Highly Efficient, Solar Thermochemical Reaction Systems (2014 R&D 100 Award Winner)
Question and Answer

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HIGHLY EFFICIENT, SOLAR THERMOCHEMICAL REACTION SYSTEMS
Robert S Wegeng, PI

FCTO Webinar

January 13, 2015

2014 R&D 100 Award Winning Technology
Acknowledgments

To the **DOE Fuel Cell Technology Office (FCTO)** for early support in the 1990s and 2000s to the micro- and meso-channel process technology that is being adapted for solar applications!

To the **DOE Solar Energy Technologies Office** for the support to the current work that is being described in this presentation!

To **FCTO** for the opportunity to present our work in this webinar!
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Project Team
Pacific Northwest National Laboratory
Southern California Gas Company
Diver Solar LLC
Barr Engineering
Infinia Technology Corporation
Oregon State University

January 13, 2015
Solar Thermochemical Reaction System
On-Sun Testing Accomplished 69% Solar-to-Chemical Energy Conversion Efficiency* During 2013

Technology Readiness Level 4 (TRL 4) Reaction System

* Solar-to-Chemical Energy Conversion Efficiency is defined as the ratio of the increase in the Higher Heating Value (HHV) in the reacting stream to the direct (non-diffuse) solar energy that is incident upon the parabolic dish concentrator.
Technical Approach

Use Concentrated Solar Power to Augment the Chemical Energy Content of Methane and Produce Syngas

Thermochemical Reaction System

Methane Steam Reforming:

\[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \]

Synthesis Gas exiting the Solar Thermochemical Reaction System has about 25-28% greater chemical energy than the incoming methane stream

Concentrated Solar Energy

Radiant Energy

Electrical Power

Electrical power generation at less than 6 ¢/kWh

Transportation Fuels and Other Chemicals

Hydrogen production at less than $2/gge
Outline

- Introduction and Summary
- Concentrating Solar Power Examples
- Previous Solar Thermochemical Processing Efforts
- Example Applications
- Micro- and Meso-Channel Process Technology
- TRL 4 System Performance
- TRL 5 System Discussion (including preliminary performance data)
- Plan for TRL 6 Demonstration
- Conclusions

- Recent Selected References
Concentrating Solar Power
Concentrating Solar Power
World’s Largest Solar Thermal Power Station: Ivanpah

- California’s Mojave Desert
- 392 MegaWatts
- 173,500 heliostats, each with two mirrors

- Developed by BrightSource Energy and Bechtel
- Unit 1 connected to the grid in September 2013
- Capital Cost: $2.2 B
- Largest investor: NRG Energy

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Previous Work by Others
Solar-to-Chemical Energy Conversion

Sandia 1980s
- Experiments consisting of the solar CO$_2$ reforming of methane
  - In conjunction with the Weizmann Institute of Science, using a heat pipe solar receiver and integrated reforming reactors
  - In a direct catalytic absorption reactor; with a 3.5 kW$_s$ solar concentrator

Weizmann Institute of Science and DLR 2000s
- Solar steam reforming of methane; 400 kW$_s$

Sandia and DLR 1990s
- Solar CO$_2$ reforming of methane; 150 kW$_s$ concentrator; chemical efficiency of 54%

DLR and CIEMAT 1990s
- Solar steam reforming of methane; 170 kW$_s$

DOE Hydrogen Program
- Several solar thermochemical water-splitting investigations
  - Requires significantly higher temperatures, advanced materials, innovative thermal recuperation methods
Solar CO₂-Methane Reforming Demonstration (~1990-1993)
Photo courtesy of Sandia National Laboratory
Applications of Solar Methane Reforming
Power Generation via Combustion Turbine

- Efficient conversion of solar energy to electricity
- High capacity factors (>90%)
- Reduced CO₂ emissions
- Competitive Levelized Cost of Electricity (LCOE); accelerated approach to grid parity for Concentrating Solar Power (CSP)

Net Solar Thermochemical Reaction
\[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \]
Applications of Solar Methane Reforming

H₂ Production

- Requires components in addition to solar reforming system, already in development or proven
- Projected H₂ production cost: < $2/gge (gallons of gasoline equivalent) based on H2A and standard assumptions
- Projected carbon emissions as low as 5.5 kg CO₂/kg H₂; or approximately ½ of conventional H₂ production via methane reforming
- Potential commercial practice by 2020

Net Reaction:

\[ \text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2 \]
Applications of Solar Methane Reforming
Production of Solar Methanol for Renewable (Thermochemical) Energy Storage

- Methanol is a commodity chemical, sold worldwide (100 million metric tons)
- CO₂ in the product stream can in principle be recycled, yielding high overall selectivity to CH₃OH
- Process enables inexpensive thermochemical energy storage for concentrated solar and other renewable energy
- Using solar energy to run endothermic operations avoids carbon emissions associated with methanol production (typically 25-40% of incoming carbon is emitted as CO₂)
- Low-carbon intensity (based on lifecycle) methanol could also be used for other purposes. For example, as an additive to gasoline to help states meet Low Carbon Fuel Standards (LCFS)

Net Reaction:
CH₄ + H₂O \rightarrow CH₃OH + H₂

150-175°C
15+ bar

CH₄ + CO + CO₂ + H₂
CH₃OH + H₂O

H₂O

Net Reaction:
CH₄ + H₂O \rightarrow CH₃OH + H₂
Core Technology/Competitive Advantage
Micro- and Meso-channel Reactors and Heat Exchangers

- In development at PNNL since mid-1990s
- Compact
- Process-Intensive
- Exploit rapid heat and mass transport in thin, engineered channels
- Exploit economies of mass production (as opposed to classical economies of scale for chemical process technology)
Core Technology/Competitive Advantage
Several prototype reactors and heat exchangers for $\text{H}_2$ production were developed during FY1997-2003 with Hydrogen Program Funding

Modular, process-intensive reactors and heat exchangers yield highly efficient systems

**Exergetic Efficiency:**

$$\varepsilon = \frac{\text{Exergy Out}}{\text{Exergy In}} = 0.85$$
On-Sun Reactor Tests in 2013
World Record Solar-to-Chemical Energy Conversion Efficiency: 69.6%

- Energy absorption with different solar screens implies 2 kW of fixed heat loss.
- High solar-to-chemical efficiency over a wide range of operating temperatures and DNI; believed to be a world record.
SunShot Project Description
Thermochemical System Evolution

TRL 3 Reactor / HXR
63%

TRL 4 Reactor / HXR
69%

TRL 5 Reaction System
Designed for 70+% Initial Testing Oct 2014
TRL 5 Solar Thermochemical Reactor
Design, Fabricate and Assemble

TRL 5 Reactor Progress

Front Plate (left), Middle Plate (center) and Back Plate (right) after CNC Machining

Nickel-coated front plate with catalyst inserts (right-of-center).
Front plate after bonding (two left images). Hermetic testing (right).
Exergy Conversion and Destruction Calculations from Phase 1 (TRL 4 System)
TRL 5 Solar Thermochemical Reaction System Assembly Within Nacelle
Test Sites
Richland, Washington (PNNL)
Brawley, California (San Diego State University)

► Pacific Northwest National Laboratory
  ■ Convenient access to national laboratory
  ■ Annual Average Solar Resource: ~5 kWh/m²/day
  ■ Summer testing is enhanced by long days
  ■ Winter months are hampered by cloud cover

► San Diego State University Branch Campus
  ■ Annual Average Solar Resource: 7-8 kWh/m²/day
  ■ High testing productivity year-round
  ■ Support from Southern California Gas Company
Concentrator Setup and Calibration

Setup of Concentrator Test Stand

Cold Water Calorimeter

Moon Tests
TRL 5 Solar Thermochemical Reaction System Assembly
Prep for On-Sun Testing
On-Sun Reactor Tests in 2014
Increase in Solar-to-Chemical Energy Conversion Efficiency Expected in 2015

- Fixed heat loss reduced to ~1 kW<sub>t</sub>
- High solar-to-chemical efficiency – in the mid-70% s – at higher DNIs; expected to be confirmed with testing at Brawley test site in 2015
Plan for SunShot Project, Phase 3
During CY2015

- Advance Solar Thermochemical Reaction System to TRL 6
  - Target solar-to-chemical energy conversion efficiency: 74-75%
- End-to-End Demonstration with Electrical Power Generation
- Continued Evaluation of Manufacturing Methods and Technoeconomics
Highly Efficient Operation: High solar-to-chemical energy efficiencies have been demonstrated in on-sun tests
- ~70% in 2013 and 2014
- Expect mid-70%s in CY 2015
- Values exceeding 80% are feasible

Process Intensive, Micro- and Meso-channel Reactors and Heat Exchangers
- Originally developed in DOE Hydrogen Program
- Now being adapted to utilize concentrated solar energy

Reasonable Costs Expected
- Strong advantage through economies of hardware mass production

Near-Term Applications Anticipated:
- Electrical power generation at ~6 ¢/kWh (LCOE)
- H₂ production at <$2/gge
- The production of other chemicals including synthetic hydrocarbon fuels
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► Project Team
  ■ Pacific Northwest National Laboratory
  ■ Southern California Gas Company
  ■ Diver Solar LLC
  ■ Barr Engineering
  ■ Infinia Technology Corporation
  ■ Oregon State University
Our Team
Integrated Solar Thermochemical Reaction System

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Questions?
Recent Selected References

Thank You

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