NH2

Nuclear Hydrogen

"Fusion Production of Hydrogen; How Fusion Energy Can Fuel the *Hydrogen Economy*"

Ken Schultz

General Atomics

14 September 2004

16th TOFE

Madison, Wisconsin

GENERAL ATOMICS

US oil use exceeds supply, and it's getting worse

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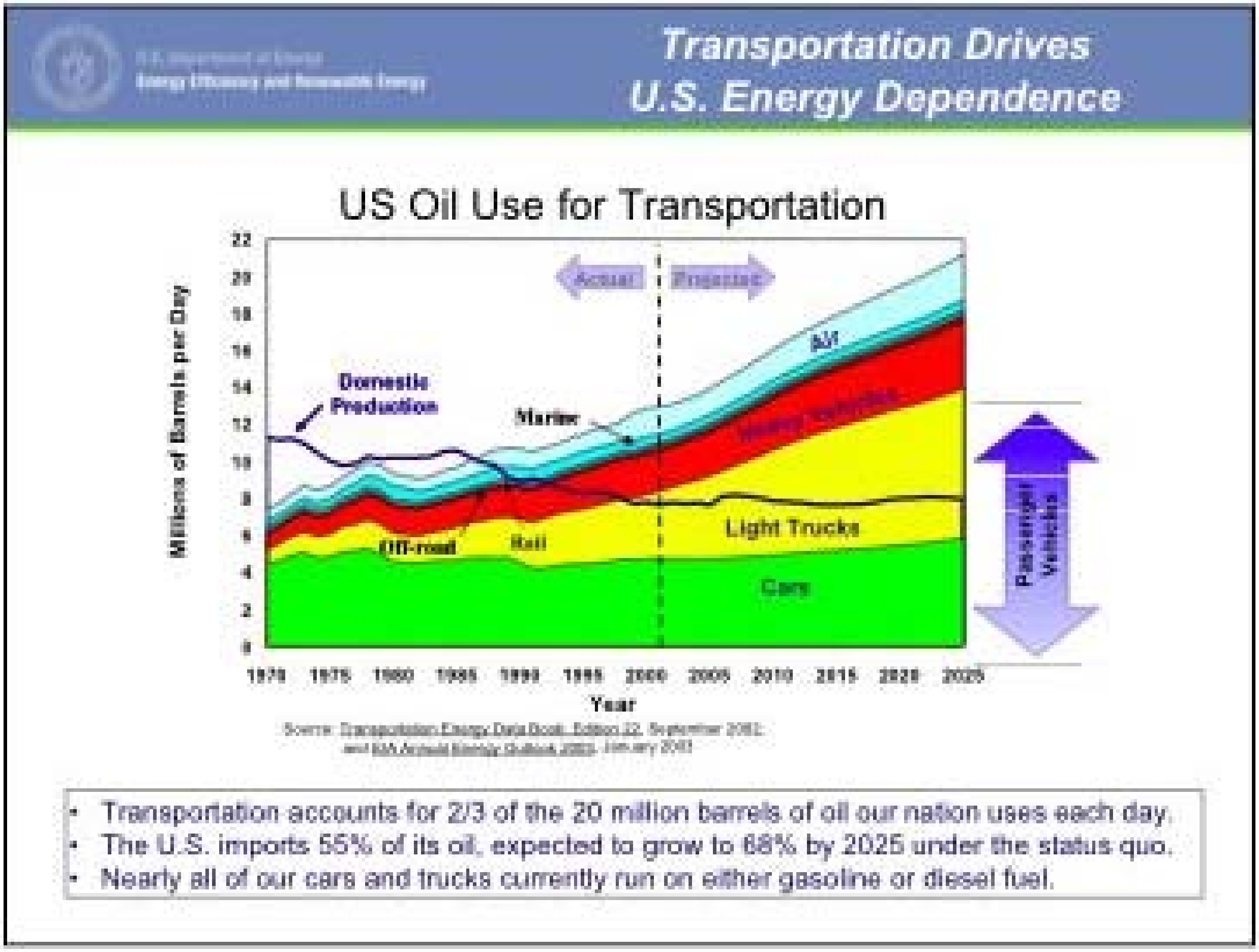
Nuclear Hydrogen



GENERAL ATOMICS

CO_2 release is a major impediment to fossil fuel use

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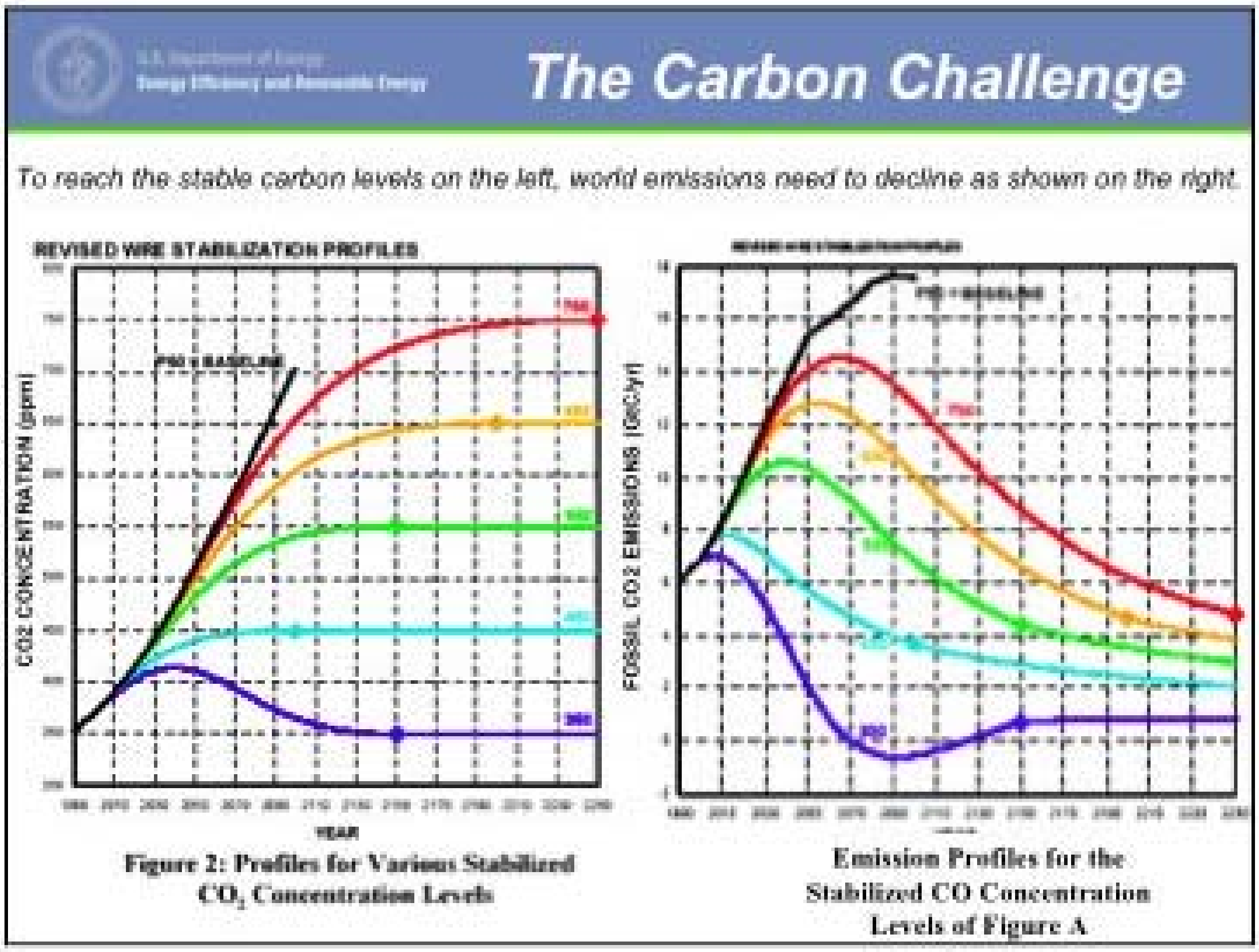

Coal emits twice the CO_2 as oil per unit energy

GENERAL ATOMICS

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 could get twice the efficiency as a gasoline engine
- The US Administration is supportive of a *Hydrogen Economy*
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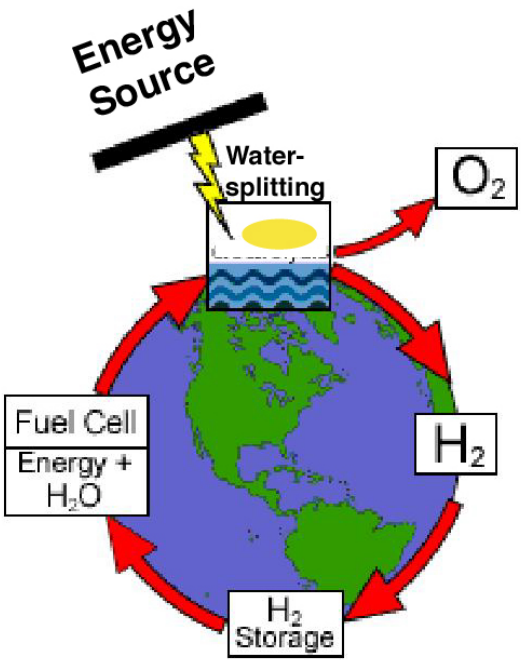

The President Supports the *Hydrogen Economy*

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Nuclear Hydrogen

"A single chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car -- producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free... Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy."

President Bush's 2003 "State of the Union Address"

GENERAL ATOMICS

Question: Where to get the hydrogen?

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- **Hydrogen is an energy carrier, not an energy source**
  - While hydrogen is the most abundant element, most is chemically bound as hydrocarbons, carbohydrates or water
  - Energy is needed to extract the hydrogen
- **Most hydrogen today is made from fossil fuels**
  - Steam reformation of methane primary source
    - $CH_4 + 2H_2O + \text{heat} \rightarrow 4H_2 + CO_2$
    - if heat from CH_4: more CO_2 released, ~3 H_2 per CO_2
- **A Hydrogen Economy only makes sense if hydrogen is produced with non-fossil, non-greenhouse gas energy**
- **Our options for clean energy are limited**
  - Nuclear fission, Solar, Renewables — *and Fusion!*
- **There is a potential opportunity for fusion**

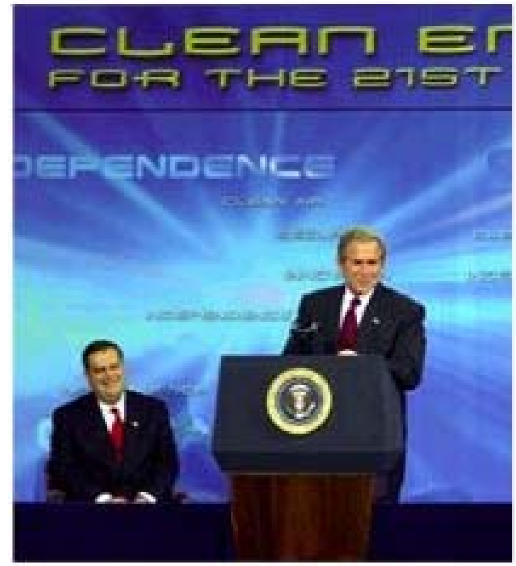
GENERAL ATOMICS

Fusion has been given an awesome responsibility:

L&IF
Lasers and Inertial Fusion

"We're also going to work to produce electricity and hydrogen through a process called fusion. .... The energy produced will be safe and clean and abundant. .... Imagine a world in which our cars are driven by hydrogen and our homes are heated by electricity from a fusion power plant."

President Bush, 6 Feb '03
"Hydrogen Fuel Initiative"



"If successful, fusion could well be the most cost effective, long-term source of hydrogen we will ever find."

Energy Secretary Spencer Abraham
National Hydrogen Assoc., 5 Mar'03

... to fuel the *Hydrogen Economy*

The Hydrogen Economy will need a lot of hydrogen

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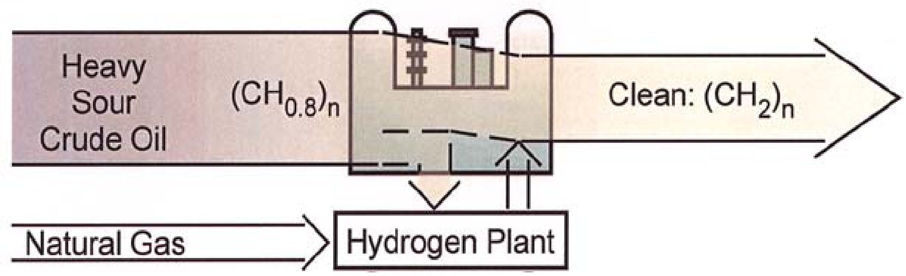
Nuclear Hydrogen

- US use now 11 million tons H_2/y (48 GWt)
- 95% produced from Natural Gas (~6% of total use)
  - Steam Methane Reformation (SMR)
    $CH_4 + 2H_2O + E = 4H_2 + CO_2$
  - Releases 74M tons CO_2/yr
- Most is used in NH_3 and oil industries
  - ~10%/y growth ➔ X 2 by 2010, X 4 by 2020

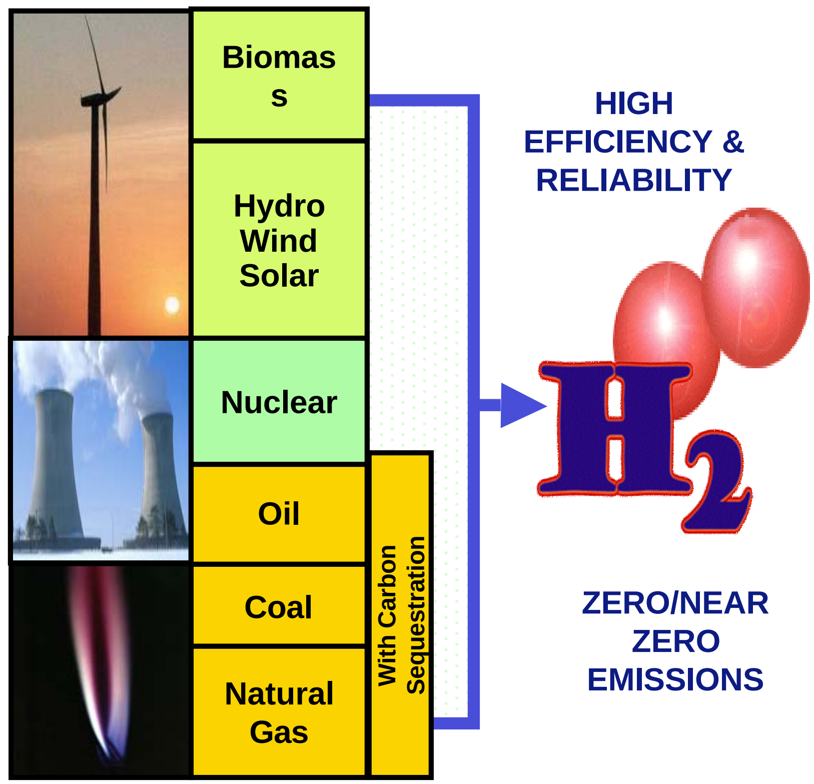


- Hydrogen Economy will need much more
  - X 18 for transportation — 200 M tons/year, ~900 GWt
  - X 40 for all non-electric energy

GENERAL ATOMICS

DOE Hydrogen Program

- $1.2 Billion over five years (FY 2004-2008)
- Production goal - provide multiple feedstock options to fuel hydrogen economy
- Significant cooperation between offices
  - Energy Efficiency & Renewable Energy (EE)
  - Fossil Energy (FE)
  - Nuclear Energy, Science & Technology (NE)
  - Science (SC)
  - Management, Budget & Evaluation (ME)
- EE has responsibility for coordinating overall DOE Hydrogen Program and R&D on delivery and infrastructure issues – $257M/yr
- NE has responsibility for R&D on production processes most suited for nuclear applications – $7M/yr
- SC has responsibility for R&D on fusion hydrogen activities
  - Currently none



Nuclear energy can help provide the hydrogen by several routes

- Electric power generation ➔ Electrolysis
  - Proven technology
  - Overall efficiency ~24% (LWR), ~36% (Hi T Reactors)
    (efficiency of electric power generation x efficiency of electrolysis)
- Electricity + Heat ➔ High temperature electrolysis or Hybrid thermochemical cycles
  - Need both electricity generation and high temperature process heat
  - Efficiencies up to ~ 50%
  - Developing technologies
- High temperature heat ➔ Thermochemical water-splitting
  - A set of chemical reactions that use heat to decompose water
  - Net plant efficiencies of up to ~50%
  - Developing technology

HTE offers potential high efficiency at high temperature

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Nuclear Hydrogen

- Electrolysis at high T substitutes heat for electricity

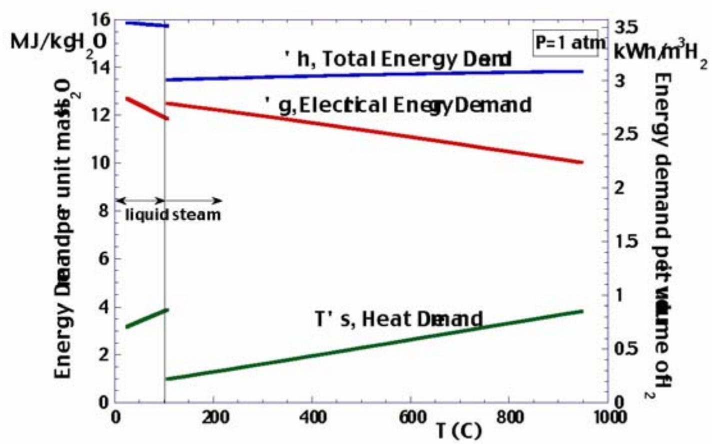


Figure 2. Overall EgyRequireants for High-Temperature Electrolysis.

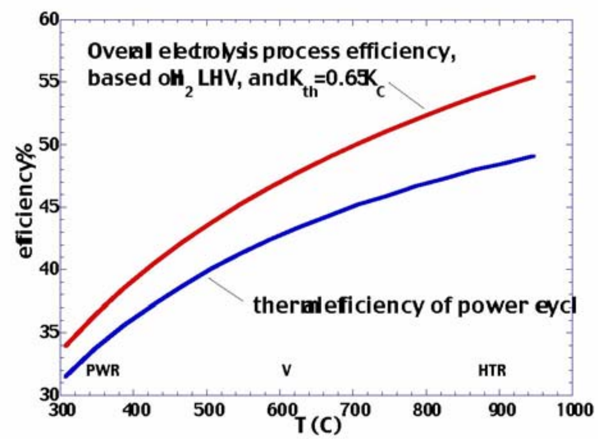
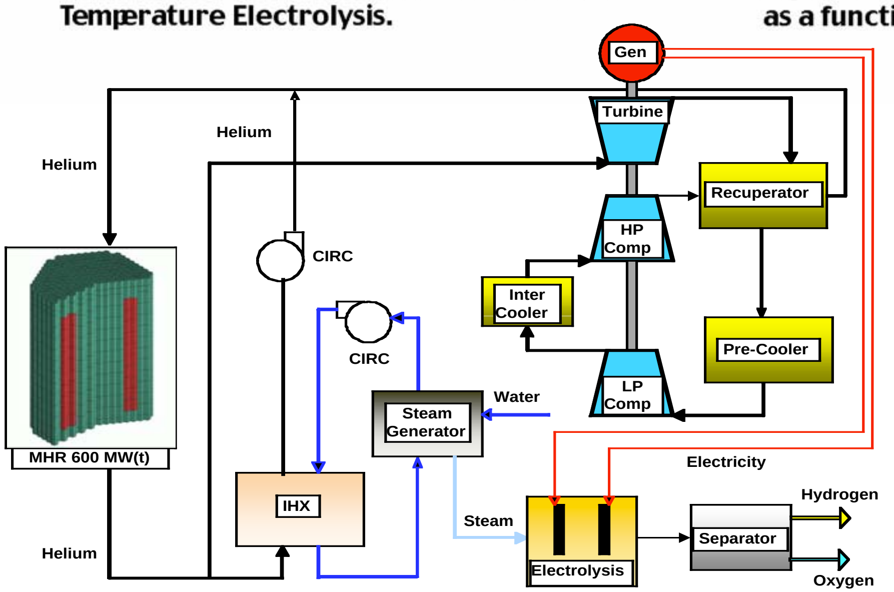


Figure3. Powercycleandelectrolysisoveralleficiencies as a function oftperature.

Figs. Courtesy of S. Herring, INEEL



Produce electricity and process heat to make steam at ~900°C

GENERAL ATOMICS

The S-I cycle is the lead thermochemical candidate in the US, Japan and France

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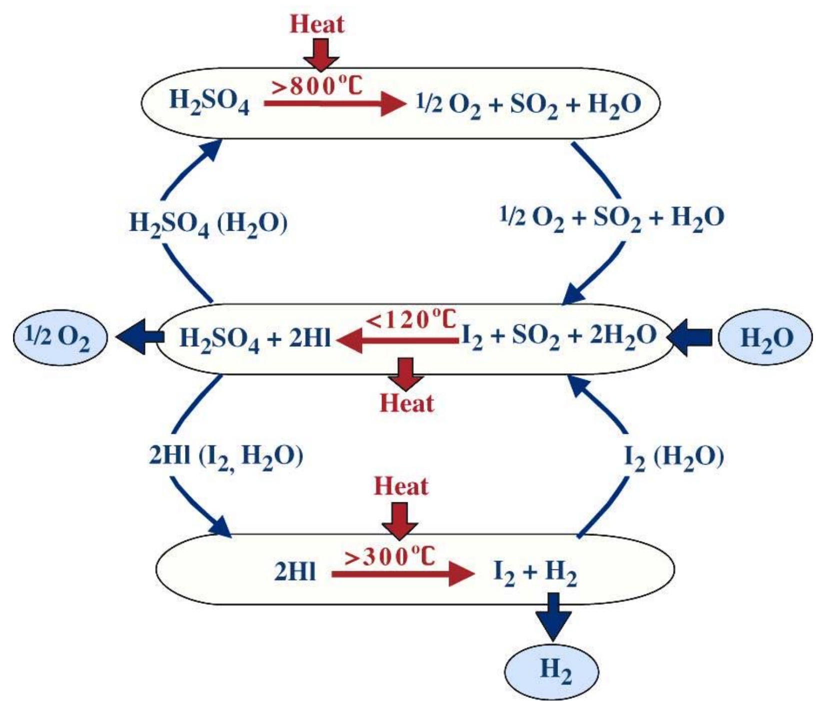
- Invented at GA in 1970s
  - Serious investigations for nuclear and solar
  - Chemistry reactions all demonstrated
  - Materials candidates selected and tested
- Advantages:
  - All fluid continuous process, chemicals all recycled; no effluents
  - H_2 produced at high pressure
  - Highest cited projected efficiency, ~50%
- Challenges:
  - Requires high temperature, ≥800°C

Sulfur-Iodine Thermochemical

Water-splitting Cycle



GENERAL ATOMICS

High temperature benefits the SI cycle

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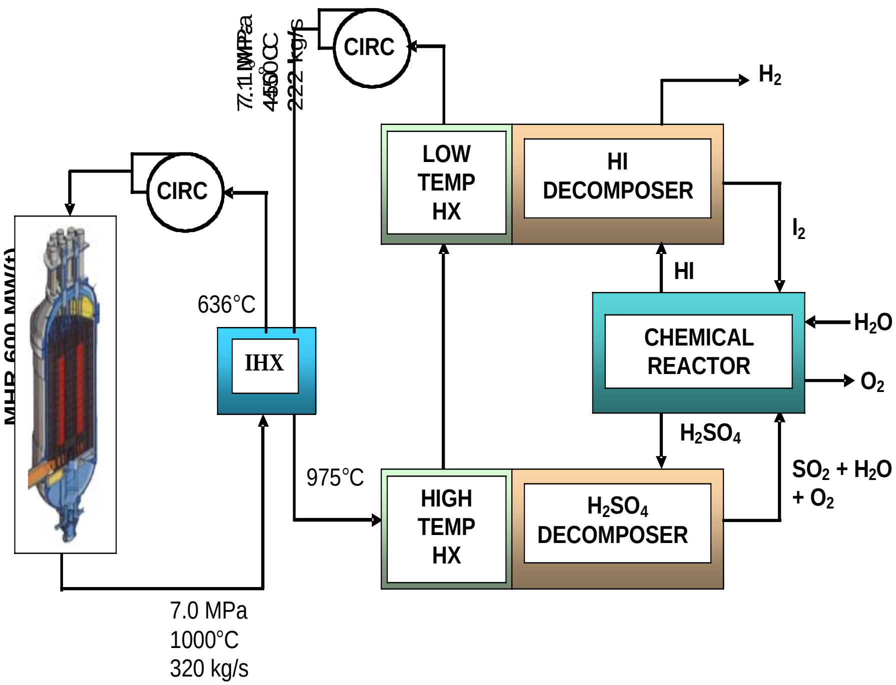

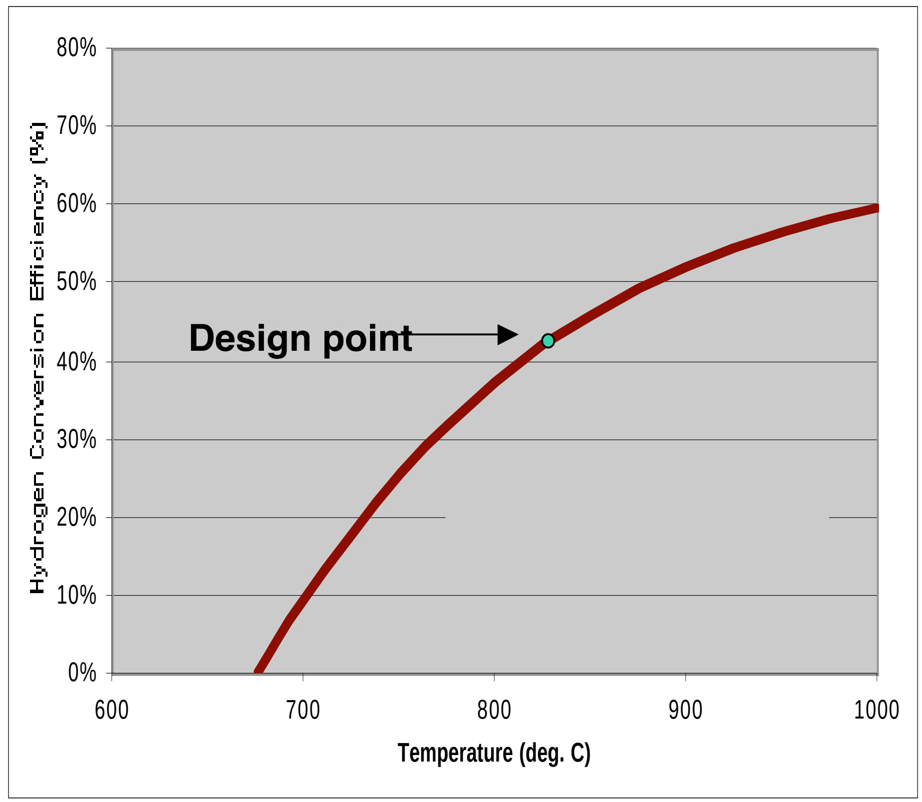

GENERAL ATOMICS

Effort will be needed to achieve practical hydrogen production from nuclear energy

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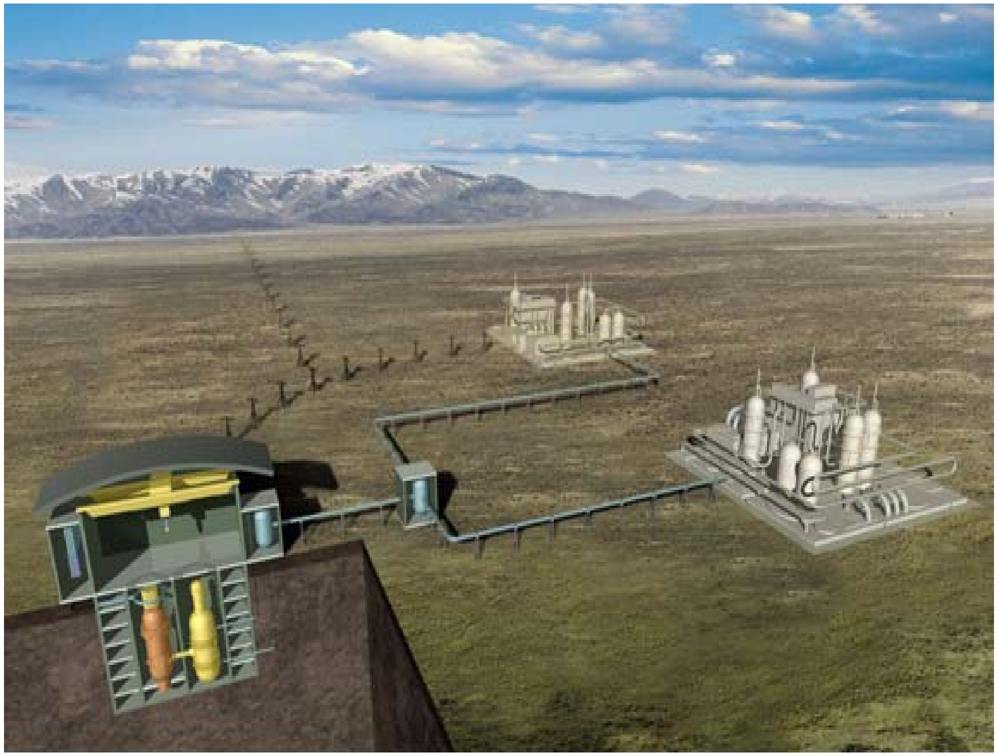
Nuclear Hydrogen

- The first steps have begun:
  - Demonstrate laboratory scale SI process operation (I-NERI: SNL, GA, CEA)
  - Conceptual design of H_2-MHR (NERI: GA, INEL, TAMU)
  - Development of HTE at INEL (INEL, Ceramatec)
  - Measure needed chemical data (SNL-L, CEA)
  - Tasks could be completed in 3 years
- Next, build a ~10 MWt Pilot Plant (~3 tons/day of H_2)
  - Design, build and operate in ~4 years
  - Operation with fossil-fueled simulated nuclear heat source
- Then, build a H_2- Nuclear Demo Plant
  - Part of Idaho "Next Generation Nuclear Power" Demonstration Project
  - Demonstrate Nuclear Production of Hydrogen by ~2015

NGNP plans to demonstrate nuclear production of H_2 at INL by 2017

- **DOE Plan:** Demonstrate S-I thermochemical water-splitting and high temperature electrolysis processes at Idaho National Laboratory



- Provide 60 MWt of heat for hydrogen production
  - Allow smooth transition between 100% electricity and 90% electricity/10% hydrogen
  - Up to 20 tons of H_2 per day
- Demonstrate prevention of failure propagation across reactor/process interface
- Maintain hydrogen purity
  - Tritium release below NRC and EPA standards
  - Radioactivity in hydrogen below 10CFR20 limits
  - Hydrogen meets fuel cell standards

Fusion can also produce hydrogen

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Nuclear Hydrogen

- **FAME** (Fusion Applications and Market Evaluation) identified hydrogen as a useful product — 1988
  - 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

More recent Sheffield and ARIES studies agree

Direct processes appear interesting....

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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

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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
    - ^{6}Li + n= T + He, ^{7}Li + 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

GENERAL ATOMICS

HTE could benefit from fusion's high temperature capability

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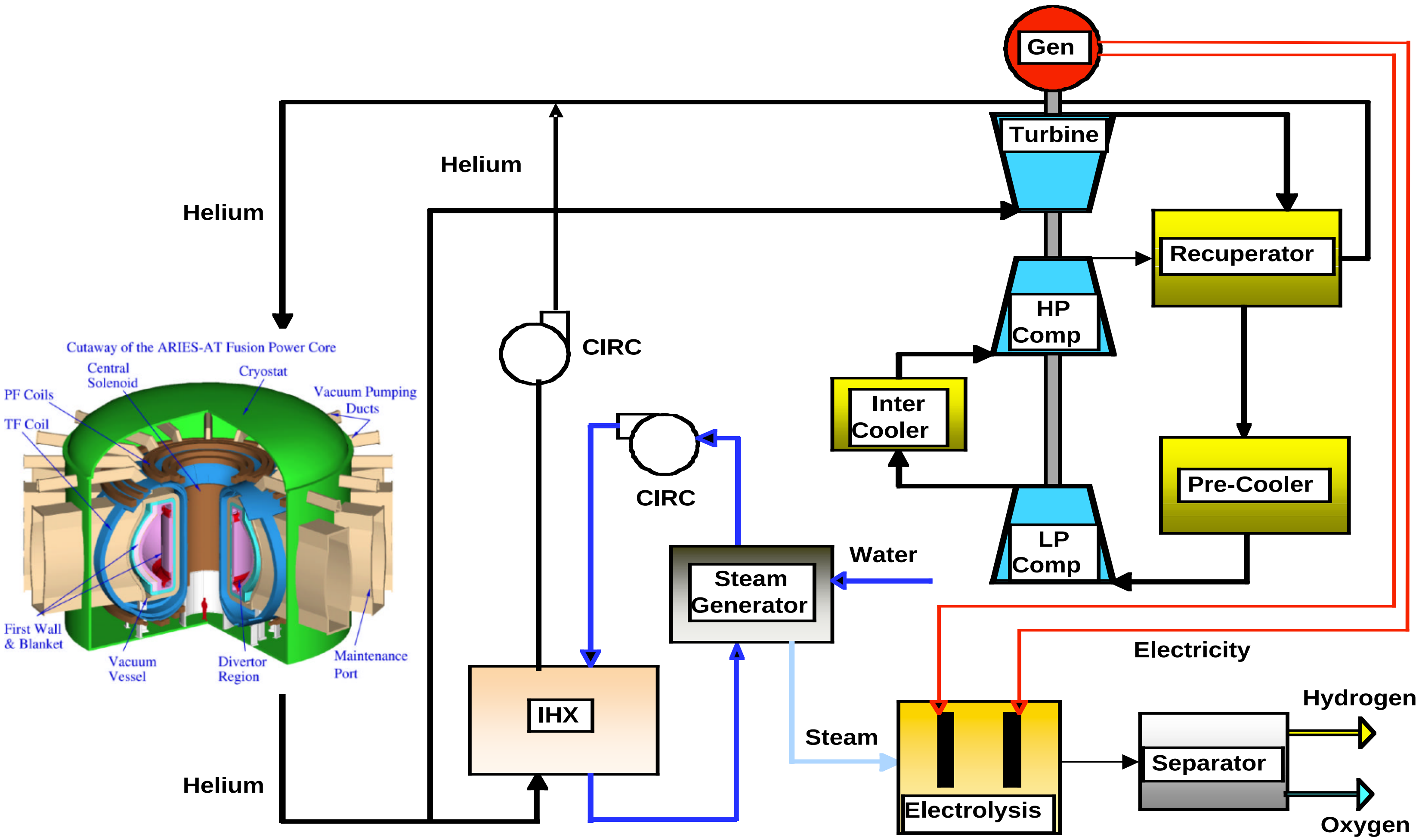
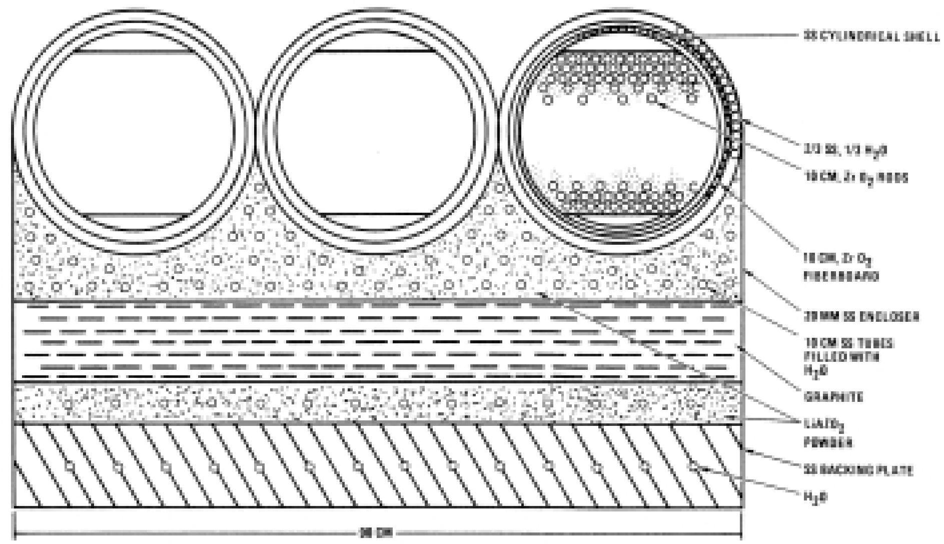
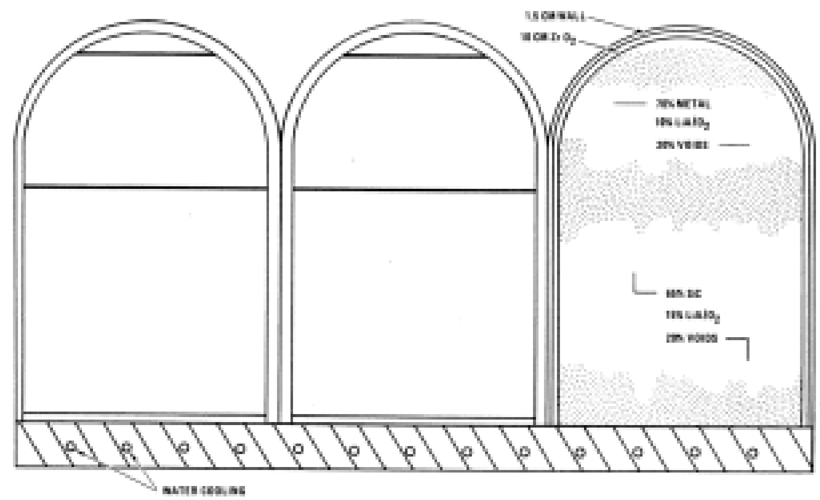


GENERAL ATOMICS

High temperature electrolysis used fusion heat and electricity

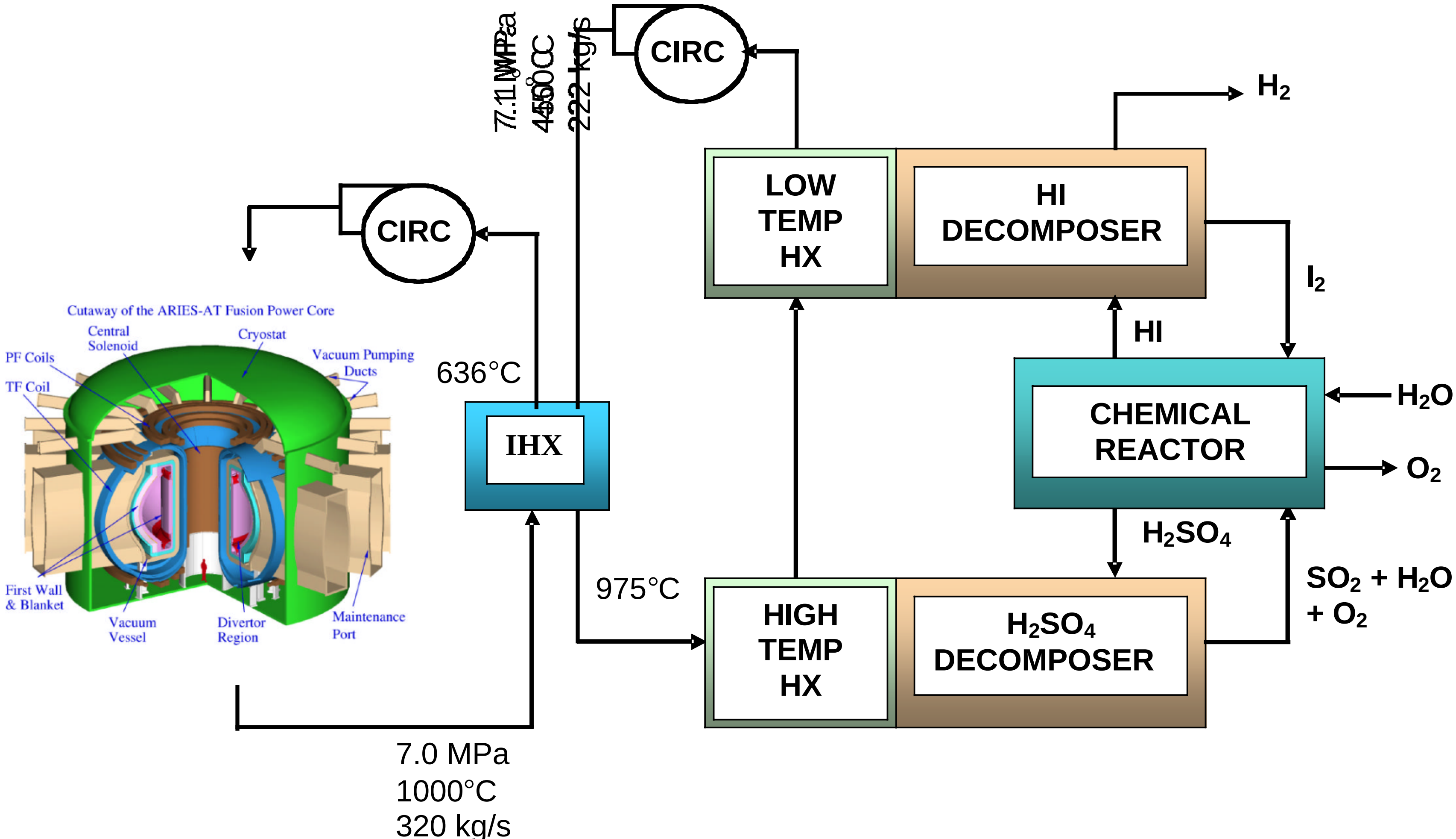
- **HYFIRE tokamak concept used 2 blanket modules**
  - 1400-1800° C steam-cooled HTE module
  - 800-1000°C He-cooled power module
  - External electrolysis
- **High heat to hydrogen efficiencies claimed:**
  - 1800°C/60% pcs gives ~70%
  - 1400°C/40% pcs gives ~50%
- **"Significant development required".....**





BNL HYFIRE study 1979

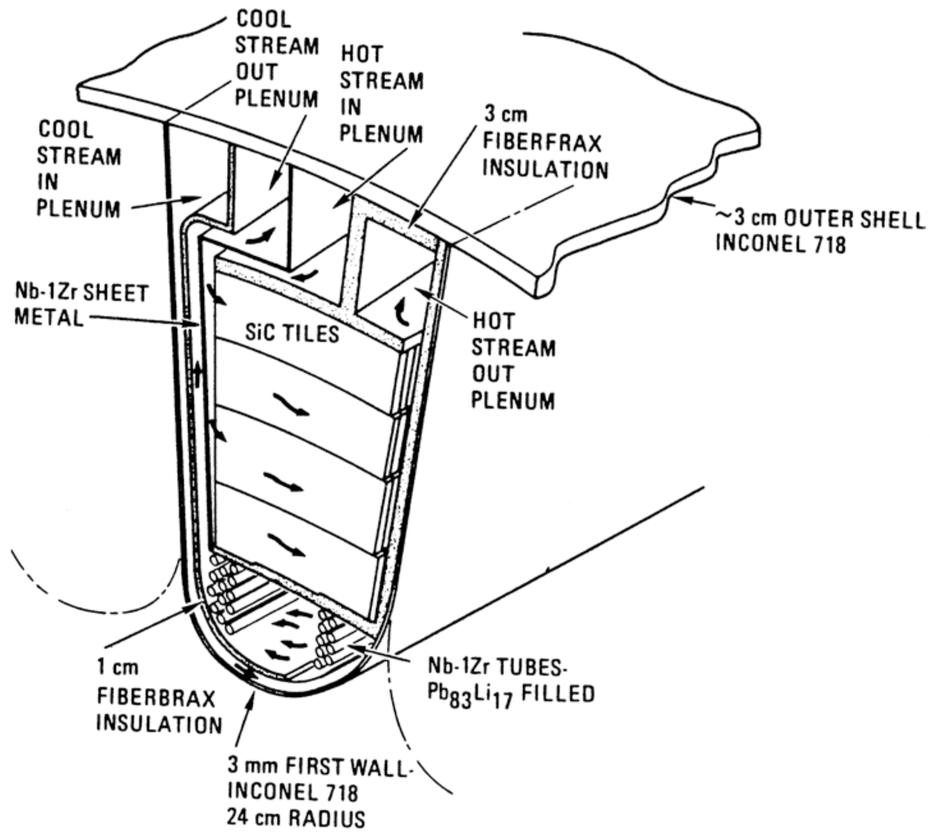
Fusion Thermochemical SI-H_2 Concept used only high temperature heat



Thermochemical water-splitting uses only heat in two coolant streams to control tritium

NH2 Nuclear Hydrogen

- 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 H_2
- He flows directly to H_2 process
- Slip-stream processing, natural barriers and SiC HX excellent tritium barrier limit release to 2.1 Ci/d, below 10CFR20 limits for unrestricted use



GA Utility Synfuel Study, 1983

GENERAL ATOMICS

Economics of hydrogen production are challenging

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Nuclear Hydrogen

- H_2 currently made from natural gas by steam reformation
  - At current ~$6.50/MBtu cost of NG, H_2 costs ~$1.50/kg or $11/MBtu
- Production of H_2 from fission projected to cost ~$1.40/kg
  - Could compete with natural gas today (at regulated utility capital rate)
  - O_2 credit for nuclear or CO_2 tax for fossil are possible
- Fusion could compete if capital cost ≤ $500/kW$_t$
  - $3B for "n[th] of a kind" 6 GW$_t$ fusion plant (w/o power conversion) *is* a believable goal

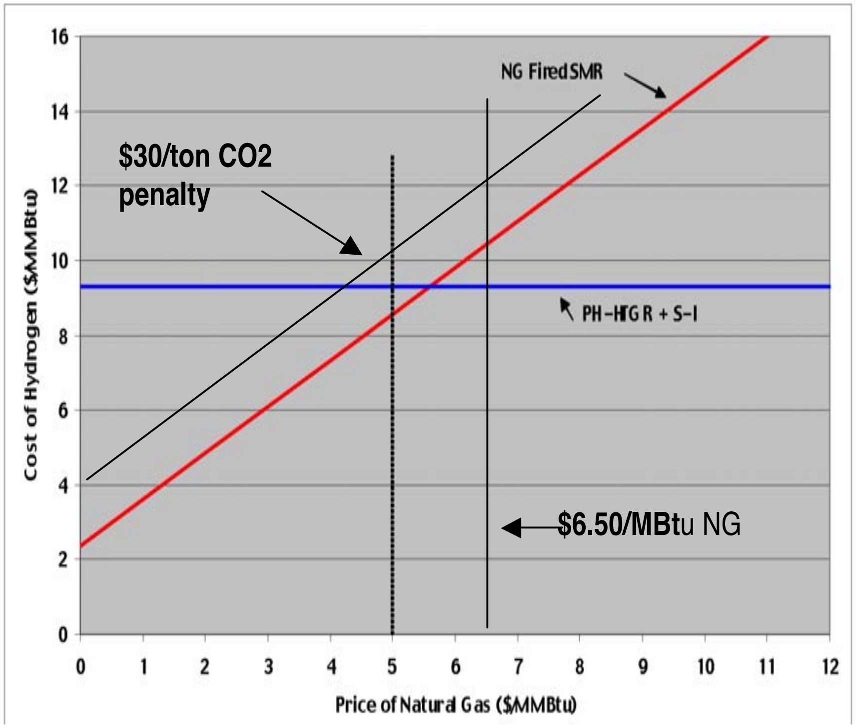

Figure courtesy of EPRI
$20/ton O_2 credit, no CO_2 penalty
Regulated utility capital cost rates used, 12.6% CRF

GENERAL ATOMICS

Low Temperature Electrolysis could be used; is it economic?

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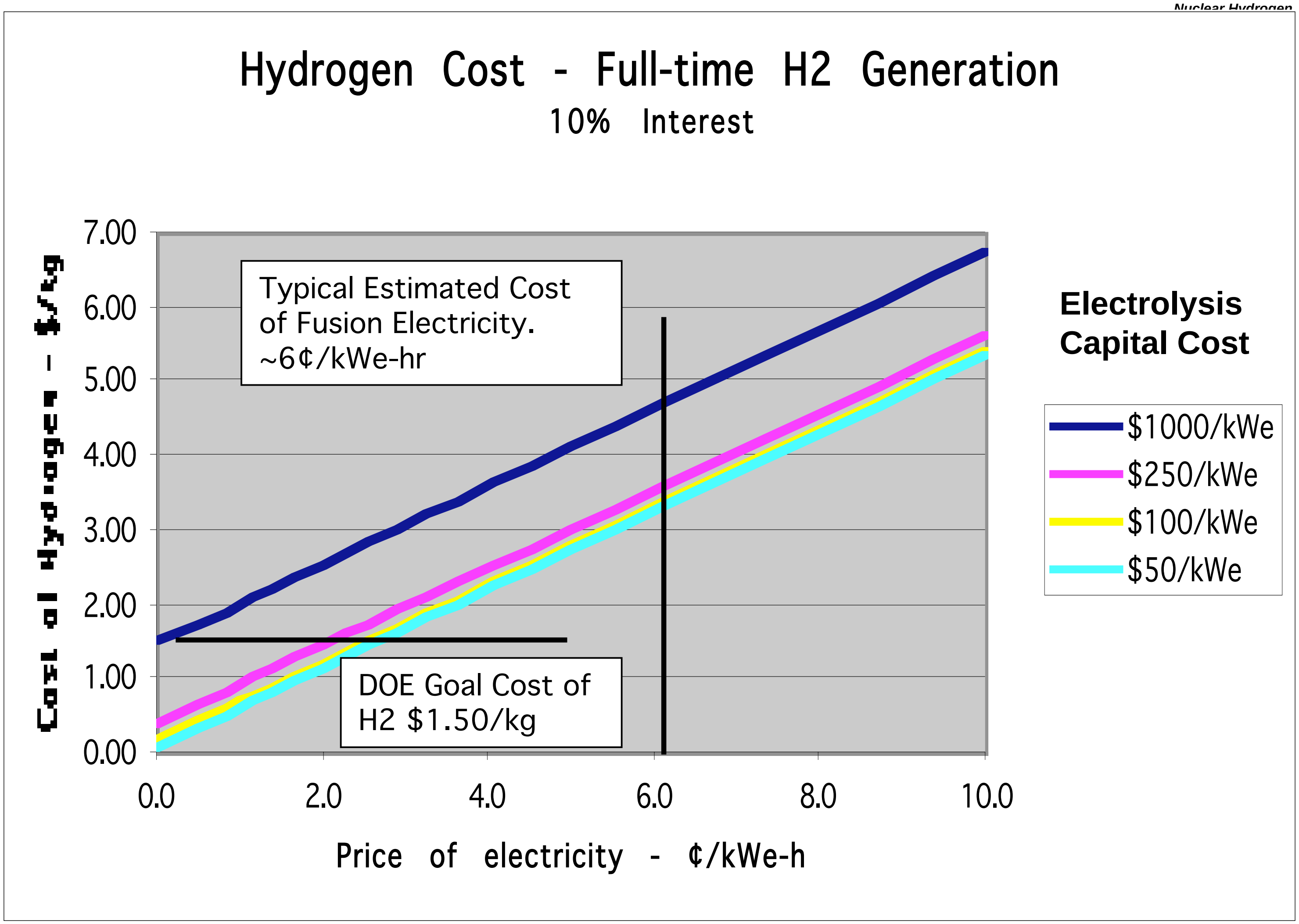
- **Capital costs are coming down:**
  - Current cost – >$1000/kWe
  - Production goal cost – $250/kWe
  - Potential ultimate cost – $50/kWe
    - Based on General Motor's ultimate goal for fuel cells (similar technology)
- **Average electricity prices hurt economics of electrolysis**
  - $1.5 - 2.0/kg of H_2 needs 2-3¢/kWe-h electricity
  - 6-7¢/kWe-hr implies$3.50-4.0/kg H_2 cost
- **Off-peak pricing could have positive benefit**
  - Operate electrolysis units only during off-peak hours
  - Electricity price might be only the fuel cost – low for nuclear
  - Would low off-peak rates compensate for lower capital utilization?

GENERAL ATOMICS

Hydrogen electrolysis costs – 100% duty cycle



GENERAL ATOMICS

Off-peak hydrogen production costs

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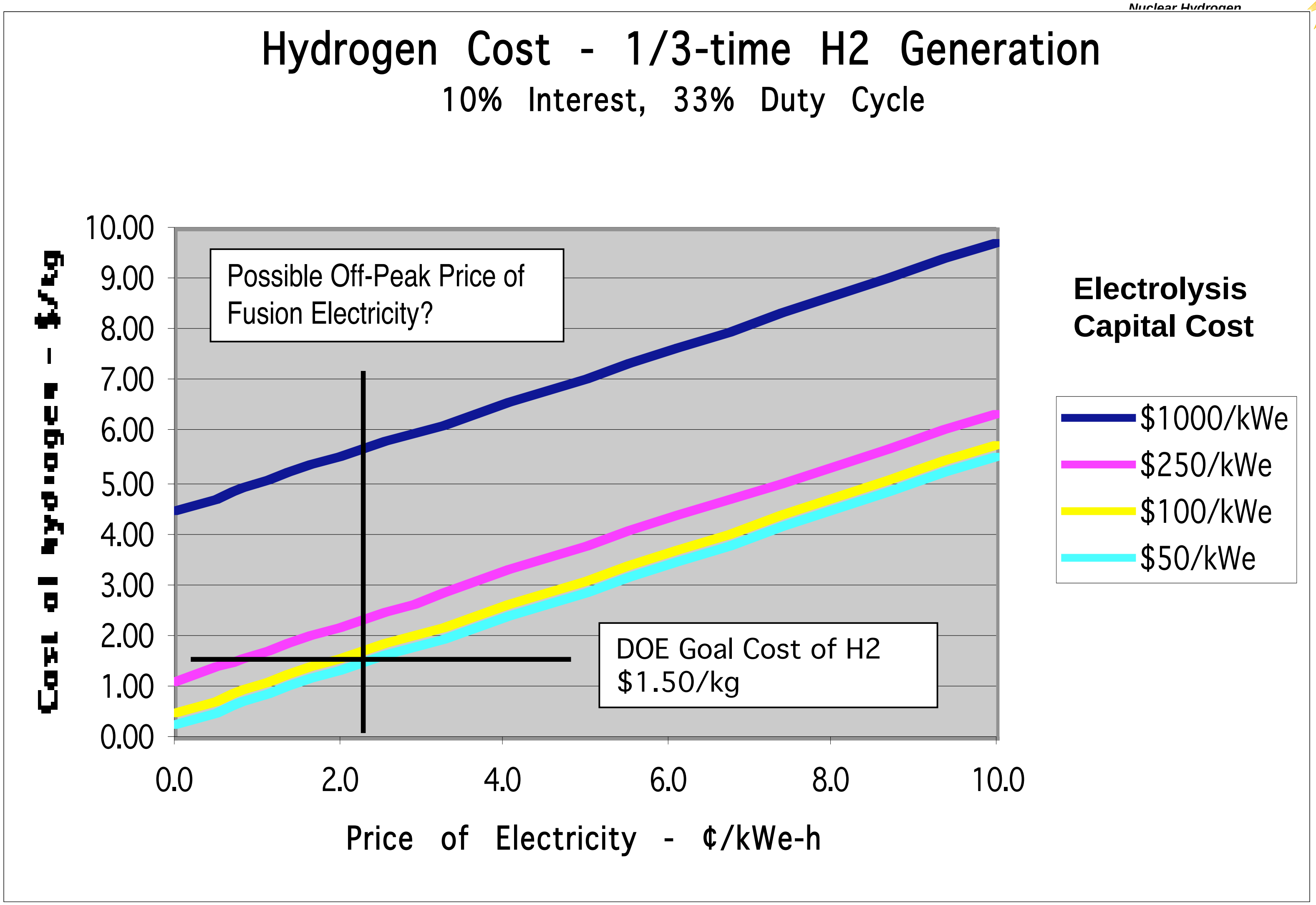

GENERAL ATOMICS

Hydrogen production could be a major role for Fusion

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- 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
- Off-peak production of hydrogen could be attractive
- With development, fusion could help fuel the Hydrogen Economy

GENERAL ATOMICS