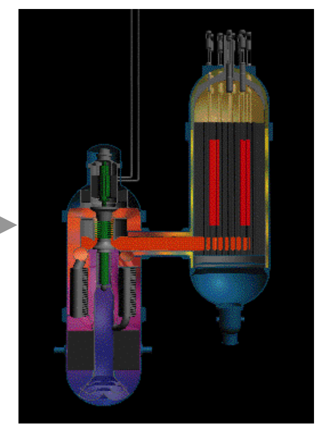
HTGR TECHNOLOGY PROGRAM

- **MATERIALS**
- **COMPONENTS**
- **FUEL**
- **CORE**
- **PLANT TECHNOLOGY**

MODULAR HTGR CONCEPT



GT-MHR



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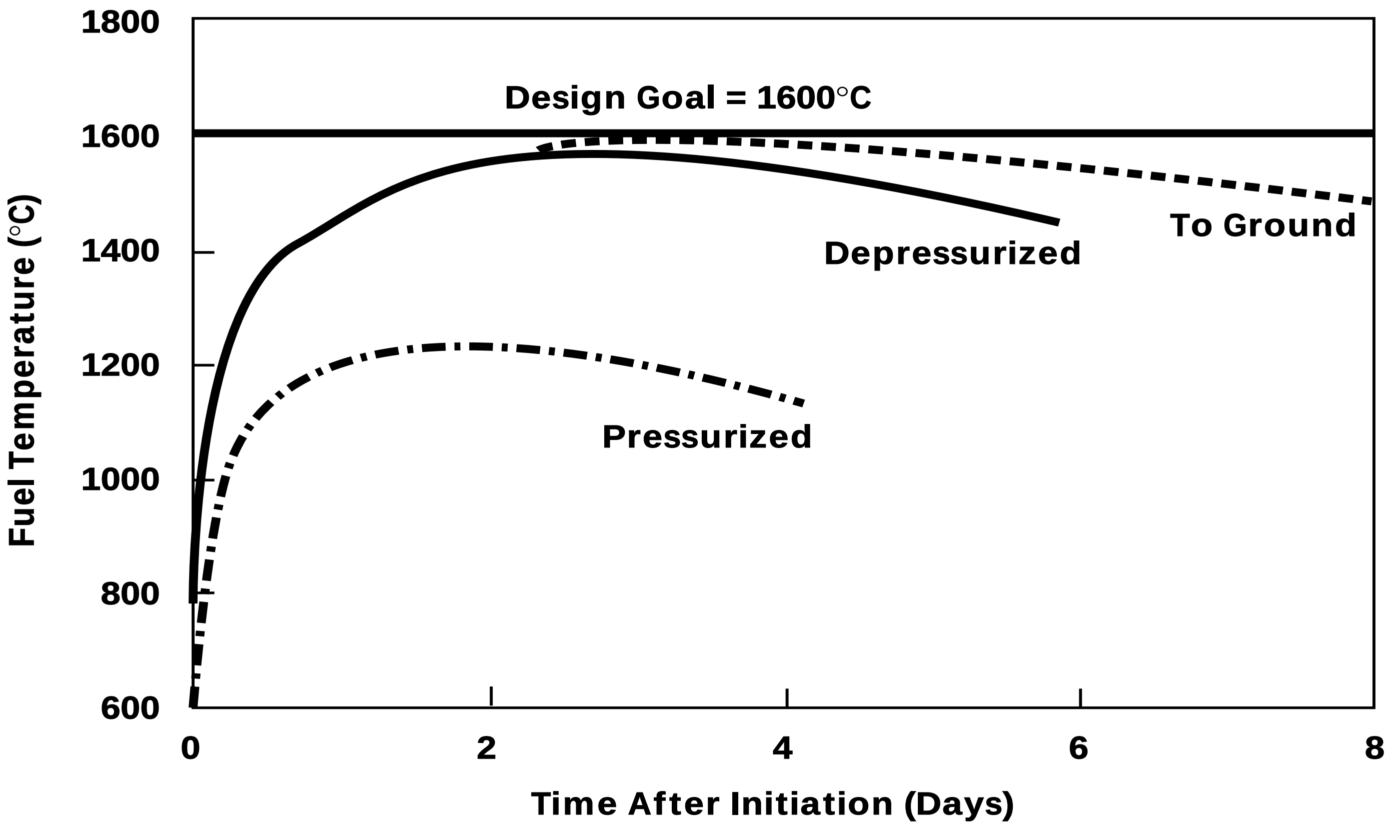
FUEL TEMPERATURES REMAIN BELOW DESIGN LIMITS DURING LOSS OF COOLING EVENTS



. . . PASSIVE DESIGN FEATURES ENSURE FUEL REMAINS BELOW 1600°C

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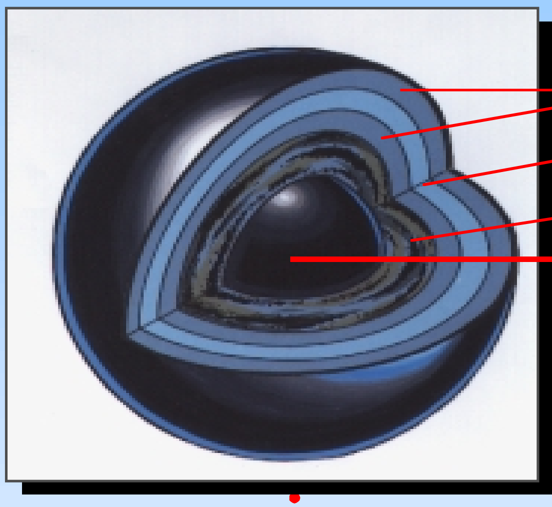
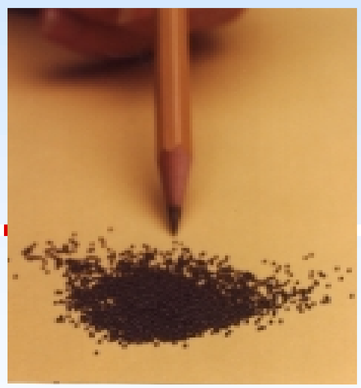
TRISO fuel particles are highly engineered

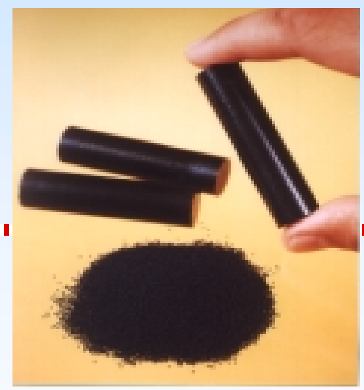


Pyrolytic Carbon
Silicon Carbide
Porous Carbon Buffer
Uranium Oxide (UO_2)

TRISO Coating



PARTICLES



COMPACTS

FUEL ELEMENTS

TRISO Coatings and Graphite are Excellent Engineered Barriers for Normal Operation, Severe Accidents, and Permanent Disposal

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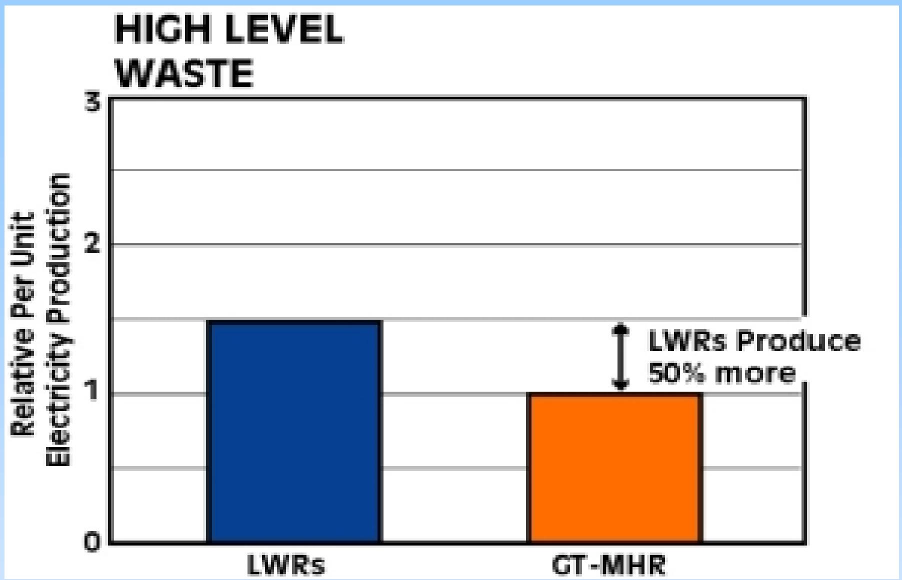
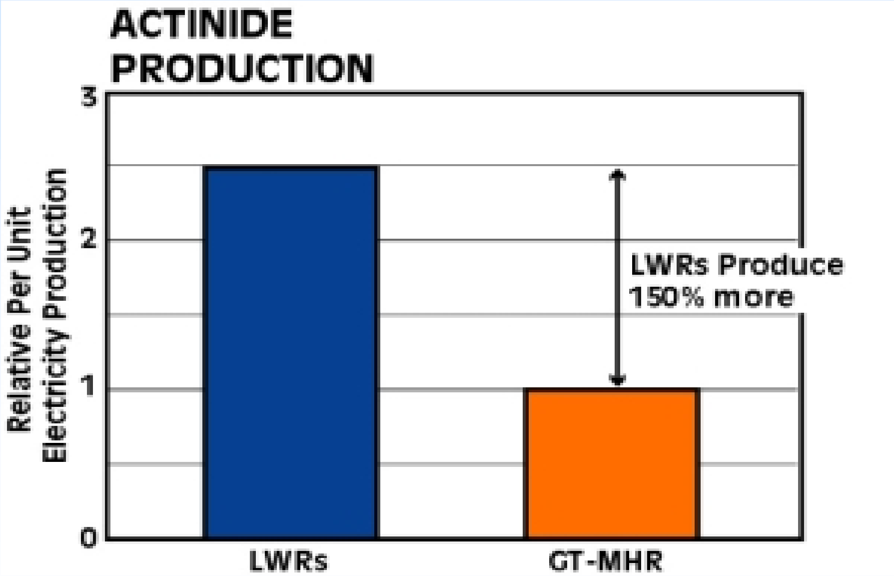
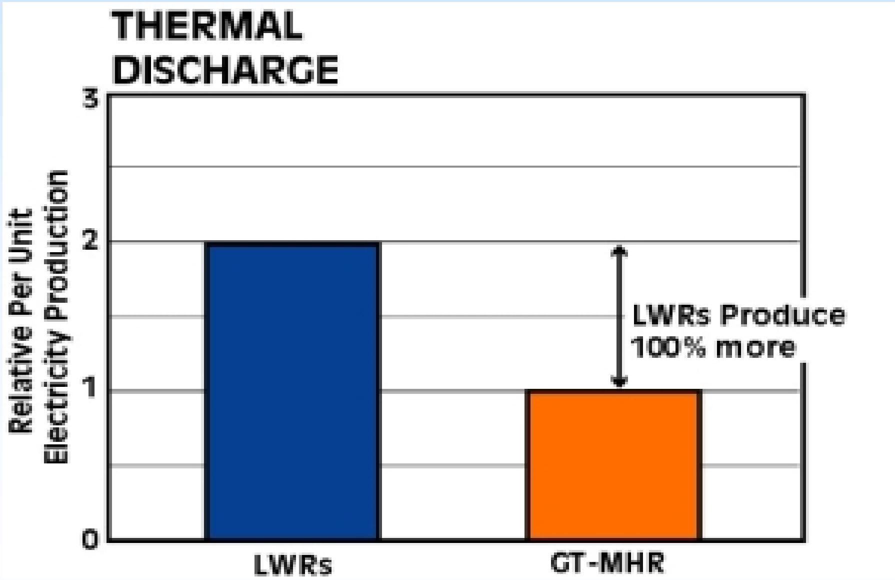


GT-MHR OFFERS MAJOR ENVIRONMENTAL BENEFITS





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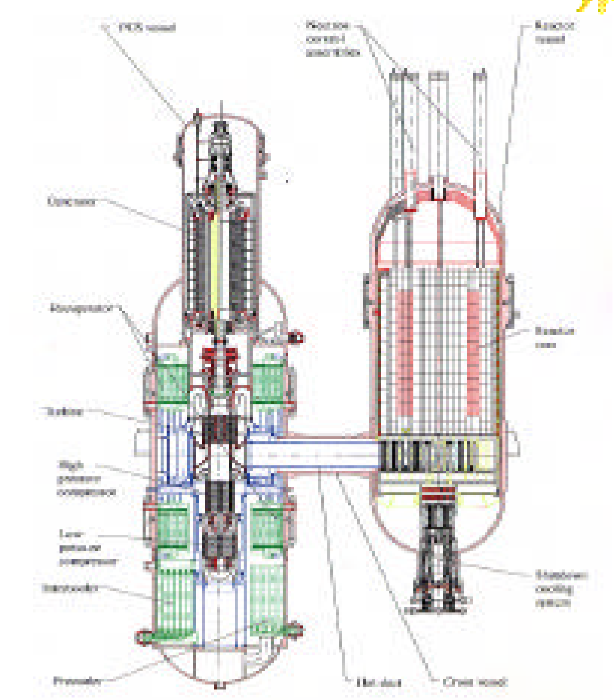
GA supported San Diego State University to develop economic models for nuclear production of hydrogen

NH2 Nuclear Hydrogen

- Modest effort, internally funded
- Provided MBA project for SDSU students
- Very positive interactions with Stuart Energy, leading developer of H_2 electrolysis units
- Initial Effort:
  - Develop simple economic models
  - Compare GT-MHR + Electrolysis with SI-MHR production of H_2
  - Provide a tool for preliminary parametric surveys

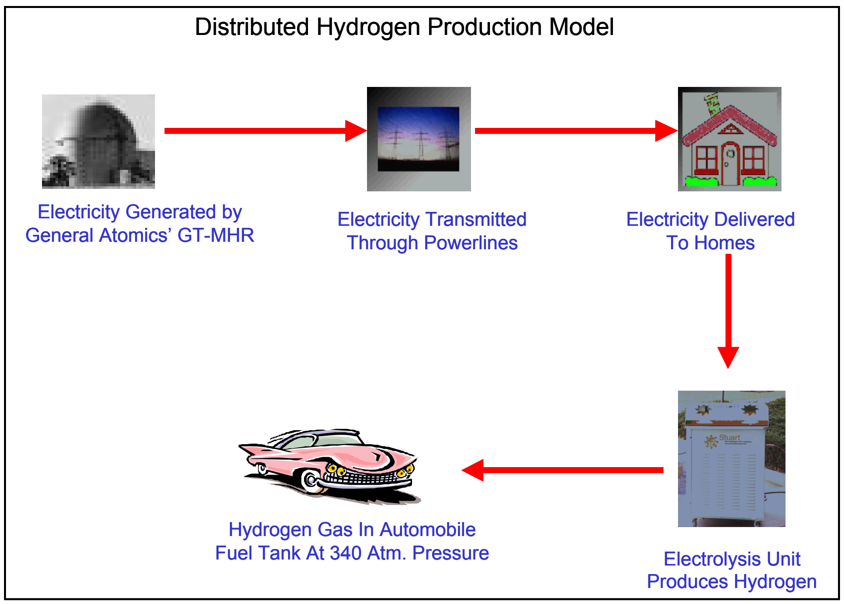


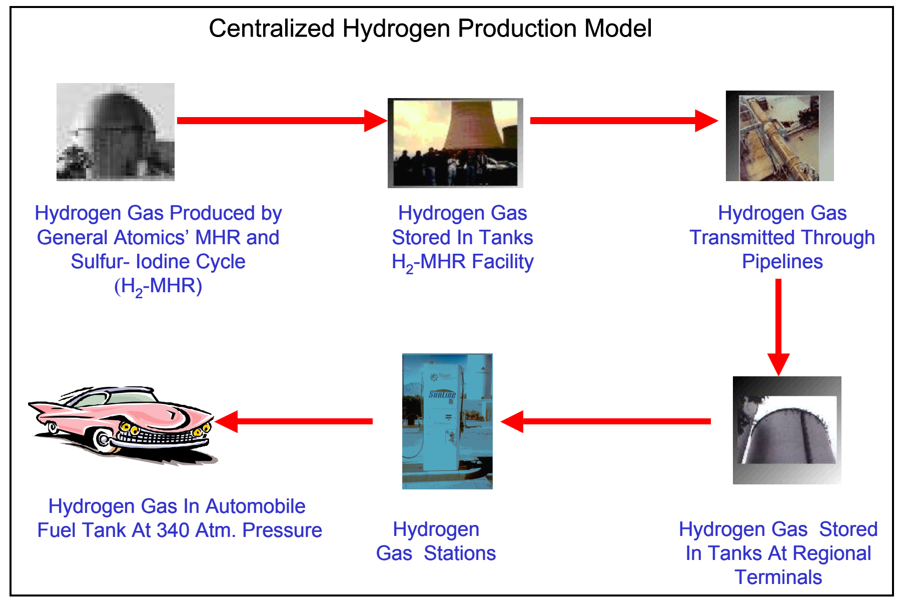
We have 2 models of H_2 production

NH2
Nuclear Hydrogen

GT-MHR + Electrolysis

MHR + SI Cycle





Economic assumptions span a wide range

Description	GT-MHR	MHR alone	SI-H_2 Cycle	H_2-MHR
Total Overnight Cost, $M	1,290	968	504 - 1,008	1,472 - 1,976
	($1120/kWe)		($210-420/kWt)	
Operating Cost, $M/year	127	95.3	33.6 - 67.2	128.9 - 162.5
Efficiency — production	48%			40 - 60%
— electrolysis	65 - 95%			
Electrolysis Unit Cost	$288M–1.2B			
	($250-1000/kWe)			
Electricity Distribution Cost Multiplier	1.0 - 3.0			
Capital Recovery Rate	5 - 20%	5 - 20%	5 - 20%	5 - 20%
Transmission distance	0-1000 mi			0-1000 mi

Intent: Use model parametrically

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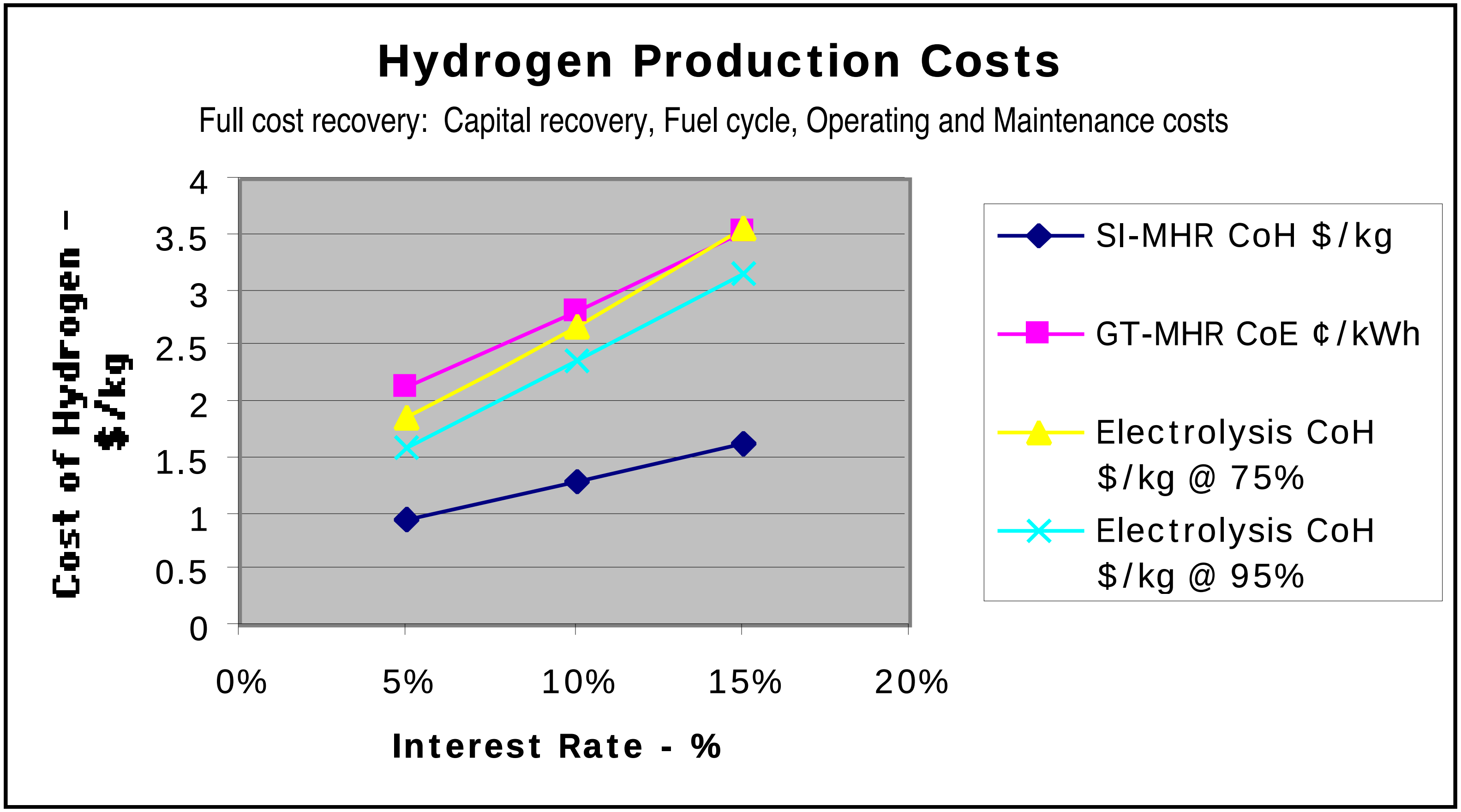
Example of Busbar H_2 Cost Estimates

Assume median SI H_2 system cost ($315/kWt) and efficiency (50%)

Electrolysis at Stuart Energy goal of $250/kWe



Nuclear Production of H_2 Appears Attractive

- **Our NERI study team identified attractive water-splitting cycle and nuclear reactor candidates**
  - **Chose Sulfur-Iodine cycle and gas-cooled reactor**
- **Complete flowsheet design and cost estimate will be done in July**
- **We expect high efficiency and low H_2 cost**

Effort will be needed to achieve economic hydrogen from nuclear energy...

NH2
Nuclear Hydrogen

- The first steps are
  - Demonstrate integrated SI loop operation
    - Follow-on NERI proposal to DOE/NE for part of this
    - Are there alternate sources?
  - Measure needed chemical data (useful for any heat source)
    - University or Lab task?
- Next proceed with a Pilot Plant
  - Initial operation with simulated nuclear heat source
  - Then move to a nuclear heat source (NP-2010?)
- Then build a H_2-producing Nuclear Demo Plant
  - NP-2010 could be this demonstration

... but the path forward appears clear