SunShot
U.S. Department of Energy

CSP Program Summit 2016

Thermochemical Storage with Anhydrous Ammonia

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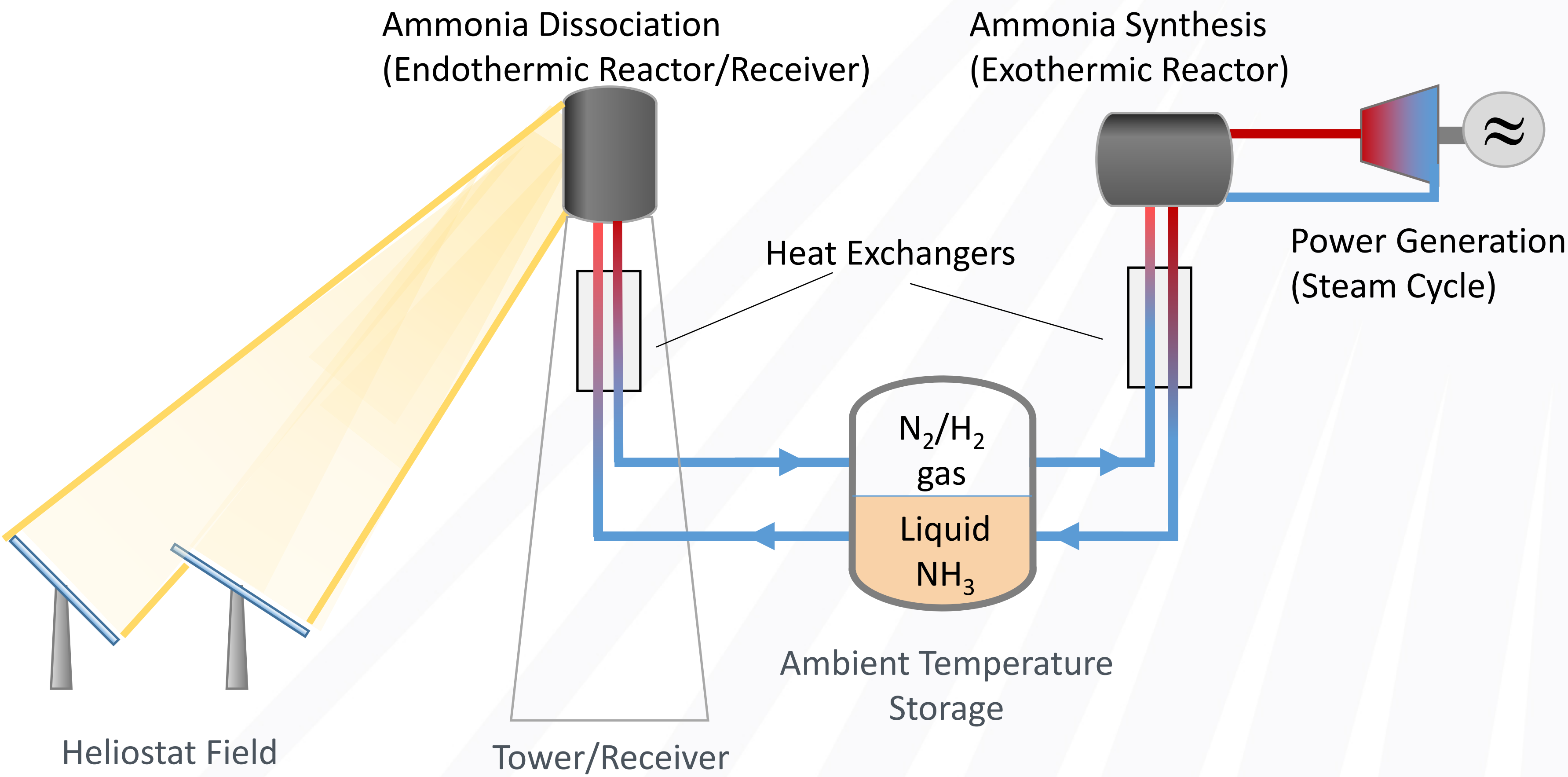
Value Proposition and Problem Statement

- Ammonia-based thermochemical energy storage is a well-developed technology that has the potential to meet the CSP:ELEMENTS performance and cost goals.
  - Target performance: Heat steam to 650°C for supercritical steam power block.
  - Plant context: 220 MW_t plant with 6 hours of storage.
  - Target cost: \$15/kWh_t.
- At start of project, two key challenges identified:
  - Ammonia synthesis had never been used to heat steam to 650°C. Is it possible?
  - Can physical storage of high pressure nitrogen/hydrogen mixture be done cost-effectively?

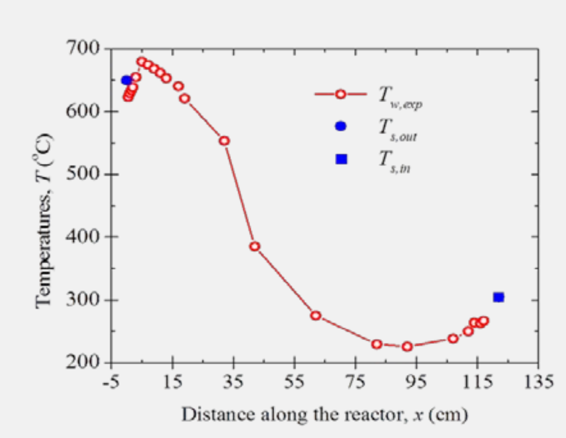
System Overview

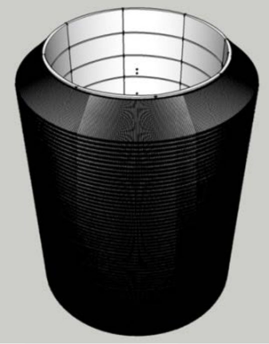


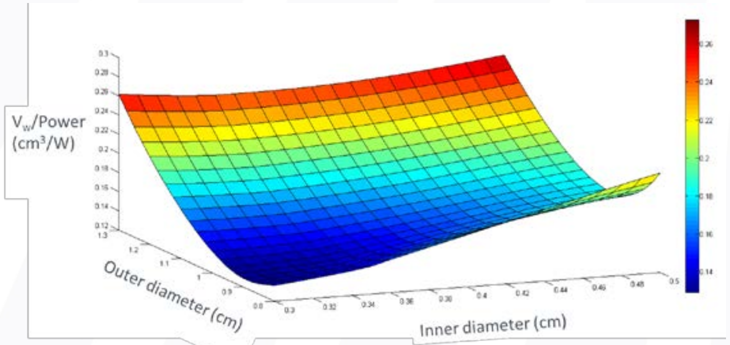
$$NH_3 + 66.6\ \text{kJ/mol} \rightleftharpoons \tfrac{1}{2}\,N_2 + \tfrac{3}{2}\,H_2$$

Objectives

- **Phase 1 Main Objectives:**
  - Demonstrate heating supercritical steam to 650°C.
  - Perform techno-economic evaluation to show cost-effective gas storage.
  - Perform initial design of endothermic reactor/receiver to demonstrate feasibility. (Won't be discussed in this talk.)
- **Phase 2 Main Objective:** Predict performance and cost of utility-scale synthesis system for ammonia-based thermochemical energy storage.







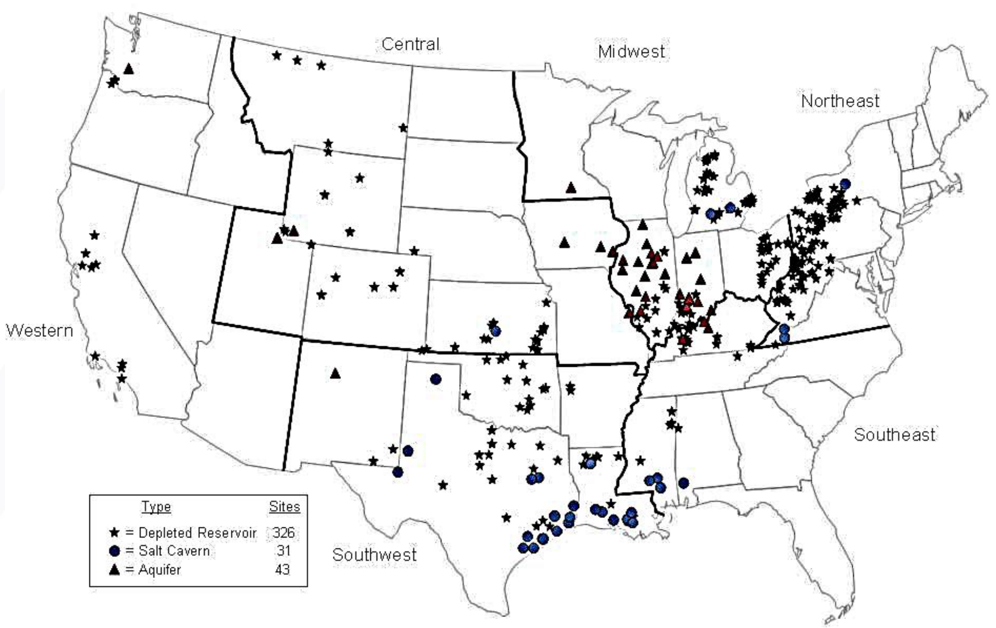
Selected Milestones and Results

- Gas storage
- Steam heating
  - Experimental
  - Modeling
- Optimizing the synthesis reactor system for low cost

Gas Storage

Gas Storage Milestone

- Need to store ambient temperature, high pressure N_2+3H_2.
- 220 MW_t plant, 6 hrs storage, needs ~24,000 m^3 at 20 MPa.
  - Comparable to two-tank molten salt.
- Underground storage concept:
  - Surrounding geology provides bulk of pressure containment.
  - Underground gas storage already widely used.
- Approaches considered:
  - depleted oil or gas wells
  - aquifers
  - salt caverns
  - rock caverns
  - tunnel drilling
  - shaft drilling



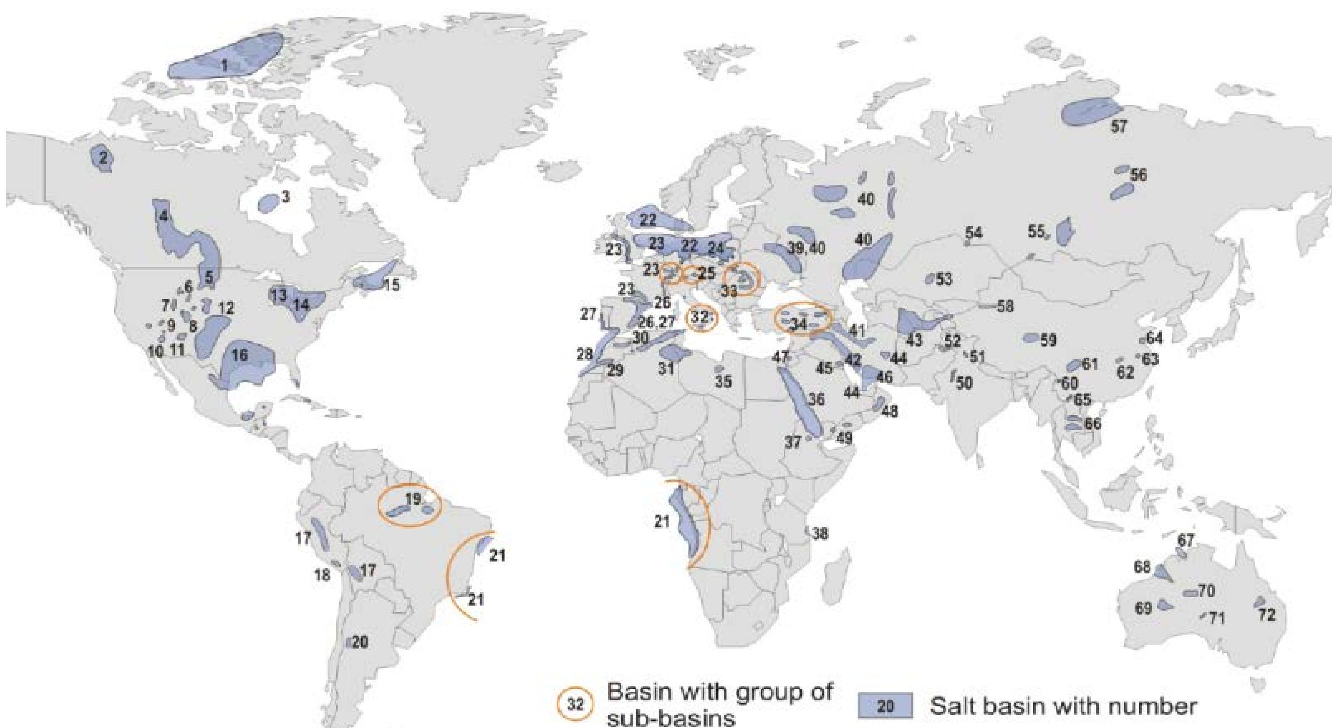
Salt Caverns

- Solution mining of salt caverns is simple, established process:
  - Fresh water pumped into salt dome or bed. Brine extracted.
- Salt caverns widely used for storage:
  - Over 2000 salt caverns in North America alone for hydrocarbon storage.
  - Pure hydrogen or hydrogen-rich gas mixtures have been stored.
- Salt cavern conditions are suitable for our application:
  - Volumes up to 500,000 m^3
  - Pressures up to ~50 MPa
  - Rock salt chemically inert to hydrogen
  - Permeability low enough to contain hydrogen gas

- Roughly $1/kWh$_t$ to create storage space (for large projects).

Salt Caverns, cont.

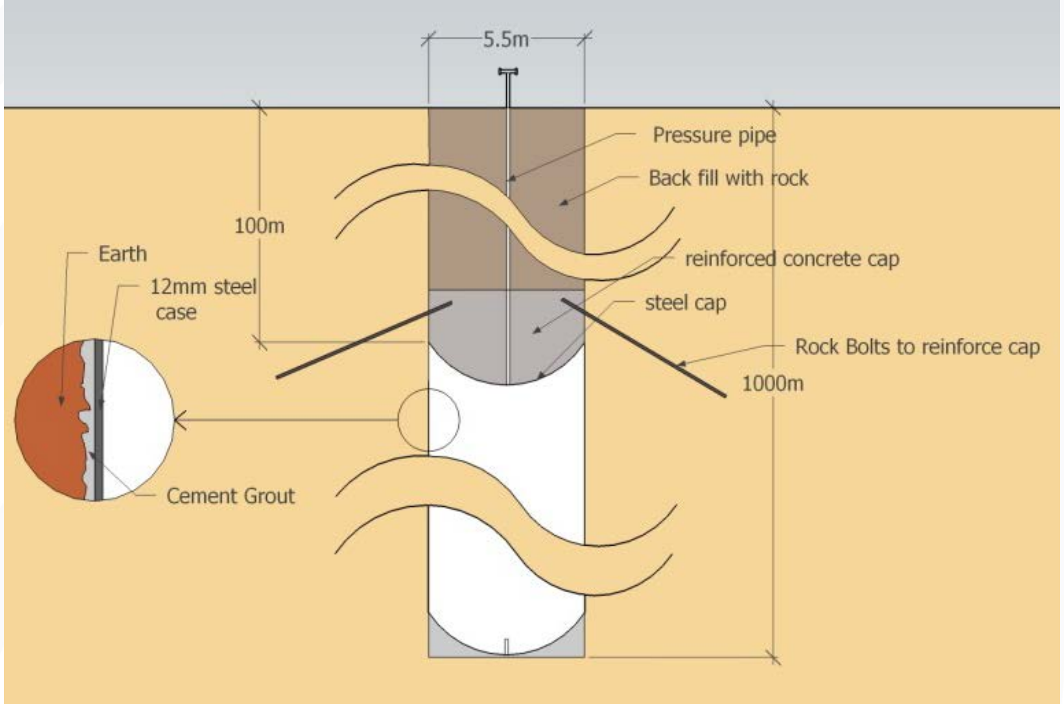
- Suitable salt deposits are present on every continent, good coincidence with high DNI areas.
- Despite this, siting CSP plants for suitable salt deposits is a significant constraint.



(modified and enlarged from compilation of KBB 2002)

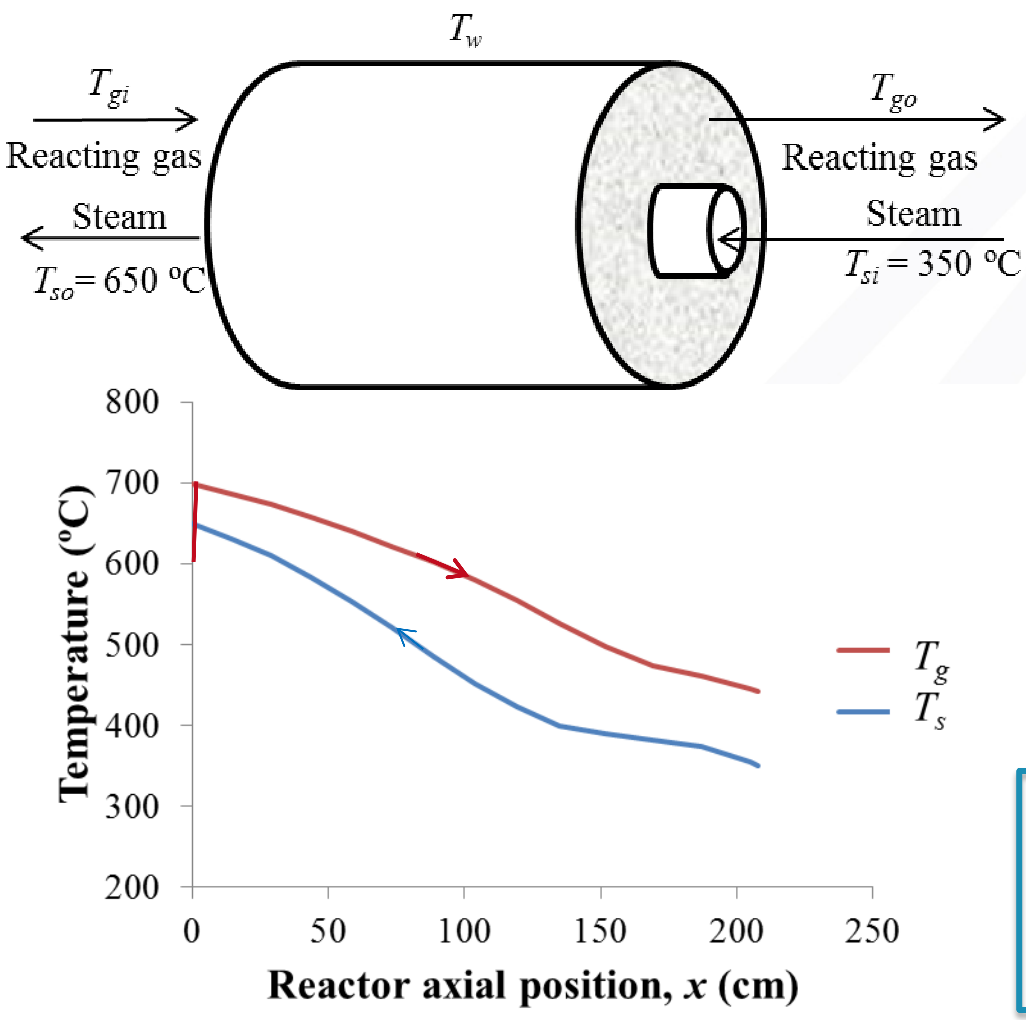
Large Diameter Drilled Shafts

- Removes site choice constraint.
- Shaft drilling routinely carried out at up to 7.5 m diameter and depths of 1000 m.
- In consultation with drilling company:
  - Cost roughly \$5/kWh_t.
- Conceptual design developed.
- Details of hydrogen impermeable lining and endcaps required.



Steam Heating

Steam Heating Milestone, Modeling

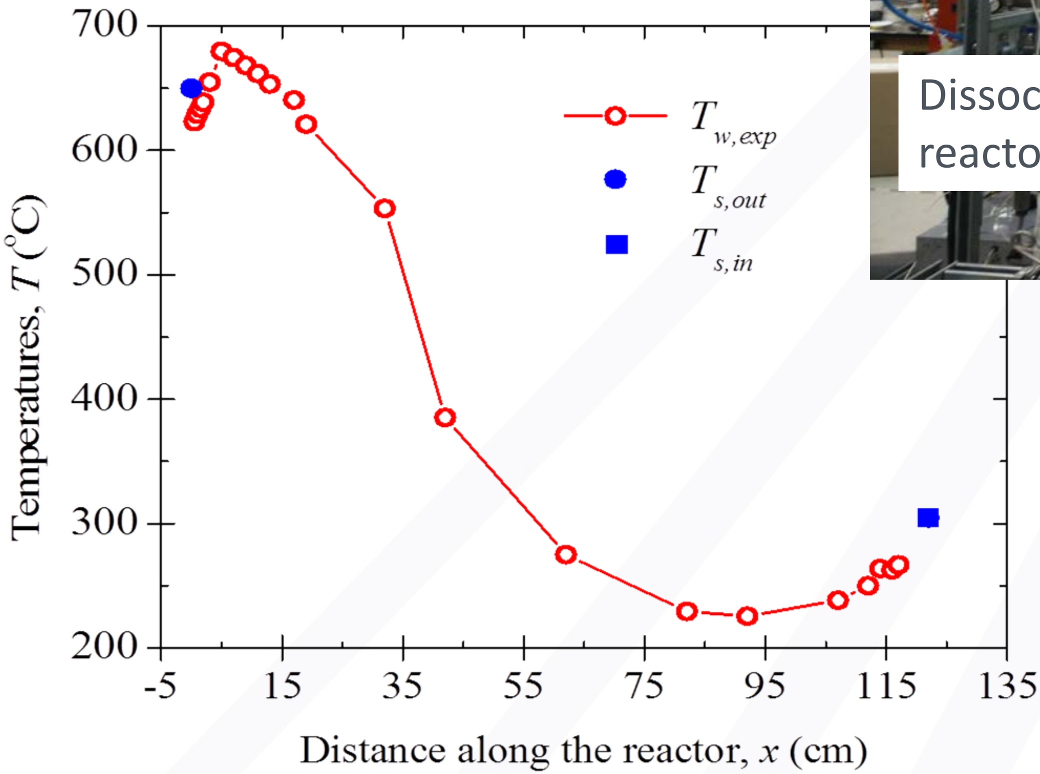


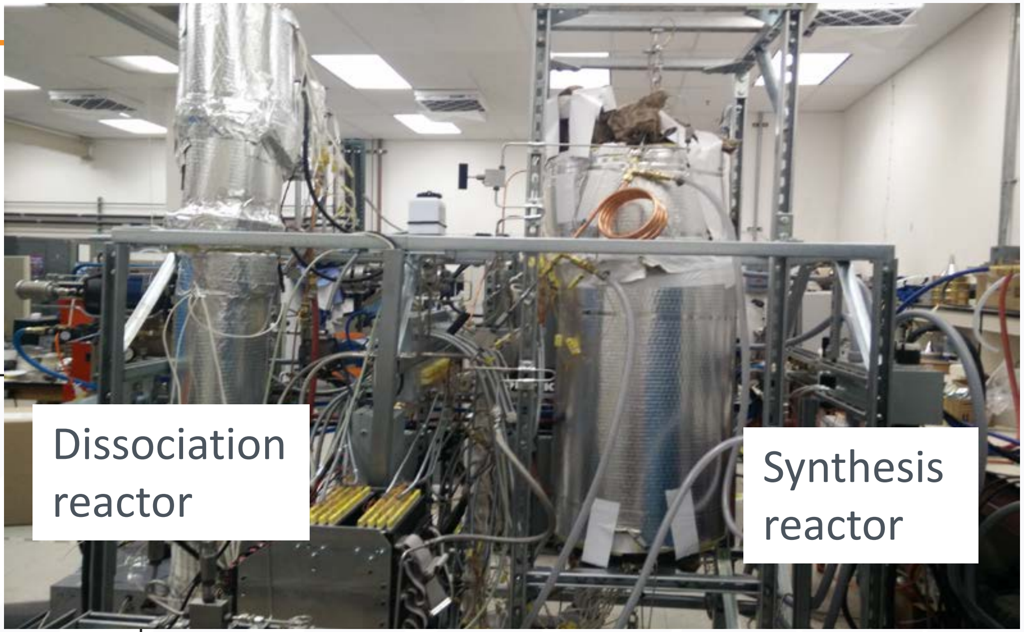
$\dot{m}_g$ = 0.3 g/s
$\dot{m}_s$ = 0.33 g/s
D_o = 2 cm
D_i = 0.5 cm

P_g = 30 MPa
P_s = 26 MPa

- Model shows supercritical steam can be heated from 350 to 650°C.

Steam Heating Milestone, Experimental





- Experiments show steam heated from 305°C to 650°C at ~100 W scale.
- Work ongoing toward heating steam at 5 kW_t scale.

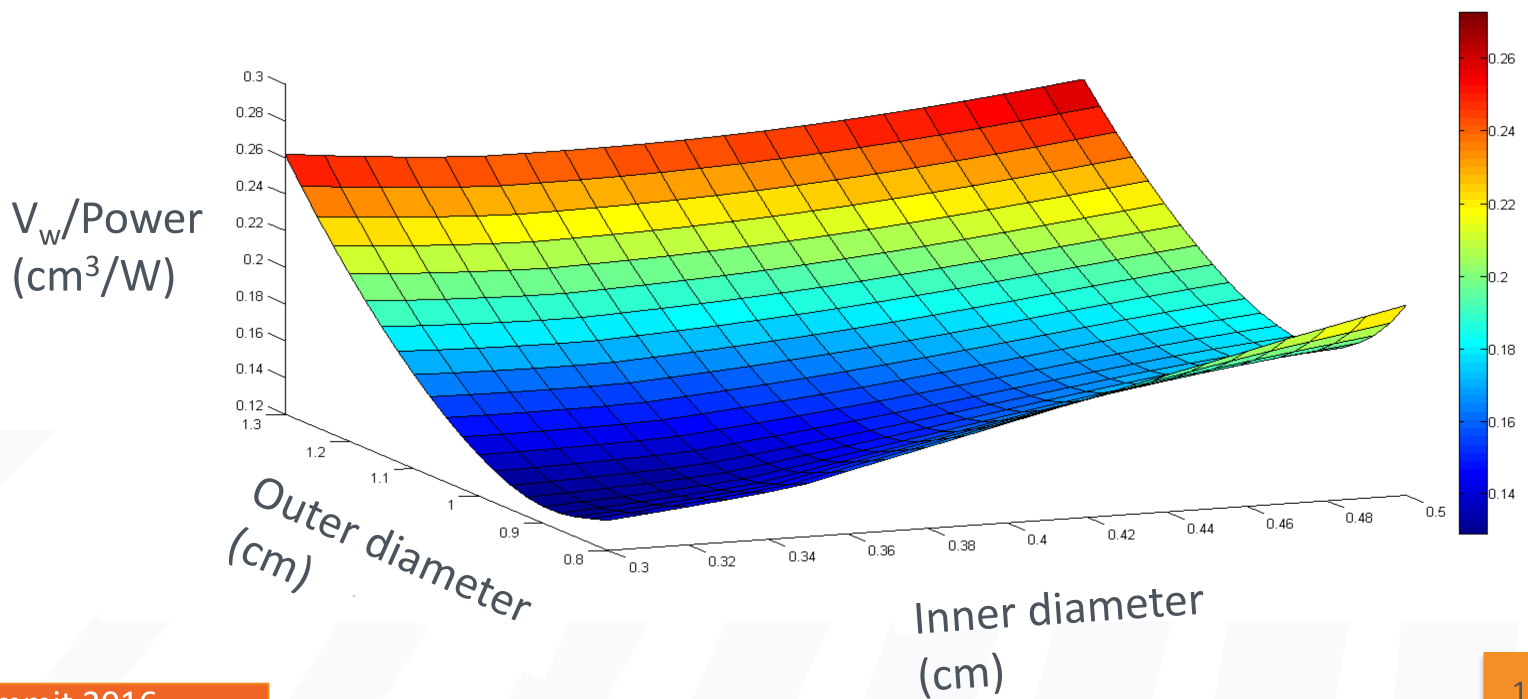
Cost Optimization

Optimized Cost Milestone

- Consider entire synthesis system:
  - Synthesis reactor
  - Recuperating heat exchanger
  - Additional preconditioning subsystems
- Modular system with different reactor designs for different temperature regions.
- Multi-parameter optimization problem with tens of parameters.
- Largest cost is wall material, including high nickel alloy in high temperature regions.
- Minimize wall material volume per unit power.

Optimizing Inner and Outer Diameters

- Optimization is driving to smaller scale.
- Not a surprising result.
- How low can we go?
  - Pressure drop will increase – and pumping power.
  - Manufacturing costs must be considered.



Path-to-Market

Path to Market

1. **Identification of partners – current to next 12 months**
   - Continuation of experiments, modeling, and design to support solar-driven closed-loop experiment.
2. **Solar-driven closed-loop experiment – 2016-2019**
   - On sun, using existing tower-based test facility or single dish.
   - Steam production but no power generation.
   - Budget around $4 million.
3. **Pilot 1 MW_e system – 2018-2021, followed by continuous operation**
   - Gas storage fabricated above ground using pressure pipe.
   - Heat recovery synthesis reactor designed for 650°C supercritical steam, but throttled to lower pressure for small off-the-shelf subcritical steam turbine.
   - Generate revenue sufficient to cover operating costs, operate for extended years as needed.
   - Budget around $15 million.

Path to Market

4. **First utility scale demonstration, 10 MW_e – 2019-2024, followed by continuous operation**
    - First trial of underground storage using shaft drilling technology.
    - Still using small off-the-shelf subcritical steam turbine.
    - Significant financial assistance package required to build the first system, but operation and balance of financial package on fully commercial basis.
    - Budget around $100 million.
5. **First full-sized system, 100 MW_e, 10+ hrs storage – 2022-2027, followed by continuous operation**
    - Underground storage either salt cavern or shaft drilled.
    - Synthesis reactor produces supercritical steam at 650°C, potentially for a supercritical steam turbine.
    - Preferential finance terms probably required, otherwise a fully commercial system.
    - Budget around $700 million.

Conclusions

- Gas storage in salt caverns or drilled shafts appears feasible within the \$15/kWh$_t$ budget.
- Ammonia synthesis can be used to heat supercritical steam to 650°C, according to experiments and modeling.
- Cost minimization of the synthesis reactor system is underway:
  - Small diameter tubes are desirable.
  - Multi-parameter optimization of modular design has potential to significantly decrease cost.
- A proposed path-to-market could achieve a full-scale system by 2027.

Acknowledgments

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QUESTIONS?