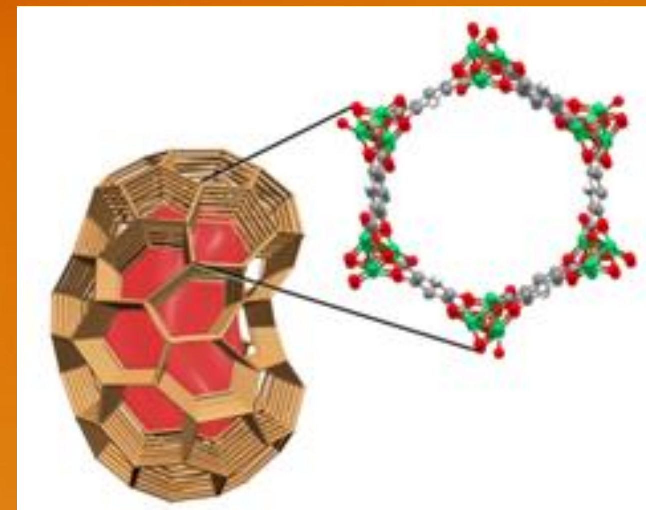
ORC 2017 Conference
Milan, Italy



Public Service of Colorado Ponnequin Wind Farm

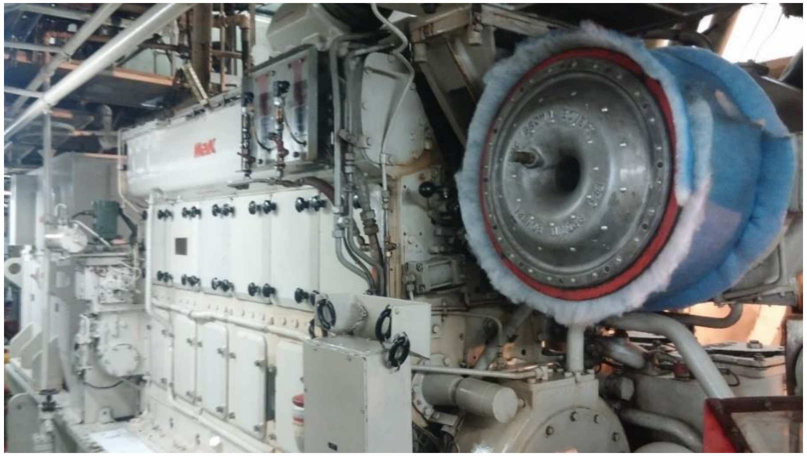
A Non-condensing Thermal Compression Power Generation System

B.P. McGrail, J.J. Jenks, R.K. Motkuri,
N.R. Phillips, T.G. Veldman, and B.Q. Roberts
Pacific Northwest National Laboratory

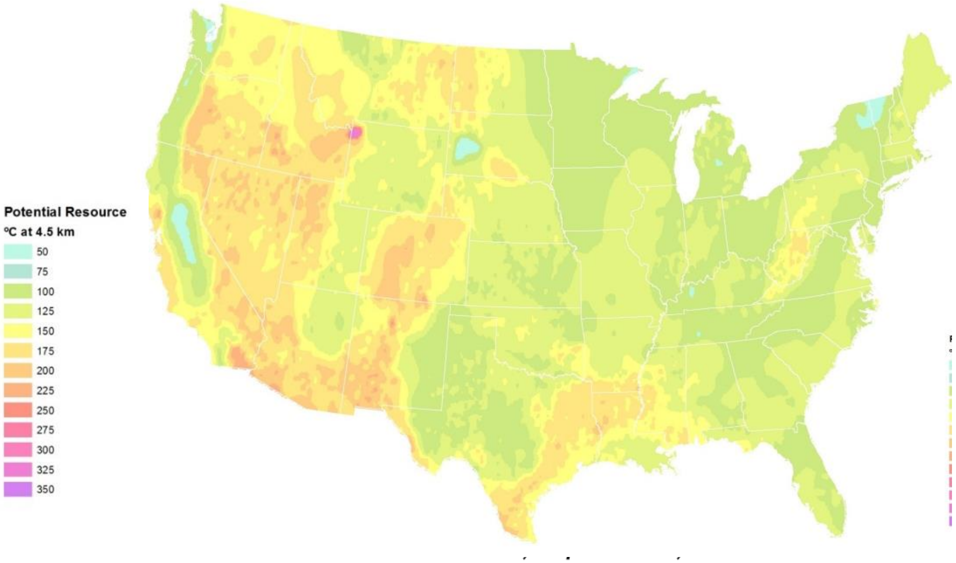
W. P. Abrams, Rockwell-Collins

Deploying New Materials in Challenging Applications

- Diesel gensets deployed on Navy ships and at FOBs use only 1/3 of the energy content of the fuel – the rest is rejected as heat to the environment
- Low temperature geothermal resources are much more geographically disperse and represent a large virtually untapped energy resource estimated at 1.6 GW_e
- New nanostructured materials provide opportunity for step-change in size, weight, and efficiency in thermal energy conversion

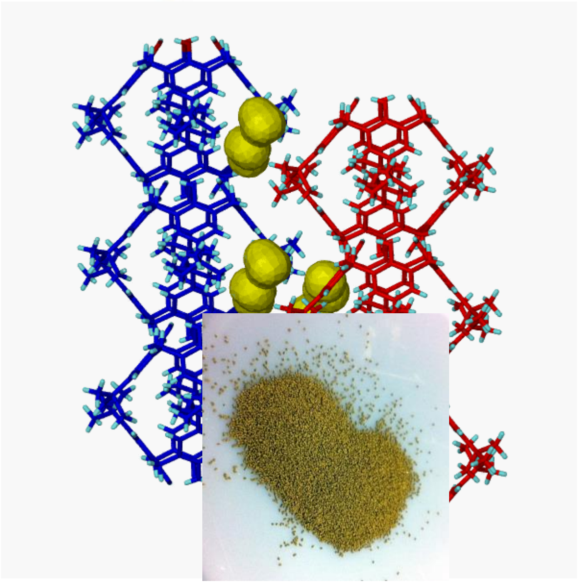


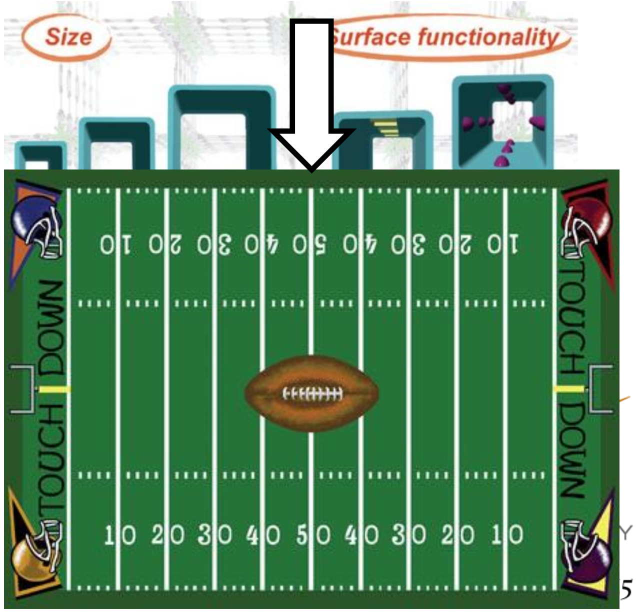
Ship Service Diesel Generator on U.S. Training Ship *Golden Bear*



Metal Organic Framework Materials

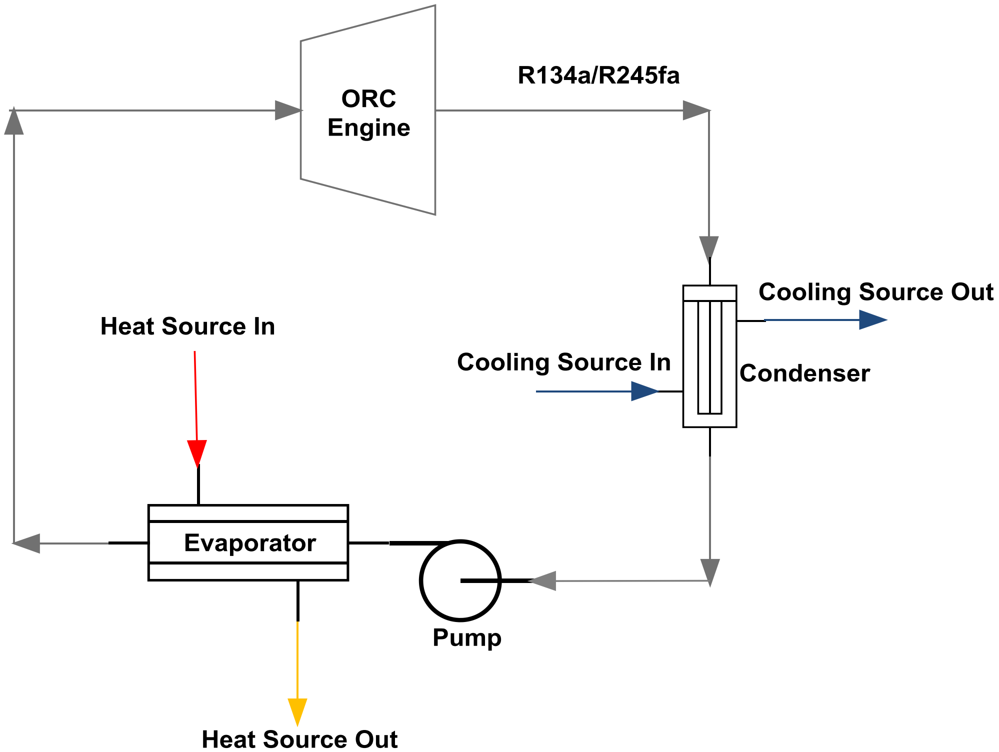
- MOFs are hybrid crystalline porous solids
- The properties of MOFs are easier to tune synthetically than those of other porous compounds
- The MOF structures are controllable by the choice of molecular building blocks
- Thermally stable up to 300°C and sometimes higher
- **Possess much higher specific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





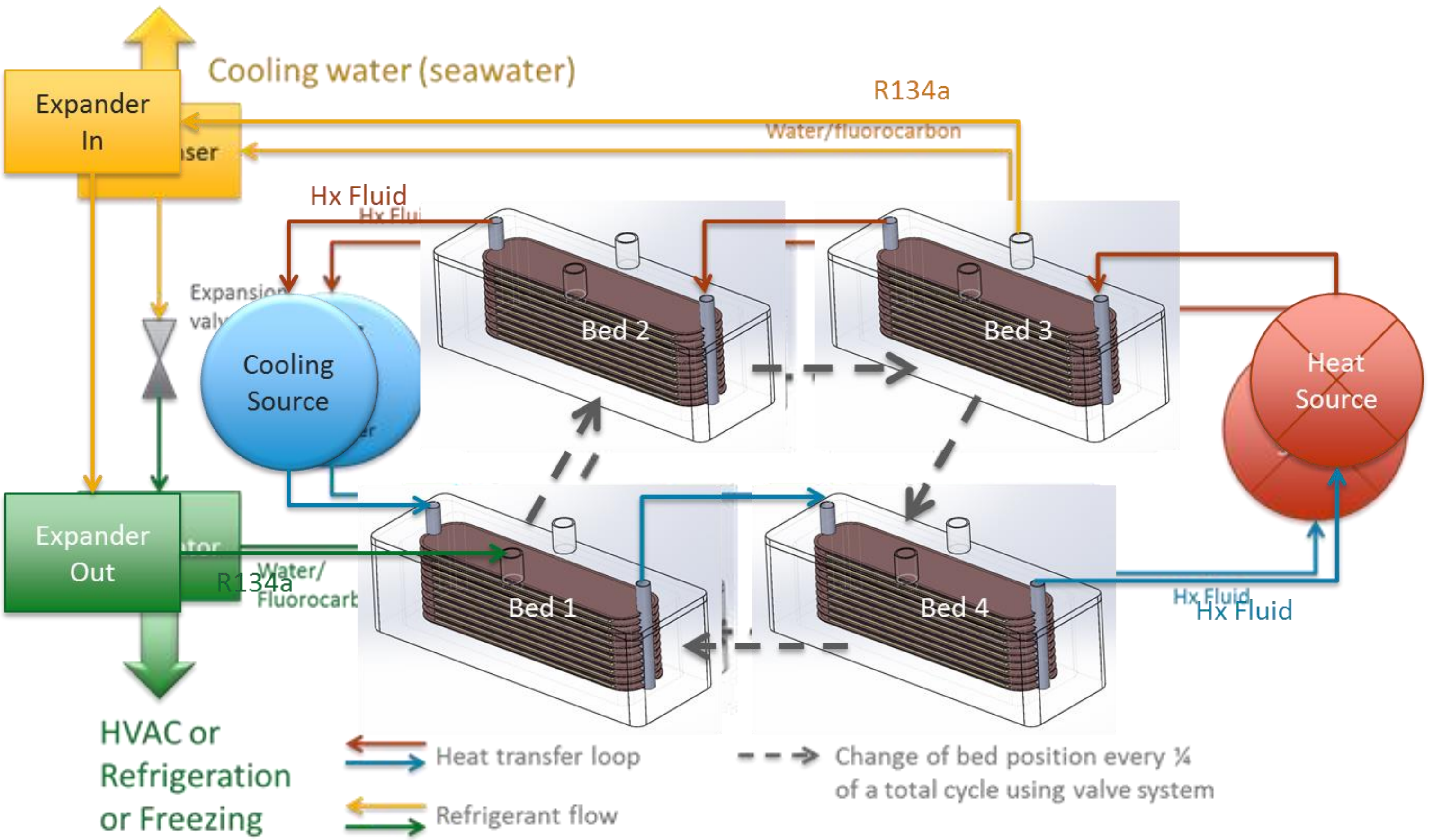
Standard ORC System

- Cycle efficiency typically <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



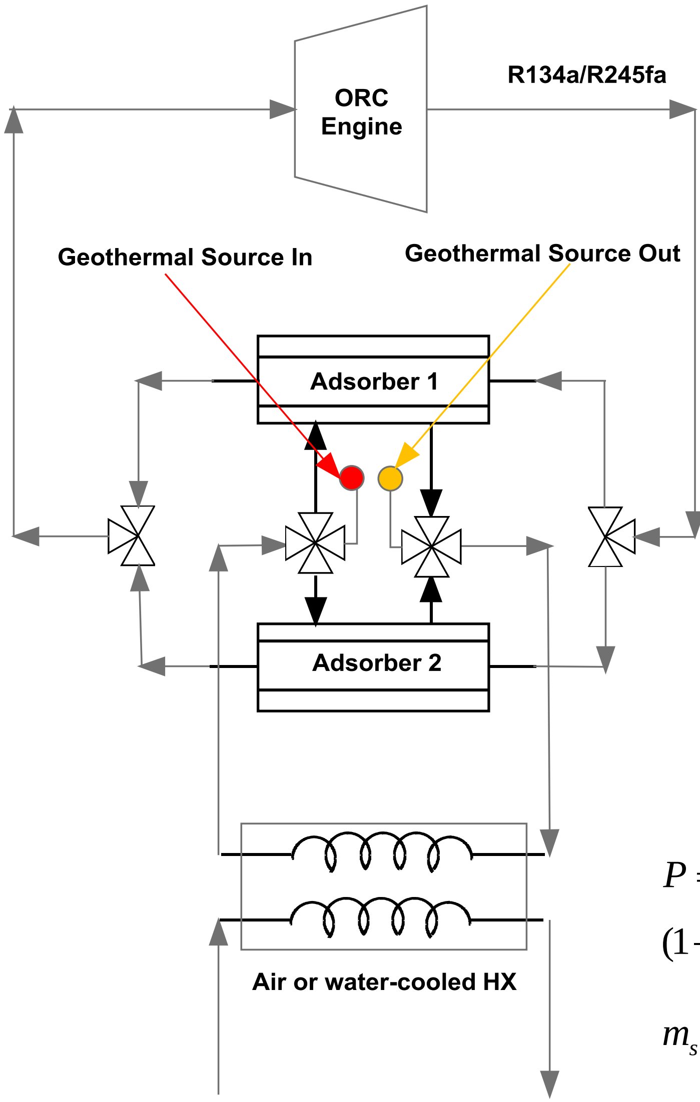
Pacific Northwest NATIONAL LABORATORY

Adsorption Cooling to the Rescue?



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

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

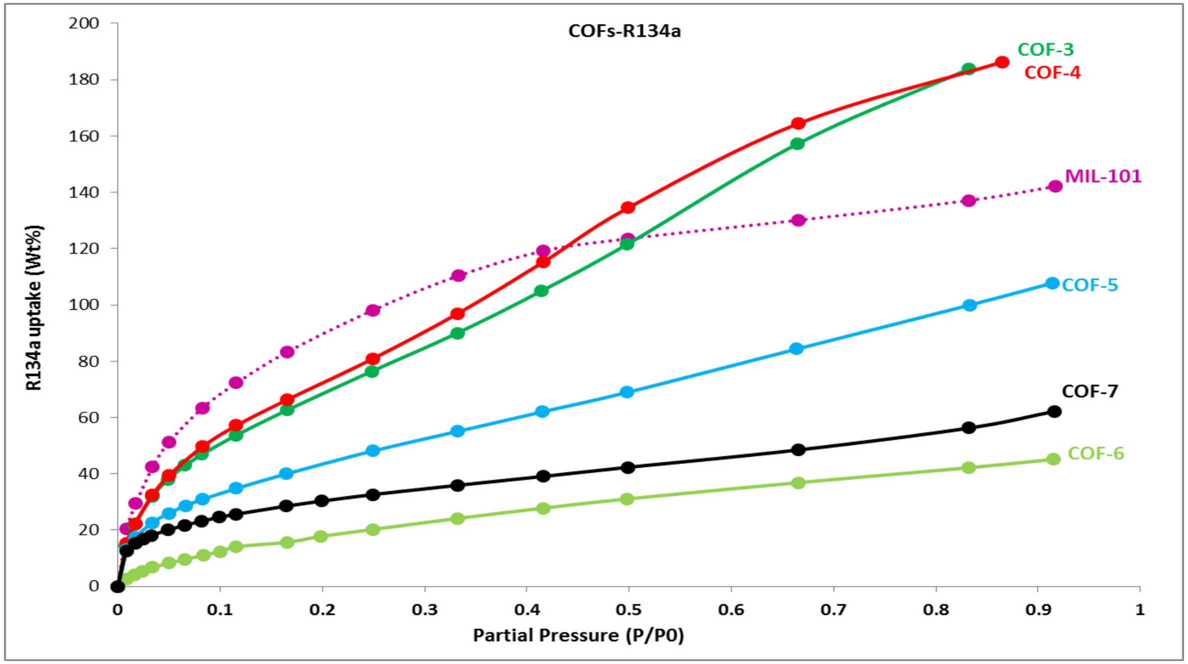
$$(1-\eta_h)\left[\dot{m}_r \Delta H_a t_c + (m_{Al} c_p^{Al} + m_s c_p^s + m_v c_p^v)(T_h - T_L)\right] = \dot{m}_w (h_w^1 - h_w^o)$$

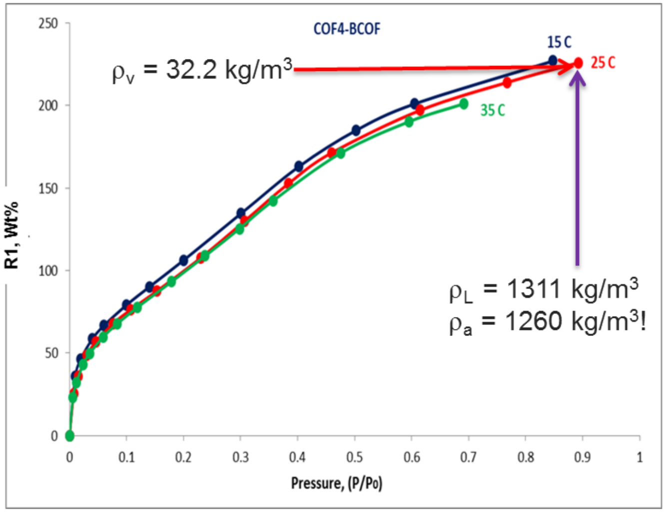
$$m_s = \frac{\dot{m}_r}{f_r} t_c$$

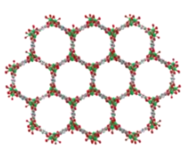
Pacific Northwest NATIONAL LABORATORY

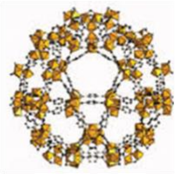
McGrail, B.P., J.J. Jenks, R.K. Motkuri, W.P. Abrams, and P. Roege. 2016. U.S. Patent Application No. 62/355,292.

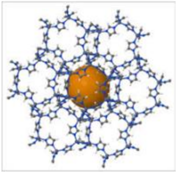
Sorbent Development

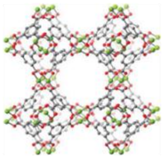


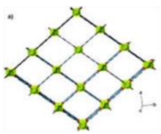


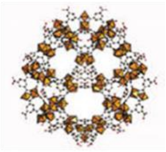

Ni-MOF-74


Cr-MIL-101


ZIF-8


Cu-BTC

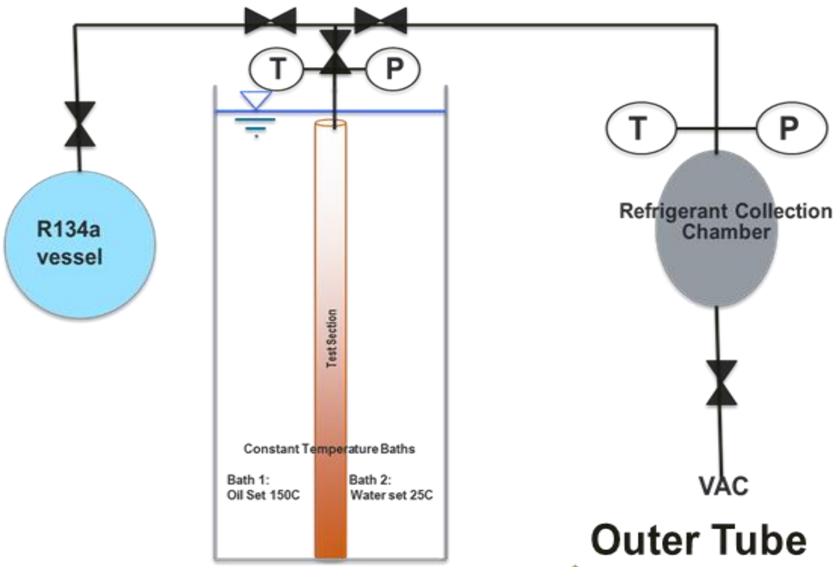

MIL-53

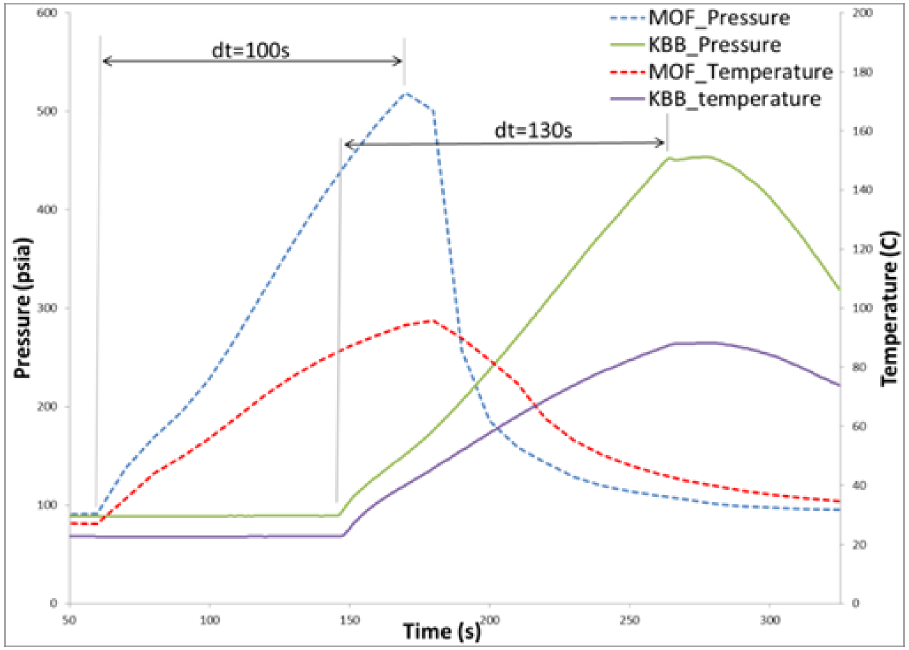

MIL-100

- 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

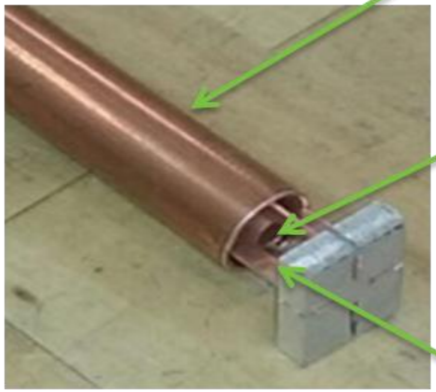
- Intensive screening of MOFs and COFs has identify superfluorophilic sorbents that can be manufactured at reasonable cost (<$80/kg)
- Both mass and volumetric loading as well as adsorption kinetics are important properties for system design

Single Tube Compression Tests





Outer Tube



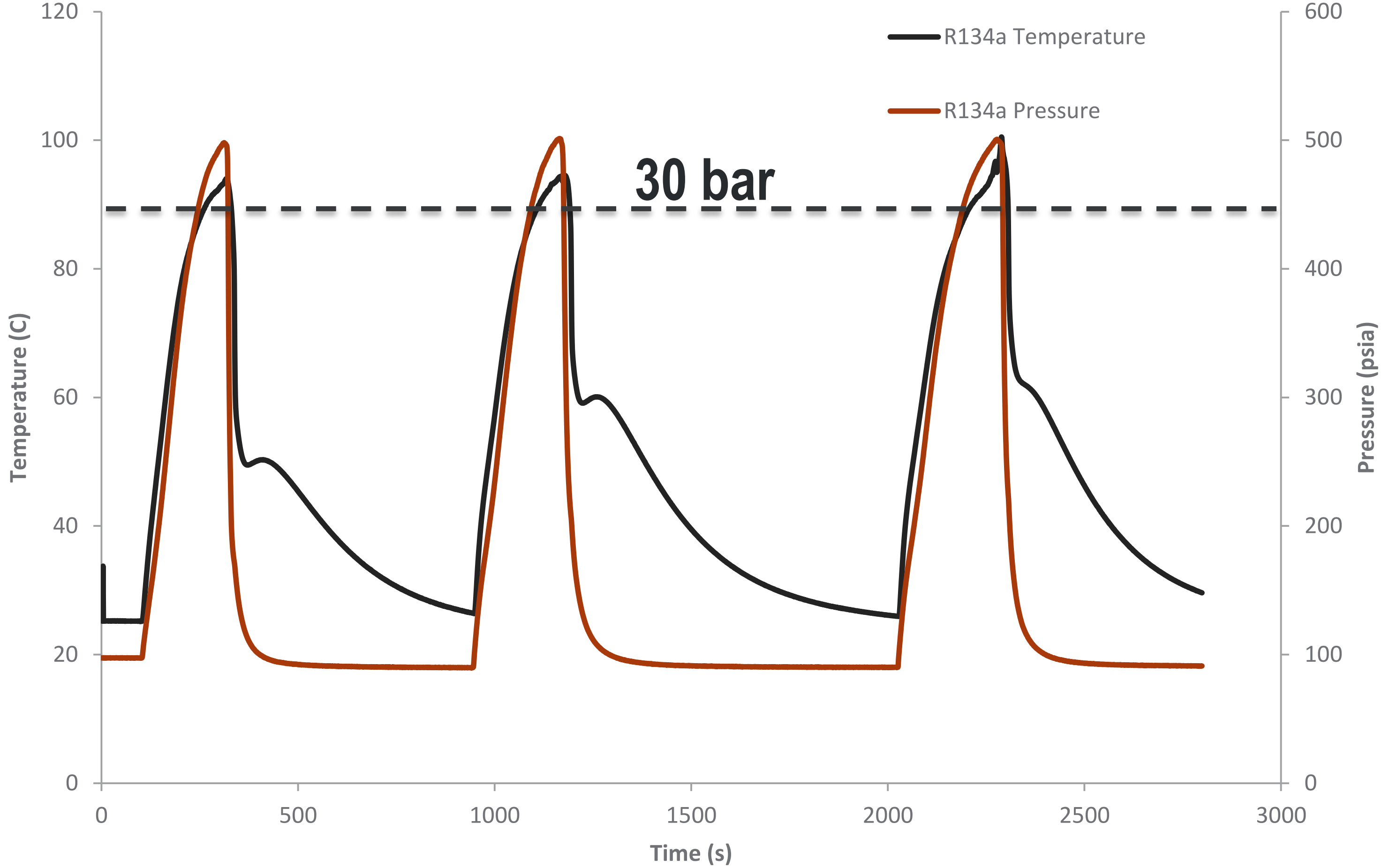
Vapor Tube: Replaced with wire mesh

Fins

MOF loads 30% more R134a and compresses 30% faster than best commercial porous carbon. This equates to 60% smaller thermal compressor to produce the same power output.

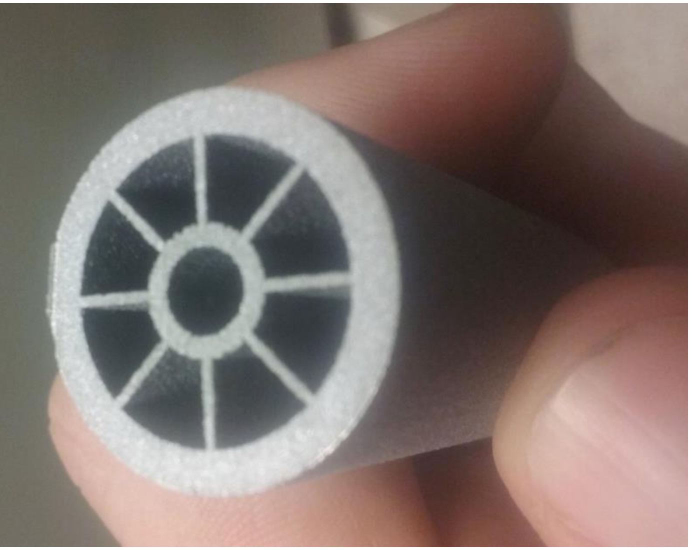
R134a Thermal Compression Cycles

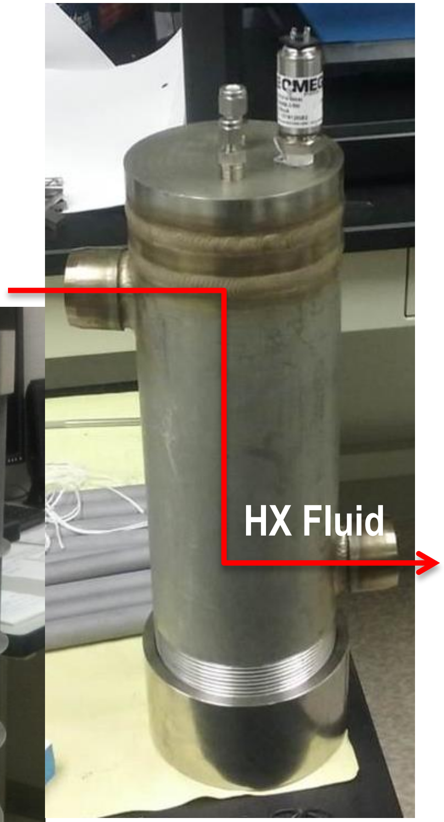
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*



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

3D Printing Enables Unique Shell/Tube Heat Exchanger Design

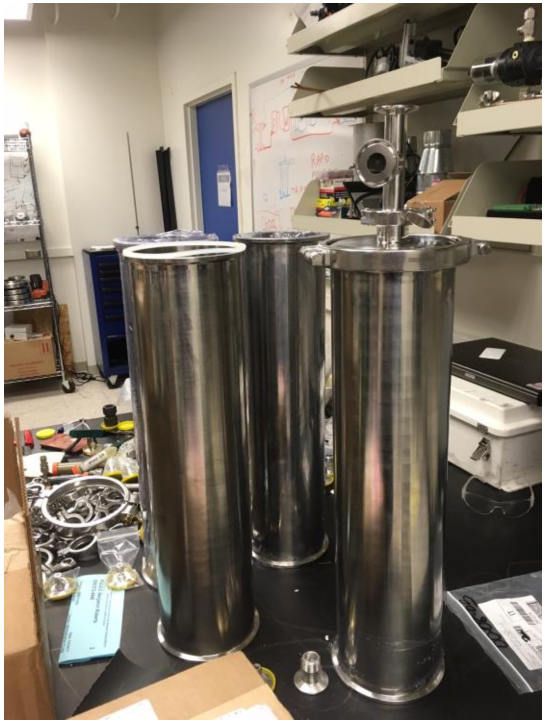




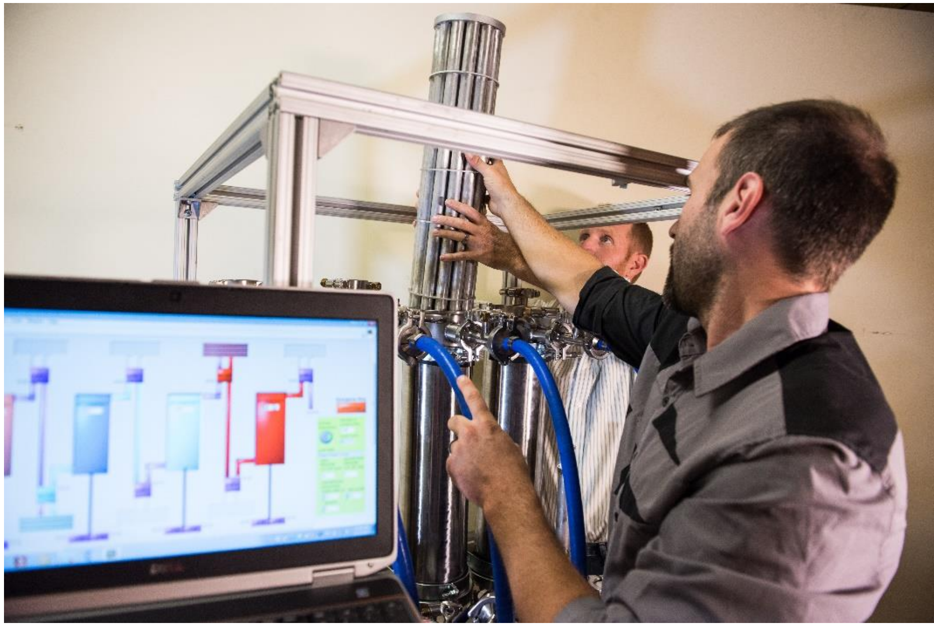
- Easily scalable from single tube to large diameter shell/tube design capable of MW scale output
- Control of porous inner tube permeability most significant challenge
- Lack of ASTM standards dictate in-house pressure testing to establish safe pressure rating for each design iteration

Prototype System Components

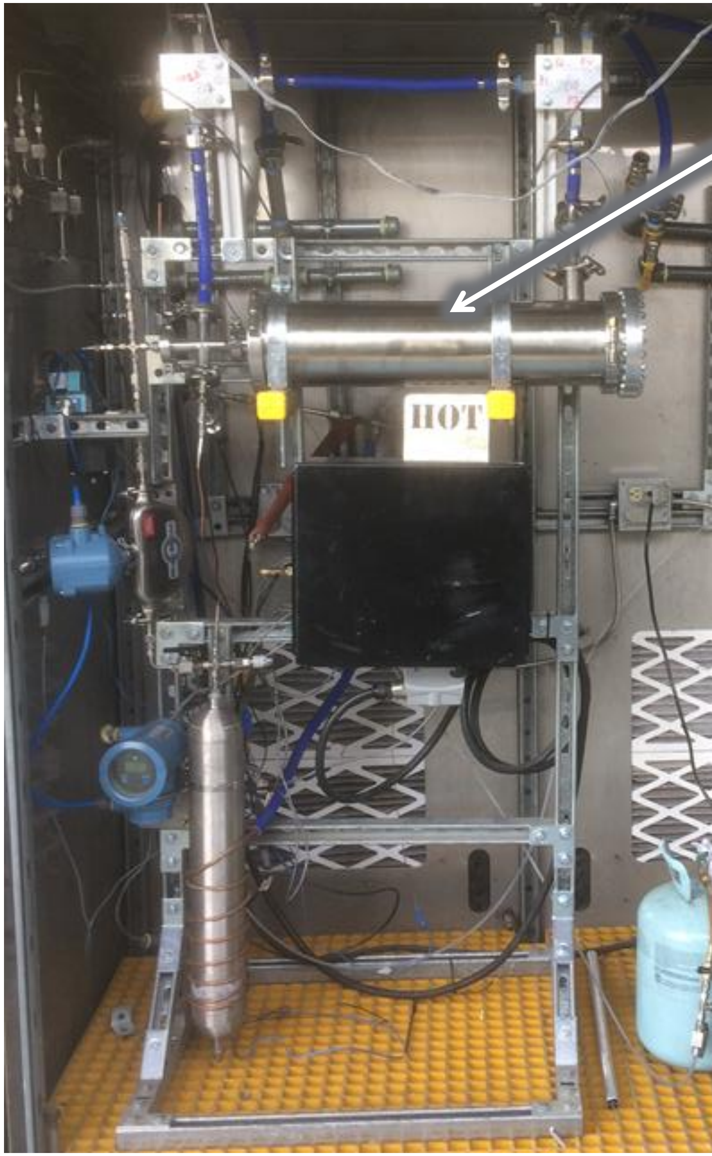
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

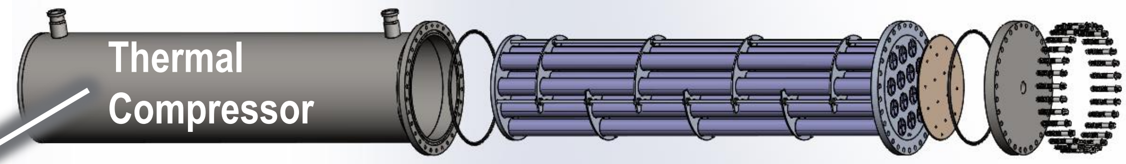


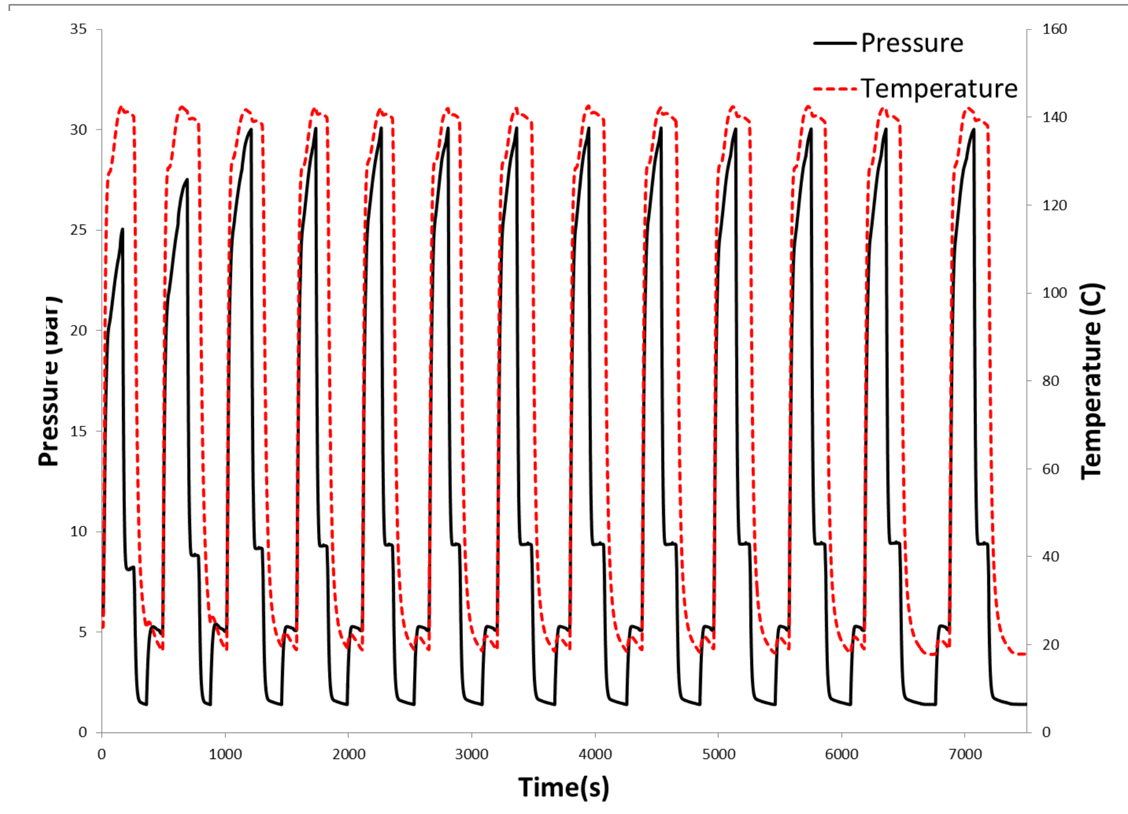
HARP System Assembly



Thermal Compressor Testing







Average mass flow will produce over 5 kW_e for this subscale design

Cost Breakdown of Thermal Compressor

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

Part	QTY	14 kW	QTY	58 kW	58 kW (optimum)
Extruded Tubes	276	$6,000.00	1,104	$24,000.00	$16,800.00
Baffels	28	$1,000.00	112	$4,000.00	$2,800.00
Endplates	8	$2,000.00	32	$8,000.00	$5,600.00
Shells	4	$2,500.00	16	$10,000.00	$7,000.00
Dip Braze	4	$7,000.00	16	$28,000.00	$19,600.00
Labor		$27,750.00		$111,000.00	$77,700.00
	Subtotal	$40,250.00		$185,000.00	$129,500.00
Sorbent	80 L	$16,800.00	320 L	$67,200.00	$47,040.00
	Cost/kg	$300	density	700 kg/m^3	
Refrigerant Valves	4	$4,000.00	4	$4,000.00	$4,000.00
HX Valves	8	$2,400.00	8	$2,400.00	$2,400.00
Ancillary valves	4	$400.00	4	$400.00	$400.00
	Subtotal	$6,800.00		$6,800.00	$6,800.00
Radiator	1	$500.00	1	$2,000.00	$2,000.00
HX Pump	1	$1,000.00	1	$4,000.00	$4,000.00
Tube/Fittings		$500.00		$2,000.00	$2,000.00
	subtotal	$2,000.00		$8,000.00	$8,000.00
	TOTAL	$65,850.00		$267,000.00	$191,340.00

LCOE Analysis

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- 1st Generation LCOE 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
- Estimated LCOE shows 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**

Conclusion

- New nanomaterials have enabled a practical new power generation technology
- 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 LCOE for commercial production units
- Next Steps
  - Extended duration thermal compressor tests
  - Integration with Viking CraftEngine
  - Demonstration system installed on Navy ship (Summer 2018)