Advanced Manufacturing,
Clean Energy Technologies and
Process Intensification

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NSF Process Intensification Meeting
VA Tech Executive Center, Arlington, VA

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Director
Advanced Manufacturing Office
www.manufacturing.energy.gov
Status Quo: Products invented here, and made elsewhere
Significance of U.S. Manufacturing

11% of U.S. GDP, 12 million U.S. jobs, 60% of U.S. Exports

U.S. Trade Balance of Advanced Technology

Swung to historic deficit, lost 1/3rd of workforce
Clean Energy: Nexus of Opportunities

Clean Energy Solutions

- Competitiveness in clean energy
- Domestic jobs
- Energy self-reliance
- Stable, diverse energy supply
- Clean air
- Climate change
- Health
Clean Energy Manufacturing Initiative – DOE

Collaboration toward:
- Common goal to collectively increase U.S. manufacturing competitiveness

Coordination for:
- Comprehensive Strategy
- Collaborative Ideas
Clean Energy Manufacturing Initiative: Objectives

1. Increase U.S. competitiveness in the production of clean energy products

- Products that generate clean energy
- Products that save energy

2. Increase U.S. manufacturing competitiveness across the board by leveraging energy productivity and low-cost domestic fuels and feedstocks

- Advanced Manufacturing Technologies
- Combined Heat & Power
- Industrial Energy Efficiency
Bridging the Gap to Manufacturing

AMO: Advanced Manufacturing Office

Technology Maturity (TRL; MRL; etc.)

R&D Investment Level

Governments and Universities

Private sector

 Doe Energy Innovation Hubs

 NSF Engineering Research Centers

 NSF IUCR Centers

 SBIR/STTR

 R&D Projects

 R&D Facilities

 Technical Assistance

 NIST Manufacturing Extension Partnership

 Concept → Proof of Concept → Lab scale development → Demonstration and scale-up → Product Commercialization
Manufacturing Sector Whitespace

Traditional Industry Sector Focus Areas

Energy Use-Impactful Manufacturing
- Transportation
- Efficient Systems
- Power Generation
- Energy Delivery

Cross-Cutting Impact Opportunities

Embedded Energy Intense Manufacturing
- Metals
- Glass & Ceramics
- Forest & Biomass
- Petrochemicals
- Extraction
- Concrete

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
Broad Topical Areas

• **Platform Materials and Technologies for Energy Applications**
  – Advanced Materials Manufacturing (Mat’l Genome, Nanomaterials, etc.)
  – Critical Materials
  – Advanced Composites & Lightweight Materials
  – 3D Printing / Additive Manufacturing
  – 2D Manufacturing / Roll-to-Roll Processes
  – Wide Bandgap Power Electronics
  – Next Generation Electric Machines

• **Efficiency in Manufacturing Processes (Energy, CO₂)**
  – Advanced Sensors, Controls, Modeling and Platforms (ie. Smart Manf.)
  – Advanced Chemical Process Intensification
  – Grid Integration of Manufacturing (CHP and DR)
  – Sustainable Manufacturing (Water, New Fuels & Energy)

• **Emergent Topics in Manufacturing**
1. Technical Assistance

2. R & D Projects

3. Manufacturing R & D Facilities

4. Process Intensification
Better Plants Program

• Voluntary pledge to reduce energy intensity by 25% over ten years over all facilities
• Over 120 Program Partners, over 1,750 plants, ~8% of the total U.S. manufacturing energy footprint
• Partners implement cost-effective energy efficiency improvements that:
  ➢ Save money
  ➢ Create jobs
  ➢ Promote energy security
  ➢ Strengthen U.S. manufacturing competitiveness
• Through the Better Plants Program, companies receive national recognition and technical support from DOE
Industrial Assessment Centers (IACs)

- IAC Program: Targets Energy Savings in Small-Medium Size Firms
- Average IAC client will save more than $46,000 in energy and process improvements (nearly 4X return in 18 months)
- Secondary benefit: Training next generation of Energy Leaders
1. Technical Assistance

2. R & D Projects

3. Manufacturing R & D Facilities

4. Process Intensification
Ultrafast, femtosecond pulse lasers (right) will eliminate machining defects in fuel injectors. *Image courtesy of Raydiance.*

Energy-efficient large thin-walled magnesium die casting, for 60% lighter car doors. *Graphic image provided by General Motors.*

Protective coating materials for high-performance membranes, for pulp and paper industry. *Image courtesy of Teledyne*

A water-stable protected lithium electrode. *Courtesy of PolyPlus*
R&D Projects: Combined Heat and Power (CHP) (Process Intensification of Electric Power)

**Advanced MicroTurbine System (AMTS) R&D Program**

- Advanced MicroTurbine System (AMTS) R&D Program
- C200 Capstone MicroTurbine Engine
- QSK60G engine

**Advanced Reciprocating Engine Systems (ARES) R&D Program**

- Advanced Reciprocating Engine Systems (ARES) R&D Program
- QSK60G engine

*Capstone photos source: capstoneturbines.com*
1. Technical Assistance
2. R & D Projects
3. Manufacturing R & D Facilities
4. Process Intensification
Shared R&D Facilities

➢ Address market disaggregation to rebuild the industrial commons

Ford River Rouge Complex, 1920s
Photo: Library of Congress, Prints & Photographs Division, Detroit Publishing Company Collection, det 4a25915.

➢ How do we get innovation into manufacturing today?
AMO-supported R&D Facilities

1. **Manufacturing Demonstration Facility** at Oak Ridge National Lab

2. **America Makes**, The National Additive Manufacturing Innovation Institute

3. **Critical Materials Institute**: A *DOE Energy Innovation Hub* at Ames National Lab

4. **Next Generation Power Electronics Manufacturing Innovation Institute**

5. **Composites Materials and Structures Manufacturing Innovation Institute** (future – active solicitation)

DOE Assistant Secretary David Danielson during ribbon cutting ceremony of the Carbon Fiber Technology Facility at Oak Ridge National Laboratory. Carbon fiber has the potential to improve the fuel efficiency of vehicles.

*Photo courtesy of Jason Richards, Oak Ridge National Laboratory.*
Program goal is to accelerate the manufacturing capability of a multitude of AM technologies utilizing various materials from metals to polymers to composites.
Critical Materials Institute

A DOE Energy Innovation Hub

- Consortium of 7 companies, 6 universities, and 4 national laboratories
- Led by Ames National Laboratory

Next Generation Power Electronics Manufacturing Innovation Institute

Institute Mission:
Develop advanced manufacturing processes that will enable large-scale production of wide bandgap semiconductors

- Higher temps, voltages, frequency, and power loads (compared to Silicon)
- Smaller, lighter, faster, and more reliable power electronic components
- $3.3 B market opportunity by 2020.¹
- Opportunity to maintain U.S. technological lead in WBG

Poised to revolutionize the energy efficiency of electric power control and conversion

¹ Lux Research, 2012.
Broad Topical Areas

• **Platform Materials and Technologies for Energy Applications**
  – Critical Materials
  – 3D Printing / Additive Manufacturing
  – WBG Power Electronics
  – Advanced Composites & Lightweight Materials
  – Advanced Materials Manufacturing (Mat’l Genome, Nanomaterials, etc.)
  – 2D Manufacturing / Roll-to-Roll Processes
  – Next Generation Electric Machines
  – Value-Added Chemicals from Biology

• **Efficiency in Manufacturing Processes (Energy, CO2)**
  – Advanced Sensors, Controls, Modeling and Platforms (ie. Smart Manf.)
  – Advanced Chemical Process Intensification
  – Grid Integration of Manufacturing (CHP and DR)
  – Water & Energy for Manufacturing
  – Alternative Fuels (Natural Gas) and Manufacturing

• **Emergent Topics in Manufacturing**

- Encompass machine-to-plant-to-enterprise-to-supply-chain aspects of sensing, instrumentation, monitoring, control, and optimization

- Enable hardware, protocols and models for advanced industrial automation: requires a holistic view of data, information and models in manufacturing

- Leverage High Performance Computing for High Fidelity Process Models

- Significantly reduce energy consumption and GHG emissions & improve operating efficiency – **20% to 30% potential**

- Increase productivity and competitiveness across all manufacturing sectors: Special Focus on Energy Intensive Manufacturing Processes

**Leverages AMP 2.0**
Advanced Materials Manufacturing

Leveraging unique capabilities for fast-tracking materials to market, while expanding and enhancing the tools & methods in the core

Core Effort for Advanced Materials
unique set of in-house capabilities in accelerated energy-materials development

Advanced Modeling, Computing, and Simulation Capabilities
leveraging and expanding on the current MGI multi-physics, multi-scale computational base

High Throughput Synthesis, Characterization & Analysis Capabilities
high productivity combinatorial discovery & development tailored to specific energy end uses

linkages in methods / data / intellectual property

Combines multi-physics, multi-scale computation with high-throughput synthesis and characterization for intelligent, focused RD&D in numerous energy technology thrusts, managed, e.g., in cross-cutting Materials Manufacturing Centers of Excellence (MMCOEs)

Leverages AMP 2.0
2D Fabrication / Advanced Roll-to-Roll Manufacturing

- Technology development for the electronic manufacturing service (EMS) sectors to move from plate-to-plate standard lithography to continuous R2R processing.
- Miniaturization of critical feature sizes to the nanoscale
- Advancing tools and methods for process control, defect sensing, and real-time feedback

- Potential Energy Applications:
  Solar, Batteries, Fuel Cell MEAs, Separation Membranes, Building Envelopes, etc.
1. Technical Assistance

2. R & D Projects

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AMO Topical Areas

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• Emergent Topics in Manufacturing
Process Intensification

- Termed in 1970s by Kleemann et al. and Ramshaw\cite{15,16}
- What does “process intensification” mean?

\textit{Process intensification is a chemical process with the precise environment it needs to flourish, results in better products, and processes which are safer, cleaner, smaller, and cheaper.}

- The BHR Group\cite{19}

\cite{15} G Kleemann, K Hartmann, Z Wiss. Tech Hochschule “Carl Schorlemmer” Leuna Merseburg 20:417, 1978
\cite{19} BHR Group: www.bhrgroup/pi/aboutpi.htm

Acknowledgement: Dane Boysen, ARPA-E
The Chemical Engineer

Process Flow Diagram

\[
\frac{Cost_2}{Cost_1} = \left( \frac{Capacity_2}{Capacity_1} \right)^m
\]

...the world is a pipe
The Chemist

- Reactions
  - Kinetics
  - Thermodynamics
  - Transport

- Many new catalysts
  - High selectivity, $S$
  - High conversion, $X$
  - High yield, $Y = X \cdot S$

- No breakthrough in last 20 years

$$aA + bB \rightarrow cC + dD$$

$$[A](t) = [A]_0 \cdot e^{-kt}, \quad k = k_0 \cdot e^{-E_a / k_B T}$$

$$dU = TdS - pdV + \sum_i \mu_i dn_i$$

Very stable

Low rates

...the world is a beaker
Process Intensification Overview

- **Objectives**
  - Significantly enhance transport rates (chemical engineer)
  - Give every molecule exactly the same processing experience (chemist)

- **Approach**
  - *Develop processes that lead to dramatically smaller equipment with*
  - Improved control of reactor kinetics
  - Higher selectivity/reduced waste
  - Higher energy efficiency
  - Reduced capital costs
  - Reduced inventory
  - Enhanced intrinsic safety
  - Fast response times

Challenge for Scaling Chemical Manufacturing is not high cost, it is the pace of Innovation Linked to high risk!
Economies of Scale

Current paradigm in the chemical process industry

- Economies of scale -- “bigger is better”
- Cost (materials) $\propto$ Area $[D^2]$
- Revenue (capacity) $\propto$ Volume $[D^3]$
- Williams equation$^{[8]}$

$m = 0.38-0.90$

$$\frac{\text{Cost}_2}{\text{Cost}_1} = \left(\frac{\text{Capacity}_2}{\text{Capacity}_1}\right)^m$$

Economies of Scale

GTL Cost vs. Capacity

Is Bigger Better?

Sasol-Chevron Fischer-Tropsch Reactor

Yes, that is a person!
How do we get down new cost reduction learning curves?
Experience Learning Curves

- 1960s Bruce Henderson of Boston Consulting Group
- 15% cost reduction every doubling of output – the “85% experience curve”
- Henderson’s Law\(^{[11]}\)
  - \(n\): number of units
  - \(a\): elasticity of cost with regard to output

\[
Cost_n = Cost_1 n^{-a}
\]

Experience Learning Curves

Total Production Costs of Midsize Cars\textsuperscript{[12]}

![Chart showing the total production costs of midsize cars with a decrease of 30% and 50% for Audi A8 and Ford P2000 respectively.](chart.png)

\[\text{Costs (\$)}\]

\[\text{Production (units/year)}\]

\[\text{Audi A8}\]
\[\text{Ford P2000}\]

Paradigm Shift

Cost ($/boe)

Scale-out (new)

Scale-up (old)

Opportunity

\[
\frac{\text{Cost}_2}{\text{Cost}_1} = \left(\frac{\text{Capacity}_2}{\text{Capacity}_1}\right)^m
\]

\[
\text{Cost}_n = \text{Cost}_1 n^{-a}
\]
Vision

Scaled Modules

- Defines challenges x3
- Engineers system
- Establish specs/standards

Integrate

Evaluates performance
Assesses economics

Modules

Reactors innovations
Process intensification

innovate

module

reactor

Integrate
Examples of Process Intensification

- Spinning disk reactor
- Static mixer reactor
- Static mixing catalysts
- Monolithic reactors
- Microreactors
- Heat exchange reactors
- Supersonic gas/liquid reactors
- Jet-impingement reactor
- Rotating packed-bed reactor

- Static mixers
- Compact heat exchanger
- Microchannel heat exchangers
- Rotor/stator mixers
- Rotating packed beds
- Centrifugal adsorber

- Reverse-flow reactors
- Reactive distillation
- Reactive extraction
- Reactive crystallization
- Periodic separating reactors
- Membrane reactors
- Reactive extrusion
- Reactive comminution
- Fuel cells

- Membrane adsorption
- Membrane distillation
- Adsorptive distillation

- Centrifugal fields
- Ultrasound
- Solar energy
- Microwaves
- Electric fields
- Plasma technology

- Supercritical fluids
- Dynamic (periodic) reactor operation
Process Intensification:
Examples of Developments
HiGEE Separation Units

Conventional Distillation Column

HiGee

L = liquid mass flux
G = gas mass flux
ρ_g = gas density
ρ_l = liquid density
a = packing area per unit volume
g = applied acceleration
E = packing voidage (capital E in the figure)
u_g = gas velocity.
The Compact Heat Exchanger

• Markets
  – Compact HEX,
    10% world market
    10% sales/year increase
  – World HEX
    1% market growth/year

Catalytic Membrane Reactors

**Hydrogen Transport Membrane**
- **Input**: $CH_4$, $C_2H_4, C_2H_6$, aromatics, $H_2$
- **Output**: $H_2O$, $H_2$
- **Reaction**: $2CH_4 + O_2 = C_2H_4 + 2H_2O$

**Oxygen Transport Membrane**
- **Input**: $CH_4$, $N_2, O_2$
- **Output**: $CO, H_2$
- **Reaction**: $CH_4 + \frac{1}{2}O_2 = CO + 2H_2$

Possible Metrics

• Cost vs. Scale – bend scaling curve by x%?

• Scale-up Costs and Predictability?

• Product Costs:
  
  Product Transportation vs Supply Transportation?
  
  Capital Efficiency vs. Chemical Efficiency
Information Needed

• Quantitative High Level Targets and Opportunities
  ($/W, $/kg, energy efficiency, CO$_2$ intensity,...)

• Direct Industry Dialog on Specific Topics:
  Workshops:  NSF: Sept 30-Oct 1
              DoD: Oct 8-9

• Quantitatively and Qualitatively: If this is such a good idea, why can’t or won’t industry do this itself?

• What is the Urgency? What issues first and why (Int’l landscape, changing energy, externalities)
Microfactories vs. Gigafactories

Example in Additive Manufacturing

Can we Print a car with a small factory (process intensified), rather than an assembly line (traditional process)

- Small Footprint Manufacturing
- Accelerated Innovation Cycles
- Sustainable Processes
- Higher Efficiency
- Reduced Risk of Stranded Capital Assets
Large-Scale, Out-of-Oven Additive Manufacturing

Big Area Additive Manufacturing (BAAM)

- **Pellet-to-Part**
  - Pelletized feed replaces filament to enable 50x reduction in material cost
- **Deposition rate >100x available additive systems**
- **High deposition rates (~20 lbs/h)**
  - FDM is 1 to 4 ci/hr
  - Large Scale is > 200 ci/hr to 400 ci/hr
- **Prototype system 8’x8’x8’ build volume**
- **Initial interest by aerospace and composites tooling industry**
Partnership with CRADA

ORNL and Cincinnati Incorporated collaborate to create commercial large-scale system

Partnership to establish US-based large-scale AM equipment manufacturer
- Targets tooling lead time and cost reduction
- Based on existing ORNL gantry system
- Cincinnati providing >$1M in cost share year one
  - First large-scale polymer AM system delivered to MDF, April 2014
- Interest from multiple automotive, aerospace and tooling industries
- Stretch form and hydroform tools demonstrated
Partnership with CRADA

Extreme Innovation First 3D Printed “Strati” Car
Rapid automotive design and innovation using large-scale polymer additive manufacturing

3D car printed “live” at IMTS
Partnership with

Extreme Innovation First 3D Printed “Strati” Car
Rapid automotive design and innovation using large-scale polymer additive manufacturing

See the Strati revealed
Friday 1 pm
AMT's ETC in N-650

https://energy.gov/eere/amo/downloads/printing-car-team-effort-innovation
https://www.youtube.com/watch?v=Uzgh8iSuTZA
What does Success Look Like?

Energy Products Invented Here...

...And Competitively Made Here!
Thank You

Questions?