MEMBRANE AND SEPARATION TECHNOLOGIES RESEARCH WORKSHOP

8:00 AM – 3:15 PM
JUNE 8, 2017
Navigant and NREL, on behalf of the United States Department of Energy, welcome you to this workshop on **Separation Processes and Membranes For Energy Efficiency**

**Introductions and Logistics**

- Overall schedule
- Breaks
  - Break: 10:40
  - Lunch: 12:15
- Airport transportation
- Introductions
<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
<th>Duration</th>
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<tr>
<td>8:30 AM</td>
<td>Introduction</td>
<td>45 mins</td>
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<tr>
<td>9:15 AM</td>
<td>Group Discussion</td>
<td>45 mins</td>
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<td>10:00 AM</td>
<td>Elevator Talks</td>
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<td>Breakout Discussion 1</td>
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<td>12:15 PM</td>
<td>Lunch</td>
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<td>1:15 PM</td>
<td>Preliminary Prioritization</td>
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<td>1:35 PM</td>
<td>Breakout Discussion 2</td>
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<td>2:55 PM</td>
<td>Final Discussion</td>
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BTO “lead(s) a vast network of research and industry partners to continually develop innovative, cost-effective energy saving solutions” for better buildings.
The Emerging Technologies group’s mission is to support building technology innovation through research primarily on TRL 2 and 3 technologies.

<table>
<thead>
<tr>
<th>Relative Level of Technology Deployment</th>
<th>Technology Readiness Level</th>
<th>TRL Definition</th>
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<tbody>
<tr>
<td>Basic Technology Research</td>
<td>TRL 1</td>
<td>Basic principles observed and reported</td>
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<td>TRL 2</td>
<td>Technology concept and/or application formulated</td>
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<tr>
<td>Research to Prove Feasibility</td>
<td>TRL 3</td>
<td>Analytical and experimental critical function and/or characteristic proof of concept</td>
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<tr>
<td>Technology Deployment</td>
<td>TRL 4</td>
<td>Component and/or system validation in laboratory environment</td>
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<td>TRL 5</td>
<td>Laboratory scale, similar system validation in relevant environment</td>
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BTO EMERGING TECHNOLOGIES RESEARCH PORTFOLIO

- Advanced windows
- Advanced refrigeration technology
- Building energy modeling
- Low global warming potential (GWP) refrigerants
- Heating, ventilating, air conditioning (HVAC)
- Solid state lighting
- Sensors and controls
- Advanced heat pumps:
  - Air source heat pumps
  - Integrated heat pumps
  - Heat exchangers
- Water heating and appliances
- Building Envelope
POTENTIAL APPLICATIONS OF MEMBRANES AND SEPARATION TECHNOLOGIES IN BUILDINGS

- Building-integrated heat & moisture exchange
- Envelope moisture barriers
- Indoor air quality sensors (CO, CO₂, VOCs, radon)
- Waste/grey-water processing
- Electric generation (fuel cells, osmotic power)
- Energy recovery ventilation
- Clothes dryers

Other C&I applications:
- CO₂ capture/separation
- Wastewater processing
- Water desalination
- Hydrogen production
- Oxygen-enriched air production

- Windows (fill-gas generation)
- Appliances
- HVAC including humidity control
- Radon barriers
BTO HAS SUPPORTED INNOVATION IN BUILDING TECHNOLOGIES THROUGH NUMEROUS R&D INITIATIVES.

See additional projects on BTO website: [http://energy.gov/eere/buildings/hvac-water-heating-and-appliances](http://energy.gov/eere/buildings/hvac-water-heating-and-appliances)
RECENT FOA AWARDS

• Advanced membrane A/C – Building Technologies Office
  - Dais Analytic (Florida)

• Electrochemical compression (ECC) A/C – Building Technologies Office
  - Xergy, Inc. (Delaware)

• Fuel Cell Membranes – Office of Basic Energy Sciences
  - Development of durable and inexpensive polymer electrolyte membranes for transportation and stationary applications. Membranes subtopic should be based on proton-conducting non-perfluorinated ionomers, but may include reinforcements or other additives
  - SBIR 2015 – 4 awards: NanoSonic (VA), NEI Corp. (NJ), Amsen Technologies, LLC (AZ), Giner, Inc. (MA)
    - http://energy.gov/eere/fuelcells/articles/sbirstr-fy16-phase-1-release-1-awards-announced-includes-four-fuel-cell

• Gas Dehydration – Advanced Manufacturing Office
  - Air Products and Chemicals, Inc.
VISION & MOTIVATION

Key Driver:

DOE’s goal is to support research to enable innovations that result in **dramatically improved efficiency** and/or **substantial cost reductions** for existing efficient equipment.

Why this specific research effort?

- Emerging field with applications in building systems
- Perceived disconnect between separation researchers and the buildings community
- Innovative solutions needed to reach 2030 energy goals
OBJECTIVE OF THIS WORKSHOP

Today’s objective:

• Gather input on where the greatest opportunities exist
• Guide prioritization of initiatives for DOE
WORKSHOP BOUNDS

• Today we focus solely on early-stage research activities that enable energy/cost savings
• Early-stage research initiatives (i.e. TRLs 2 and 3) focus primarily on basic technology research or research to prove feasibility.

Our discussion excludes:
» Policy issues
» Regulatory actions, such as efficiency standards
» Market transformation activities
Separation processes and membrane science for building applications

Jason Woods
National Renewable Energy Laboratory

BTO Separations Workshop
8-June-2017
Separation processes and membrane science for building applications

• Building research needs

• Separation and membranes processes

• The interface between membranes & buildings
Building research needs
Buildings consume **73%** of US electricity.
Buildings needs

• More efficient technology for HVAC and appliances
New homes behave differently
Buildings needs

• More efficient technology for HVAC and appliances
• Improved humidity control
Buildings needs

• More efficient technology for HVAC and appliances
• Improved humidity control
• Moisture durable walls
Ventilation becomes more important as building efficiency improves.
Ventilation from outdoors is not always desirable.
Buildings needs

- More efficient technology for HVAC and appliances
- Improved humidity control
- Moisture durable walls
- Management of ventilation and indoor air quality
Separation processes & membrane science
Separation process

An operation that transforms a mixture of substances into two or more products of different compositions.

Air $\rightarrow$ Dry air & $H_2O$

Air $\rightarrow$ $O_2$, $N_2$

Untreated water $\rightarrow$ pollutants and $H_2O$

Crude Oil $\rightarrow$ propane, gasoline, kerosene, diesel, fuel oil
Fractionation / distillation
Pollutant separation
particles (electrostatic precipitator)
SO$_2$ (Limestone slurry - liquid absorption)
CO$_2$ (amine liquid absorption)
Pollutant removal with micro-/ultra-filtration
Gas separation
Electrodialysis for purifying or concentrating liquids
Separation processes

• Fluid being treated
  o Liquid
  o Gas

• Driving potential
  o Pressure
  o Concentration
  o Electric charge
  o Temperature
  o Phase separation
Separation processes

Mass transport
from bulk fluid to interface
across interface (or membrane)
from interface to second bulk fluid
Symmetrical Membranes

Isotropic microporous membrane

Nonporous dense membrane

Electrically charged membrane

Anisotropic Membranes

Loeb-Sourirajan anisotropic membrane

Thin-film composite anisotropic membrane
Polysulfone (phase inversion)

Polypropylene (biaxially stretched)

UHMW Polyethylene (phase inv. + stretching)

anisotropic membrane
Fluid channel spacers

Spencer 3

Spencer 4

Applying separations and membrane science to buildings
Buildings research needs

• More efficient technology for HVAC and appliances
• Improved humidity control
• Moisture durable walls
• Managing ventilation and indoor air quality
Gas/vapor separation

Humid air

Water vapor transfer

Dry air
(to conditioned space)

Water vapor
(to ambient)

Compressor

N₂ or O₂

H₂O

dense membrane selective to water vapor

Vapor transfer

Selectivity H₂O/N₂ [ ]

Water vapor permeability [Barrer]

Liquid absorption

HVAC, appliances, and humidity control

Liquid absorption – internally cooled

Profiles:
\( p_v \) = vapor pressure
\( T \) = temperature
\( \omega \) = concentration

Cross section view

Air \hspace{1cm} Absorbent \hspace{1cm} Water

\( p_v \)

\( T \)

Membrane \hspace{1cm} Plate
Electrochemical compression

Heat pump process

By Evan Mason - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=20284870
Moisture durable envelopes
Indoor air quality and ventilation

- **Outdoors**: humid air
- **Indoors**: dry air
- **Ventilation airstream**: between indoors and outdoors
- **Exhaust airstream**: from indoors to outdoors

Water vapor transfer:
- From humid indoor air to dry outdoor air

Pollutant separation:
- Exhaust air from indoors is separated from the ventilation airstream.

Image of a dehumidifier equipment.
Jason Woods, PhD (jason.woods@nrel.gov)
Buildings and Thermal Sciences
Research needs

• Improved capacity of absorbents / adsorbents
• Stronger, more durable membranes that resist degradation (e.g., ozone) and fouling (e.g., pollutants or surfactants), but without sacrificing performance
• Novel fabrication or bonding techniques
• Improved transport to membrane surface
Liquid-desiccant heat exchanger experiments

LDHX experimental setup

Photo
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SLI.DO INTRODUCTION

**Step 1:** Go to www.Slido.com

Mobile or Computer
SLI.DO INTRODUCTION

**Step 2**: Enter Event Code – **2986**

Mobile or Computer
How tall was the world's tallest giraffe?

- 13 ft
- 15 ft
- 17 ft
- 19 ft
- 21 ft
SLI.DO POLL – INTRODUCTIONS

Event Code: 2986

Introductions

1. Name
   Type your answer here ...

2. Organization
   Type your answer here ...

3. Email
   Type your answer here ...

Powered by slido
SLI.DO POLL – LARGE GROUP INTRODUCTION

What is your area of expertise?

- HVAC
- Envelopes
- Appliances or Refrigeration
- Power or Water
- Other

*Multiple answers permitted
In which of the following areas would additional DOE funded separations-related research have the greatest impact (i.e. energy savings potential)?

- HVAC
- Envelope
- Appliances or Refrigeration
- Power or Water
SLI.DO POLL – LARGE GROUP DISCUSSION

Event Code: 2986

What is an important building-related separations/membrane challenge for DOE to tackle?

Type your answer here ...
LARGE GROUP DISCUSSION

• What trends do you see in the membrane/separation industries (including research areas, applications, etc.)?
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ELEVATOR TALKS

• 3-4 minute presentations by each of the following:
  - Ryan Huizing
  - Jeff McCutcheon
  - Saeed Moghaddam
  - Bamdad Bahar
  - Peter Luttik
  - Roderick Jackson
The McCutcheon Lab at UConn

**Membrane Processes**

- Forward Osmosis
- Pressure Retarded Osmosis
- Membrane Distillation
- Reverse Osmosis
- Membrane Fabrication

**Membrane Fabrication**

- Polymer film
- Casting rod
- Glass plate
- Pressure retarded osmosis

**Membrane Characterization**

- Surface: Concentration (mol/m^3)
- % Porosity
- Pure diameter, µm

**Membrane Design and Prototyping**
What this center provides:
- Contract research services
- Separations solutions across disciplines (water, solvent, vapor, gas)
- Scale-up and techno-economic assessment services
- Access to UConn infrastructure

We will serve:
- End users of membrane products
- Companies seeking a proving ground for new separations technology
- Membrane producers
Membrane-based Absorption Cycles for High Performance Heat-driven Cooling, Dehumidification, and Water Heating

Saeed Moghaddam
Nanostructured Energy Systems (NES) Laboratories

NREL, June 8th, 2017
Why membrane-based absorption?

- Enables compact, light, and low-cost absorption systems for small-scale applications
- Enables significant increase in absorption rate, implementation of ILs
  - \( \text{COP}_{\text{cooling,cycle}} \approx 1.7 \)
- Enables compact plate-and-frame heat and mass exchangers (HMXs)
- Prevents desiccant entrainment
- Enables high COP

These systems and their hybrid configurations can:
- address humidity challenges in buildings in all climates
- by handling latent load separately, greatly enhance HVAC systems efficiency
What Kind of Membranes?

- **Surface properties**
  - Hydrophobic (to constrain the absorbent)
  - Hygroscopic membranes allow the solution to migrate to the airside

- **Transport characteristics**

- **Durable**
  - 10-15 years of reliable operation
  - Chemically inert to not react with anything in air

- **Bondable**
  - Depends on the substrate material

- **Cost**
  - Depends on the system
    - < $1/ft² for dehumidification
What Kind of Membranes?

- Membrane properties are vastly different
- Type of membrane, material properties, thickness, hybridization, selectivity, etc. have to be carefully tuned for an ideal membrane
References

- S. Moghaddam, M. Mortazavi, S. Bigham, Compact and Efficient Plate and Frame Absorber, UF-15794, 2015
- S. Moghaddam, D. Chugh, S. Bigham, 3D Microstructures for rapid Absorption and Desorption in Mechanically Constrained Liquid Absorbents, UF-14936, 2013.
Why Ion Exchange Membranes For Energy Conversion

Ion transport is fundamental to nearly every process involving the transfer or conversion of chemical to electrical energy. Ion-transport membranes underpin many biological systems and are crucial to a diverse array of energy-related applications including: fuel cells, electrolyzers, batteries, electrochromics, chemical separators, membrane reactors, and sensors.

Controlling the movement of ions and molecules through nanoscale channels offers revolutionary pathways for development of new products. This technology is new, transformational, disruptive, and value added.

NO ONE CHEMISTRY can address all the opportunities in this arena. Must be open minded with respect to ion exchange chemistries, and be willing to work with any and all chemistries for any specific application.

I do, however, believe that ALL chemistries are improved by “compositing” or “reinforcement” technology. Our company is focused in this area, with an emphasis on intelligent microstructural design of composite membranes with improved stability, operational range, impurity tolerance, and transport efficiency and selectivity.
Ion Exchange Membranes: The Problem

Fundamental understanding of ionic transport in novel, nanostructured systems can drive dramatic improvement in energy conversion efficiencies.

- **The Problem:**
  - Ion Exchange Media are inherently weak. Therefore have to be reinforced by compositing to become stronger.
  - It’s important also to know how package them into useful devices, creating great products for critical applications.

- **The Solution:** Ion Exchange Media - Two Key Properties
  - Can transport ions under electric field (cations, anions).
  - Can transport polar molecules (pervaporation). Difference in concentration, temperature, pressure.

- **DOE Support:**
  - Xergy originally developed Compositing systems to meet BTO cost and performance targets for Electrochemical Compressors
  - Most recently received 3 ARPA-E awards to further develop Anion Exchange membranes
Composite membranes are key, because of their thinness and high performance. However, proper packaging membranes into functioning devices is non-trivial.

- 10 times thinner means 10 times lower cost
- Thinness means shorter distance for ions or molecules to travel. Means lower resistance, higher performance.
- Thinness without compromising on strength. Compositing provides mechanical reinforcement for otherwise weak materials.
- Lower cost plus higher performance = Leads to new possibilities i.e. Innovation

Suddenly, we have literally hundreds of product opportunities.
- Several Billion dollar scale applications.
Recent Case Studies

- Alkaline Fuel Cells
  - New class of fuel cells with much lower precious metal Catalyst loadings!

- Advanced Energy Recovery Ventilators
  - New class of ERV’s with higher performance

- Vacuum Membrane Desalination
  - New class of Desalination/Purification

- Ionic Liquid Desiccants
  - New class of desiccants to improve HVAC systems

- Sensors
  - New classes of low power, non-invasive sensors that Can dramatically improve smart systems (CO2, etc.)

DOE’s GOAL should be to create the ‘membrane production Infrastructure’ and then the new applications will ‘come’! It would be good if DOE can also sponsor a few ‘low hanging’ decent applications to establish markets and a decent ‘business’ base for the membrane producers! Eventually, entrepreneurs will take over and apply new Membranes to new applications.
Membrane enabled LDAC

DOE workshop June 8, 2017

Confidential
Independent Sensible and Latent Heating and Cooling

- 3-way all-plastic heat exchanger
  - Air – Desiccant – Water
- Desiccant absorbs moisture from the air stream
- Cooling water cool the air and carry away heat generated by the moisture absorption
- 7AC technology minimize the desiccant required to 1/10 of the chilled water flow
The Membrane Difference

No Desiccant Carry-Away

- Desiccant is separated from the air stream by a thin layer of membrane
- Gas permeable membrane allows cold, concentrated desiccant to absorb moisture in the air stream
- Thin membrane also allows heat transfer between the air and desiccant
- Membrane facilitates standard face velocity at <0.5” pressure drop
The LDAC System

- A full system is consisted of
  - Conditioner
  - Regenerator
  - Close circuit desiccant management system
  - Water chiller
- Chilled water (chiller evaporator) “power” the conditioner to provide cool, dry air to building
- Hot water from chiller (condenser) is re-used to re-concentrate the desiccant
Efficient dehumidification and cooling

**Psychometric Effects:**
- Vapor Compression Overcools and then Reheats
- Desiccant Wheels Overheat and Require Post Cooling

<table>
<thead>
<tr>
<th>Water Content of Air</th>
<th>Dry Bulb Temperature</th>
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<tbody>
<tr>
<td>100% RH</td>
<td>100°F</td>
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<tr>
<td>70% RH</td>
<td>80°F</td>
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<tr>
<td>50% RH</td>
<td>70°F</td>
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</table>

Psychometric Effects:
- Total h=23 btu/lb
- Overcool air to dew point of desired humidity ratio
- Vapor Compression & Reheat: h=17.5 btu/lb
- Reheat air for occupant comfort
- Separate Sensible Cooling
- Liquid 7AC Dry Membrane
- 7AC Wheels
- Initial 85°F 70%RH
- Liquid
- Target 75°F 50%RH

7AC Technologies – Confidential
LDAC system solutions for each of 8AC Zones™

1. Evaporative cooling
2. LDAC + dilution
3. LDAC + ACC or dilution
4. LDAC
5. LDAC + AdvDH coil
6. LDHP + AdvDH coil
7. LDHP
8. LDHP + dilution
Basic LDAC can be modified for superior performance in 8 Zones™
Benefits

- High efficiency from reduced lift without reheat/post cool
- Improved comfort from Independent humidity control
- No condense/no defrost cycle
- Simplified ERV
- Water based systems
Lower temperature lift improves compressor efficiency up to 66%

- Lower condensing temperature due to evaporative cooling of condensing (~10°F)

- Conventional system has lift about 65°F compare to 40°F for 7AC

- Higher evaporating temperature due to removal of latent cooling requirement (~15°F)

Low lift benefits for advanced HP solutions and heat driven solutions

*Based on 10 Summit Copeland Compressor
* Single Point EER
Drivers?

- ASHRAE standards for efficiency, ventilation and humidity management
- Building and district heating and cooling optimization incl. cogeneration and other waste heat use
- Heat pumps humidity and frost control
- Compatible with low lift innovative heat pump technologies
- Optimized evaporative cooling
- Compatible with flammable global warming potential refrigerants and zero refrigerant
1. DEVAP License exclusivity was critical for investors
2. 7AC funded CRADA supports system test verification and system modelling
   • Integration with OEM systems
3. DOD/DOE demonstration confirmed performance potential
   • Further demonstration support would accelerate industry acceptance, including end user adoption
4. IN2 partnership supports testing of advanced solutions
   • Vouchers to further intensify cooperation
5. HPC partnership explores molecular level membrane performance
   • Optimize hydrophobicity/hydrophilicity characteristics
   • Understand near Knudsen flow characteristics during evaporation and absorption
   • Optimize membrane design including manufacturability issues
6. Industry partnerships for market access and commercialized product
   • Stage gate process
   • Early adoption OEMs
   • 2018 deadline
7. Roll to roll manufacturing support to accelerate next generation low cost solutions
8. Advanced solutions require further support
   • Heat driven solutions with Mass CEC
   • Advanced heatpumps applications
   • Net zero solution
   • Integration of LDAC model in energy plus
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<td>10:40 AM</td>
<td>Break and Transition</td>
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<td>10:50 AM</td>
<td>Small Group Discussion</td>
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<tr>
<td>11:50 AM</td>
<td>Report Back to the Large Group</td>
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</tbody>
</table>
As a small group:

- Discuss items driving towards our key objective (described on next slide)
- Develop a list of potential initiatives

There will be an opportunity at the end of each breakout session to capture (via Sli.do) any topics of interest we did not have time to discuss.

[60 mins]

[6-7 mins/group]
Objective:
Discuss Concepts, Enabling Science, and applications that can result in membrane/separation-based energy savings in building technologies.
# BREAKOUT DISCUSSION 1 – ROOM ASSIGNMENTS

<table>
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<th>Group 1 (ROOM 1 – X248)</th>
<th>Group 2 (ROOM 2 – X324)</th>
<th>Group 3 (Room 3 – X326)</th>
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<tbody>
<tr>
<td>Bill Goetzler (Facilitator)</td>
<td>Matt Guernsey (Facilitator)</td>
<td>Jason Woods (Facilitator)</td>
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<tr>
<td>Omar Abdelaziz</td>
<td>Bambad Bahar</td>
<td>Daniel Betts</td>
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<td>Jason Lustbader</td>
<td>Roderick Jackson</td>
<td>Eric Kozubal</td>
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<tr>
<td>Jeffrey McCutcheon</td>
<td>Brian Johnson</td>
<td>Sven Mumme</td>
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<td>Saeed Moghaddam</td>
<td>Peter Luttik</td>
<td>Jim Peters</td>
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<tr>
<td>Sameer Rao</td>
<td>Lu Mi</td>
<td>Michael Wofsey</td>
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<tr>
<td>Ed Trudeau</td>
<td>John Pellegrino</td>
<td>John Zhai</td>
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<tr>
<td>Jeffrey Urban</td>
<td>Robert Tenent</td>
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Confidential and Proprietary
BREAKOUT DISCUSSION 1 – REPORT OUT

Report back on the initiatives discussed

[25 mins]
SLI.DO POLL

Event Code: 2986

Are there additional topics you did not have the opportunity to discuss?

Type your answer here ...
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<tr>
<th>Time</th>
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<tbody>
<tr>
<td>8:30 AM</td>
<td>Introduction</td>
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<tr>
<td>9:15 AM</td>
<td>Group Discussion</td>
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<tr>
<td>10:00 AM</td>
<td>Elevator Talks</td>
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<td>10:30 AM</td>
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<td>12:15 PM</td>
<td>Lunch</td>
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<tr>
<td>1:15 PM</td>
<td>Preliminary Prioritization</td>
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<tr>
<td>1:35 PM</td>
<td>Breakout Discussion 2</td>
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<td>2:55 PM</td>
<td>Final Discussion</td>
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<tr>
<td>2:55 PM</td>
<td>Final Discussion</td>
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Please select your top 5 initiatives

- Initiative 1
- Initiative 2
- Initiative 3
- Initiative 4
- Initiative 5
- ...

In selecting your top 5 initiatives, please consider:
1. Impact
2. Alignment with DOE mission
3. Criticality of DOE involvement
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<td>Break and Transition</td>
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<td>1:50 PM</td>
<td>Small Group Discussion</td>
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<td>Report Back to the Large Group</td>
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Based on the Sli.do responses, each group will collaborate to refine the highest-voted initiatives.

- Group 1 will discuss Initiatives 1, 4, and 7.
- Group 2 will discuss Initiatives 2, 5, and 8.
- Group 3 will discuss Initiatives 3, 6, and 9.

Each group will report back on each of the respective top-initiatives.

There will be an opportunity at the end of each breakout session to capture (via Sli.do) any topics of interest we did not have time to discuss.
Further flesh-out the previously discussed initiatives in order to:

1. Refine initiative title and objective(s)
2. Identify detailed technical challenges
3. Determine most promising applications
4. Identify partnership and collaboration opportunities
5. Characterize desired high-level outcomes (consider both energy and non-energy benefits)
BREAKOUT DISCUSSION 2 – REPORT OUT

Report back on the best initiatives discussed

[25 mins]
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</table>
FINAL DISCUSSION

- Any additional thoughts or ideas that we have not yet discussed?

- Combinations of existing ideas?
- New ideas?
- New twists?
- Important but missing details?
- New perspectives?
- Closing thoughts?
Thank you for your inputs

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DOE BTO Website for Emerging Technologies:
http://energy.gov/eere/buildings/emerging-technologies