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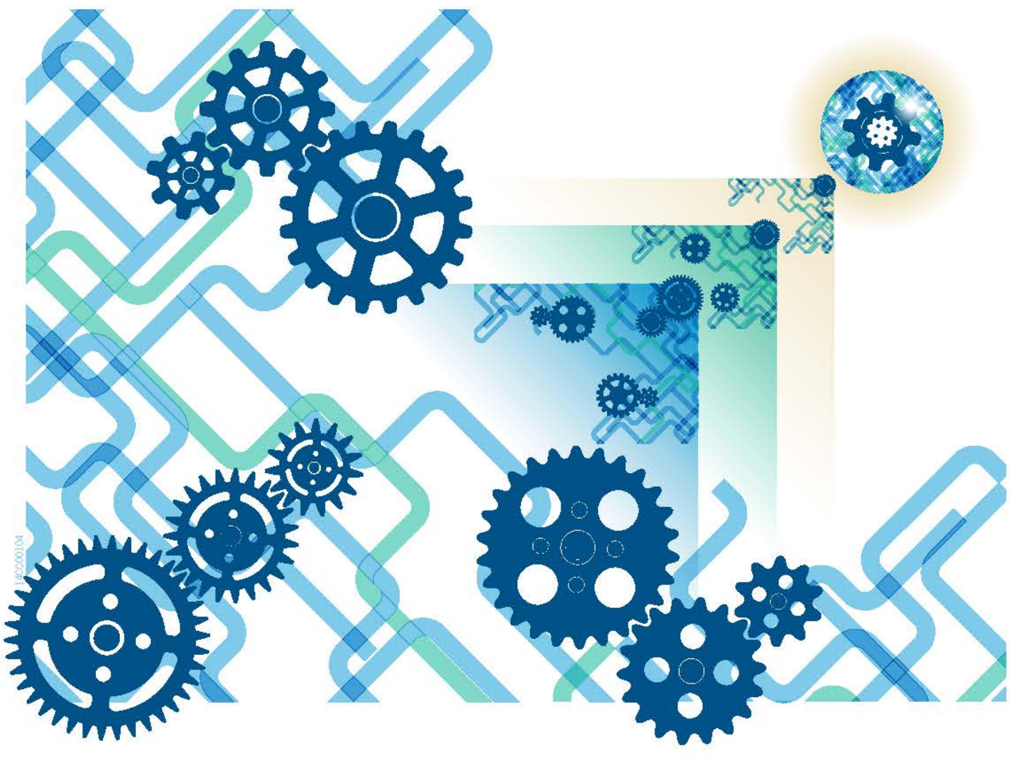
Report from National Science Foundation

Process Intensification Workshop



Washington, DC, September 30 - October 1, 2014

Acknowledgement

The workshop organizers wish to recognize the participants of the workshop. The participant's comments and input was used directly in the production of the summary report. The workshop organizers also wish to acknowledge the support from the National Science Foundation Chemical, Bioengineering, Environmental, and Transport Systems Organization within the Directorate of Engineering for the financial support of this workshop under Grant No. 1450788.

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Organizers

Marianthi Ierapetritou (Chair), Rutgers University
Michael Baldea (Co-Chair), The University of Texas at Austin
Bond Calloway (Co-Chair), Savannah River National Laboratory
Maria Burka (Co-Chair), National Science Foundation
Thad Adams, Savannah River National Laboratory

Attendees

Thad Adams	Savannah River National Laboratory
Rakesh Agrawal	Purdue University
Michael Baldea	The University of Texas at Austin
Dane Boysen	DOE Advanced Research Projects Agency-Energy
Kyle Brinkman	Clemson University
Maria Burka	National Science Foundation
Richard Calabrese	University of Maryland
Bond Calloway	Savannah River National Laboratory
Prodromos Daoutidis	University of Minnesota
Ravi Dixit	Dow Chemical Company
Kevin Drost	Oregon State University
Mario Eden	Auburn University
Thomas Edgar	The University of Texas at Austin
Bruce Eldridge	The University of Texas at Austin
Michael Flickinger	North Carolina State University
Ed Gatzke	University of South Carolina
Jeffrey Grenda	Exxon-Mobil
Ignacio Grossmann	Carnegie Mellon University
Adam Harvey	Newcastle University
Robert Huss	Eastman Chemical Company
Marianthi Ierapetritou	Rutgers University
Kai Jarosch	Velocys, Inc.
Mark Johnson	DOE Energy Efficiency & Renewable Energy, Advanced Manufacturing Office
JoAnn Lightly	National Science Foundation
Fernando Lima	West Virginia University
Ryan Lively	Georgia Institute of Technology
Vasilios Manousiouthakis	University of California Los Angeles
David Marler	Exxon-Mobil
David Miller	National Energy Technology Laboratory
Sharon Robinson	Oakridge National Laboratory
Darlene Schuster	American Institute of Chemical Engineers
Joseph Scott	Clemson University
Jeffrey Siirola	Carnegie Mellon University/Purdue university
Joseph Smith	Missouri University of Science & Technology
Tom Van Gerven	Katholieke Universiteit Leuven
David Vernon	Humboldt State University
Goetz Veser	University of Pittsburgh
Dionisios Vlachos	University of Delaware
Phillip Westmoreland	North Carolina State University
Benjamin Wilhite	Texas A&M
Monica Zanfir	Praxair, Inc.

NSF Process Intensification Workshop
Washington, DC
September 30-October 1, 2014

Summary

The National Science Foundation (NSF) sponsored workshop on Process Intensification (PI) was held September 30 - October 1, 2014 in Washington, DC. Forty people attended from academia, industry, federal government, and the DOE national laboratory system. The objective of the workshop was to be a colloquium where the main contributions in the area of process intensification would be discussed and the challenges identified. Bringing together academic and industrial participants, the workshop provided a unique forum to identify the existing successes and future opportunities in the process area.

The workshop consisted of four presentation sessions (Appendix I) including one general session covering the main concepts of PI, and three application sessions including PI opportunities for different industrial sectors, such as chemical, petrochemical, energy, and pharmaceutical. It also highlighted advances in the fundamental sciences of reaction engineering, separation processes and environmental engineering.

Participants were asked to complete a questionnaire (Appendix II) providing input regarding the challenges and opportunities in PI, how their research fit into this area, and how the Smart Manufacturing initiative can interact with activities in PI. This report summarizes input received through the questionnaires, and from workshop presentations and discussions.

Figure 1 – Dividing Wall Column Pilot Plant at The University of Texas at Austin

1.0 Introduction

The PI concept becomes transformational by dramatically changing the scale-up cost relationship between surface area and volume, hereby eliminating the “big-is-beautiful” philosophy of plant design[1]. In spite of these advantages, there are still significant technology and commercial barriers for the implementation of PI technologies. These include: 1) the lack of a unified framework for the identification of intensification opportunities and design of intensified processes. In turn, this potentially leads to 2) significant missed

[1] Reay, D., C. Ramshaw, and A.P. Harvey. Process Intensification: Engineering for Efficiency, Sustainability and Flexibility. Butterworth-Heinemann. 2013.

opportunities by American industry, especially given the reemergence of domestic manufacturing and the construction, for the first time in decades, of new chemical facilities in the U.S. This problem is exacerbated, by 3) the lack of a well-established forum where industry and academia can identify existing needs, validate solution concepts, and define future research directions.

In a broader context, a National Research Council Study in 2007[2] found that U.S. chemical engineering had lost much competitive ground to Asia and Europe: "the strong past U.S. position in the following subareas, several of which constitute the core of chemical engineering, has been weakened and is expected to continue to weaken in the near future:

- transport processes;
- separations;
- heterogeneous catalysis;
- kinetics and reaction engineering;
- process development and design; and;
- dynamics, control, and operational optimization."

PI represents, in effect, the nexus of many of the aforementioned fundamental areas of Chemical Engineering. Involvement in PI projects will create many educational and training opportunities where U.S. students can naturally acquire fundamental skills while engaging in cutting-edge research that is highly relevant to the domestic industry.

General Discussion

Significant discussion occurred during breakout sessions on the definition of process intensification, smart manufacturing and the linkage to process science and process systems engineering. The organizers of the workshop offered the following definition, which is adapted from the definition provided in the European Roadmap for Process Intensification.

> *Process intensification is a set of often radically innovative principles ("paradigm shift") in process science, chemistry and equipment design, which can bring significant (more than factor 2) benefits in terms of process and chain efficiency, capital and operating expenses, quality, wastes, process safety, etc.*[3] *Smart Manufacturing (SM) is the application of real-time, networked and data based Manufacturing Intelligence to facilitate dynamic market demand, added product value, and high velocity technologies and products with increased expectations for environmental sustainability and zero safety incidents*[4]*.*

The PI and SM paradigms are embodied within the field of process science and systems engineering, and are core courses taught in chemical engineering programs. Classical core areas within process science and engineering that underpin PI and SM concepts and applications are transport processes; separations; catalysis; kinetics and reaction engineering; process development and design; and dynamics, control and process optimization. Together, PI and SM use fundamental science and engineering to affect a paradigm shift in capital and operational costs while providing a high degree of safety and sustainability.

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[2] National Research Council Study in 2007, http://www.nap.edu/openbook.php?record_id=11867&page=R1
[3] Adapted from European Roadmap of Process Intensification. 2007.
[4] From J. Davis, email. 10/15/14.

European Efforts

Various organizations have been created to foster the development of PI (EUROPIC-TU Delft, Process Intensification Network-Newcastle University, European Federation of Chemical Engineering Working Party on Process Intensification, etc.). University efforts are closely aligned with industrial companies through a series of public-private funded partnerships. Masters level courses exist and are available on the internet.

Significant efforts in PI have been funded by the European Union. European efforts in PI have evolved from a "toolbox" of technologies approach to an integrated multidisciplinary approach for understanding the relationships between fundamental science and process engineering. A consistent approach has been developed and applied by the entities throughout Europe, comprising four main concepts:

- European PI efforts start by asking the basic question, "What is the limiting factor (rate, environmental, safety, capital cost, etc.) in the process or enterprise?"
- European PI efforts involve analyzing the underlying elementary physical and chemical processes with the goal of providing the optimal pathway for each molecule processed.
- When applying PI, all scales within an enterprise (molecular to plant to enterprise) are considered.
- Metrics for PI should be set to achieve a step change in plant footprint, environmental release, capital/operating cost, or other metric of interest. PI disrupts cost paradigms and is not business-as-usual process optimization.

The EU continues to fund large programs associated with PI and SM. The Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) program defines a metric for fossil fuel, nonrenewable raw material and CO_2 footprint reductions as follows: 1) 30% reduction in fossil energy intensity through a combination of techniques that also include process intensification, 2) 20% reduction in non-renewable primary raw materials intensity, and 3) 40% reduction in CO_2 footprint.

Research efforts in PI cover the full spectrum of technologies. A brief sampling includes:

- Oscillatory Baffled Reactors (OBRs)
- Spinning Disc Reactors (SDRs)
- Rotating Packed Beds (RPBs)
- Heat Pipes
- Reactive Extraction (RE)
- Non-thermal plasmas
- Rotating pack beds
- Micro-reactors (developed and deployed)

Figure 2 – SPIRE is an European Union Public-Private Partnership Research and Development program that will advance the process industry through development of advanced process intensification and smart manufacturing techniques

U.S. Efforts

U.S. efforts in PI are less organized and structured. Individual projects are funded within universities and companies. In some cases, multi-national companies have long standing funded expertise within this area. In other cases, initial efforts in PI have started recently within industry. Some PI concepts have been deployed within industry, such as dividing wall columns at Eastman Chemical Company, and centrifugal absorption at Dow Chemical Company.

Academic Efforts - Oregon State University houses the Microproducts Breakthrough Institute (MBI) which specializes in micro-reactor and heat exchanger technology. MBI and the company Velocys originated from efforts started at the Pacific Northwest National Laboratory in the early 1990's. The University of Texas Process Science and Technology Center has developed divided wall distillation systems, membrane reactors, microchannel reactors, reactive distillation, chemically enhanced separations, and rapid prototyping of mass transfer devices for various chemical industry applications. Micro-reformer and catalysis intensification concepts have been developed by the University of Delaware's Catalysis Center for Energy Innovation. Conversion of batch processes (solids handling) to continuous process, which is another form of process intensification, is being developed by the Center for Structured Organic Particulate Systems at Rutgers University. Computational tools that rapidly assess all possible combinations of potential separation systems have been developed by several contributors. Membrane reactors are being developed for a variety of applications. Novel biocatalytic coatings and structured bioreactive materials have been developed by North Carolina State University to perform a variety of reactions within novel micro-reactors.

Industrial Efforts - Catalytic plate reactor technology for steam methane reforming has been demonstrated at the pilot scale and is close to commercial deployment in the U.S. Pressure Swing reforming for syngas production has been deployed within industry.

Figure 3 – Development of Wet Granulation processes to convert batch powder processing units to continuous powder processing systems – Rutgers University

Government Efforts - The Advanced Manufacturing Office (AMO) in the DOE Office of Energy Efficiency and Renewable Energy presented the need for process intensification within the chemical industry. Recently, a National Network for Manufacturing Innovation (NNMI)[5] initiative has been launched by the President's National Science and Technology Council (NSTC). This initiative is led by NSTC's Advanced Manufacturing National Program Office and is hosted by the Department of Commerce, National Institute of Standards and Technology, and an interagency team with participation from all Federal agencies involved in U.S. manufacturing. Eventually, this NNMI manufacturing initiative is expected to encompass up to 15 Institutes for Manufacturing Innovation with $1 billion in funding proposed by President Obama. To date, this initiative has established a Critical Materials Institute, a Manufacturing Demonstration Facility for Additive Manufacturing & Low-cost Carbon Fiber, and a Next Generation Power Electronics National Manufacturing Innovation Institute. These institutes are large collaborations with partners from academia and the private and public sectors. AMO discussed the manufacturing initiative and stated there was a formal request for information and a workshop (October 2014) on the subject of small, highly-efficient modular chemical processes.

[5] National Network for Manufacturing Innovation: A Preliminary Design. Executive Office of the President, National Science and Technology Council, Advanced Manufacturing National Program Office, January, 2013.

2.0 Challenges and Opportunities

Questionnaire responses and discussions during break-out sessions delineated two broad challenge categories related to Process Systems Engineering and Process Science Engineering. One involves improved understanding of macroscopic behaviors and properties of intensified processes, while the other encompassed the mezo-, micro- and atomistic scales. Additionally, several practical challenges in the development of intensified processes, and organizational challenges related to process research, development, and industrial adoption were noted.

Process Systems Engineering: This approach takes a "top-down" perspective on intensification. Of significant interest for future research in this area are new methods for process design, including the identification of new intensification pathways and new ways to combine phenomena into novel physical devices. Also of interest was the development of computational methods to evaluate and optimize these concepts. Participants argued that the development of efficient shortcut methods for identifying optimal intensified configurations, either for individual units (e.g., mass, heat integrated distillation columns, dividing wall columns), or at the level of the entire flowsheet, must be undertaken since analysis using rigorous models is combinatorially complex and becomes computationally prohibitive when the number of components and conventional unit operations is large.

Several contributors emphasized that considering operational flexibility and control at the design stage is particularly important for intensified processes due to the inherent loss of degrees of freedom available for control and economic optimization. In the same vein, research efforts should focus on identifying new degrees of freedom and control handles for intensified processes. It was pointed out that current knowledge and research focus largely on continuous processes, and that intensification of batch operations has received comparatively little attention. As a consequence, understanding the interaction of design and operations in intensified batch processes is of high interest.

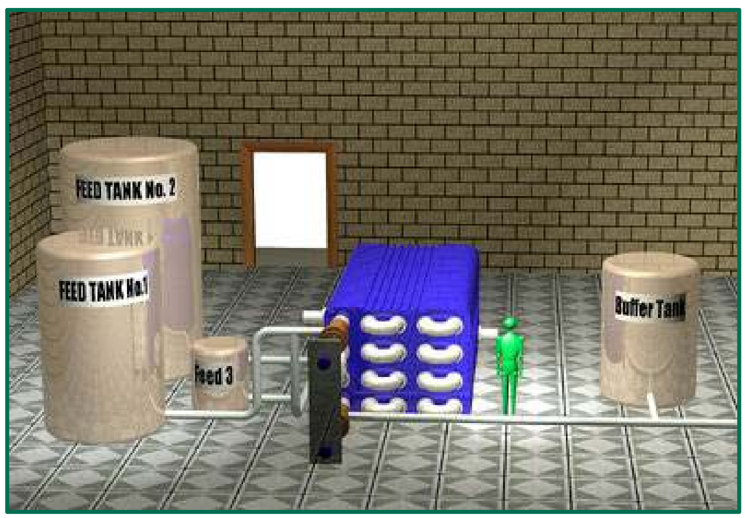

Figure 4 – Oscillatory Flow Reactors allow conversion of traditional batch processes to continuous processes – University of Cambridge - http://www.ceb.cam.ac.uk/pages/ofm-process-intensification.html

According to participants, knowledge of scaling-up benefits of intensified units to large-scale processes is currently scarce. Moreover, the underlying principle of "numbering up" micro-structured units to reach the desired production capacity can increase capital costs significantly beyond the price of a conventional large-capacity unit. For example, microchannel reactors frequently have much better heat and mass transfer and higher reaction rates than conventional large equipment, but the benefits frequently don't scale when "numbered up." This is a gap between research and practice that should be addressed. It was mentioned that a micro-reactor, which gives 1000 times faster reaction rates, is very compelling, but not when it is 10,000 times more expensive than a traditional large scale reactor, when numbered up. Micro-distillation, which achieves an effective HETP of 5 mm implies 120 times the efficiency of a column with 24 inch HETP, but numbering up to match a typical industrial column would mean tens of thousands of the micro-units, for many times the cost of a conventional distillation column. Thus, higher efficiency isn't the only goal – developing cost-effective higher efficiency systems should be considered.

The results of efforts mentioned should converge toward a holistic solution, whereby synthesis, design, and control are considered together with sustainability. This integrated framework should be capable of quantifying the uncertainty related to process parameters and fluctuating operating conditions. This would include factors such as switching between multiple operating points with different product quality and/or production rates.

Process Science Engineering: This comprises research efforts that contribute to process development from a "bottom-up" perspective. These include the development of new materials, as well as improving the fundamental understanding of process phenomena. The need for materials for separation applications, notably membranes, which have superior stability and durability over time, especially in difficult operating conditions such as high temperature, was featured prominently. Along the same line, materials with embedded biological components (e.g., desiccated cells) were also mentioned.

From a phenomenological perspective, participants emphasized the need for reliable methods that link microscopic structure to macroscopic properties and performance (e.g., size and/or chemical activity) with "materials by design" applications in mind. Participants underlined the need for a better understanding of the effect of (turbulent) flow on chemical and physical phenomena occurring in non-Newtonian and complex fluids (emulsions, dispersions, surfactants) at the micro and mezo-scale, and the development of equipment design equations based on this understanding.

Advanced Process Control: According to participants, advanced process control will be important for real-time control and operational optimization of complex, intensified processes and smart prediction of product quality. New approaches under development include advancements in software, modeling, hardware, smart materials and sensors.

Particularly promising is a new generation of amperometric, potentiometric and impedimetric electrochemical sensors that enable real-time monitoring in harsh environments and reduce the need for sample acquisition. Advanced process controls will be especially important to support the deployment of PI for closely integrated operations configured into a small, or modular, production platform.

Integration of Intensified Process, Budget-Planning and Regulatory Models: Coupling these models will provide a holistic enterprise model that will enable industry and investors to rapidly assess the potential impacts, risks, benefits and financial return of investments to improve manufacturing processes. A holistic EM enterprise planning model could provide life cycle costs, assess the impacts of budgets against regulatory milestones, and provide production projections as a basis for economic modeling. These new modeling tools would help stimulate new investment in process intensification.

Practical challenges: Several workshop participants pointed out that the manufacturability of devices that incorporate new intensified process concepts can have a significant impact on their market and industry success. Manufacturing challenges include materials processing (e.g., making defect-free membranes on a large scale), fabrication of metal microstructures (e.g, microchannel reactors), and reliably incorporating materials of different natures such as metals and ceramics, in a single unit (e.g., membrane reactor).

The participants also pointed out that the lack of adequate pilot scale facilities has slowed progress in the development of new PI concepts, and may have hindered the overall acceptance of PI in industry.

Organizational challenges: The need for a coherent funding strategy involving both industry and government sources was emphasized. It was also pointed out that in many cases, industrial players are risk averse and thus slow to innovate. Unless there's a very well defined market need, equipment manufacturers choose to incrementally improve on existing equipment concepts (mostly integrated reaction/separation, advanced distillation) rather than innovate.

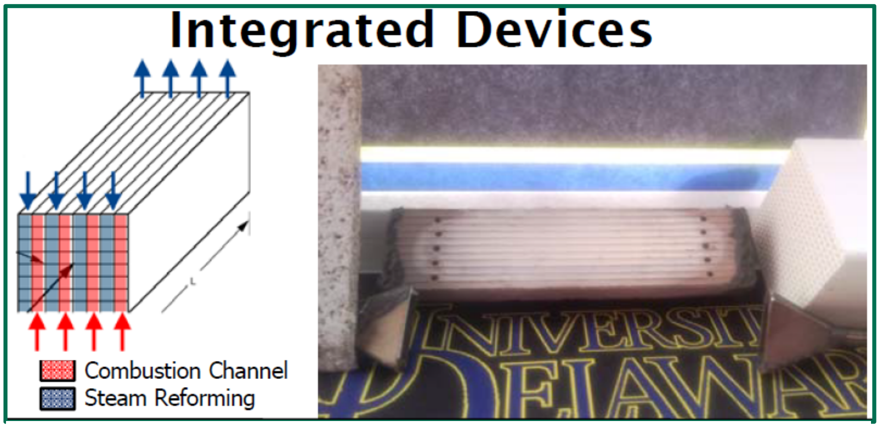

Figure 5 – Integrating multiple functions within a single device or unit operation is an example of process intensification – University of Delaware

Opportunities: Workshop discussions revealed a broad palette of opportunities for developing new PI concepts and/or applying existing ones. These opportunities include:

a) Distributed power generation and Distributed chemical processing. In this area, the need for efficient processing of natural gas (especially monetizing stranded/associated gas deposits) was emphasized. The opportunity for developing processes for simultaneous H_2 production and CO_2 sequestration was identified, along with the development of intensified processes using ethane-based (rather than petroleum-based) chemistries for the production of products such as low-cost plastics.

b) Wastewater treatment. The water and energy nexus was identified, and it was pointed out that process intensification concepts can be used for developing more efficient processes for treating wastewater, including cleaning drilling fluids and municipal waste. The use of renewable resources, such as wind, for powering such systems was mentioned.

c) Energy efficiency and productivity improvements can be gained from converting batch processes to continuous ones (e.g., in the food and pharma industries).

d) Improving energy efficiency from waste heat capture.

e) Processing biofuel and more efficient aqueous-phase chemistries (e.g., aqueous reforming of organic compounds for hydrogen generation).

f) Intensification of CO_2 capture using novel materials, including supported anhydrous biological materials.

g) Product intensification. This can lead to substantial energy and water savings (e.g., an "intensified detergent" carrying an improved surfactant, requires less detergent and less water to perform the same cleaning task).

h) Treating low-concentration, high-volume materials such as ores from mining or waste from nuclear power generation.

3.0 Areas of Collaboration between Industry, Academia and National Labs

US based companies are moving toward collaborations that are targeted with specific project deliverables. This reflects the divergence of federal funding away from traditional areas of chemical engineering research in process science and process systems engineering. To fill the gap in the chemical industry workforce, some chemical companies are developing targeted research programs with universities. This is likely the case for large chemical companies, but may not reflect the industry as a whole. In 2011, Dow Chemical launched their 250 million dollar university partnerships program. Eastman Chemical Company launched its Eastman Innovation Center, and Eastman Chemical Center of Excellence providing support to North Carolina State University and University of North Carolina-Chapel Hill. Industry consortia are a good means of collaborating with industry in areas where research would not normally be funded by individual partners (e.g. water industry).

Workshop participants provided written responses that were used to develop the contents of this, and other sections of this report. A summary of potential areas of collaboration is provided.

Separations – Divided Wall Columns, Evaporation

Computational tools that allow for rapid optimization of structure packing combined with rapid prototyping. The need exists for a method to rapidly and efficiently evaporate water in a variety of chemical processes. Development of novel evaporation PI technology is a potential area of government-industry-university collaboration.

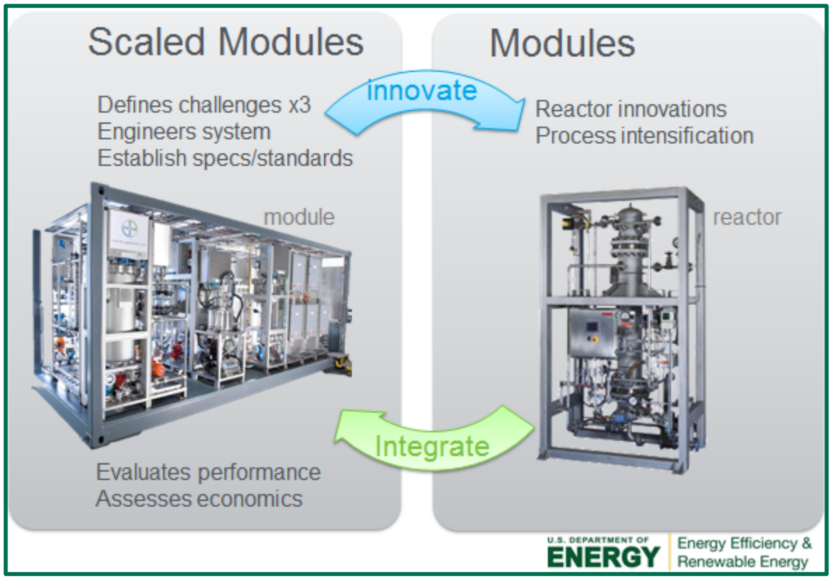

Figure 6 – One Possible Future for Chemical Processing – Scaled Modules that include reactor innovations and process intensification

Separations – Membranes

High impact industrial applications (e.g. Propylene, Ethylene), including operating conditions, are areas where collaboration can occur. Industrial test beds for membranes developed by researchers are needed. High temperature separations and chemical synthesis are two key areas where additional development is needed.

Separations – Solvent Extraction-Liquid-Liquid, Gas-Liquid

There have been advancements of centrifugal contactors over those previously developed by US DOE. Many of these designs are being developed and tested in Europe. However, no U.S. experience exists with multi-stage single rotor systems.

Scale-up of carbon capture processes remains technically challenging since the scale of the equipment is much larger than anything previously manufactured. New approaches for reducing the size of the process equipment or developing new predictive scale-up approaches through computation could be developed.

Microchannel Reactors/Heat Exchangers

At the microscale of interest, surface tension is very important, and some transport mechanisms are neglected in larger systems, such as transport due to surface tension gradients (both temperature and concentration induced). Thermal gradients may become significant depending on the fluid composition and operation conditions. There is no generalized design methodology that incorporates both surface tension and thermal gradient effects for gas/liquid reactor design. Moreover, the design distributed actuators for controlling the operation of microchannel reactors is an open question.

Bio-composite Materials for Reactive-Separations

These thin (<10 to ~50 μm thick) materials whose microstructure is formed by drying, preserve the viability and reactivity of cells in a dry state. Due to their thinness, they can be highly reactive biocatalysts following rehydration. Further research on biocomposite biomimetic leaves and low water mixing-limited gas absorbers could enable using engineered cells in very large scale multi-phase reactors for distributed conversion of natural gas to chemicals, carbon capture and other separations applications.

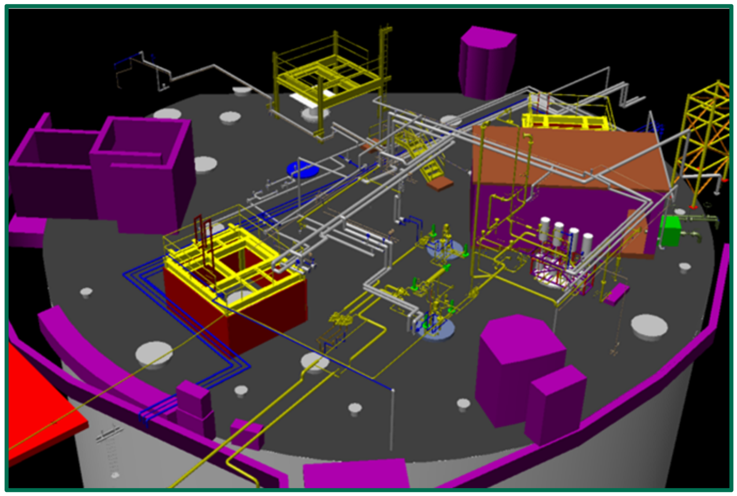

Figure 7 – An example of chemical processes that are conducted at the feed chemical storage location – Treatment of radioactive waste through small column ion exchange and rotary microfilters – Department of Energy Savannah River National Laboratory

Catalysis

Catalysis continues to be a well-funded area, both industrially and with government funding. Fundamental understanding of catalysis continues to enhance the performance of both new and existing chemical processes.

4.0 How PI and Smart Manufacturing (SM) are Linked

What are the intersection points between PI and SM?

The responses to the questionnaires and the discussions emphasize that PI and SM are very tightly connected, but the main differentiation is that SM focuses on operations. Specifically, SM is the development and application of tools to intensify the level of operations necessary for the safe and efficient operation of highly interconnected, complex plants. This includes tools for monitoring, sensing, communicating, and coordinating activities.

The consensus among participants was that PI targets new technologies and innovative process modifications, whereas SM is required for the efficient operation of the developed advanced manufacturing platforms. Specific ideas include the commercialization of micro-channel technology, the use of bio-composite modules that require the use of bio-sensing elements, and the use of micro-reactors requiring advanced automation technologies to adapt to fluctuating market needs.

Other intersection points mentioned were: 1) the integration of manufacturing data with advanced computer simulation and modeling; 2) the utilization of models to identify gaps in fundamental understanding for processes and products that can be addressed through PI; 3) enterprise-wide optimization; 4) reduction of process scale leading to more "agile" modular processes; 5) on-line data acquisition and modeling that can lead to more robust control strategies.

It was mentioned that a crucial step for the commercialization of any technology is the efficient and cost-effective production of equipment and instrumentation. It was also mentioned that for some industries, it is useful to keep the activities separate, placing more focus on the need for development of PI technologies.

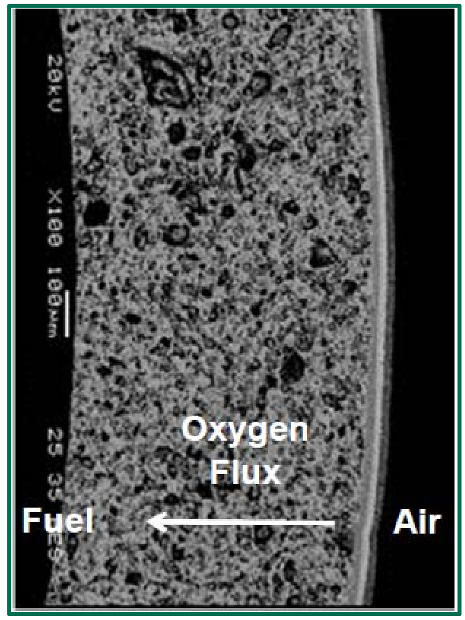

Figure 8 – Oxygen Separation Membranes Example – Praxair – High impact industrial applications (e.g. Propylene, Ethylene), including operating conditions, are areas where collaboration can occur. Industrial test beds for membranes developed by researchers are needed. High temperature separations and chemical synthesis are two key areas where additional development is needed

What is the current state of knowledge within your company on SM or supply chain modeling?

Responses from participants and discussions during the workshop point to the fact that there is a large range of adaptations of SM in current industry, as well as awareness of the opportunities in this area among the academics. To summarize, there were a number of no responses at all, or responses pointing to the limited use of SM tools. There were also a number of responses that mentioned the use of SM for enterprise-wide optimization, supply chain management, data management and integration. Participants also called for application of SM tools early in technology development.

What are the possible metrics for a future federally funded research program?

The group consensus was that detailed metrics would be process specific. The EU SPIRE program has broad metrics that could be leveraged for a U.S. based program.

1) "A reduction in fossil energy intensity of up to 30% from current levels by 2030 through a combination of, for example, cogeneration-heat-power, process intensification, introduction of novel energy-saving processes, and progressive introduction of alternative (renewable) energy sources within the process cycle.
2) By 2030, up to 20% reduction in non-renewable, primary raw material intensity versus current levels, by increasing chemical and physical transformation yields and/or using secondary (through optimised recycling processes) and renewable raw materials. This may require more sophisticated and more processed raw materials from the raw materials industries. A full life cycle cost analysis is required to consider all effects of using secondary and renewable feedstocks (e.g. water usage) and to prove the sustainability advantage[6] ."

[6] http://www.suschem.org/documents/document/20120124124146-sustainable_process_industry_1209c(1).pdf

Appendix I

Workshop Agenda

Tuesday September 30

7:45 – 8:00am	Greeting, coffee, and check-in	East/West Falls Church
8:00 – 10:30am	Presentations Introduction - Process Intensification Mark Johnson Jeff Grenda Mario Eden Tom Edgar Adam Harvey (25 min each +5 min Q&A)	East/West Falls Church
10:30 – 10:40am	Break	
10:40 – 12:00pm	Break-out Session 1 Challenges and Opportunities Coordinator: Ignacio Grossmann	Ballston/Farragut West/Vienna
12:00 – 1:00pm	Lunch break	
1:00 – 1:30pm	Report from Break-out Session	East/West Falls Church
1:30 – 3:00pm	Presentations Applications I: Reactions/Separations Dion Vlachos Phil Westmoreland Mike Flickinger Bruce Eldridge (20 min)	East/West Falls Church
3:00 – 3:30pm	Break	Ballston/Farragut West/Vienna
3:30 – 5:00pm	Break-out Session 2 Applications I: Reactions/Separations Coordinator: Thomas van Gerven	East/West Falls Church
5:30	Report from Break-out Session	
6:00	Dinner (on your own)	

Workshop Agenda (continued)

Wednesday October 1t

8:30 – 10:00am	Presentations Applications II - Energy/Chemicals/Pharmaceutical Michael Baldea Prodromos Daoutidis Bond Calloway Marianthi Ierapetritou (20 min)	East/West Falls Church
10:00 – 10:30am	Break	
10:30 – 12:00pm	Break-out Session 3 Applications II - Energy/Chemicals/Pharmaceutical Coordinator: Rakesh Aggrawal	Ballston/Farragut West/Vienna
12:00 – 1:00pm	Lunch Break	
1:00 – 1:30pm	Report from the Break-out session	East/West Falls Church
1:30 – 3:00pm	Presentations Applications III - Energy and Environment Fernando Lima David Vernon Dickson Ozokwelu Monica Zanfir (20 min each)	East/West Falls Church
3:00 – 4:00pm	Full Group Moderated Discussion / Panel Coordinators: Michael Baldea, Marianthi Ierapetritou, Bond Calloway	East/West Falls Church
4:00	Adjourn	

Appendix II

NSF Process Intensification Workshop Questionnaire
Washington, DC, September 30-October 1, 2014

Chair: Marianthi Ierapetritou, Rutgers University
Co-chairs: Michael Baldea, The University of Texas at Austin
Bond Calloway, Savannah River National Laboratory

The goal of this two-day workshop is to identify theoretical challenges and practical open questions in the area of Process Intensification (PI), and initiate some funding opportunities. In preparation for our meeting, we kindly request your assistance with:

- Describing your current work on or most closely related to PI
- Identifying one or two future challenges and applications of PI
- Identifying areas where industry/academia interactions are most needed to foster progress in PI
- Defining goals and metrics for PI applications (examples: % reduction in fossil energy intensity, % reduction in non-renewable, primary raw material intensity, efficiency improvements of up to % in CO2-equivalent footprints, % lower capital/operating cost? % reduction in physical plant footprint? More information regarding PI targets can be found on www.suschem.org, at: http://www.suschem.org/documents/document/20120124124146-sustainable_process_industry_1209c(1).pdf

The questions below are provided as a guidance; please be as descriptive as possible but keep in mind that the form should not exceed three total pages when filled out.

Your name:

Your institution:

1. Please provide a description of your projects concerning (or closely related to) PI:
   a. What is the area you are working in? (e.g., energy/fuels, chemicals, pharma)
   b. What is/are the key issue(s) you are addressing? (1 paragraph)
   c. Why is this issue significant? (1 paragraph)
   d. Please describe your approach to solving the problem (theoretical? Computational? Experimental? A combination?) (1 paragraph)
   e. What are the expected outcomes? Contributions to PI in general? (1-2 paragraph)
   f. Is this work done in collaboration with industry? If possible, please describe the interest of the sponsor in PI.
2. Please identify one or two PI challenges and/or applications that require further research:
   a. What is the challenge/research topic?
   b. Why is this important?
   c. What is the current state of knowledge and what is the gap that must be bridged?
   d. What are the main difficulties that must be overcome?
   e. What will be the benefits of accomplishing this goal? (please refer to metrics above if relevant)
   f. What are the resources required?
3. Please discuss your perspective on industry/academia collaborations in PI:
   a. Are you currently interacting with industry on PI-related projects? (related to 1.f above)
   b. What are the areas of your research where such interaction would be most needed/beneficial?
   c. What kind of input/contribution would be required from the industry partner?
   d. What commercialization opportunities do you anticipate for your research?
4. How are PI and Smart Manufacturing Linked? (please refer to the following website for more information on smart manufacturing http://smartmanufacturing.com/)
   a. What are the intersections points between PI and SM?
   b. What is the current state of knowledge within your company on Smart Manufacturing or supply chain modeling?