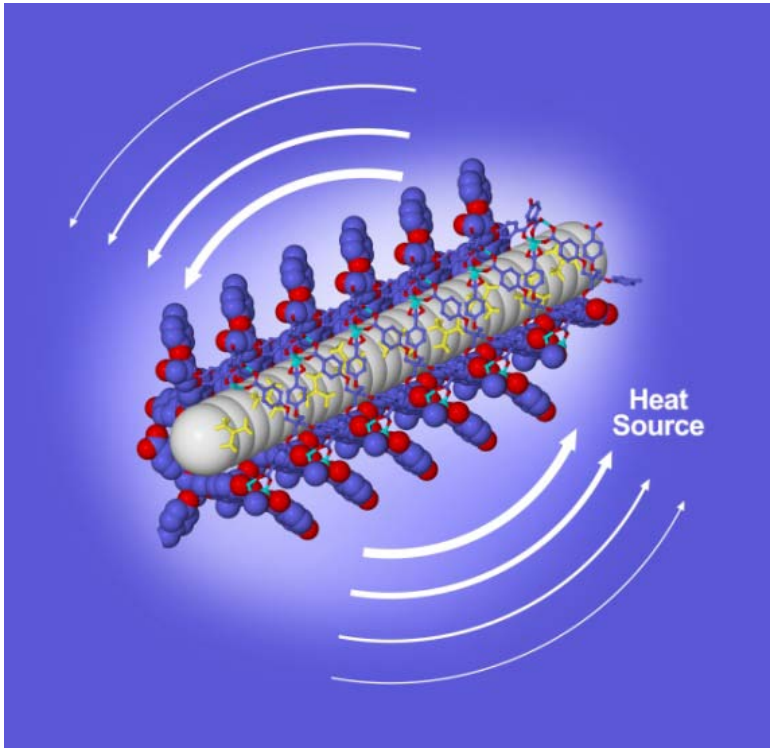

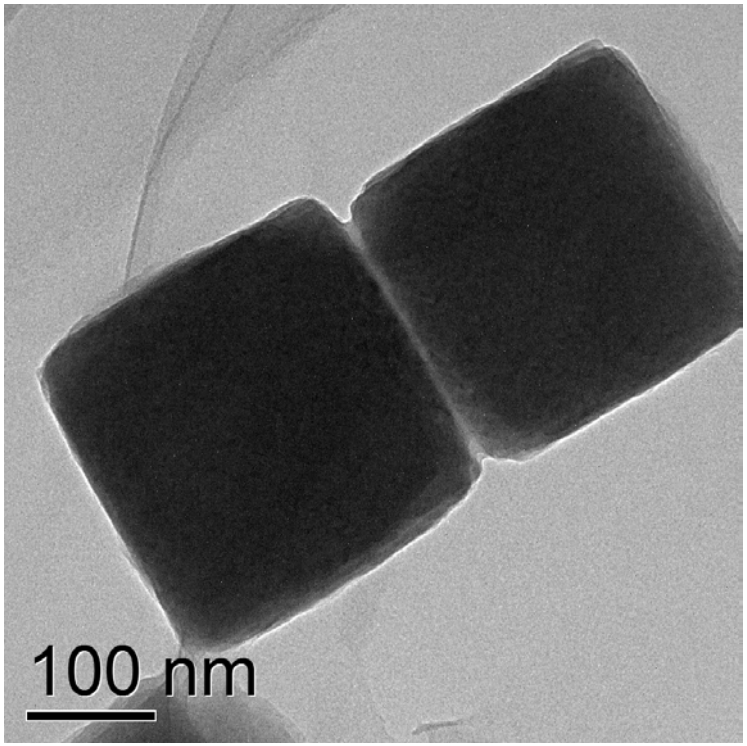

Metal Organic Heat Carriers for Enhanced Geothermal Systems

May 19, 2010

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Pacific Northwest National Laboratory
Specialized Materials and Fluids and Power Plants

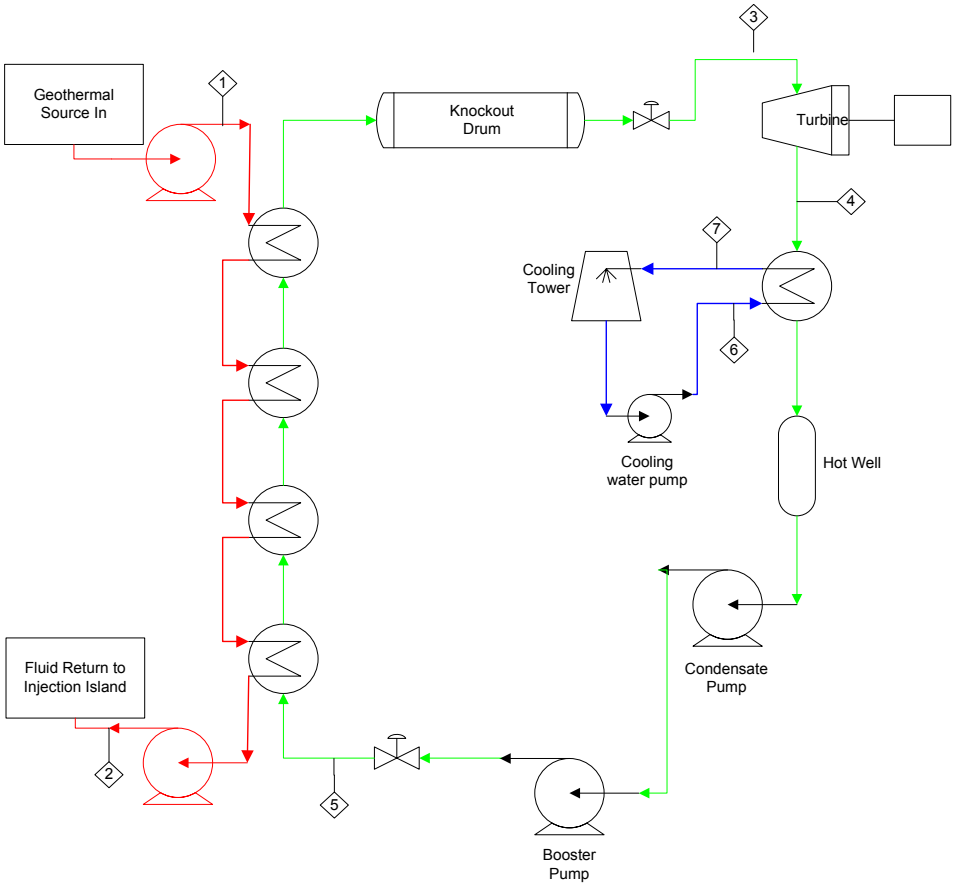
Project Overview

Award Number	56595
Total Project Funding Request	$1,236,432
Actual Start Date	9/01/2009
Planned Completion Date of the Project	09/30/2012
FY09 Funding	$456,000
FY10 Funding Expected	$476,432
Actual Costs through 05/7/10	$166,817
Cumulative Percent Spent	13%
Cumulative Percent Complete Timeline	19%

- This project addresses Energy Conversion Barrier N - Inability to lower the temperature conditions under which EGS power generation is commercially viable
- PNNL is partnering with Ormat Technologies, Inc. for loan of a portable ORC unit to support full cycle testing

Relevance/Impact of Research

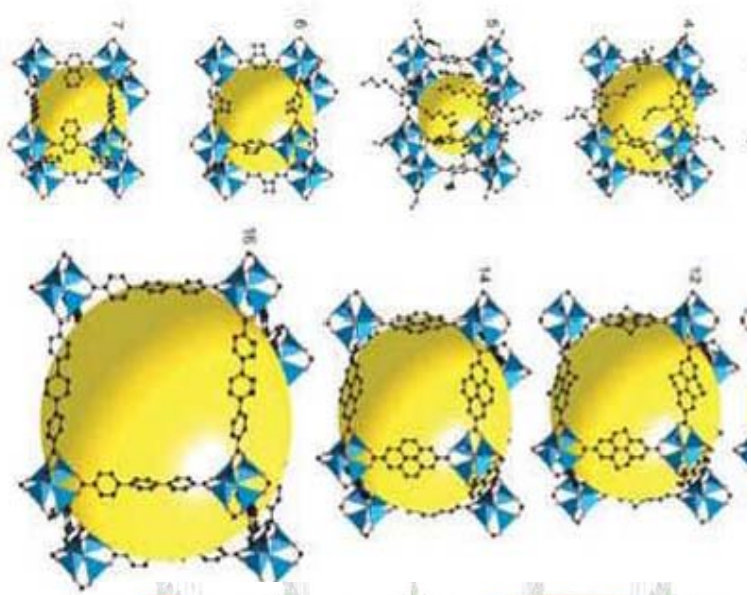
- Develop nanophase materials that interact at the molecular level with various working fluids
- Improve ORC efficiency by 10 to 20%
  - Boost the heat carrying capacity of the working fluid
  - Increase thermal conductivity
- Equal or potentially exceed molar density of the liquid or vapor phase states of the pure working fluid.

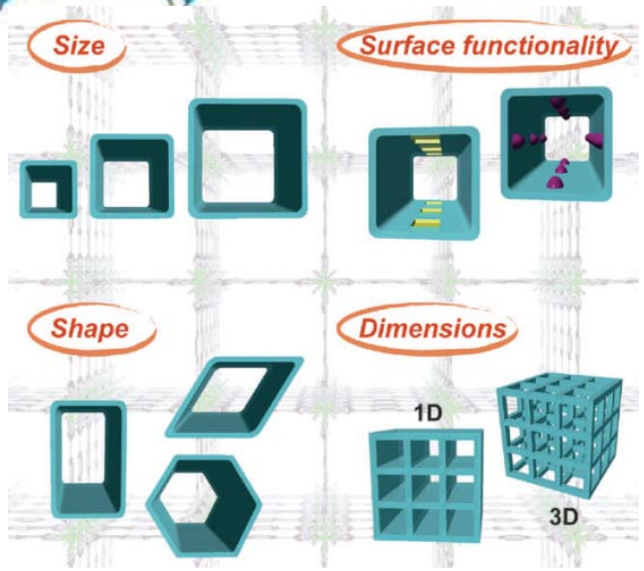


$$\frac{q_3^M}{q_3} = 1 + x_M \left(\frac{\Delta H_d}{\Delta H_v} - 1 \right)$$

Metal Organic Heat Carriers

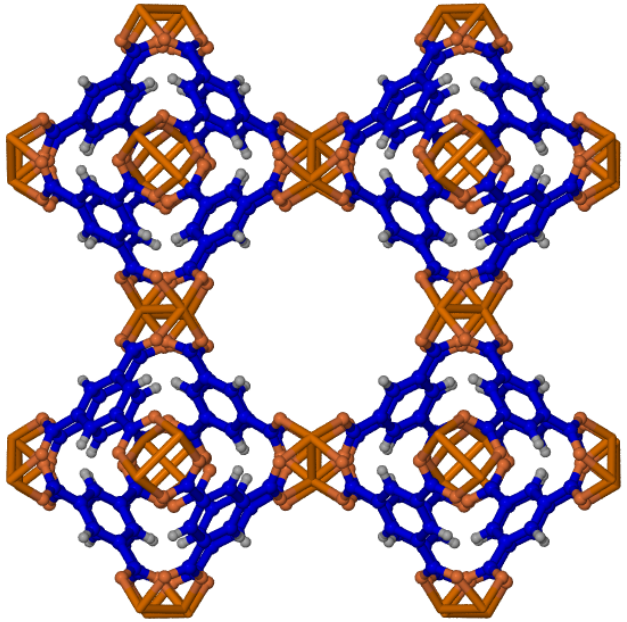
- Synthesis under mild conditions and templating techniques available to produce nanophase forms
- Many combinations of metal ions and organic linkers
- High structural and thermal stability >500 ° C
- Surface area 25 to 6000 m^2/g
- Tunable pore size, shape and chemical functionality

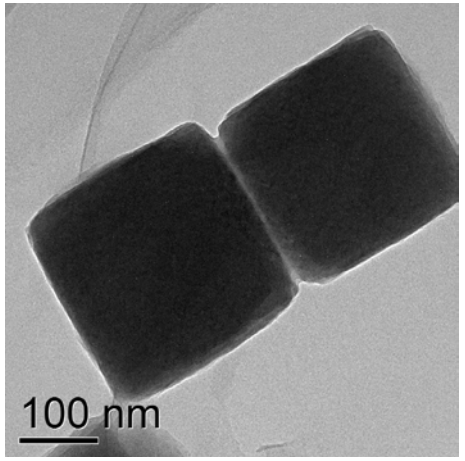




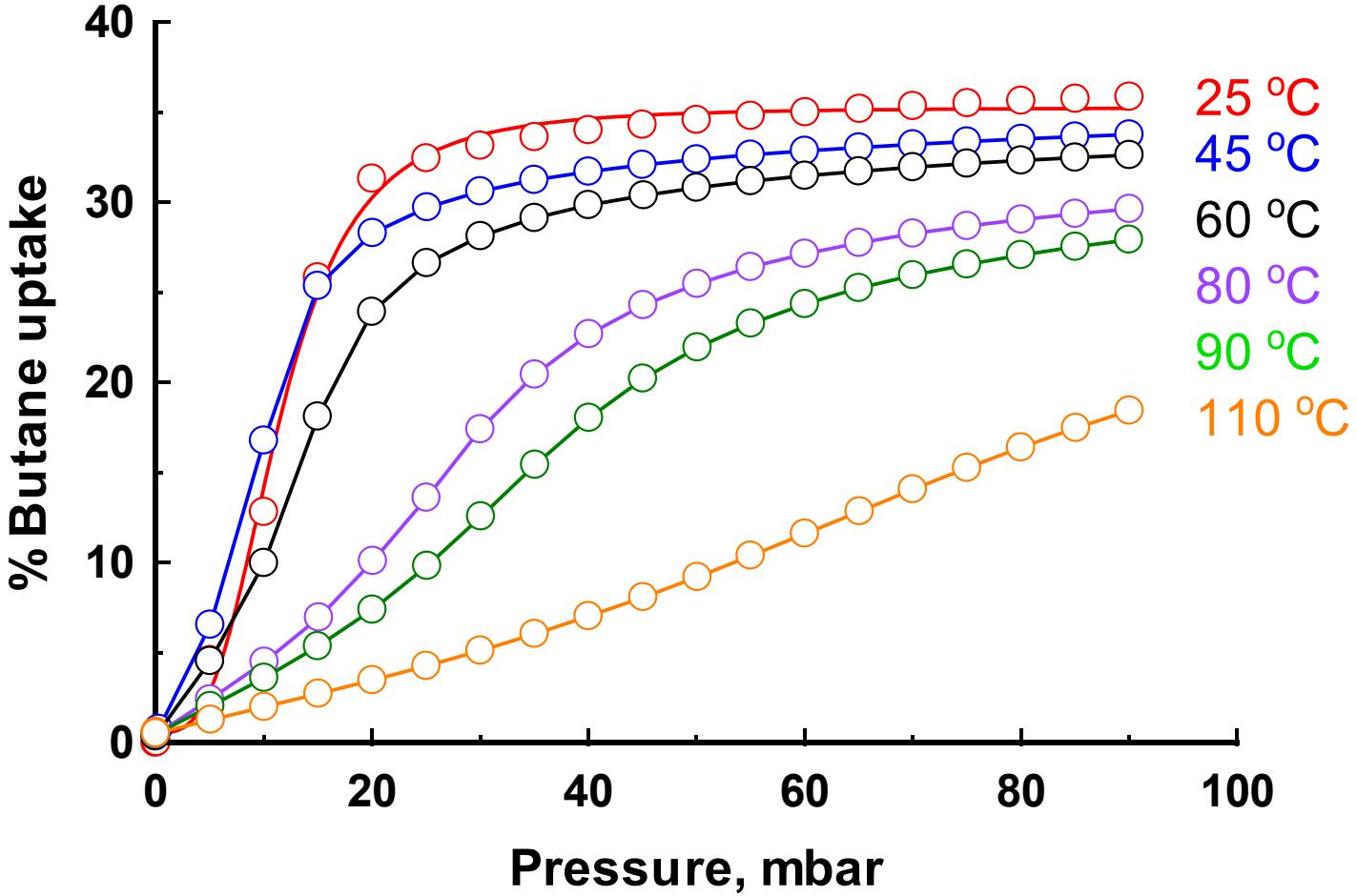
Highlights to Date

- Successfully synthesized several MOHC's with different organic linkers for initial evaluation, including nanophase form
- In depth characterization work underway (porosity, thermal stability, structure)
- Confirmed large uptake capacity (>30 wt%) using IGA-100 for various working fluids including a commercial product (Dow J) with Cu-BTC
- Using TG-MS, peak desorption temperatures are consistently 1.5 to 2X above standard boiling point of working fluid

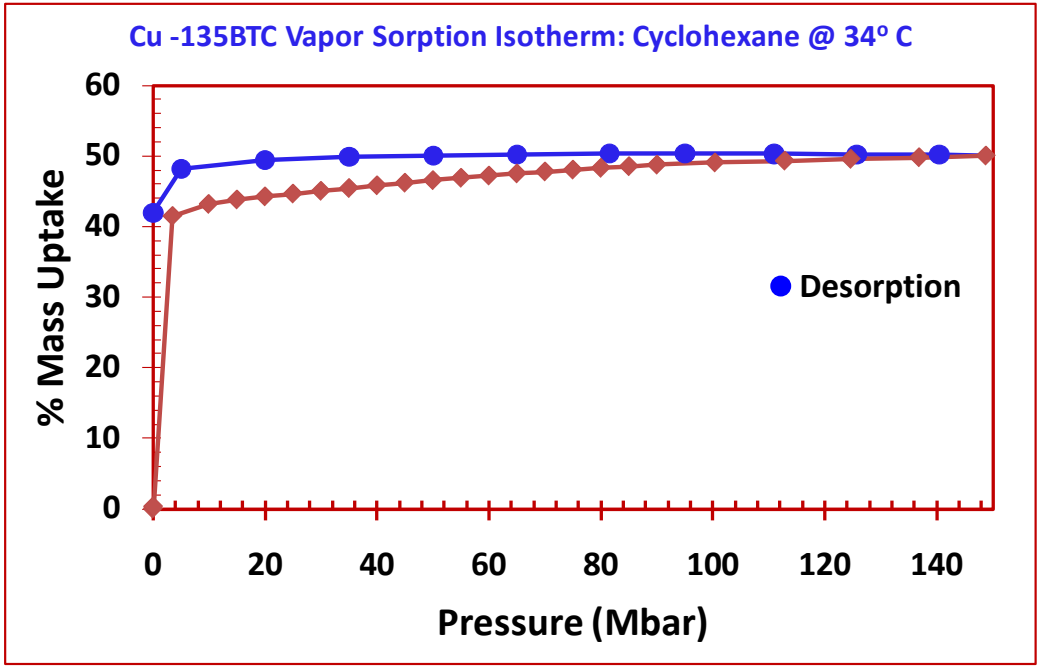


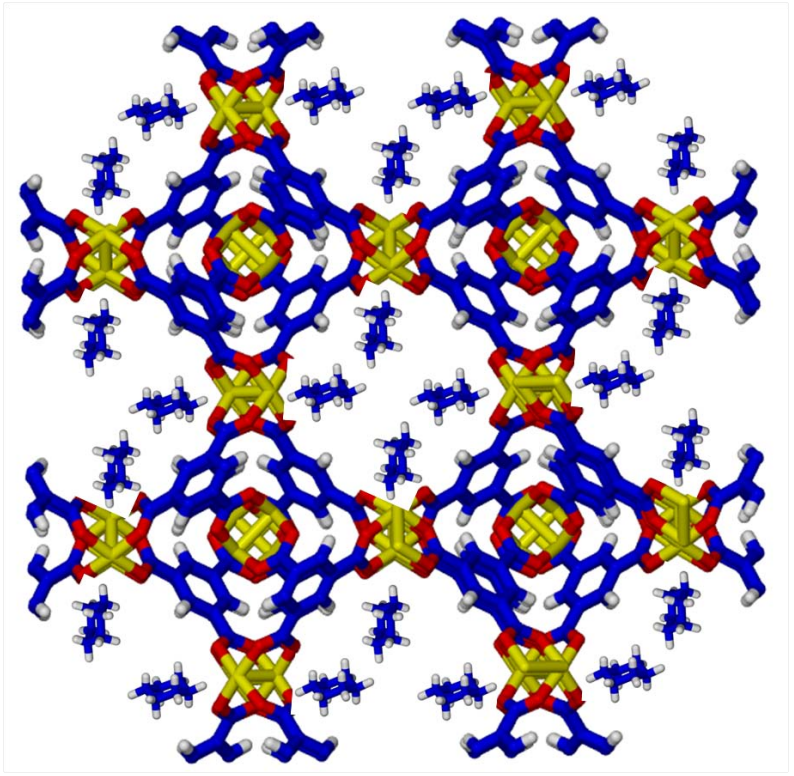


Adsorption of Butane with Cu-BTC

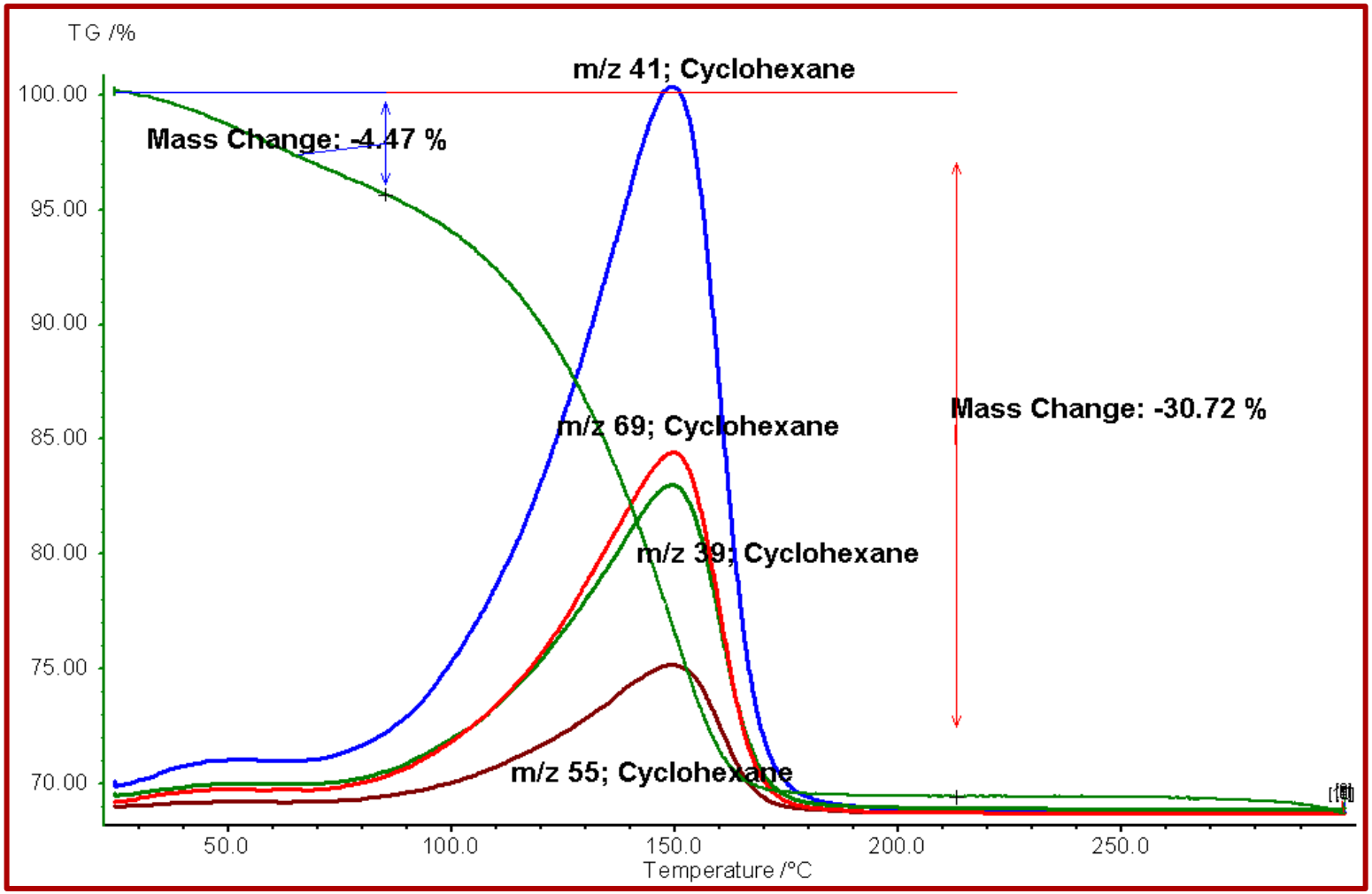


Adsorption of Cyclohexane





Desorption Behavior of Cyclohexane

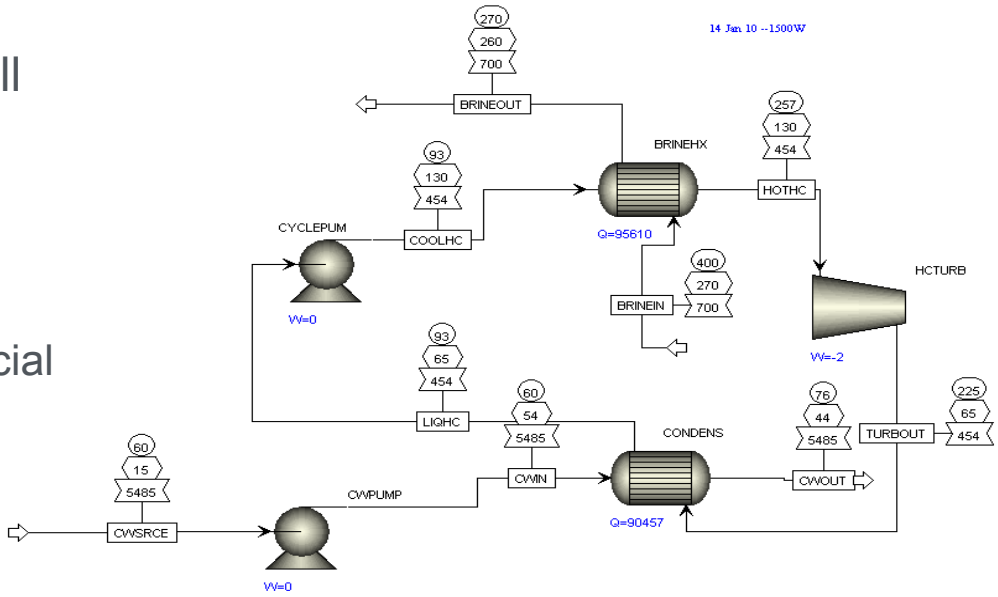


Preliminary Adsorption Thermodynamics of Various Alkanes on Cu-BTC

Working Fluid	Heat of Desorption (J/g)	Heat of Vaporization (J/g)	Peak Desorption Temp (°C)	Standard Boiling Point (°C)	Weight Capacity (%)
Cyclohexane	1217	356	145	81	50
Hexane	670	365	125	69	45
Pentane	186	357	75	36	40
Cyclopentane	350	407	95	49	35
Butane	180	386	35	-0.5	35

Test Loop System Development

- Test loop system design and procurement was implemented a full year ahead of original schedule
  - The 1.5 kW test loop system to be operational early in FY11
  - Microturbine will provide a needed bridge prior to testing with commercial equipment
- MOHC Performance Evaluation
  - Calculate cycle performance
    - Cycle efficiency and turbine power output
  - Compare cycle performance with and without MOHC's
    - Dependence on low, medium and high source temperatures
    - Evaluate MOHC's solids loading influence on optimization



- Instrumentation Plan
  - Cycle state pressures and temperatures
  - Gas, hot and chilled water loop mass flow rate
  - Turbine power output measurement system

Accomplishments, Expected Outcomes and Progress

- Milestones
  - Demonstrate synthesis of at least one candidate MOHC at nanoscale, 3/31/2010 (Complete)
  - Complete physical and thermodynamic property measurements for at least one MOHC with multiple working fluids, 9/30/2010 (On Schedule)
  - Biphasic fluid test loop system operational performance tests complete, 3/31/2011 (Ahead of Schedule)
- Performance Outcomes and Measures
  - Demonstrate achievement of a minimum 15 wt% loading for at least one organic working fluid with at least one MOHC candidate material (Exceeded Performance Requirements)
  - Demonstrate at least 20% greater heat capacity of at least one biphasic fluid candidate (Complete)
- Deliverables
  - Issue journal article on synthesis and properties of MOHCs, 7/30/2010, (On Schedule)
  - Issue PNNL report on biphasic fluid test loop system design, development, and testing, 12/31/2010 (On Schedule)

Project Management/Coordination

- Project Management Plans
  - Managing press and business/venture capital interest in MOHCs technology has been the most significant and unexpected management challenge
    - Project has been highlighted in numerous technical magazines including: *Scientific American, Popular Science, Technology Review, Discover Magazine*
    - *Over 100 business inquiries*
  - MOHCs patent application filed
- Schedule
  - Project is either on or ahead of schedule in meeting all planned milestones and deliverables
- Application of Resources and Leveraged Funds
  - PNNL investments in microturbine and facility modifications to accommodate Ormat loaned equipment have been leveraged to accelerate and expand testing over original plan

Mandatory Summary Slide

- MOHC nanomaterials synthesized to date are meeting or significantly exceeding performance requirements in terms of mass loading and binding energies with selected working fluids
- Aggressive steps have been taken to accelerate cycle performance testing and leverage non-EERE funding opportunities for facilities and equipment support
- Submission of peer reviewed publications and presentations at technical conferences to occur shortly

Supplemental Slides

Optional Slide

- "Novel Metal Organic Heat Carriers for Enhanced Geothermal Systems and Waste Heat Recovery," To be presented at Nanofluids: Fundamentals and Applications II, August 15-19, 2010, Montreal, Canada