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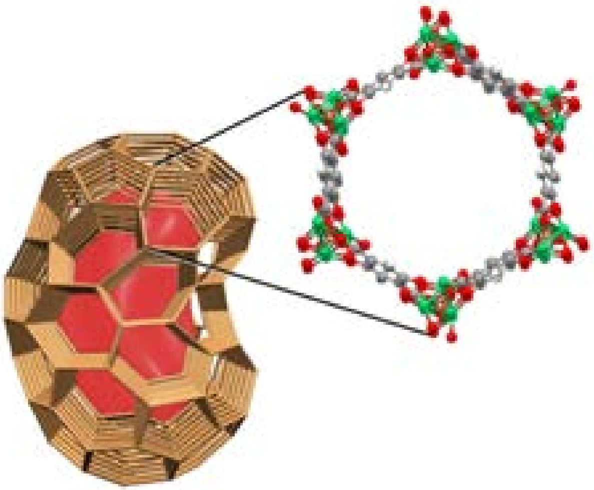


Harmonic Adsorption Recuperative Power System

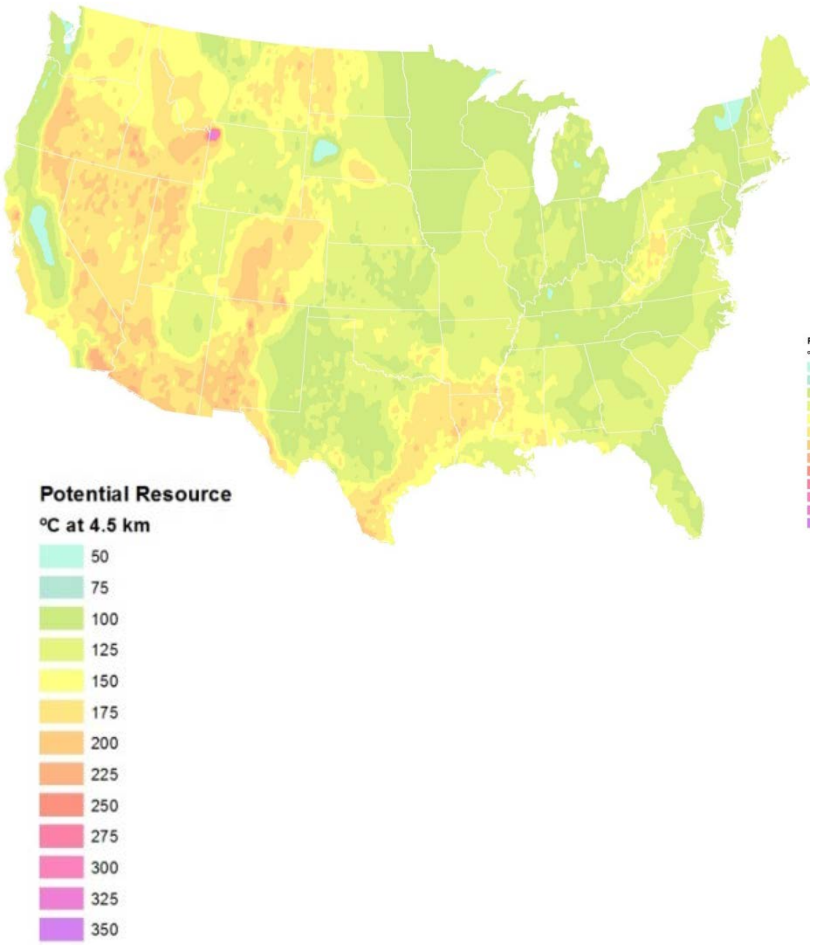
Project Officer:: Joshua Mengers
Total Project Funding: $3M/3 yr
November 14, 2017

Principal Investigator
B. P. McGrail
Pacific Northwest National Lab

Systems Analysis, and Low Temperature Resources

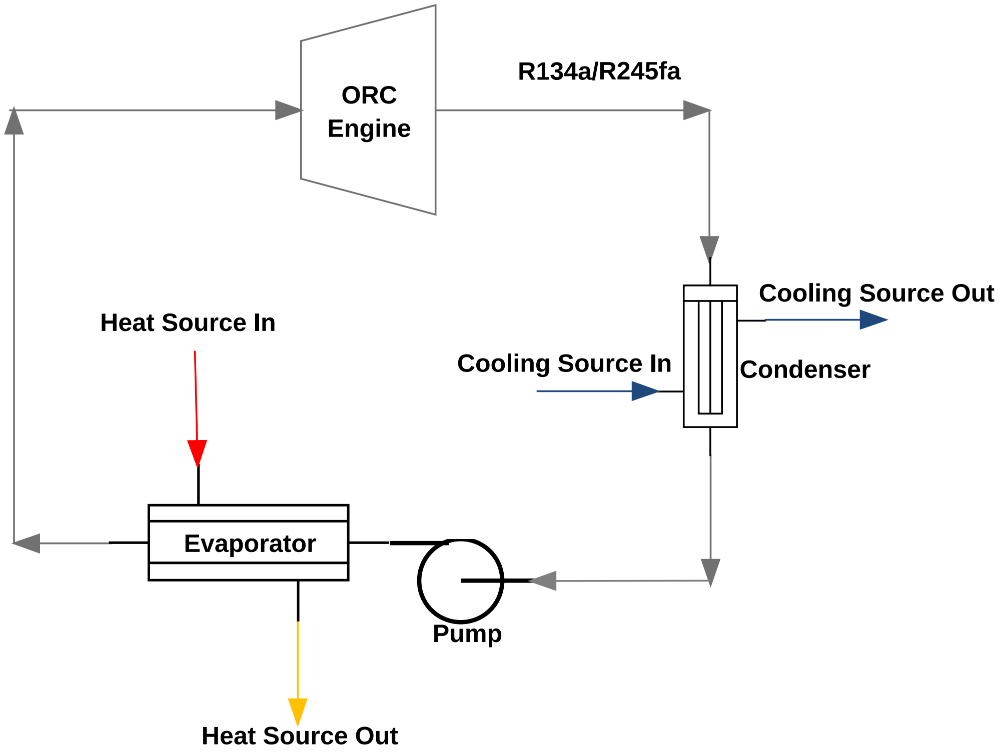
Relevance to Industry Needs and GTO Objectives

- Low temperature geothermal resources are much more geographically disperse and represent a large virtually untapped energy resource estimated at 1.6 GWe
- Current technology (binary cycle/ORC) has low thermal conversion efficiency and relatively high capital equipment costs that make LCOE's unattractive except in niche markets
- New nanostructured materials provide opportunity for step-change in size, weight, and efficiency in thermal energy conversion



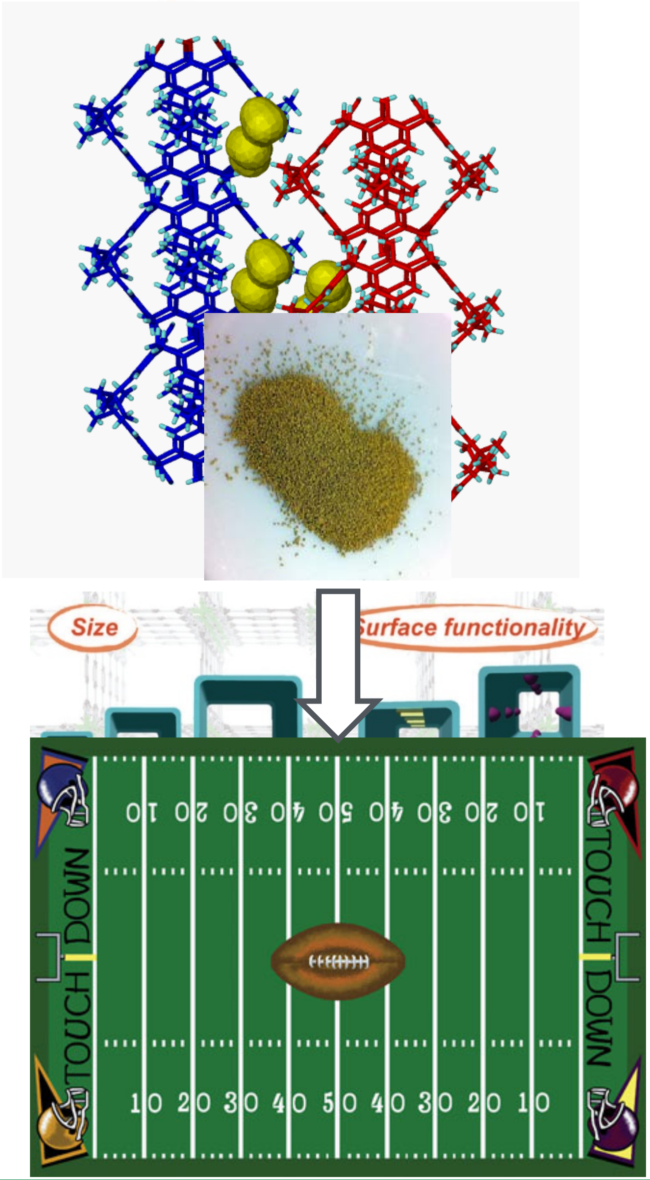
Standard ORC System

- Cycle efficiency <10%
- Large condenser and evaporator components
- Significant parasitic loss and cost of high pressure pump
- Air cooled system suffers from rapid decline in power output with increasing ambient temperature



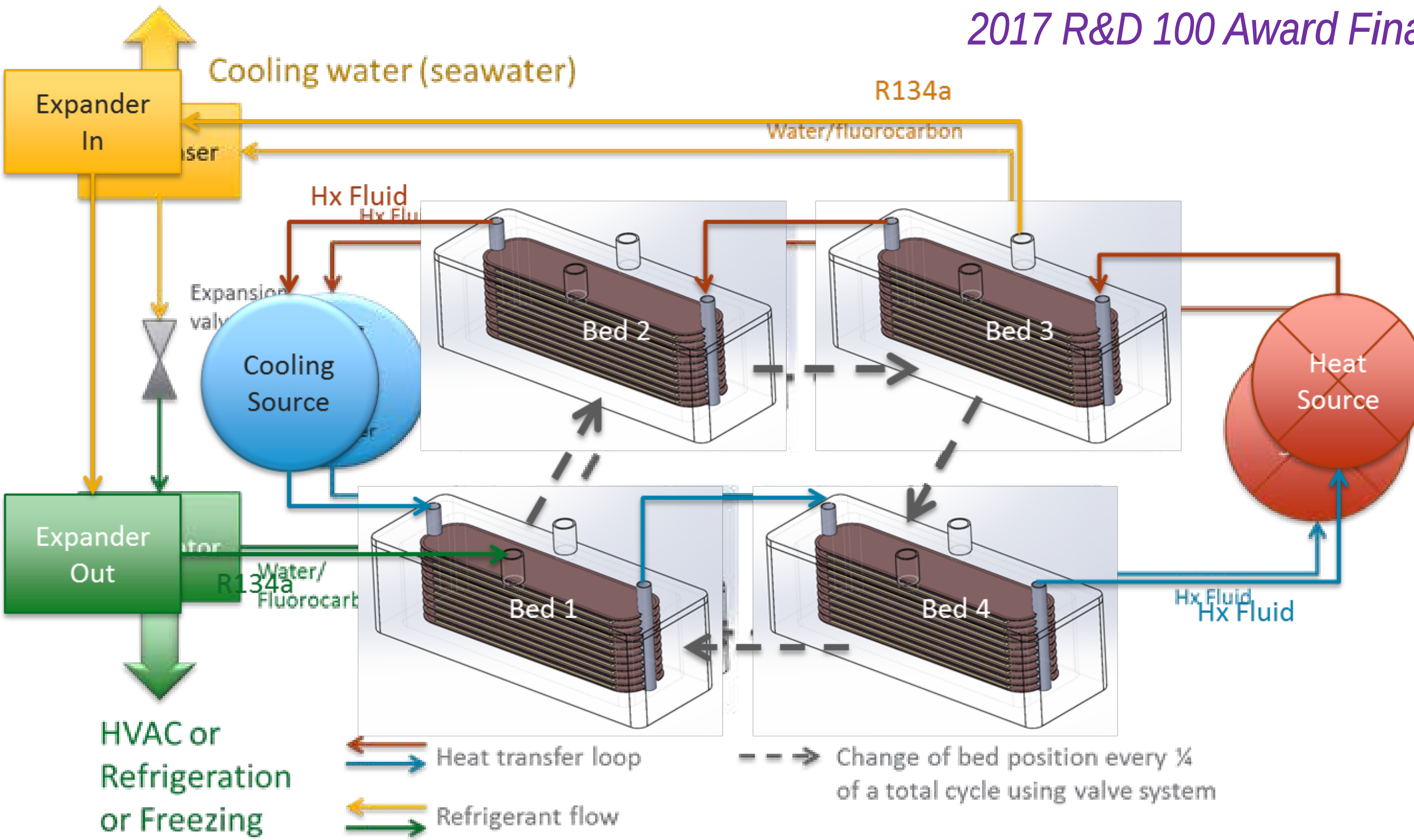
Metal Organic Framework Materials

- MOFs are hybrid crystalline porous solids
- The properties of MOFs are easier to tune synthetically than those of other porous compounds
- The MOF structures are controllable by the choice of molecular building blocks
- Thermally stable up to 300°C and sometimes higher
- Possess much higher specific surface area (>8,000 m^2/g) than possible in any other traditional crystalline material



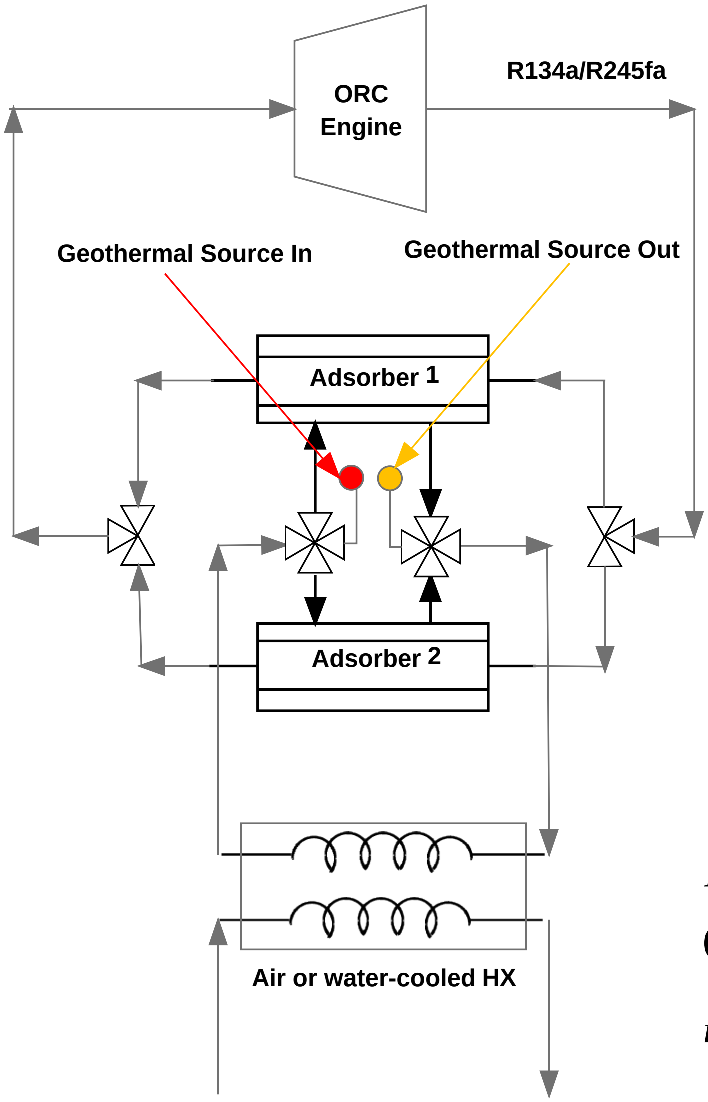
Adsorption Cooling to the Rescue?

2017 R&D 100 Award Finalist



Same thermal compressor system design for cooling can be used to produce power

Hybrid Adsorption Recuperative Power Cycle (HARP)



- Adsorption modules replace evaporator, condenser, and high pressure pump
- Refrigerant is never physically condensed as a bulk liquid in the cycle
- By avoiding bulk liquid condensation, pressure and temperature of the working fluid exiting the engine can be reduced producing ≈40% more power
- Elimination of high pressure pump reduces system cost and parasitic losses

$$P = \eta_e \dot{m}_r (h_r^1 - h_r^o)$$

$$(1-\eta_h)\left[\dot{m}_r \Delta H_a t_c + (m_{Al} c_p^{Al} + m_s c_p^s + m_v c_p^v)(T_h - T_L)\right] = \dot{m}_w (h_w^1 - h_w^o)$$

$$m_s = \frac{\dot{m}_r}{f_r} t_c$$

McGrail, B.P., J.J. Jenks, R.K. Motkuri, W.P. Abrams, and P. Roege. 2017. U.S. Patent Application No. 62/355,292.

Sorbent Development

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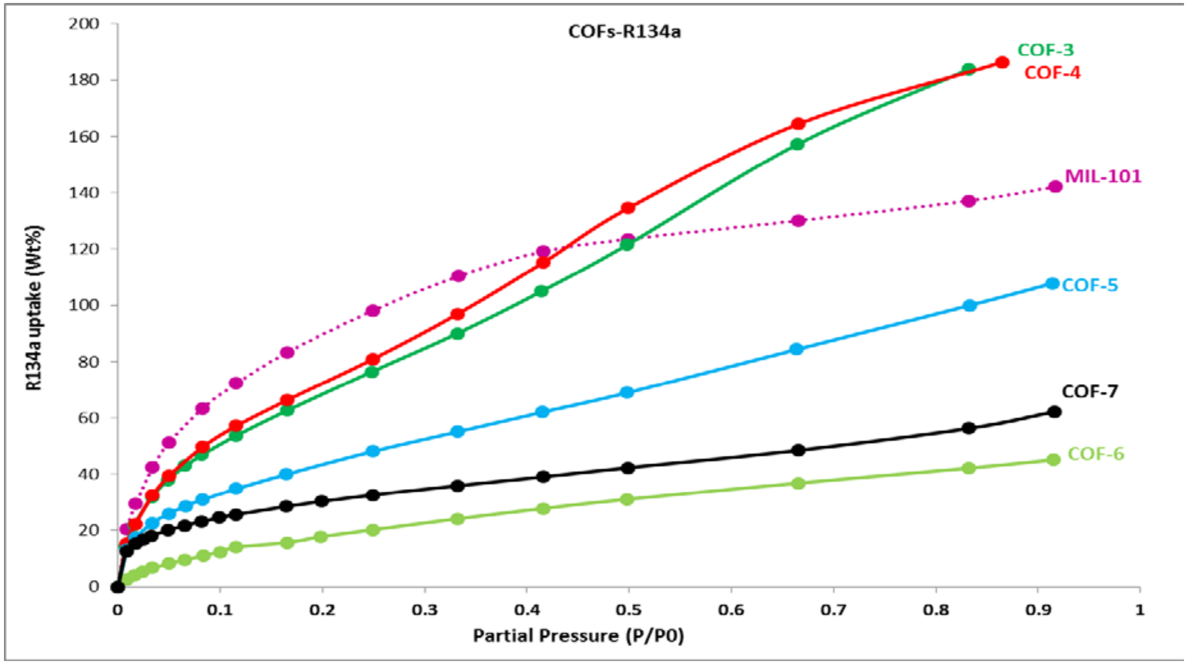
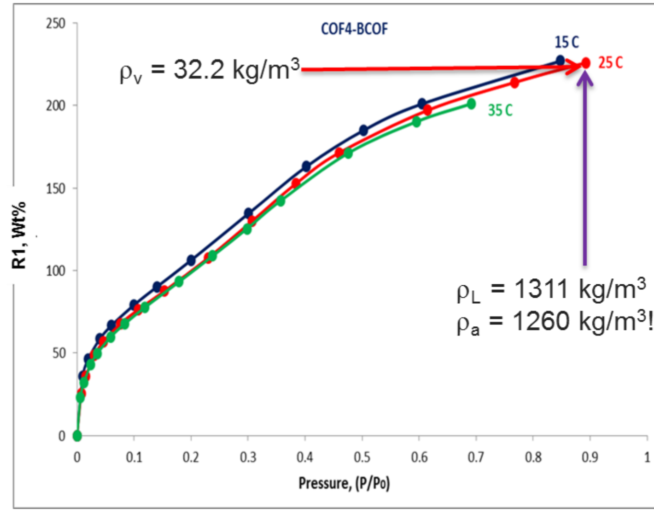
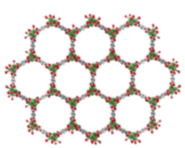
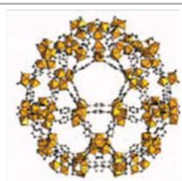
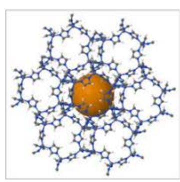
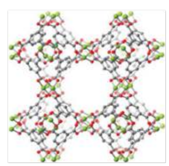


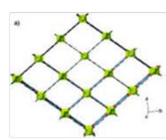


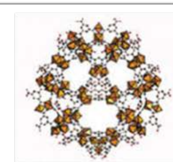

Ni-MOF-74


Cr-MIL-101


ZIF-8


Cu-BTC

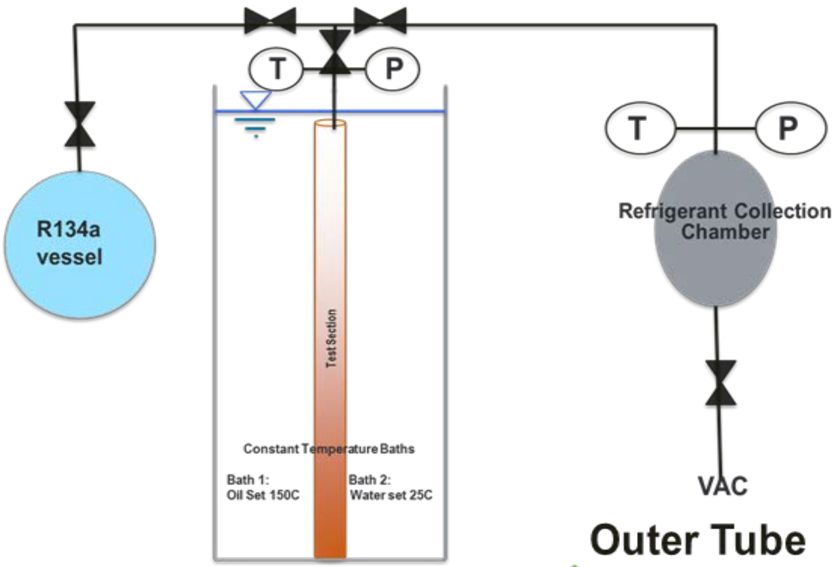

MIL-53

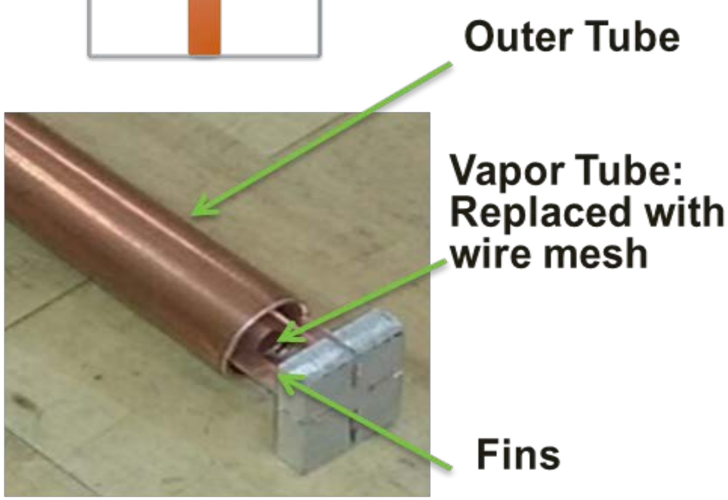

MIL-100

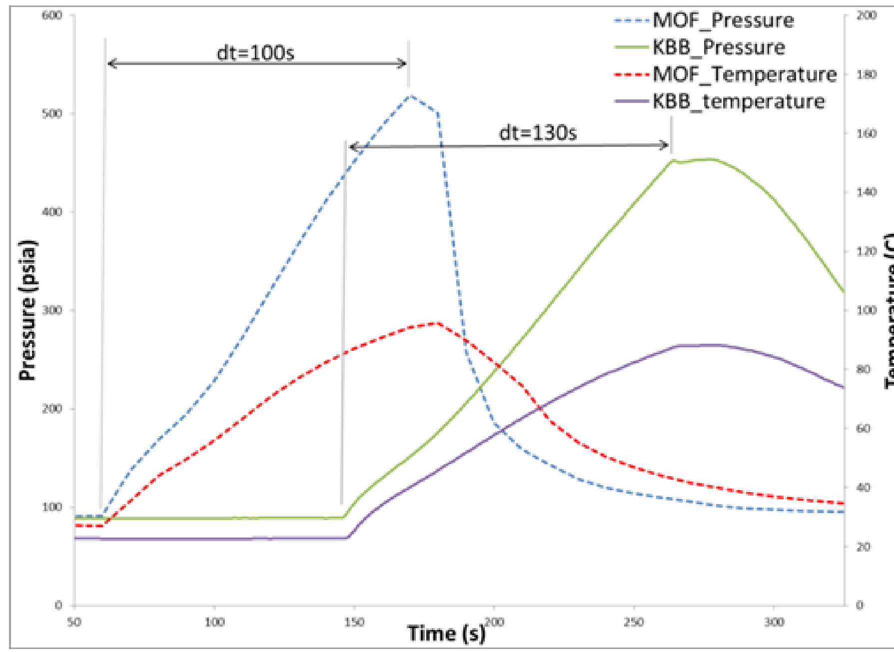
- Intensive screening of MOFs and COFs has identified superfluorophilic sorbents that can be manufactured at reasonable cost (<$80/kg)
- Both mass and volumetric loading as well as adsorption kinetics are important properties for system design

- Superfluorophilic properties generate near liquid density in sorbent pore network while well under the vapor dome of the refrigerant
- Higher working capacity achieved by combined pressure-temperature swing in cycle

Single Tube Compression Tests







R134a Thermal Compression Cycles

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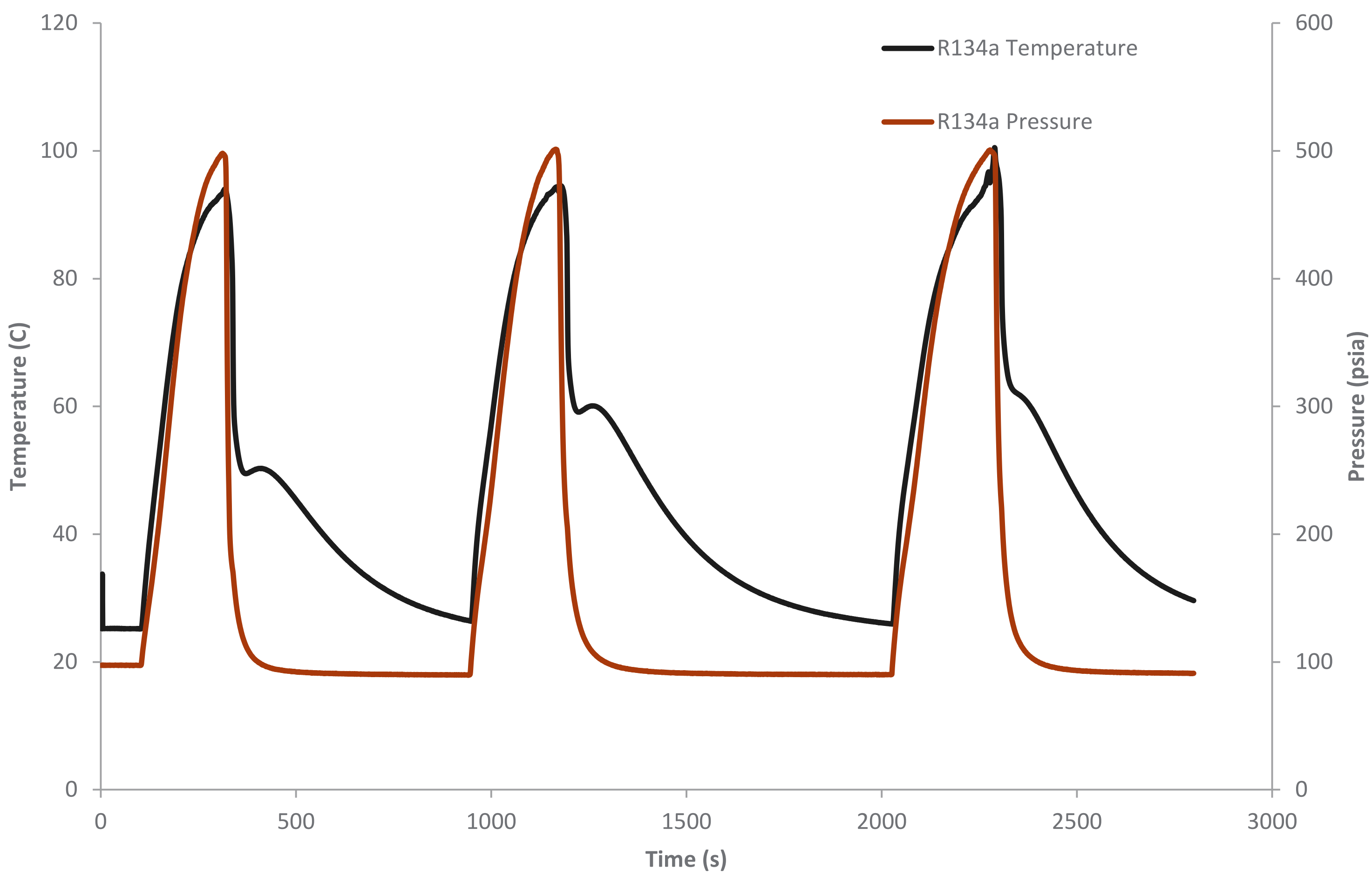

Cycles demonstrate the power of adsorption compression – over 20X more pressure than heating without sorbent

3D Printing Enables Unique Shell/Tube Heat Exchanger Design

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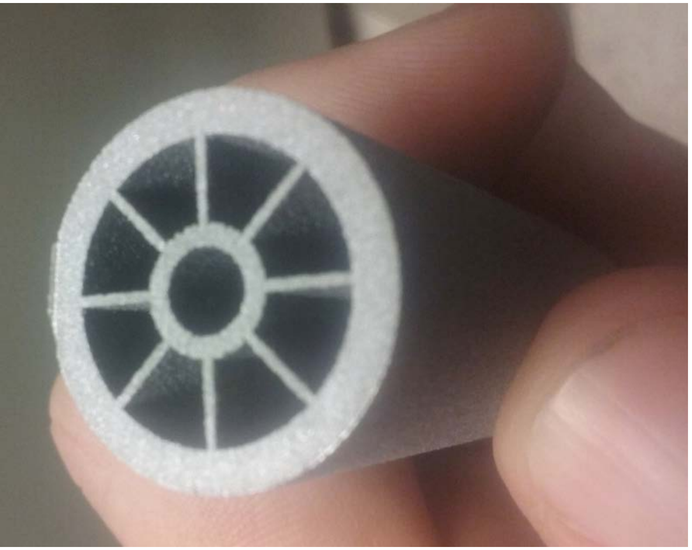
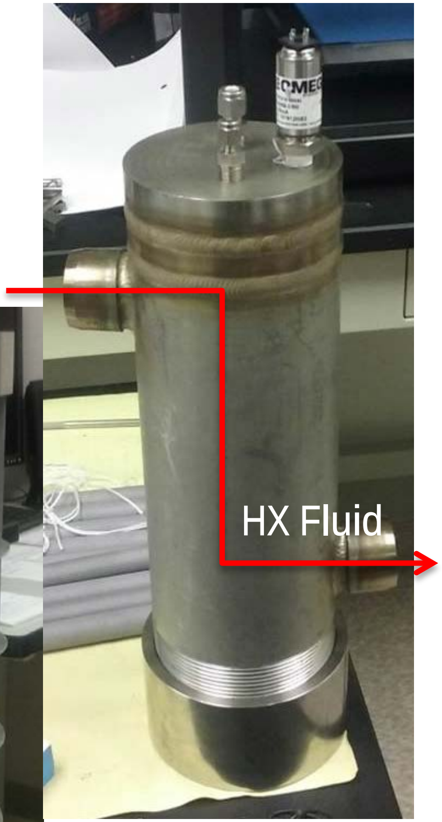
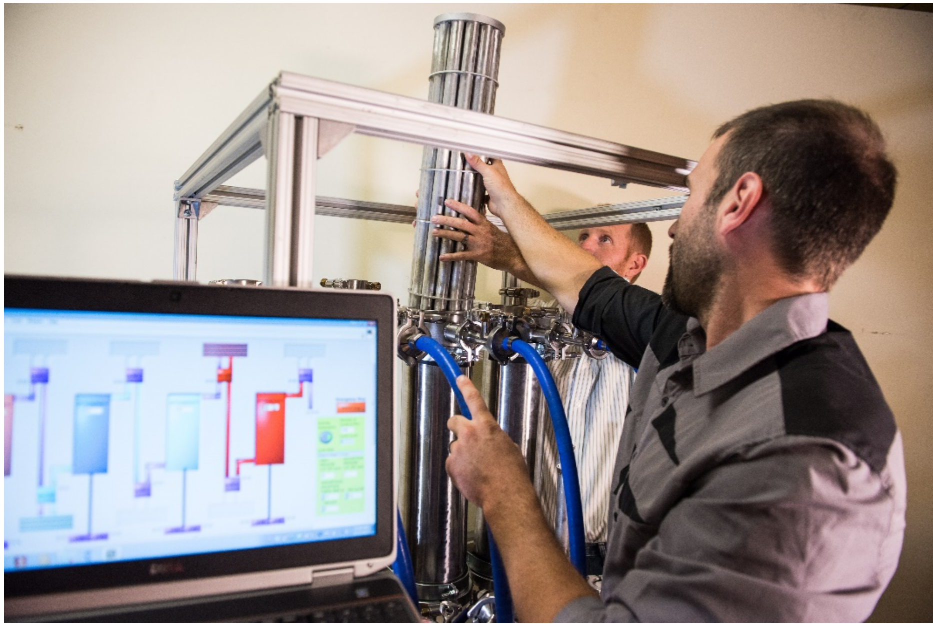




- Easily scalable from single tube to large diameter shell/tube design capable of MW scale output
- Control of porous inner tube permeability most significant challenge
- Lack of ASTM standards dictate in-house pressure testing to establish safe pressure rating for each design iteration

HARP System Assembly



Thermal Compressor Testing

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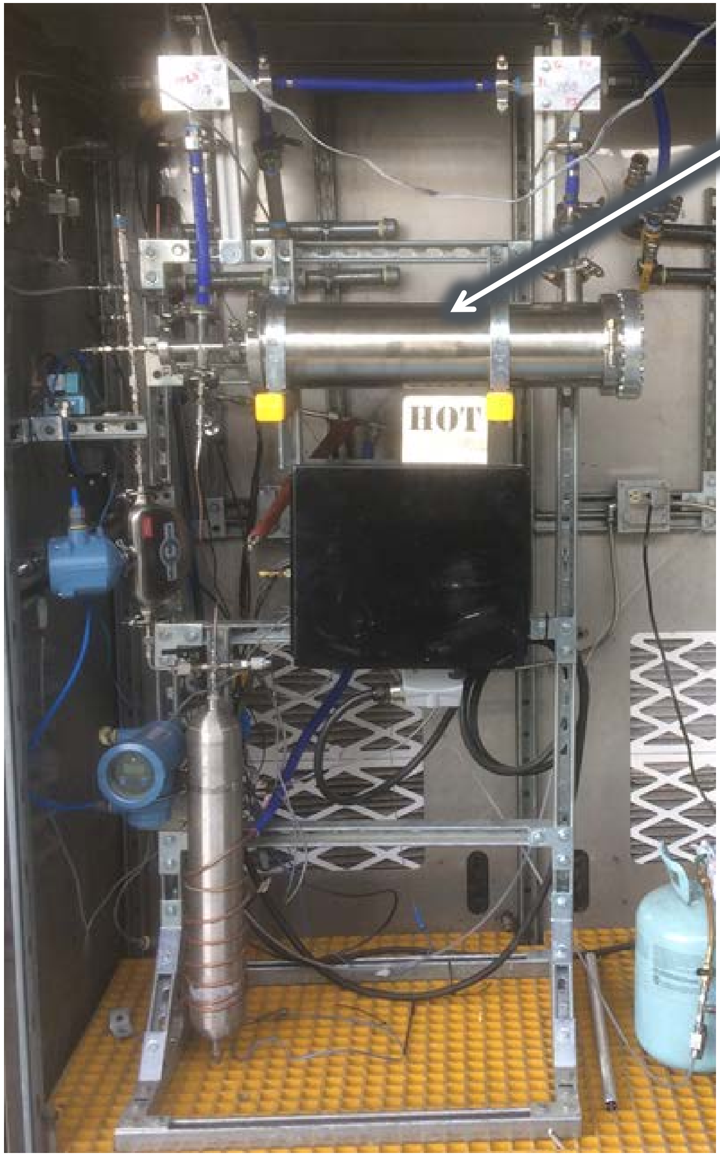

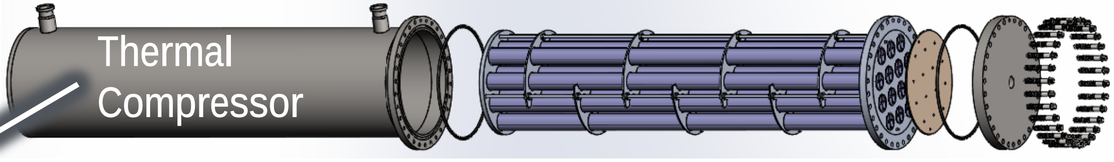

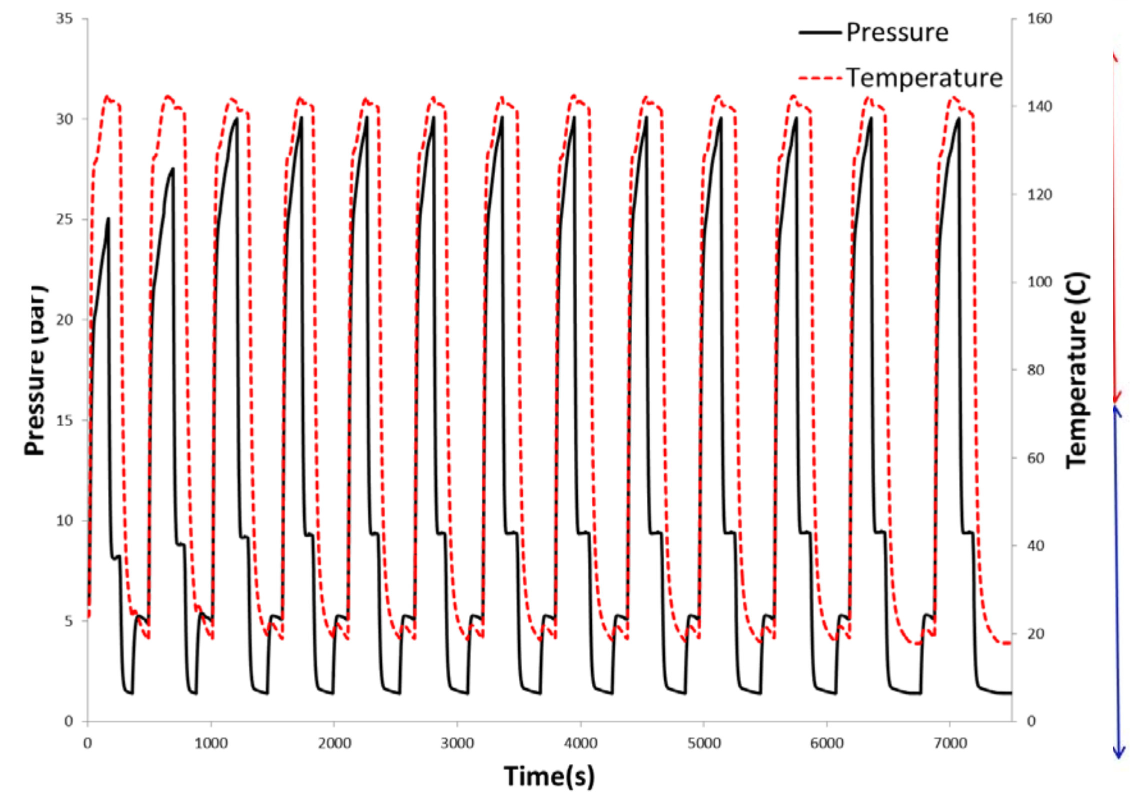

Average mass flow will produce over 10 kW_e for this subscale design

Cost Analysis for HARP System

- 1st generation cost analysis updated based on actual performance data generated in TCTF and based on hard quotations for our initial HARP development unit
- Nth unit cost estimates provided for unit in commercial production under assumed progress factor of 0.8 to 0.9
- Estimates show potential for very attractive power generation cost

Cost Estimate based on PNNL Single Unit (one-off) and Production Model

EES MODEL PARAMETERS	UNIT	HARP
Number of expanders	Units	4
Heat consumption	kW	273
Net electric power	kW	58
Annual operating hours	hours	8,300
Net electricity production	kWh	481,400

BUDGET PARAMETERS	UNIT	POWERPACK
Period of depreciation	Years	10
Annual insurance cost	$	1,059
Annual service cost	$	5,000
Straight Line Depreciation*	$	(2,477.00)

BUDGET PARAMETERS	UNIT	1st Gen
CraftEngine™ System (incl. additional power cost)	$	48,000
Thermal Compressor	$	191,340
Site Installation	$	19,000
Total profit (20% OH and G&A;20%EBIT)	$	39,360
Net investment cost	**$**	**297,700**

BUDGET PARAMETERS	UNIT	1st Gen	Production
Production cost per kWh	$/kWh	0.0744	0.0486

Technical Accomplishments and Progress

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Qtr	Milestone	Met or Unmet
Q1 FY16	Adsorption module design complete for bench-scale system	Met
Q2 FY16	Initial assessment of HARC technology impact on geothermal resource recovery complete	Met
Q3 FY16	Fluorophilic sorbent identified with manufacturing cost < or = $80/kg	Met
Q4 FY16	Bench-scale HARC system testing begins	Met

Qtr.	Milestone	Met or Unmet	Explanation if Unmet
Q1 FY17	Demonstration field site selected (12/31/16)		Revised under project plan for FY18 AOP
Q2 FY17	Go/no-go System performance and production cost estimates validate LCOE <=0.07/kWh	Met	Continuation Application submitted. **Go decision** received from GTO July 2017
Q3 FY17	Field demonstration system design complete (6/30/17)	Met	Thermal Compressor Design-Complete. Integration into Viking ORC after testing
Q4 FY17	Updated full-scale system performance and production cost estimates validate LCOE < or = to $0.05/kWh	Met*	Revised performance target drafted based upon feedback from TMT

Technical Accomplishments and Progress

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- Patent application filed June 2017
  McGrail, B.P., J.J. Jenks, R.K. Motkuri, W.P. Abrams, and P. Roege. 2017. U.S. Patent Application No. 62/355,292
- Energy Innovation Award received July 2016 at Future Energy Conference, Sydney, Australia
- Presentations
  - McGrail, B. P., J. J. Jenks, W. P. Abrams, R. K. Motkuri, N.R.J. Phillips, T. G. Veldman, B. Q. Roberts, “A Non-condensing Thermal Compression Power Generation System”, ORC 2017, Milan, Italy, 2017
  - Motkuri, R. K. V. R. Vemuri, J. Zheng, and B. P. McGrail, “Robust Metal Organic Frameworks for Adsorption CCHP Applications”, 253rd ACS Meeting, San Francisco, California, 2017.
  - McGrail, B. P., J. J. Jenks, R. K. Motkuri, and W. P. Abrams, “Nanomaterials Deployment in Compact Cooling, Heat, and Power System,” Defense Logistics Agency Worldwide Energy Conference, National Harbor, Maryland, 2017 (INVITED)
  - McGrail, B. P., J. J. Jenks, R. K. Motkuri, W. P. Abrams, J. P. Abrams, J. B. Haight, and T. C. Hightower, “A New Harmonic Adsorption Recuperative Power System for Geothermal and other Low Grade Heat Sources”, Future Energy Conference & Exposition, Sydney, Australia, 2016.
  - Jenks, J. J., B. P. ,McGrail, and R. K. Motkuri, “Analysis of Metal Organic Frameworks for use in Fluorocarbon CCHP Applications”, ASME 2016 10th International Conference on Energy Sustainability, Charlotte, North Carolina, 2016.
- *Publications*
  - McGrail, B. P., J. J. Jenks, W. P. Abrams, R. K. Motkuri, N. R. Phillips, T. G. Veldman, and B. Q. Roberts. 2017. "A Non-Condensing Thermal Compression Power Generation System." *Energy Procedia* **129**(Supplement C):1041-1046
  - Zheng, J., R. S. Vemuri, L. Estevez, P. K. Koech, T. Vargas, D. M. Camaioni, T. A. Blake, B. P. McGrail, and R. K. Motkuri. 2017. "Pore-Engineered Metal-Organic Frameworks with Excellent Adsorption of Water and Fluorocarbon Refrigerant for CCHP Applications." *J. Am. Chem. Soc.* **139**(31):10601-10604

Research Collaboration and Technology Transfer

- Hosted visit to PNNL by Viking Heat Engine senior engineers (January 2016) for project kickoff and feasibility review
- PI visited Viking Heat Engine facilities (Remscheid, Germany) for update in November 2016
- Partnered with Rockwell-Collins and Advanced Thermal Sciences, Inc. on HARP system development and deployment
  - Thermal compressor design for HARP system transferred to Rockwell-Collins for CCHP demonstration system to be deployed on USTS *Golden Bear* in 2018
- Synthesis conditions for selected MOF sorbent for HARP system transferred to InnaVenture LLC for synthesis trials in their pilot-scale reactor system under exclusive IP license
- HARP system being used for Ph.D candidate dissertation at UC-Davis
- Post-doc student from University of Padova expected in 2018

Future Directions & Summary

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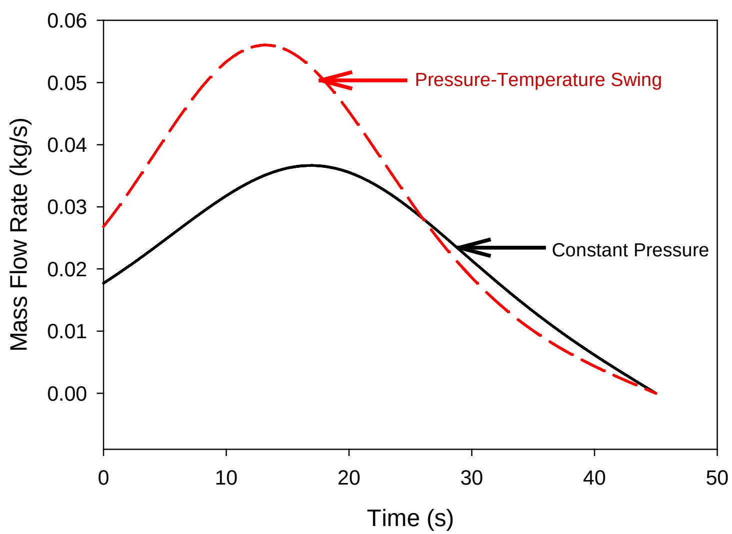
- Optimize HARP cycle using full four bed thermal compressor
  - Pressure-temperature swing
  - Heat recuperation
- Extended duration thermal compressor tests
- Integration with Viking CraftEngine
  - Power generation
  - Output curves versus heat source and cooling source temperatures
- Validation of production model cost estimates



- HARP cycle is transformational technology in cost/performance of power generation systems for low grade geothermal resources
- Illustrates ability to rapidly advance new high performance materials into practical application
- System operates with non-toxic, standard fluorocarbon refrigerants and commercially available ORC expander units
- Easily configurable to CCHP system with balance of plant using proven commercial off the components that reduce cost, improve reliability, and enables more rapid commercialization
- High conversion efficiency and simple design suggest very attractive power production cost for commercial production units
- HARP system well matched for deployment in the smaller-scale (<10 MWe) distributed power generation market