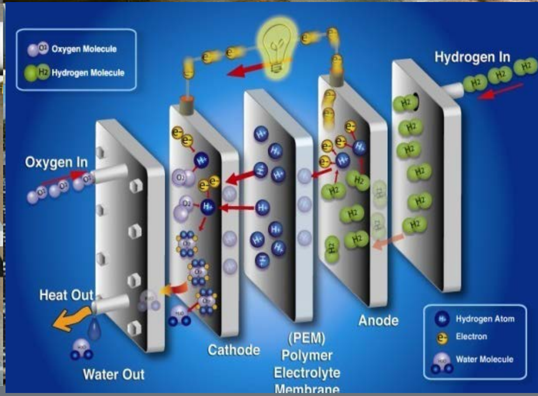
Highly Efficient, Solar Thermochemical Reaction Systems (2014 R&D 100 Award Winner)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

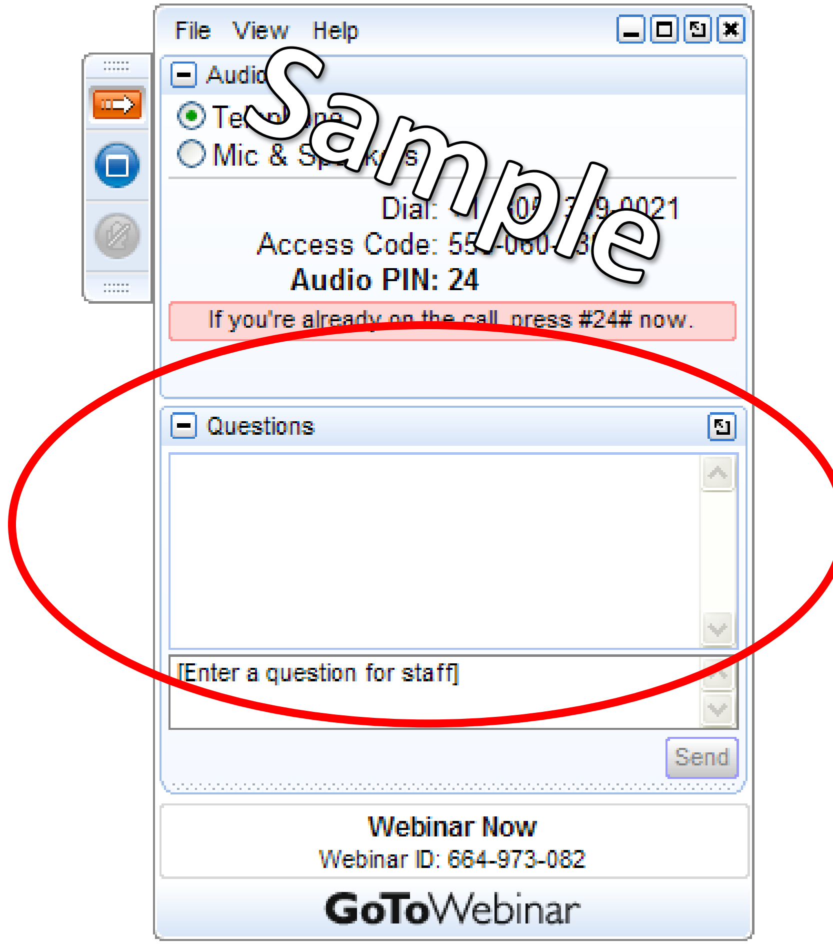




U.S. Department of Energy
Fuel Cell Technologies Office

Question and Answer

- Please type your question into the question box



HIGHLY EFFICIENT, SOLAR THERMOCHEMICAL REACTION SYSTEMS

Robert S Wegeng, PI

FCTO Webinar **January 13, 2015**

Pacific Northwest
NATIONAL LABORATORY

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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

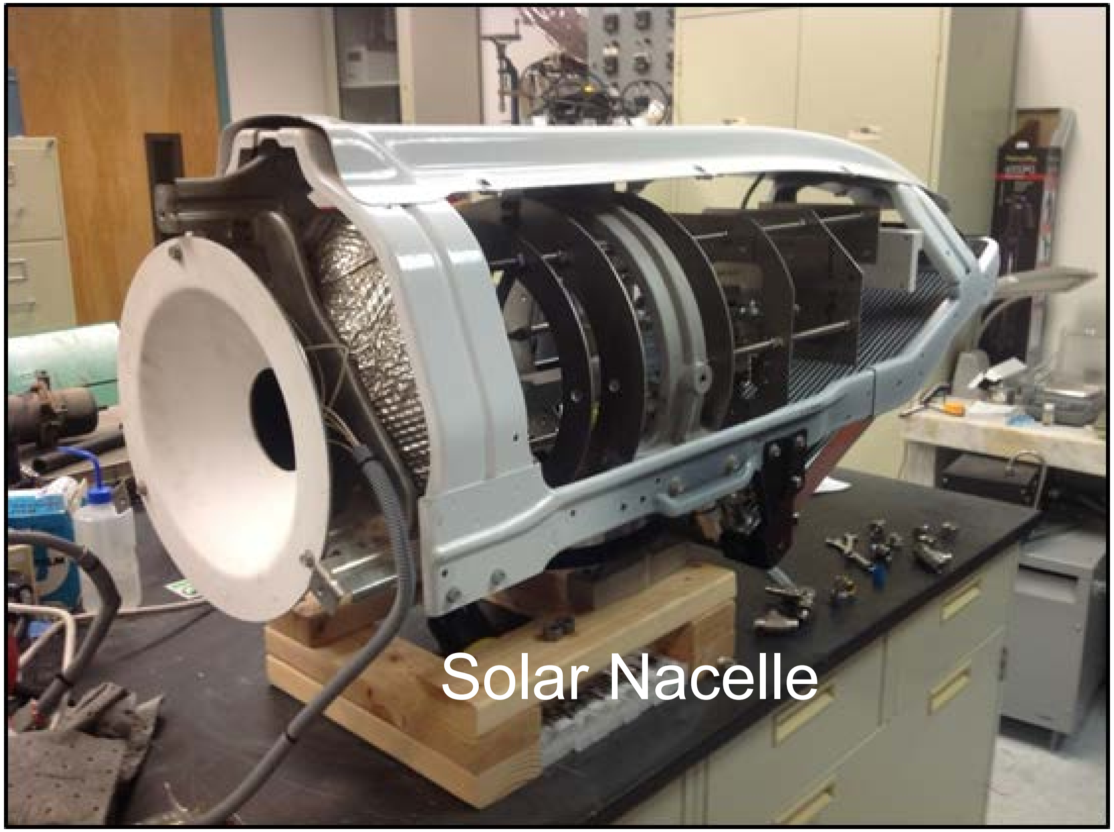
Infinia Technology Corporation

Oregon State University

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

Concentrated Solar Energy

Radiant Energy

Natural Gas

Biomass

Thermochemical Reaction System

Methane Steam Reforming:

$CH_4 + H_2O \rightarrow CO + 3H_2$

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

Electrical power generation at less than 6 ¢/kWh

Electrical Power

Transportation Fuels and Other Chemicals

Hydrogen production at less than $2/gge

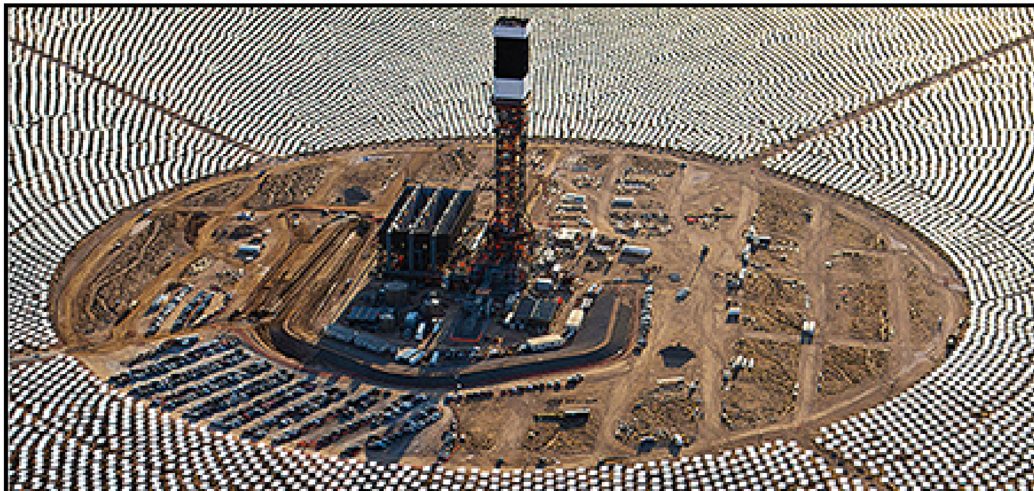
Outline

- 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

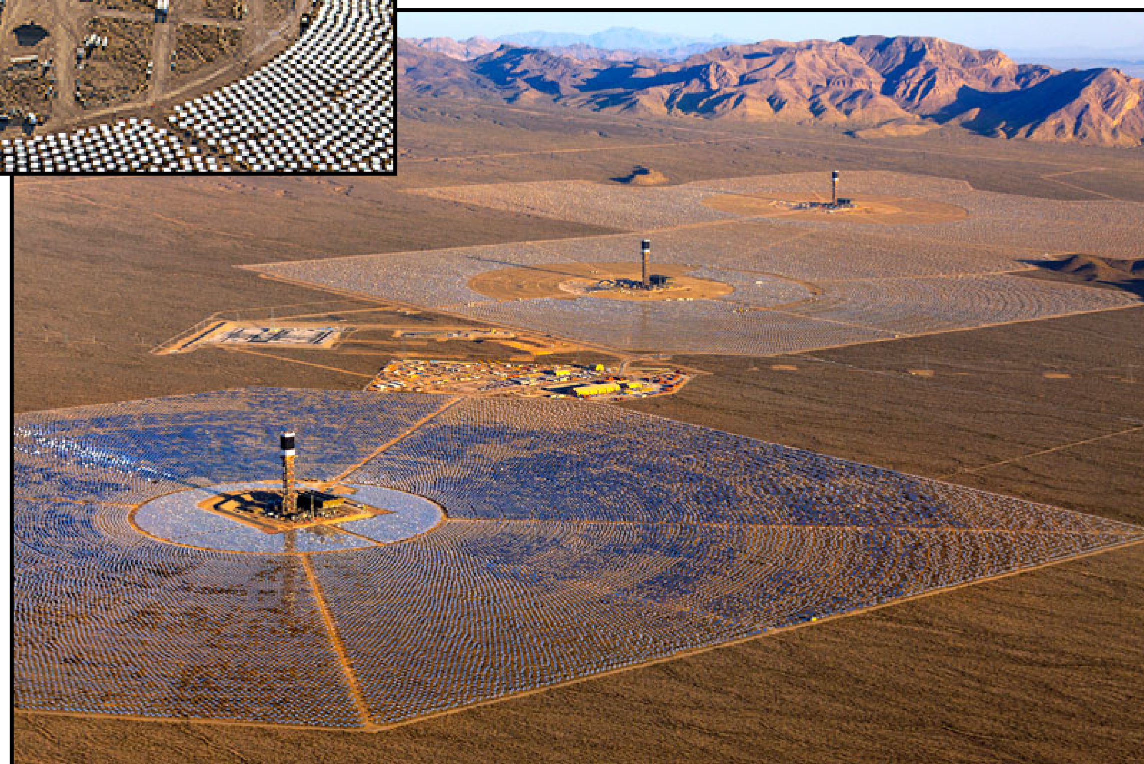
- Recent Selected References

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

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

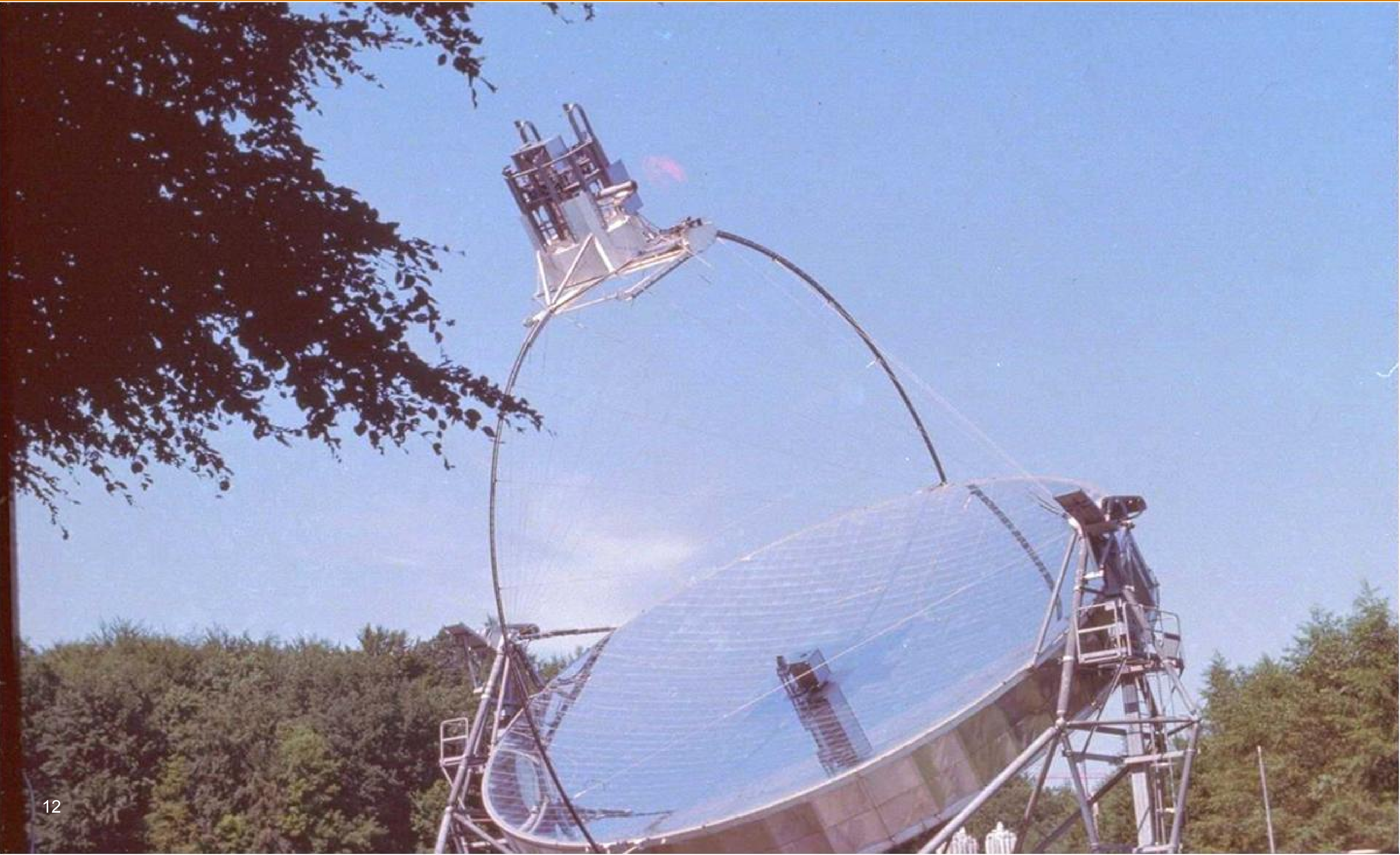
- Solar steam reforming of methane; 170 kW_s

DOE Hydrogen Program

- Several solar thermochemical *water-splitting* investigations
  - Requires significantly higher temperatures, advanced materials, innovative thermal recuperation methods

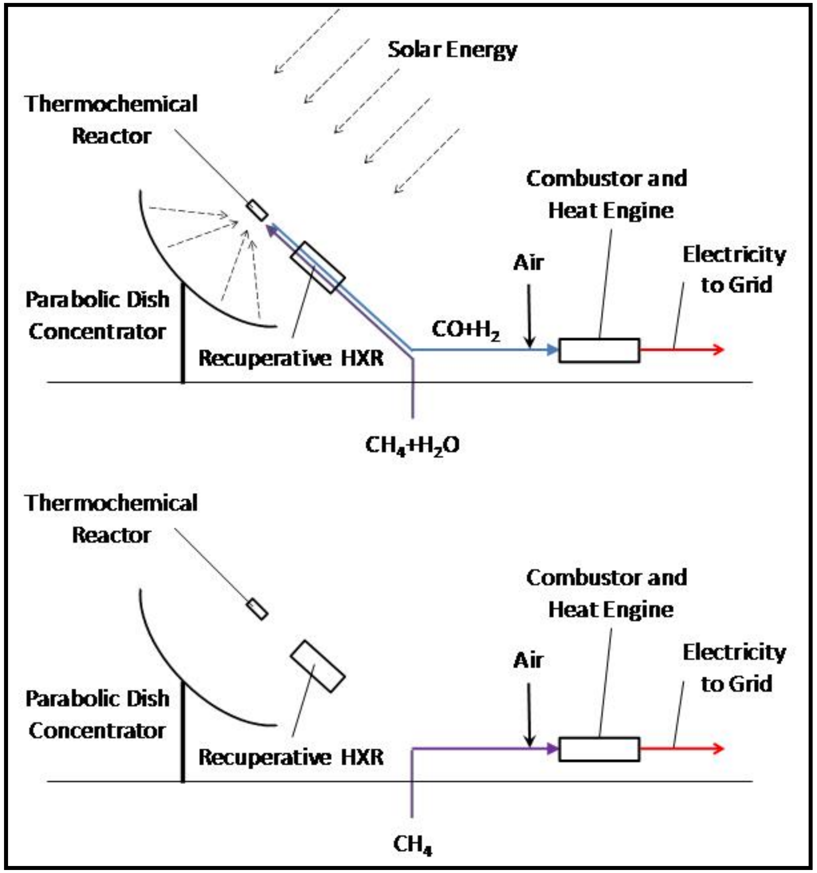
Solar CO_2-Methane Reforming Demonstration (~1990-1993)

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 CO_2 emissions
- Competitive Levelized Cost of Electricity (LCOE); accelerated approach to grid parity for Concentrating Solar Power (CSP)



Net Solar Thermochemical Reaction

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

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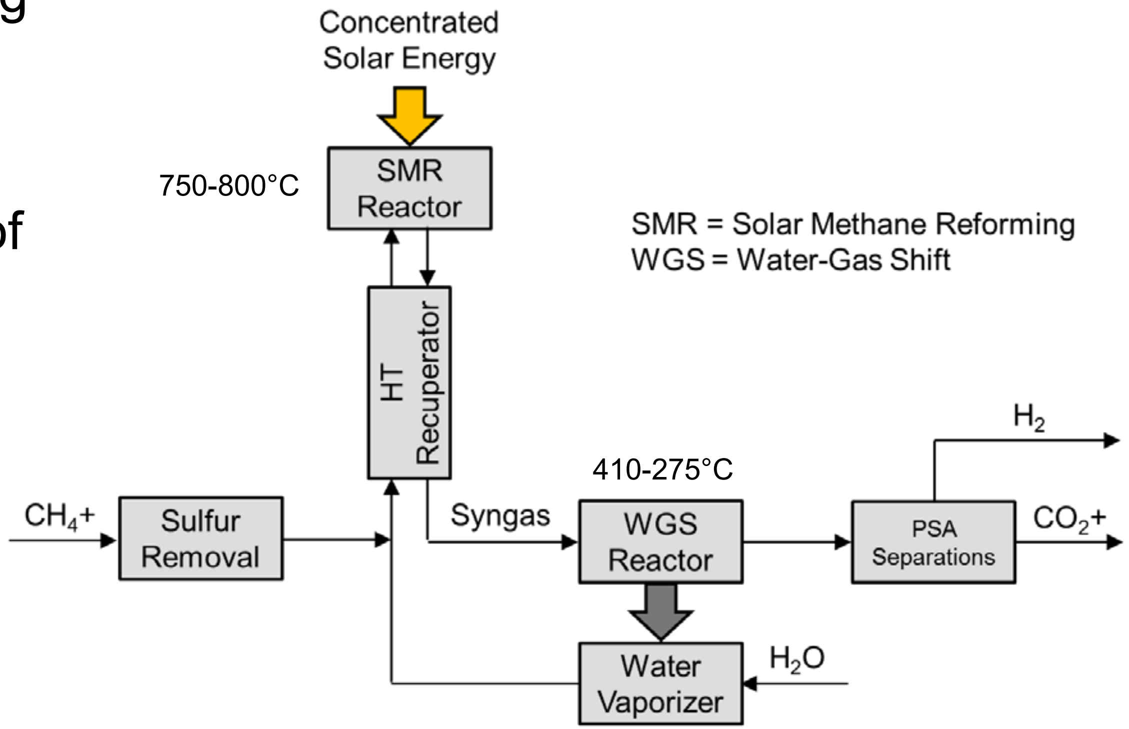
Applications of Solar Methane Reforming
H_2 Production

- Requires components in addition to solar reforming system, already in development or proven
- Projected H_2 production cost: < $2/gge (gallons of gasoline equivalent) based on H2A and standard assumptions
- Projected carbon emissions as low as 5.5 kg CO_2/kg H_2; or approximately ½ of conventional H_2 production via methane reforming
- Potential commercial practice by 2020



Net Reaction:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

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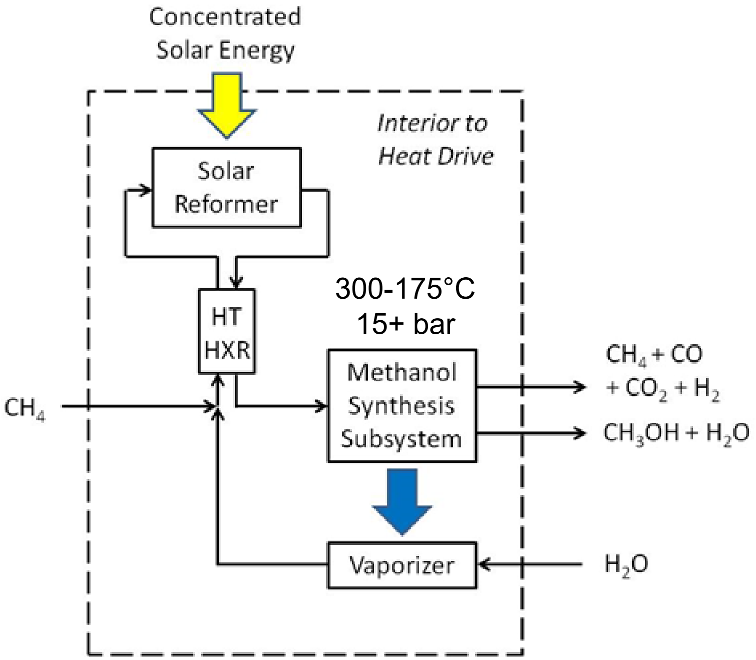
Applications of Solar Methane Reforming

Production of Solar Methanol for Renewable (Thermochemical) Energy Storage



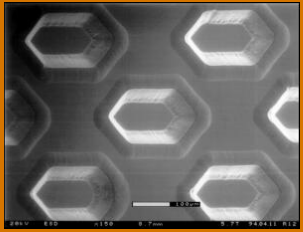
Net Reaction:

$$CH_4 + H_2O \rightarrow CH_3OH + H_2$$

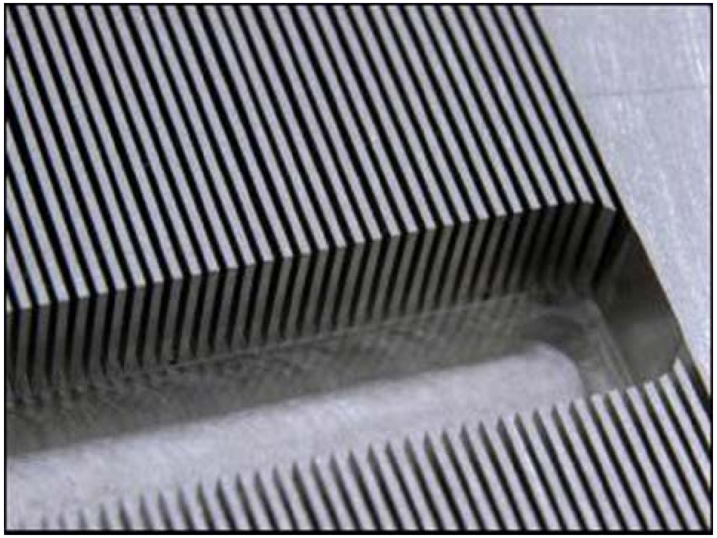
- Methanol is a commodity chemical, sold worldwide (100 million metric tons)
- CO_2 in the product stream can in principle be recycled, yielding high overall selectivity to CH_3OH
- Process enables inexpensive thermochemical energy storage for concentrated solar and other renewable energy
- Using solar energy to run endothermic operations avoids carbon emissions associated with methanol production (typically 25-40% of incoming carbon is emitted as CO_2)
- 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)

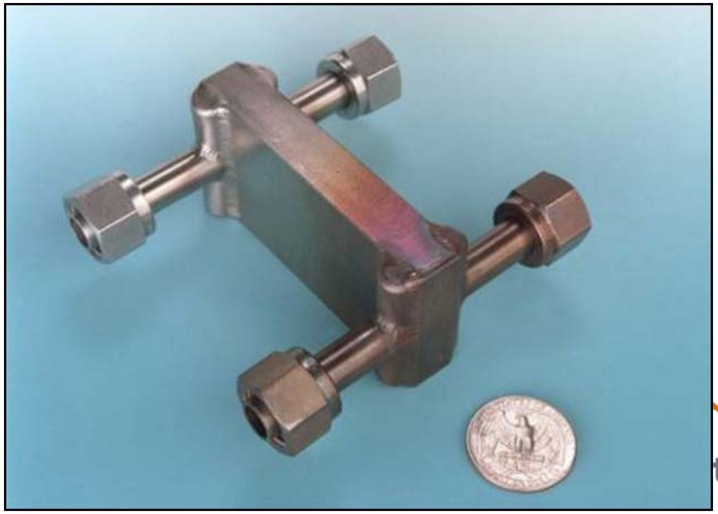
Core Technology/Competitive Advantage

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)

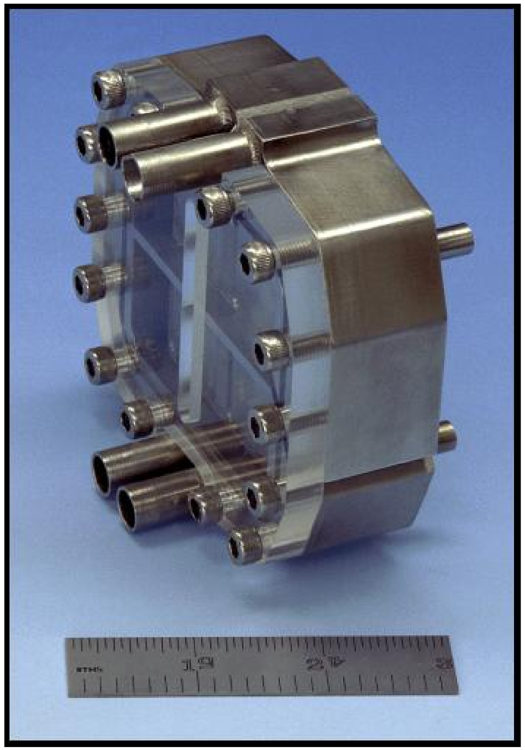




Core Technology/Competitive Advantage

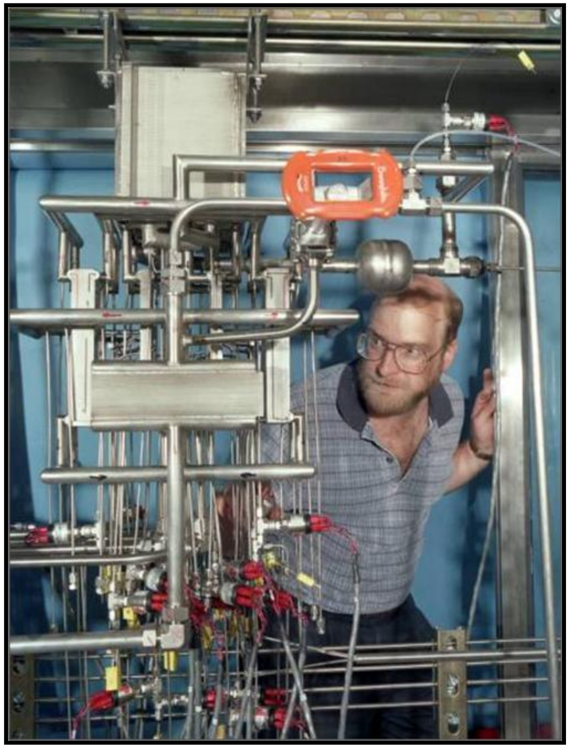
Several prototype reactors and heat exchangers for H_2 production were developed during FY1997-2003 with Hydrogen Program Funding

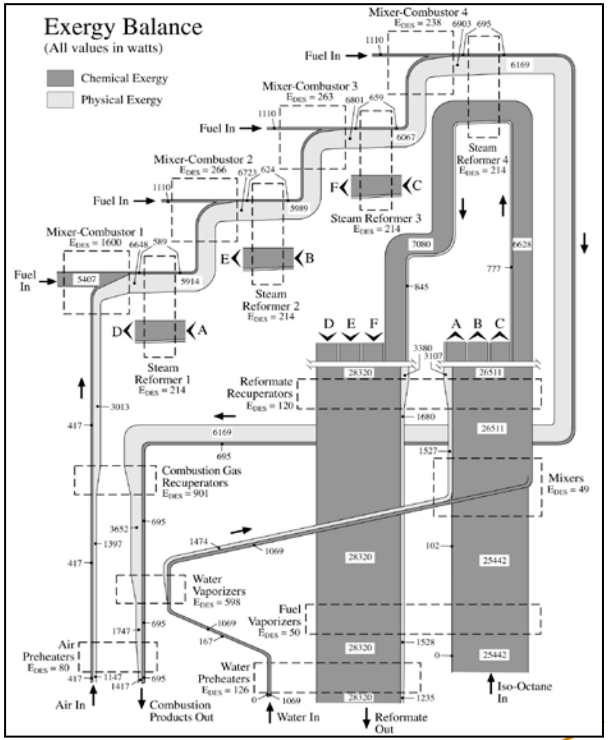
Modular, process-intensive reactors and heat exchangers yield highly efficient systems



1999 Recipient of R&D 100 Award

Exergetic Efficiency: $\varepsilon = \frac{Exergy\ Out}{Exergy\ In} = 0.85$





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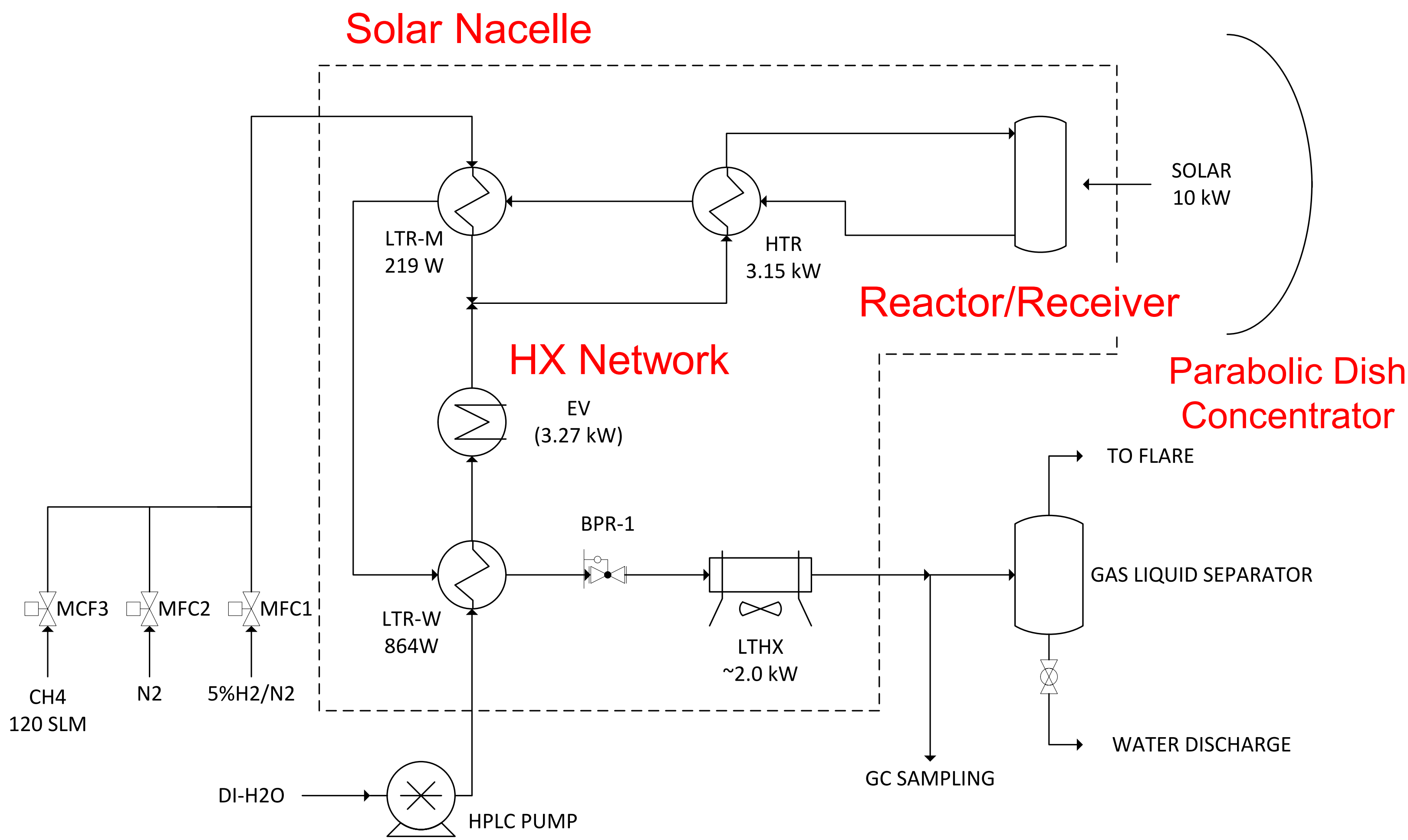
Reactor Test System Process Flow Diagram



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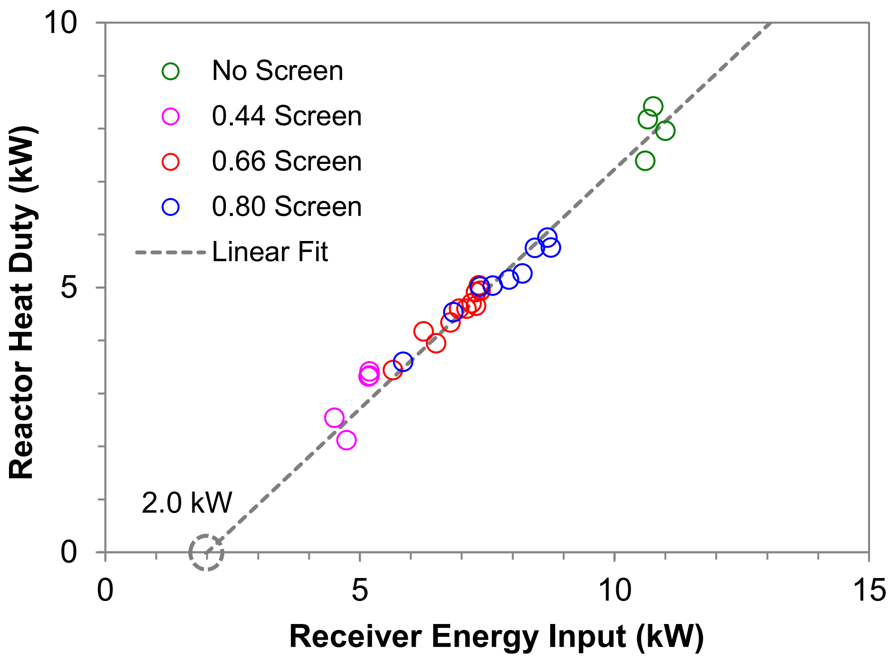
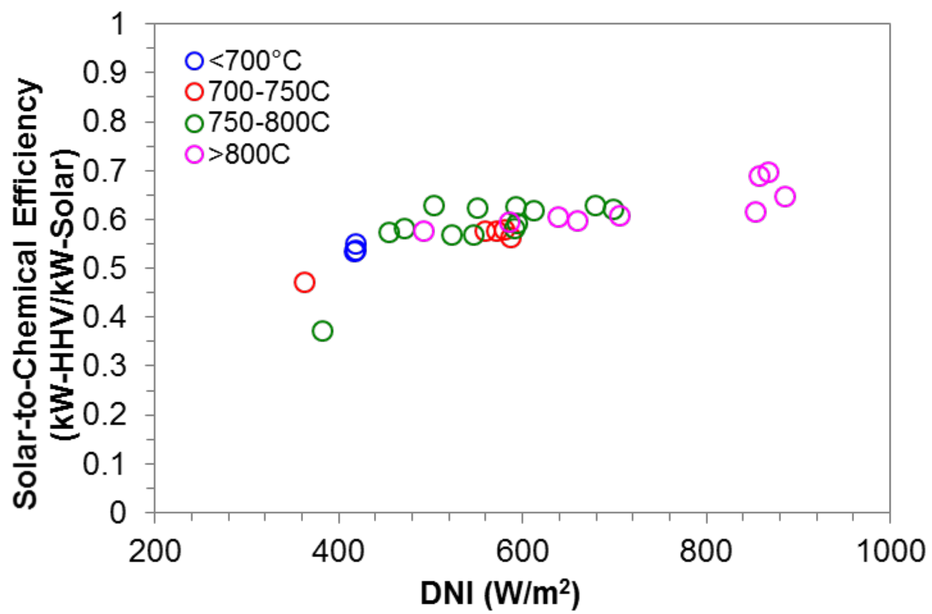
On-Sun Reactor Tests in 2013

World Record Solar-to-Chemical Energy Conversion Efficiency: 69.6%





- Energy absorption with different solar screens implies 2 kW_t fixed heat loss
- High solar-to-chemical efficiency over a wide range of operating temperatures and DNI; believed to be a world record

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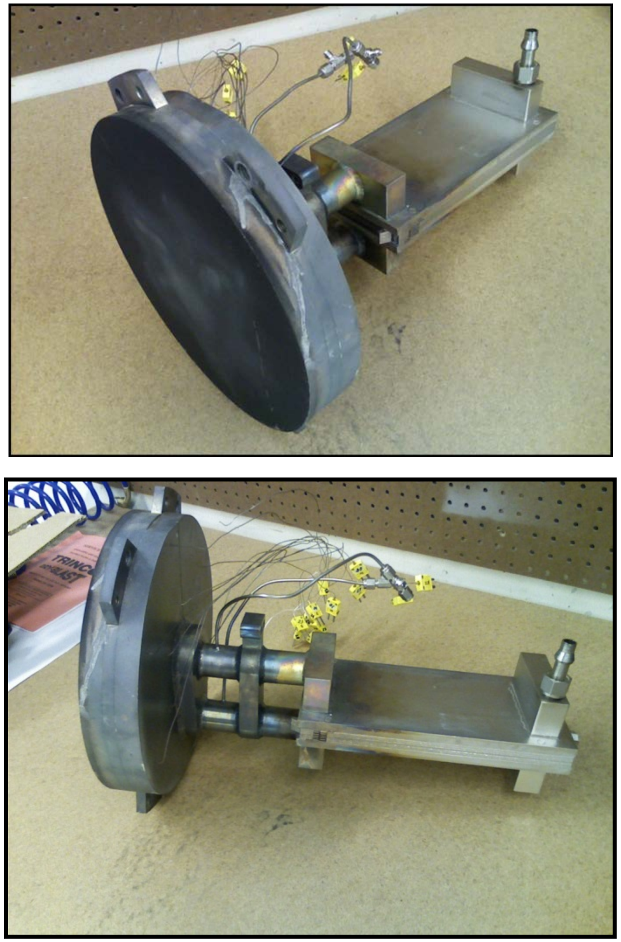
SunShot Project Description
Thermochemical System Evolution



TRL 3 Reactor / HXR
63%

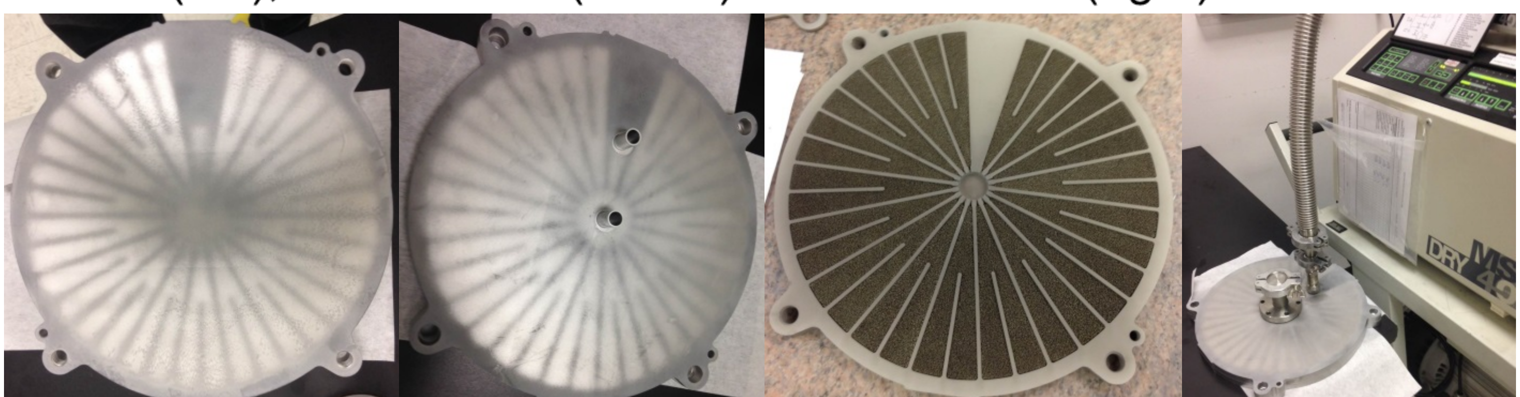
TRL 4 Reactor / HXR
69%

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

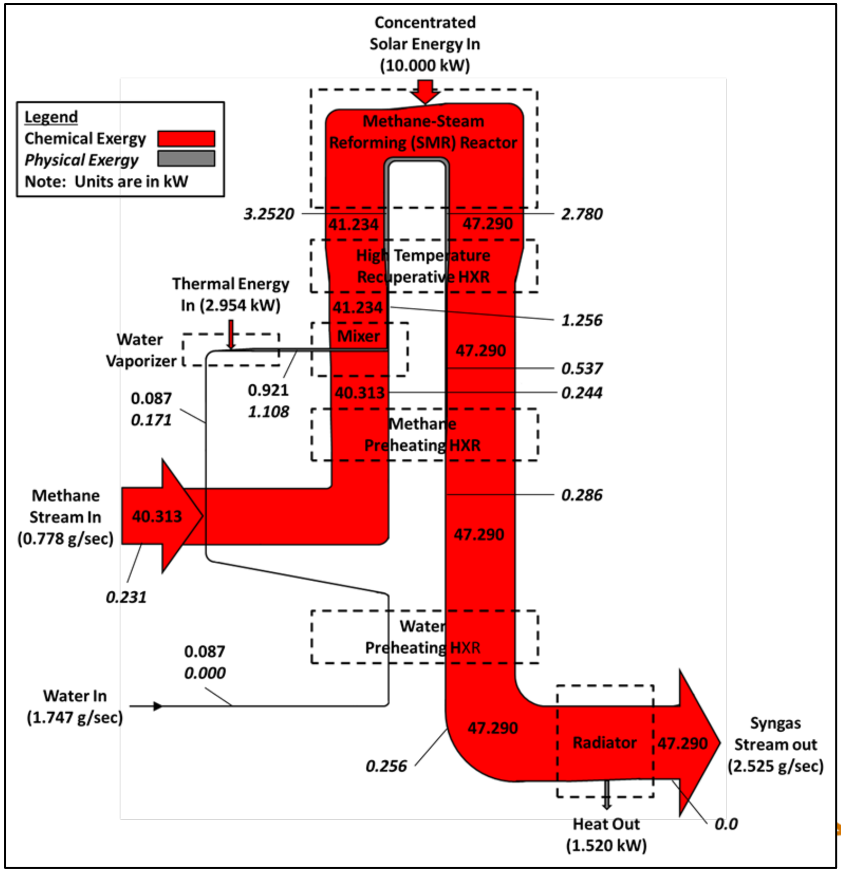


Nickel-coated front plate with catalyst inserts (right-of-center).
Front plate after bonding (two left images). Hermetic testing (right).

TRL 5 Solar Thermochemical Reaction System Assembly

Heat Exchanger Network

Exergy Conversion and Destruction Calculations from Phase 1 (TRL 4 System)



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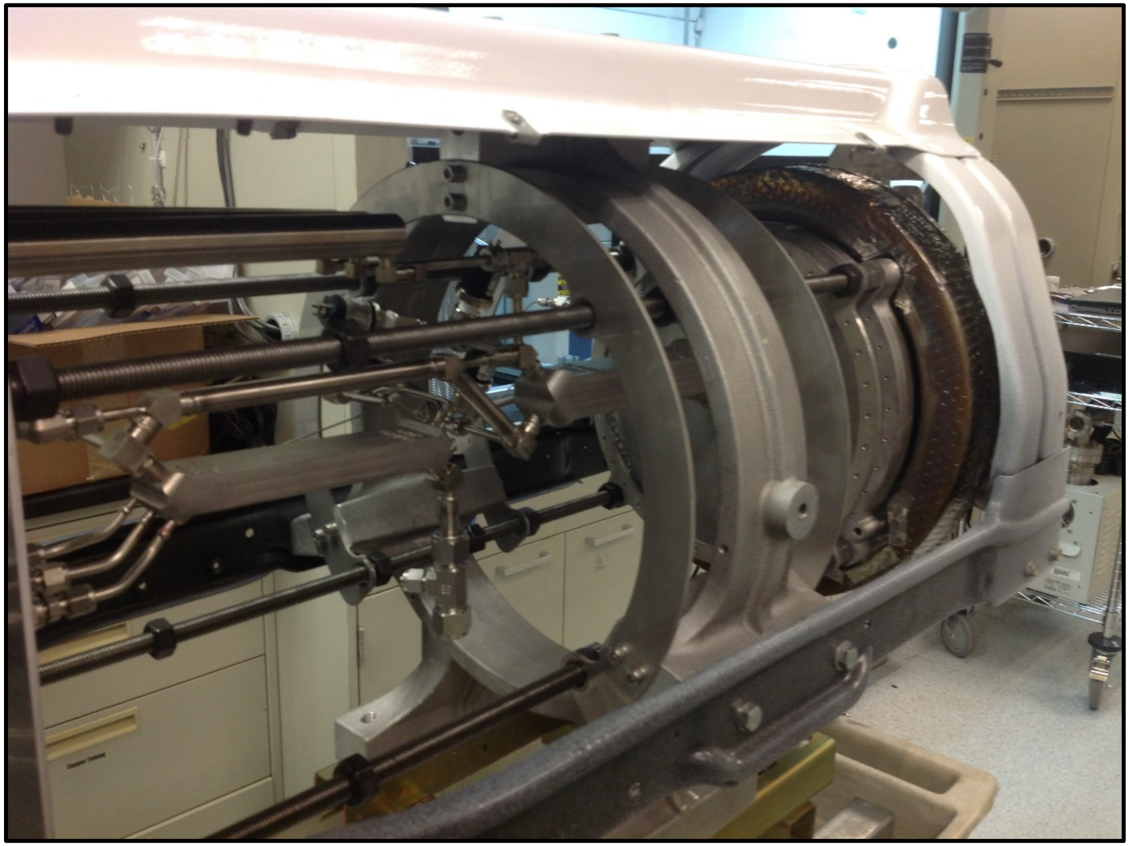
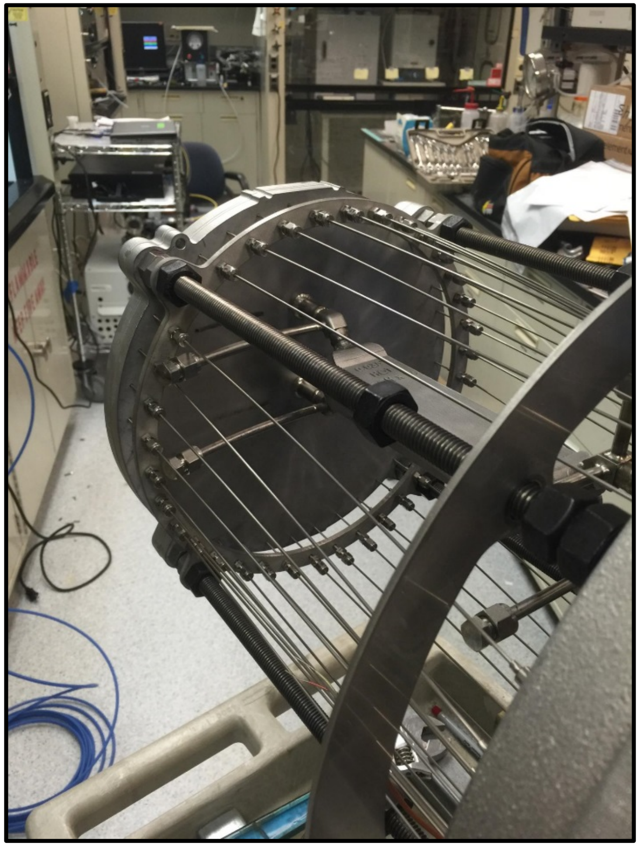
TRL 5 Solar Thermochemical Reaction System Assembly
Within Nacelle





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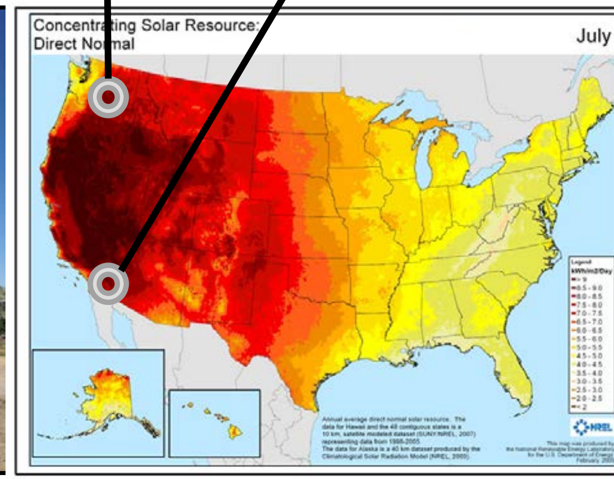
Test Sites
Richland, Washington (PNNL)
Brawley, California (San Diego State University)

- Pacific Northwest National Laboratory
  - Convenient access to national laboratory
  - Annual Average Solar Resource: ~5 kWh/m^2/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/m^2/day
  - High testing productivity year-round
  - Support from Southern California Gas Company

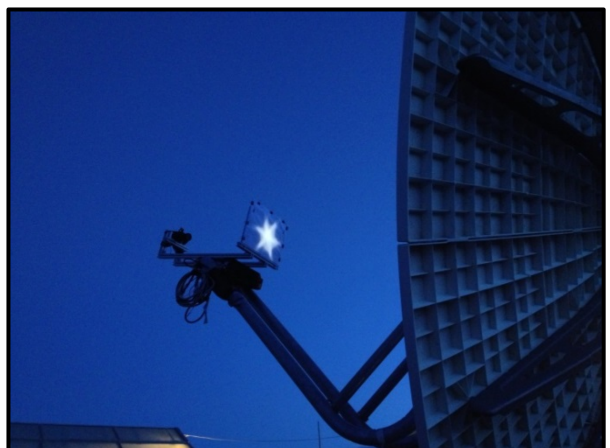
Richland Brawley



Concentrator Setup and Calibration

Setup of Concentrator Test Stand

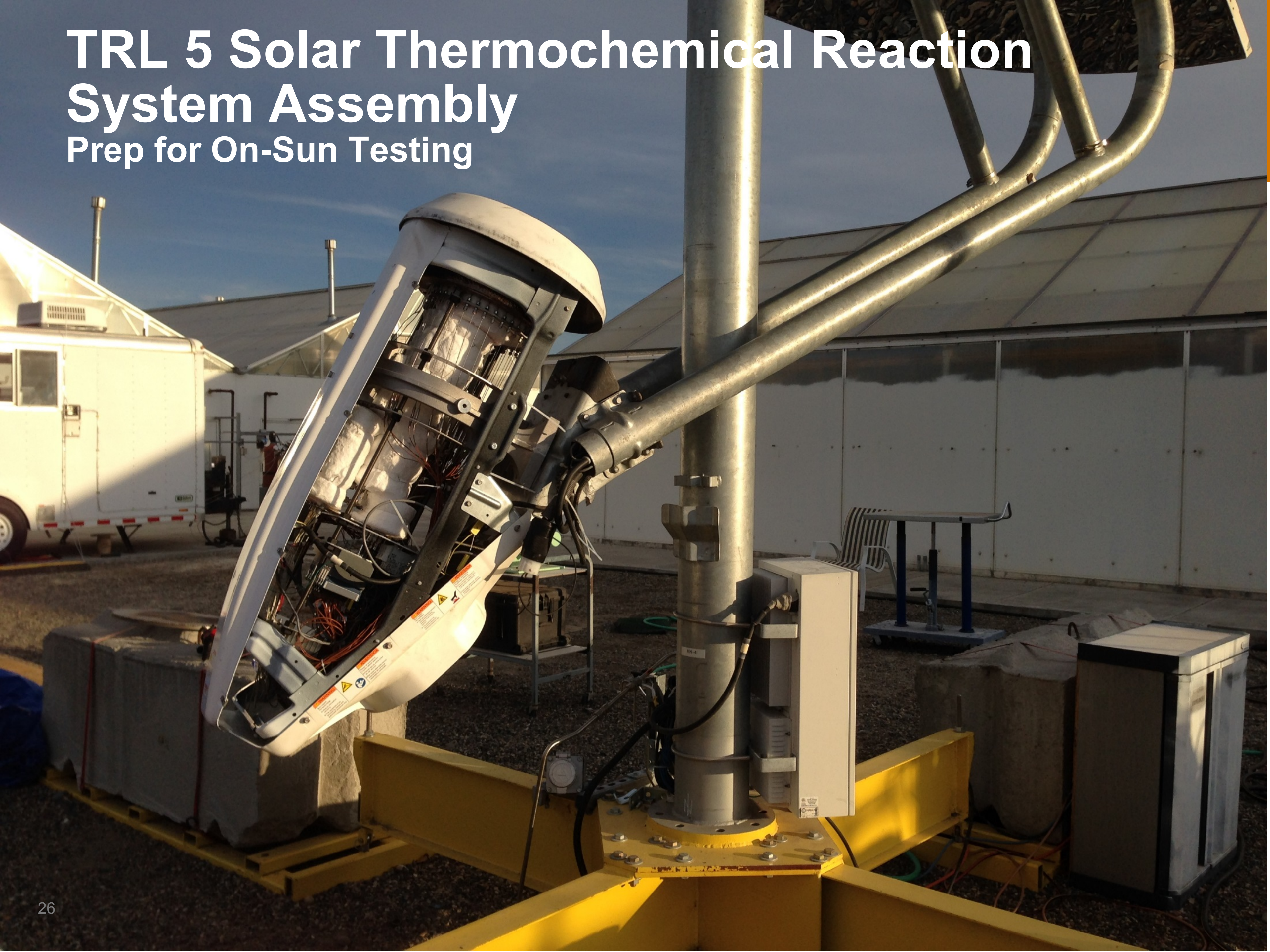
Cold Water Calorimeter



Moon Tests

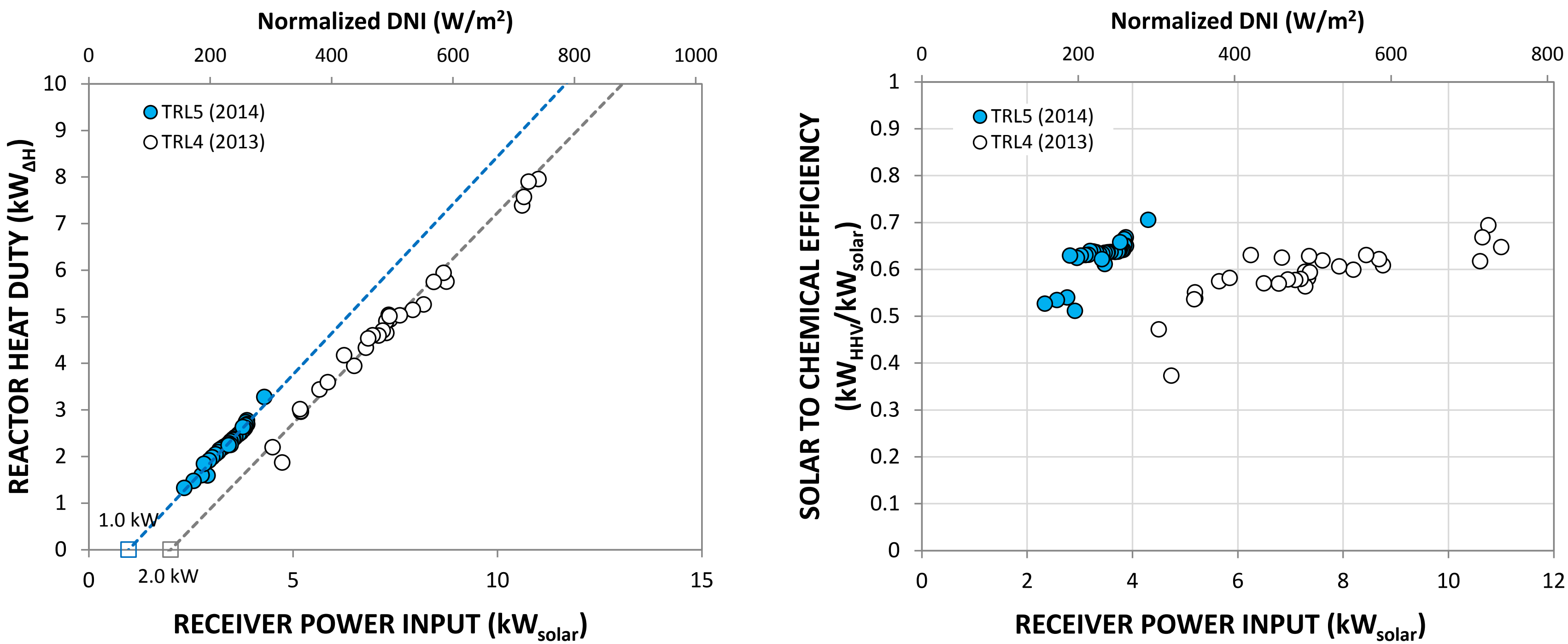
TRL 5 Solar Thermochemical Reaction System Assembly

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_t
- 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

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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

Conclusions

- 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)
  - H_2 production at <$2/gge
  - The production of other chemicals including synthetic hydrocarbon fuels

Acknowledgments

- US Department of Energy Solar Energy Technologies Program
  - Program Managers and Staff
- US Department of Energy Fuel Cell Technology Office
  - Initial funding of microchannel reactors and heat exchangers (circa 1996-2003)
- 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

Robert Wegeng (PI, Project Manager)

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Dan Palo (Barr Engineering), Ward TeGrotenuis, Richard Zheng

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SunShot U.S. Department of Energy

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Questions?

Recent Selected References

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Thank You

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