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# High Temperature Nuclear Reactors for Hydrogen Production


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(NE-74)


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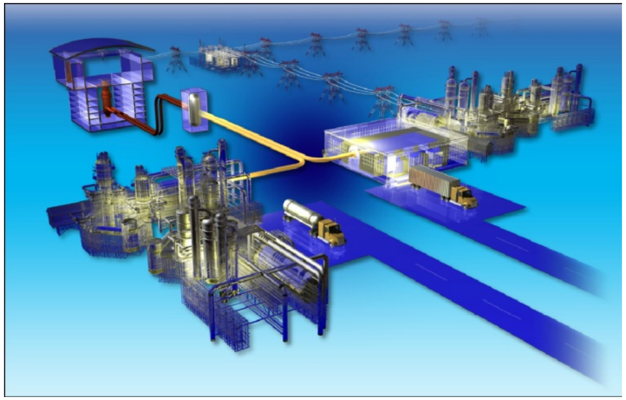
# Next Generation Nuclear Plant (NGNP) Mission and Program Objectives

**Mission: Demonstrate high-temperature gas-cooled reactor (HTGR) technology to produce electricity and high temperature process heat**



Chronicle / Penni Gladstone

***Program Objectives***

- Partner with industry to commercialize HTGR technology
- Collaborate with the Nuclear Regulatory Commission (NRC) to establish a licensing framework for HTGRs
- Draw upon the national laboratories, universities, and international community to perform the Research and Development (R&D) necessary to decrease the technical risk

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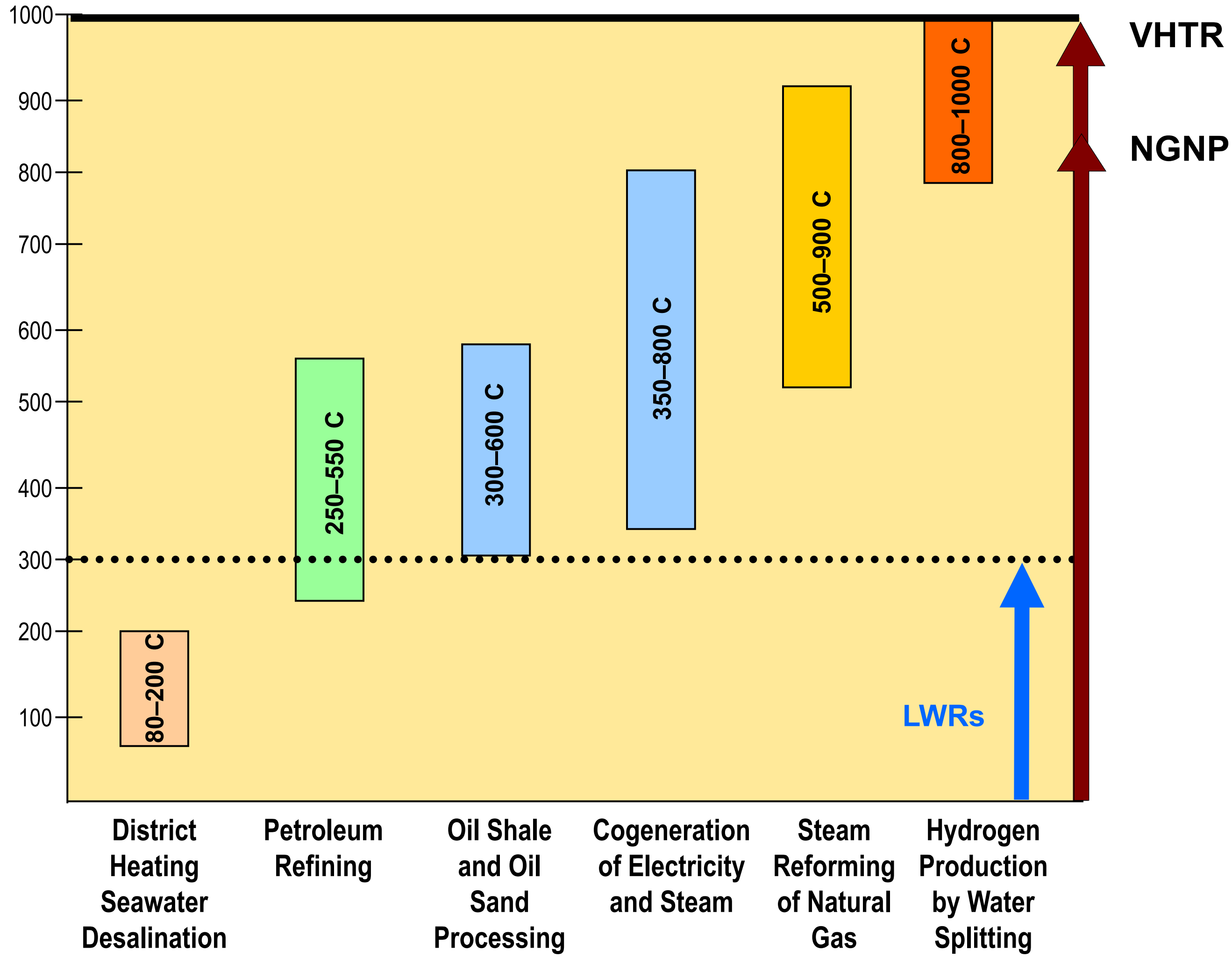
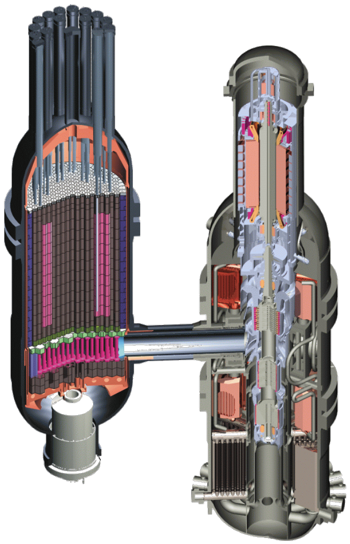
# Potential Contribution of Fission Reactors to Process Heat Industries

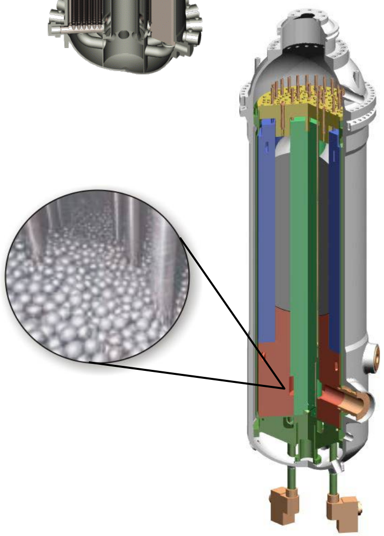



VHTR—Very High Temperature Gas-Cooled Reactors; LWR – Light Water Reactors

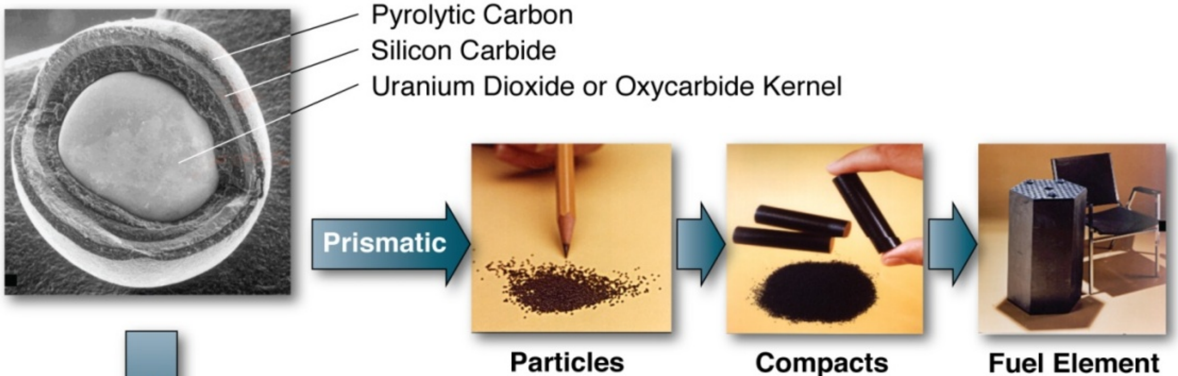
# NGNP – Features and Characteristics

- **Helium cooled** – noble gas does not chemically react
- **High outlet temperature** – 750°C or greater for high energy conversion efficiency and process heat uses
- **Coated particle fuel** – excellent fission product retention under operating and accident conditions
- **Passive safety features** – ensure public health and safety
- **Small to medium power output** – good fit for industrial applications
- **Improved fuel utilization** – up to three times the burnup of light water reactors

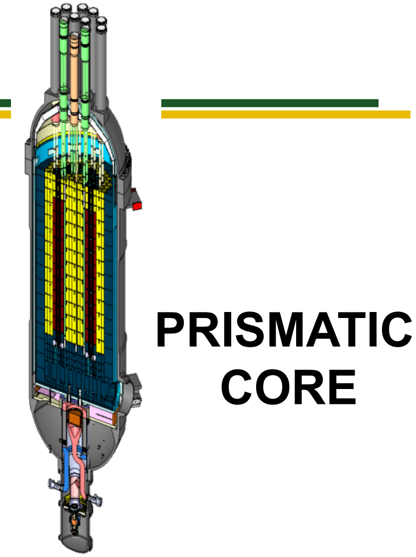


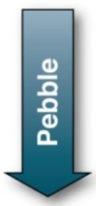


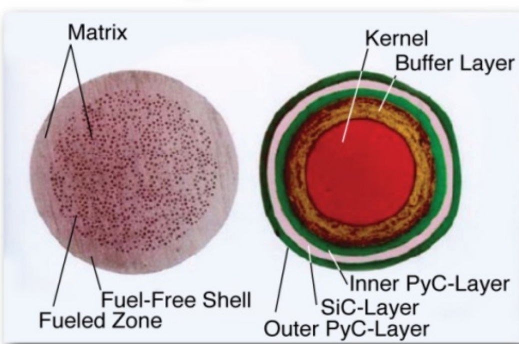
# Key to HTGRs – Tri-Structural Isotopic (TRISO) Fuel



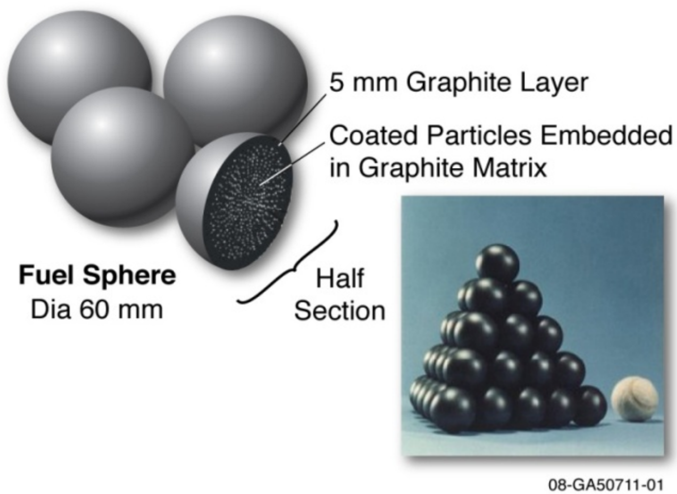

TRISO-coated fuel particles (left) are formed into fuel compacts (center) and inserted into graphite fuel elements (right) for the prismatic reactor

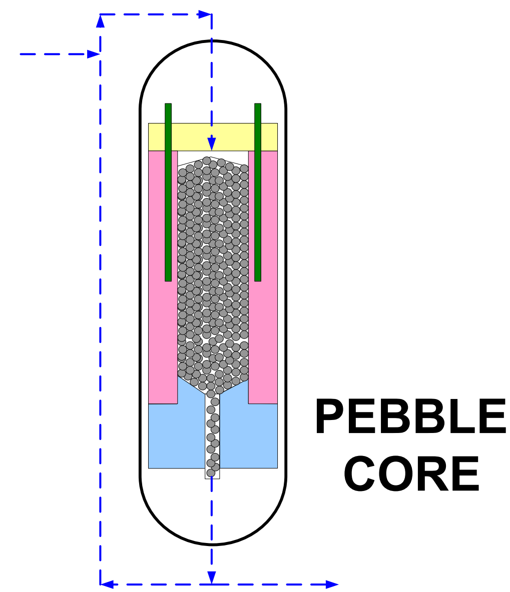



TRISO-coated fuel particles are formed into fuel spheres for pebble bed reactor



# NGNP PROJECT STATUS

# NEAC Review of NGNP Phase 1

- **EPAct mandated review by Nuclear Energy Advisory Committee (NEAC) prior to proceeding to Phase 2**
- **NEAC Report forwarded to Congress – October 17, 2011**
- **DOE Response**
  - Continue Phase 1 R&D
  - Postpone initiation of Phase 2 design activities
  - Continue to engage NRC to ensure regulatory framework is in place to support commercialization of this technology
  - Work to establish public-private partnership

# NUCLEAR HYDROGEN PRODUCTION R&D

# High Temperature Steam Electrolysis

***Accomplishments***

- R&D on cell & stack manufacturing for high temperature steam electrolysis (HTSE).
- 1080-hour 15 kW integrated laboratory scale operation at Idaho National Laboratory.

**Small-Scale Test Area at INL**

**Integrated Laboratory-Scale Experiment (>5,000NL/h, 15kW) at INL**

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# Overview of Project Activities (FY12)

## Pressurized Test

- **Pressurized operation of 10-cell advanced technology stack at 1.5 MPa**
  - Required development of completely new test apparatus
  - Upgrading of laboratory gas delivery systems to allow for pressurized operation

## 4 kW Test

- **Demonstrate HTSE at 4kW scale for 1,000 hours with advanced technology, internally manifolded, electrode-supported cells**
  - Required modification of test stand for higher flow rates and heat recuperation

## Small-Scale Testing, Advanced Technology Cells and Stacks

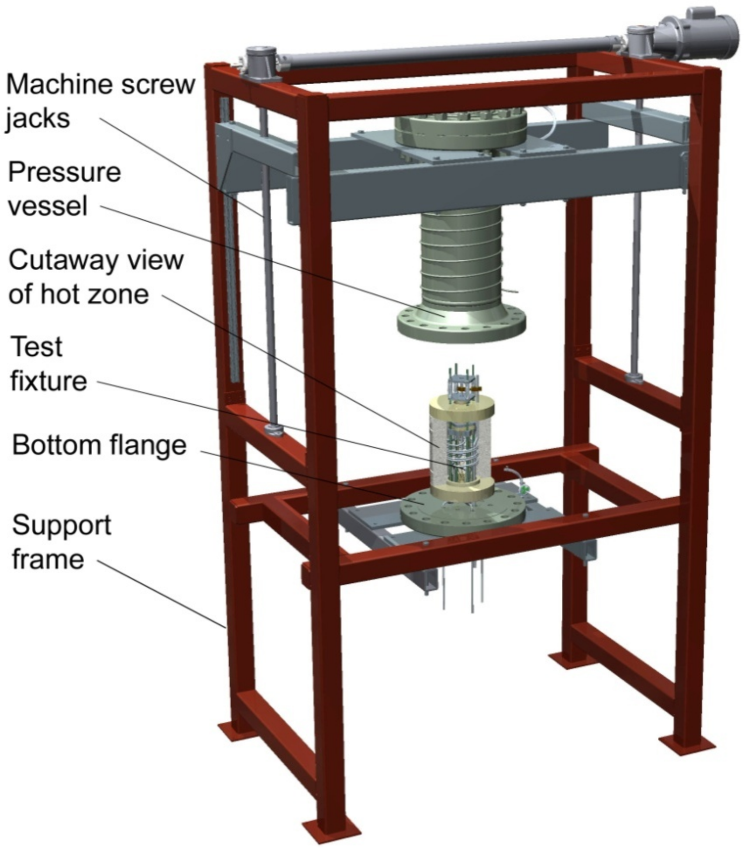
- **Continue testing and characterization of advanced cells and stacks with a focus on performance (initial and long-term)**

## Analytical and Modeling Activities

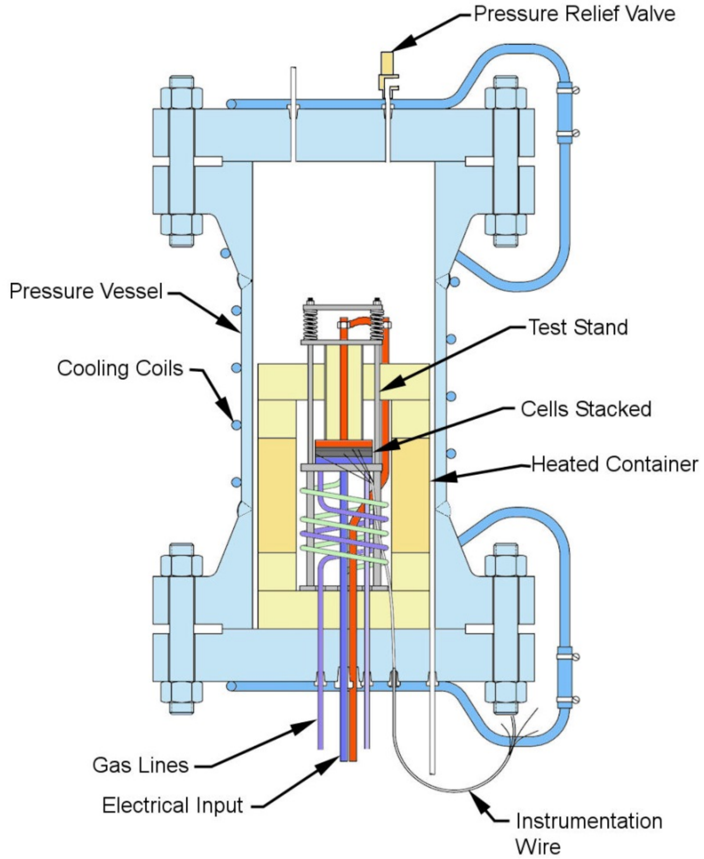
- **System analysis of biomass pyrolysis process for distributed production of synthetic crude / liquid fuels**
- **Economic analysis of distributed hydrogen production from HTSE**

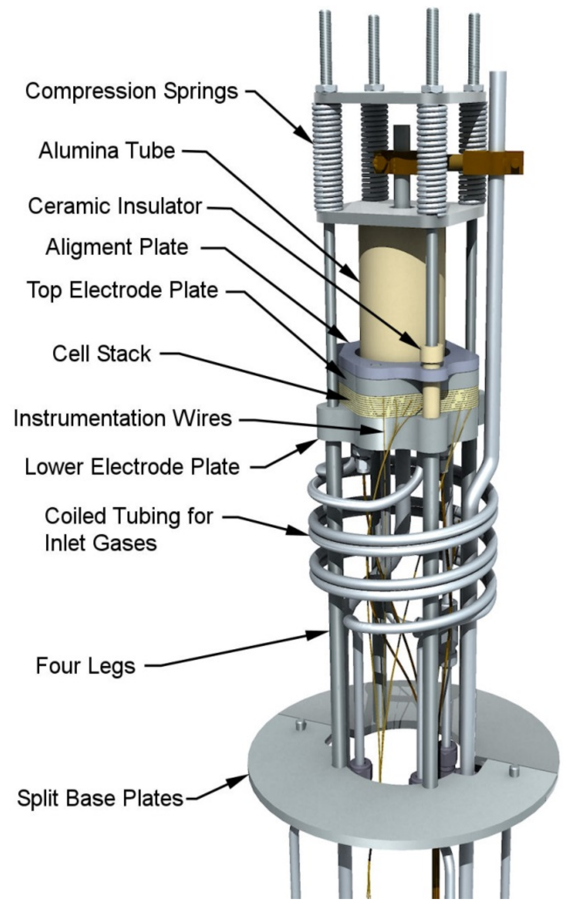
# Pressurized Test (1.5 Mpa / 217.5 psi)

Test Stand




# Vessel and Test Fixture for Pressurized HTSE Test



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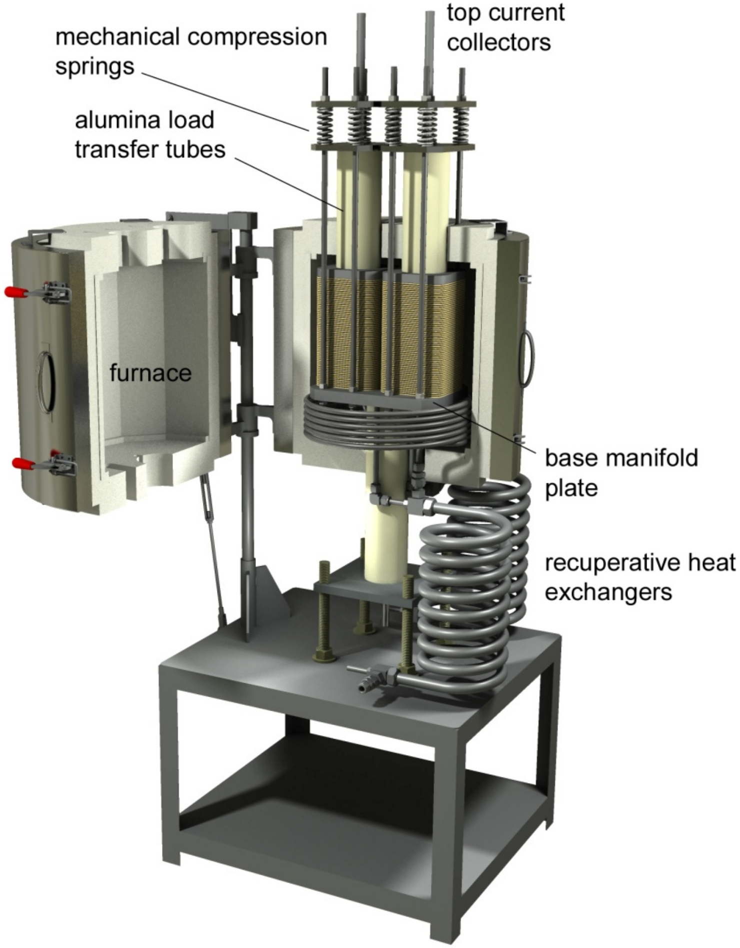
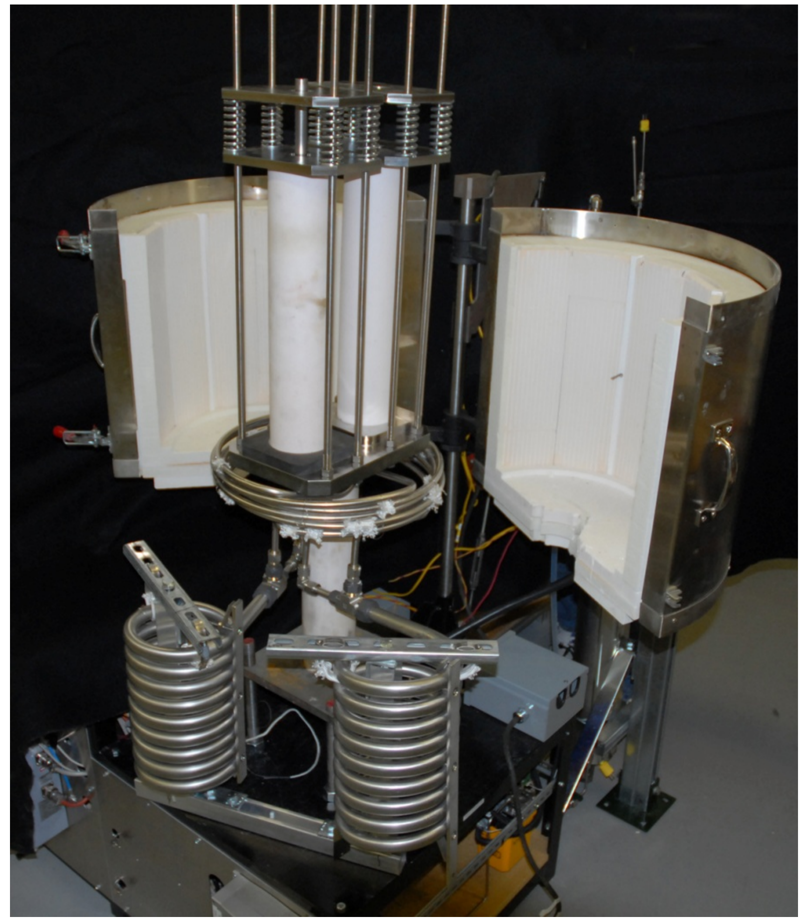
# 4 kW Test of Advanced Cell Stack



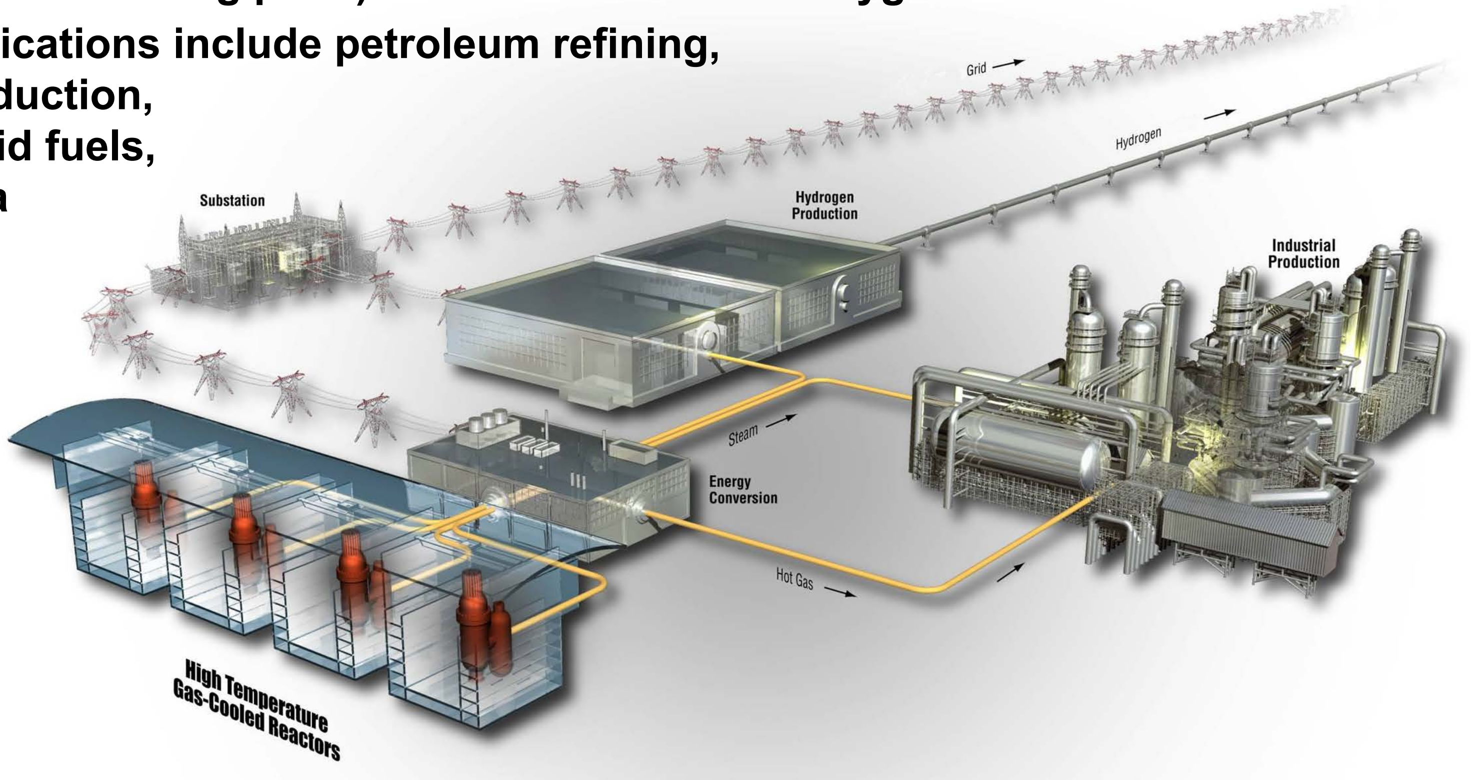



***4 kW test stand, assembled***

# NGNP / HTSE Conceptual Design

## *NGNP Concept for Large-Scale Centralized Nuclear Hydrogen Production based on High-Temperature Steam Electrolysis*

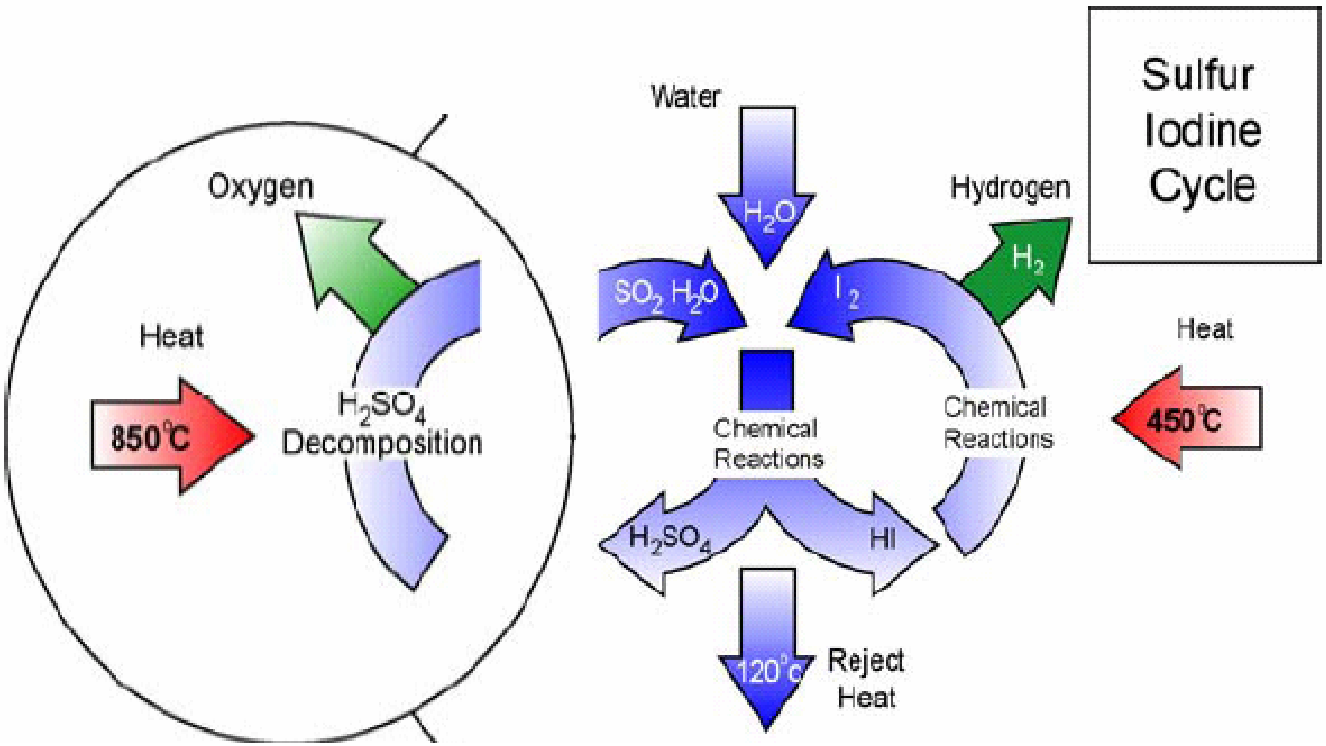
- **Direct coupled to HTGR reactor for electrical power and process heat**
- **600 MWth reactor could produce ~85 million SCFD hydrogen (similar to a large steam methane reforming plant) and 42 million SCFD oxygen**
- **Potential applications include petroleum refining, ammonia production, synthetic liquid fuels, hydrogen as a direct vehicle fuel**



# Thermochemical Cycle R&D Activities Under Nuclear Hydrogen Initiative (NHI) (ended FY 2009)

- **Idaho National Laboratory**—Membranes, catalyst testing
- **Argonne National Laboratory (ANL)**—Alternates cycles (Ca-Br), flowsheet analysis $SO_3$ electrolysis
- **Oak Ridge National Laboratory (ORNL)**—Inorganic membranes, materials
- **Sandia National Laboratories (SNL)**—Sulfur cycle development/testing, membranes, materials, heat exchanger development
- **Savannah River National Laboratory (SRNL)**—hybrid sulfur cycle development
- **General Atomic (GA)**—Sulfur Iodine Development
- **Universities**—process development, materials testing

# Sulfur-Iodine (S-I) Cycle



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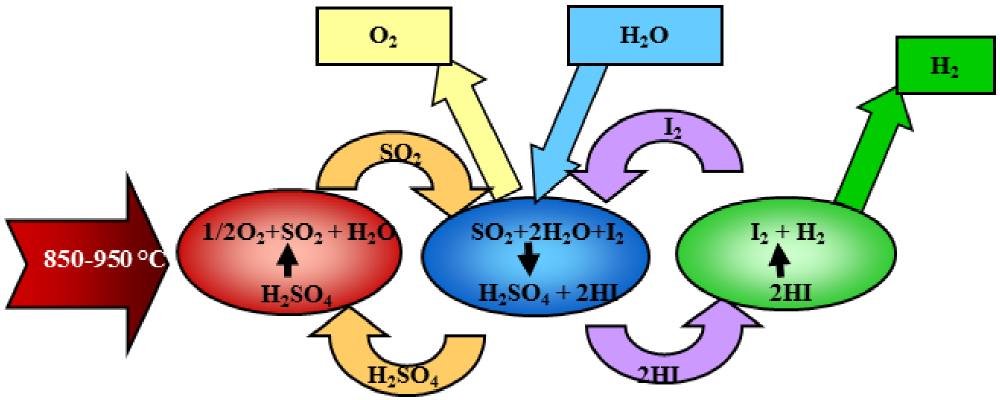
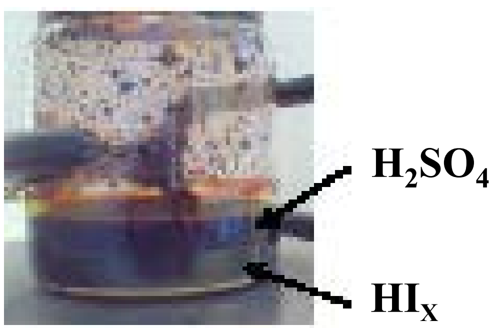
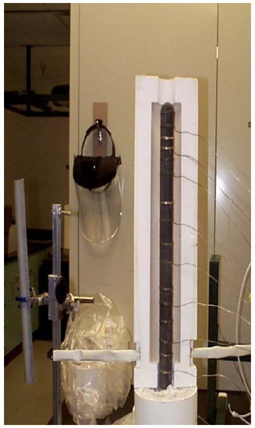
# Thermochemical R&D: Sulfur – Iodine Cycle




Bunsen Reaction Products (for SI)



Sulfuric Acid Decomposer (~900°C)

Integrated Laboratory-Scale Experiment (60 NL/h) at GA

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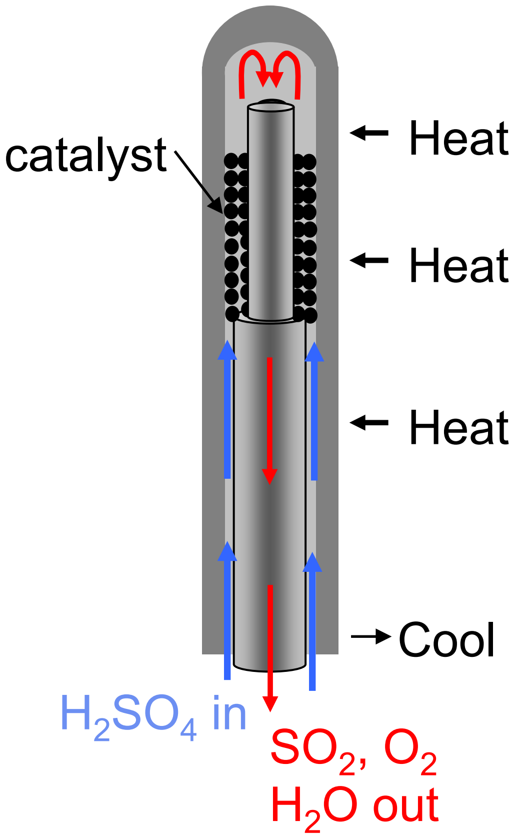
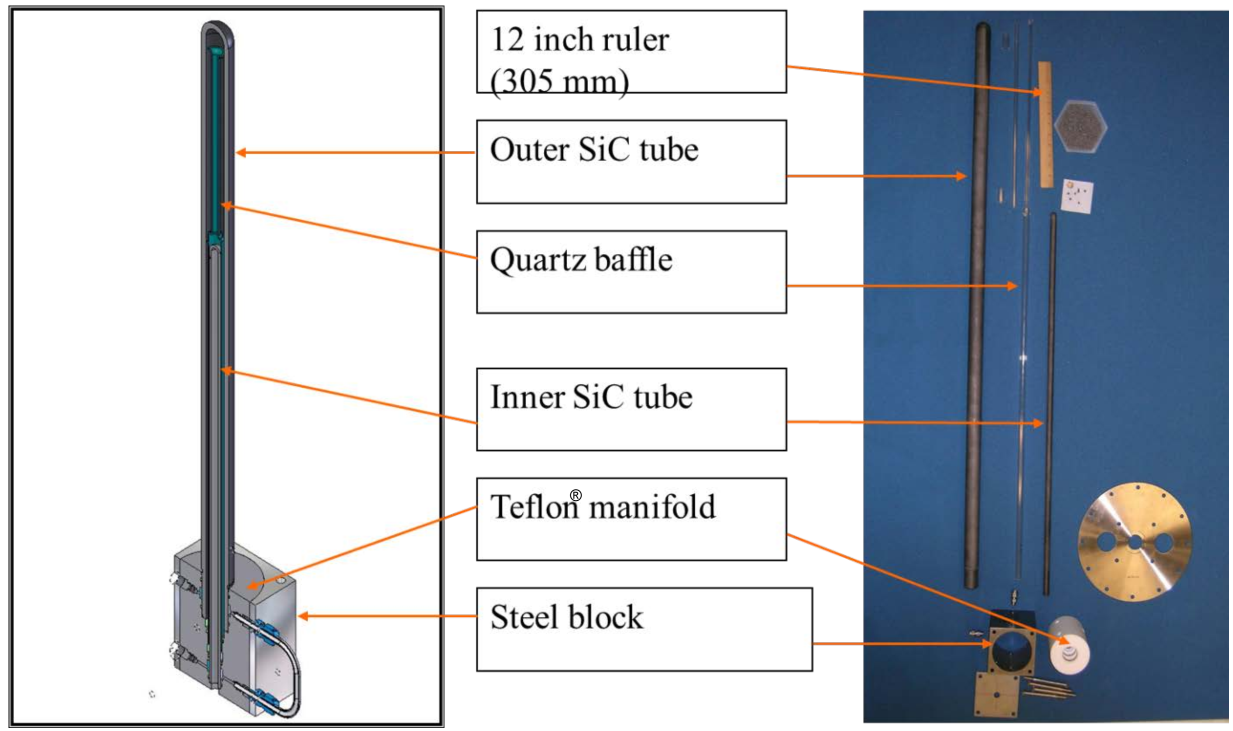
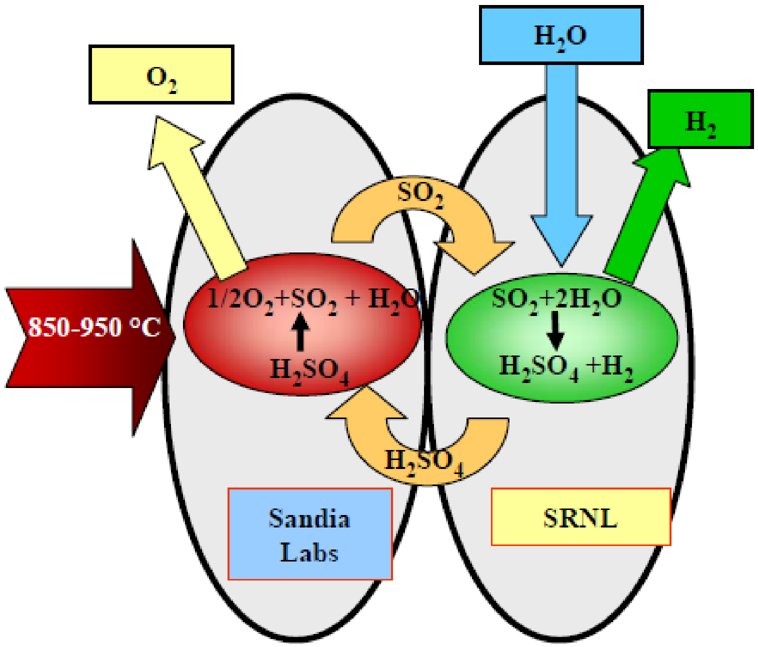
# Thermochemical R&D: Sulfuric Acid Decomposer



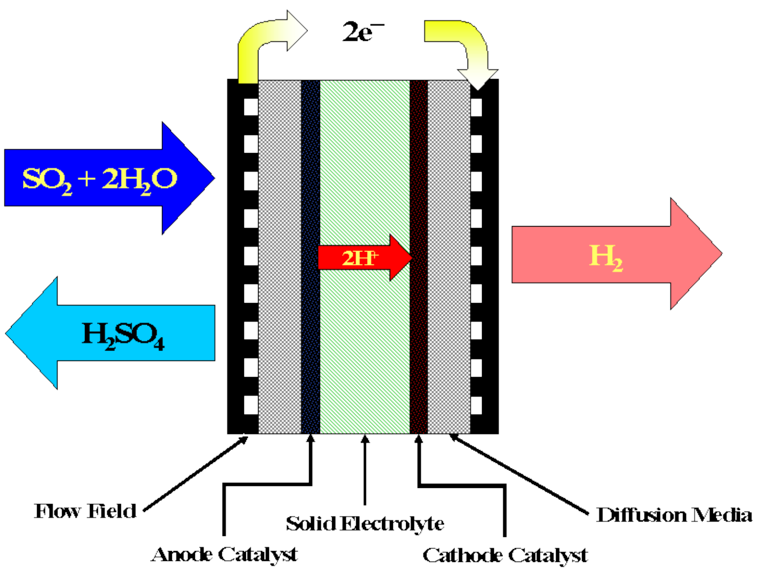




**Sulfuric Acid Decomposer (~900ºC)**

# Thermochemical R&D: Hybrid Sulfur Cycle




## $SO_2$ Depolarized Electrolysis




***Hybrid-Sulfur***

(1) $H_2SO_4 \rightarrow H_2O + SO_2 + 1/2O_2$

(2) $2H_2O + SO_2 \rightarrow H_2SO_4 + H_2$

**Baseline SRNL approach: Anolyte consists of $SO_2$ dissolved in concentrated sulfuric acid**

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# Thermochemical R&D: Hybrid Sulfur Cycle

**Hybrid Sulfur Chemistry**

$H_2SO_4 \leftrightarrow H_2O + SO_2 + ½O_2$
(thermochemical; 800–900 C)

$SO_2 + 2\ H_2O \rightarrow H_2SO_4 + H_2$
(electrochemical; 80–120 C)

Net Reaction: $H_2O \rightarrow H_2 + ½O_2$

**Sulfur Dioxide Depolarized Electrolyzer (SDE)**

Anode Reaction:

$SO_2 + 2H_2O \rightarrow H_2SO_4 + 2H^+ + 2e^-$ $E_o = -\ 0.158$ V

Cathode Reaction:

$2H^+ + 2e^- \rightarrow H_2$ $E_o = 0.000$ V

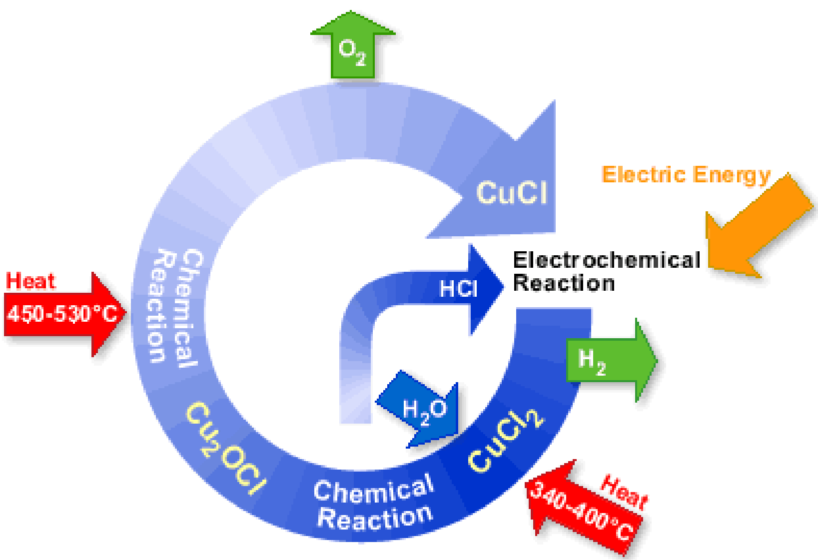
Net Reaction:

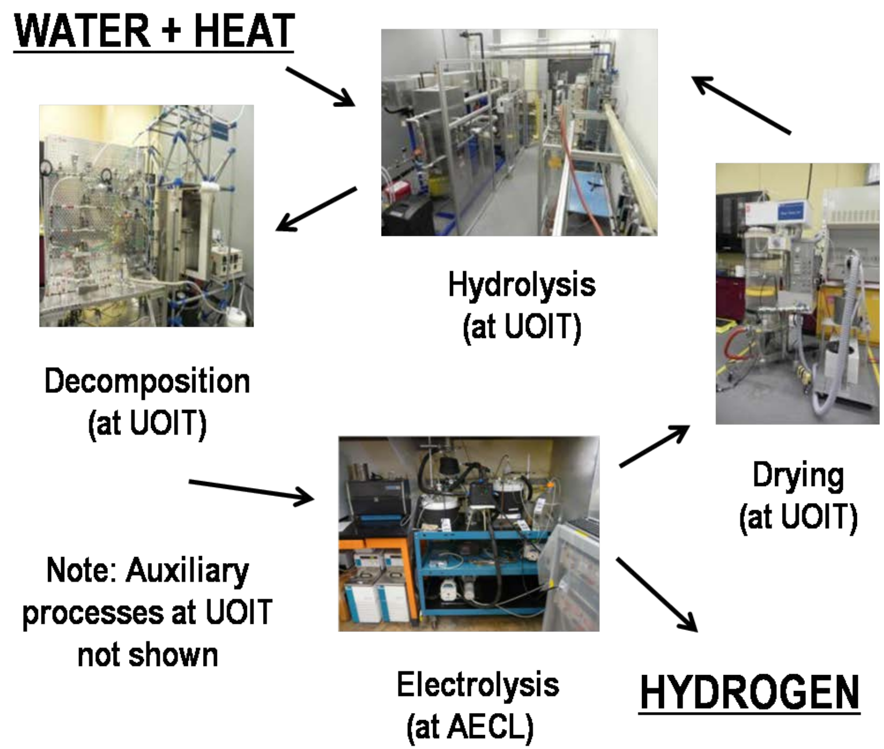
$\mathbf{SO_2 + 2H_2O \rightarrow H_2SO_4 + H_2}$ $\mathbf{E_o = -\ 0.158}$ **V**

# Cu-Cl Hybrid Thermochemical Cycle

***Accomplishments***

- CuCl/HCl electrolyzer operation demonstrated by AECL.
- Lab-scale non-electrolysis steps successfully performed in 2011 by Canadian program.




AECL – Atomic Energy of Canada, Ltd.
UOIT—University of Ontario Institute of Technology

# Alternative Cycles Lab Work

- Hybrid Ca-Br – Argonne National Lab - 45%
  - **$CaBr_2 + H_2O(g)$ = $CaO + 2HBr$ — 750 C**
  - $CaO + Br_2$ = $CaBr_2 + ½O_2$ (g) — 550 C
  - $2HBr(g)$ = $H_2 + Br_2$ (g) — 25 C
- K-Bi – Penn State University
  - $0.3\ K_3Bi + H_2O(g)$ = $KOH(l) + H_2$ (g) + 0.3 Bi — 575 C
  - **$KOH(l) + 0.3\ Bi$ = $.5\ O_2$ (g) + $0.5H_2$ (g) + $0.3\ K_3Bi$ — 575 C**
- Mg-I – University of South Carolina - 45%
  - $6MgO + I_2$ (s) = $Mg(IO_3)_2$ (s) + $5MgI_2$ (aq) — 150 C
  - $Mg(IO_3)_2$ (s) = $MgO + I_2$ (g) — 600 C
  - $5MgI_2 + 5H_2O(g)$ = $5MgO + 10\ HI(g)$ — 400 C
  - **10 HI (g) = $5H_2(g) + 5I_2(g)$ — 500 C**
- Hybrid Cu-Cl – ANL - 42%
  - $2Cu + 2HCl(g) \rightarrow 2CuCl\ (l) + H_2(g)$ — 450 C
  - $4CuCl \rightarrow 2CuCl_2 + 2Cu$ — 25 C
  - **$2CuCl_2(s) + H_2O(g) \rightarrow CuO \bullet CuCl_2\ (s) + 2HCl(g)$ — 400 C**
  - $CuO \bullet CuCl_2\ (s) \rightarrow 2CuCl(l) + ½O_2(g)$ — 550 C
- Hybrid Cl - Clemson University - 34%
  - **Cl2(g) + H2O (g) = 2HCl (g) + ½O2 (g) — 850 C**
  - 2HCl (g) = H2(g) + Cl2(g) — 75 C
- $Cu\text{-}SO_4$ Tulane University - 52%
  - **CuO + SO2 (g) + H2O = Cu SO4 + H2 (g) — 25 C**
  - CuSO4 = CuO + SO2 (g) + ½O2 (g) — 850 C

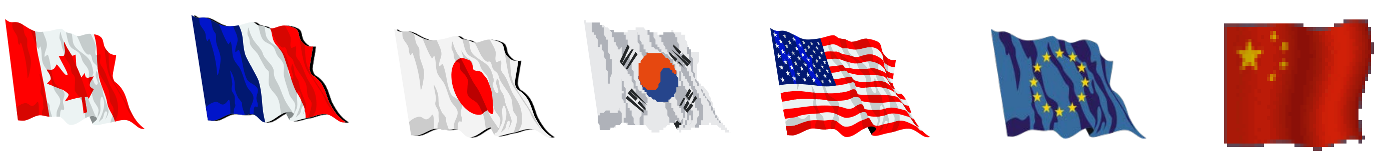
# Thermochemical NERI Projects

- *S-I Thermo-Physical Measurements*
  - *Mark Thies*
  - *Clemson University*
- *SO2 and HBr Electrolysis Studies*
  - *John Weidner*
  - *University of South Carolina*
- *S-I Modeling Studies*
  - *Shripad Revankar*
  - *Purdue University*

# International R&D Cooperation

- Generation IV International Forum (GIF) Very High Temperature Reactor (VHTR) Hydrogen Production Project
- Project arrangement in force since 2008
- 7 current members

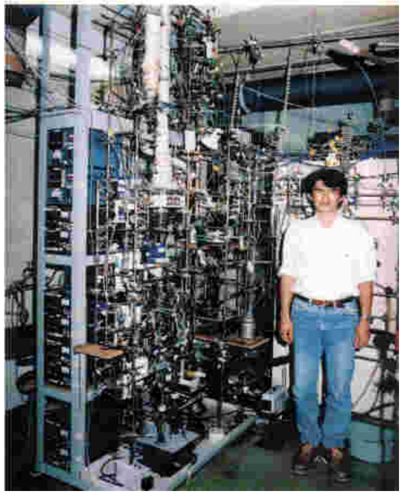
*CA, FR, JP, KR, US, EU, CN*



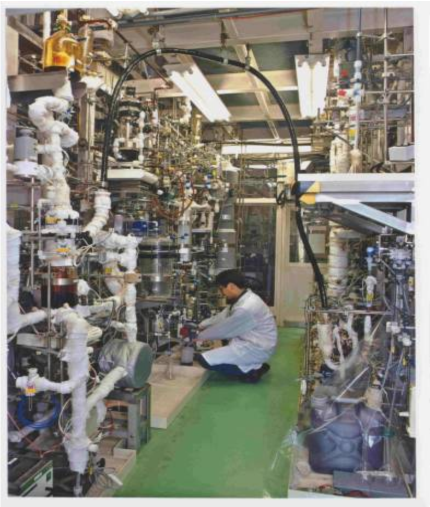
# International Sulfur Iodine Cycle R&D

***Accomplishments***

- Lab-scale(1NL/h) test at Japan Atomic Energy Agency (JAEA).
- Bench-scale(30 NL/h) test at JAEA.
- "Semi-Integrated" lab-scale operation at elevated pressure by SNL, GA, & Consumer Electronics Association (CEA) in 2008; at JAEA in 2014.



**Lab-Scale (1 NL/h) Test at JAEA**



**Bench-Scale (30 NL/h) Test at JAEA**

**Integrated Laboratory-Scale Experiment (60 NL/h) at GA**

# SUMMARY

# NGNP and Hydrogen Path Forward

- Continue R&D in HTGR fuels, materials and code validation experiments
- Continue licensing efforts with the NRC
- Continue contract with industry to develop economic/business analyses regarding commercializing HTGRs, and to provide data and analysis to DOE that could inform DOE on R&D efforts
- NE-RE Hybrid Energy Study looking at future options for incorporating high temperature hydrogen production once HTGRs are available

NHI

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