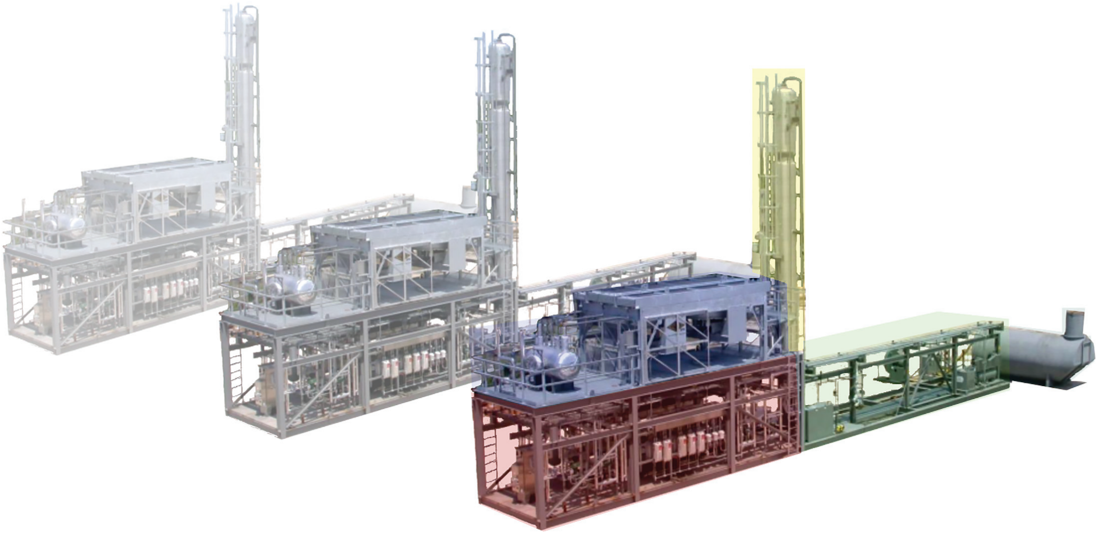
RAPID
Transforming Process Industries



ROADMAP OVERVIEW

A Public-Private Partnership Between U.S. DOE EERE & AIChE®

In late 2016, the U.S. Department of Energy announced the establishment of the Rapid Advancement in Process Intensification Deployment (RAPID) institute, the 10th Manufacturing USA Institute. This represented a critical step in the federal government's effort to double U.S. energy productivity by 2030. RAPID was established with the mission to:

LEAD a national effort to research and develop high-impact modular chemical process intensification solutions for U.S. Manufacturing.

BRING together private and public entities to co-invest in R&D projects that advance innovative technologies and address high-impact manufacturing challenges.

BUILD RAPID membership through an inclusive and attractive value proposition.

OPERATE the Institute efficiently to benefit a wide range of stakeholders.

PROVIDE members with access to process intensification resources, tools, expertise, and facilities.

ESTABLISH a technical education and workforce development program.

INTRODUCING RAPID

When it comes to improving energy efficiency and lowering investment requirements in the process industries, modular chemical process intensification (MCPI) has been a long-standing concept. In general, though, MCPI deployment in energy-intensive industries has been limited by several barriers, including:

- Capital costs and RAM (reliability/availability/maintenance) risk involved in committing to new processes
- High complexity of an intensified, modular system, without simplifying standardization techniques
- Insufficient software and design tools and data to develop intensified processes
- Challenge (technical, economic, and re: intellectual property) of developing standardized design and manufacturing protocols for a complex new technology space at an early point in its technical and commercial development
- Limited understanding of design and operation of MCPI technologies across a broad range of key industry participants

The Rapid Advancement in Process Intensification Deployment (RAPID) Institute is focused on addressing the barriers listed above to enable the development of breakthrough technologies to boost energy productivity and energy efficiency through manufacturing processes in industries such oil and gas, pulp and paper, and chemical manufacturing. RAPID will leverage approaches to MCPI — such as combining multiple process steps such as mixing, reaction, and separation into single more complex and intensified processes — with the goal of improving productivity and efficiency, cutting operating costs, and reducing waste.

WHAT IS MODULAR CHEMICAL PROCESS INTENSIFICATION?

While the concepts of process intensification and modular process designs are not new, there is still a significant lack of clarity on what these terms do (and do not) include. The roots of process intensification extend back at least to the 1970s, when process developers began to seek dramatically different configurations and design principles to make transformative changes in cost/performance parameters. Advances in process optimization were able to deliver sizable improvements in some cases, with more sophisticated integration of heating and coolant flows via process analysis as one example. Other areas include development of very active and selective catalysts and advanced process control methods.

Current process intensification builds on, and moves beyond, the concepts in novel process design and reaction engineering listed above. Van Gerven and Stankiewicz (2009) provide four guiding principles for PI:

- Maximize effectiveness of intramolecular and intermolecular events
- Provide all molecules the same process experience
- Optimize driving forces at all scales and maximize the specific surface areas to which they apply
- Maximize synergistic effects from partial processes

RAPID has distilled these guiding principles into the following concrete approaches:

1. Advances in hardware and control strategies to combine multiple process steps into a single unit. Such processes have the potential to reduce capital costs through a reduction in distinct process steps and also the potential to improve energy efficiency by reducing recycle streams and improving heat/mass transfer inefficiencies created by the use of stand-alone process steps.

2. Application of significantly enhanced driving forces — both chemical and physical — to drive chemical and transport processes. This would include the use of rotation to enhance buoyancy driven processes and the use of non-traditional energy sources to drive heat, mass, and momentum transport (*e.g.*, ultrasonic mixing, microwave heating, etc.).

The overall goal in both of the above is to use enhanced molecular level knowledge of processes, new advances in materials, and emerging modeling capabilities to create a step change in the capital and/or energy efficiency of a process.

FOCUS AREA OVERVIEW

RAPID has highlighted six focus areas to organize the scope of research and development activities in the institute. These include three application areas that were selected based on the high level of energy/capital intensity or their potential to benefit from widely distributed modular technologies — Chemical and Commodity Processing, Natural Gas Upgrading, and Renewable Bioproducts.

Three additional areas were selected that focus on the underpinning science and technology that will be required for broader utilization of MCPI technologies — Intensified Process Fundamentals, Modeling and Simulation, and Module Manufacturing.

CHEMICAL AND COMMODITY PROCESSING

The chemical and commodity processing focus area includes activities and projects relevant to the chemical processing industry and petroleum refining operations. A major consideration for applications in this sector is the desire to utilize the large asset base that already exists in the commodity chemical manufacturing space. Accordingly, efforts will be expended that advance modular and intensified technologies for retrofitting and debottlenecking of existing processes.

NATURAL GAS UPGRADING

The natural gas upgrading (NGU) focus area includes activities and projects with the objective of upgrading the value of natural gas and natural gas liquids. As domestic natural gas production increases, smaller and more remote wells will likely increase in number, which will generate a need for smaller-scale, modular solutions to enable economic production. With an emphasis on these distributed settings, the NGU focus area will explicitly address both performance improvements and cost reductions within the full scope from upstream extraction through downstream.

RENEWABLE BIOPRODUCTS

The renewable bioproducts focus area encompasses both mature industries such as the Pulp & Paper industry or producers of ethanol with conventional technologies, as well as emerging technology areas such as distributed biorefining which explores a wide range of biomass feedstocks for conversion into diverse products ranging across fuels, energy, chemicals, and materials. While the technology driving these industry segments is very different, the group has a common goal of converting renewable feedstocks into value-added products and has some of the same basic challenges impacting overall capital and energy efficiency.

INTENSIFIED PROCESS FUNDAMENTALS

The intensified process fundamentals focus area includes activities and projects relevant to crosscutting unit operations relevant to intensified and modular processes. These unit operations include efficient chemical separations, chemical reactor design and catalysis, mixing, and heat transfer. The efforts in this focus area center around platform technologies that can be used in multiple realizations in varying applications of modular processing.

MODELING AND SIMULATION

The modeling and simulation focus area includes activities and projects relevant to modeling and simulation of intensified and modular processes. The lack of readily available modeling tools and design data is a major barrier to widespread development and deployment of MCPI in energy-intensive sectors of the U.S. economy. The crosscutting area of modeling and simulation will develop modeling tools for the design of processes, controls, components and systems that will enable accelerated development of intensified and/or modular systems.

MODULE MANUFACTURING

The module manufacturing focus area includes activities and projects relevant to manufacturing and supply chain issues associated with MCPI. Efforts include considerations for reducing the cost and improving the reliability of modular subsystems and intensified components that are pre-assembled, transported, and installed at a chemical processing site.

OVERVIEW OF RAPID ROADMAPPING

RAPID has several tasks that will help in achieving its missions, but chief among these is establishing a portfolio of projects that are capable of transforming the U.S. process industries through the application of MCPI. In order to insure the development of a high impact project portfolio, RAPID undertook a structured roadmapping process in 2017 to reach the following goals:

- **Define** gaps within each of the 6 focus areas (Chemical and Commodity Processing, Natural Gas Upgrading, Renewable Bioproducts, Intensified Process Fundamentals, Modeling and Simulation, and Module Manufacturing) that are large enough to have significant impact if addressed and which could be bridged and thus make a significant contribution to the deployment of MCPI
- **Identify** the gaps that span focus areas and therefore have the potential to create the broadest benefit if addressed
- **Align** RAPID members on the most-relevant gaps to allow for prioritization

The output of the roadmapping process is a set of gaps, or areas for improvement, that will be used to guide project selection beginning in the fall of 2017.

INSTITUTE WIDE GAPS

Prior to the launch of RAPID, the idea that modular technologies and process intensification could be used to address capital and operating cost challenges had been discussed in multiple venues. A review of several different roadmaps/ workshop reports where gaps impacting MCPI deployment are noted identified four overarching gaps, or improvement needs:

- Awareness among decision makers of the existence of MCPI options, as well as tools to quantify their benefits
- Process design and control tools to manage novel MCPI processes
- Management of high technical risk associated with novel technologies in terms of both initial and longer term performance
- Management of scalability/manufacturability issues with novel technologies

During the roadmapping process, several key themes emerged as gaps, or improvement needs, and areas of high potential impact. It is notable that the themes identified are well aligned with the aggregated findings (four themes listed above) of several previous studies. These include:

1. The need for basic "input" data to develop models for PI systems and a structure for sharing/access to such data

Several of the RAPID focus area working groups identified that basic data needed to screen concepts and evaluate new technologies was lacking — often due to the complexity associated with data acquisition in two phase systems such as adsorption. Beyond basic thermodynamic data, the need for long-term stability data, for example, in membrane and/or adsorption systems, was highlighted as a hurdle toward implementation of these technologies.

2. Modeling tools to evaluate and screen PI applications

This gap showed up uniformly in all of the focus areas identified. The specific needs touched on both the scope of available modeling tools and the accessibility of these tools to a broad audience. Specifically, tools were needed — similar to process modeling tools for conventional technologies — that would allow the screening of new technologies/unit operations. These tools would need to be capable of providing basic heat and material balances to feed into techno-economic evaluations and would need to be compatible with traditional unit operations in order to allow for the comparative assessment of hybrid process schemes. Beyond tools for process design, models for control and optimization of intensified systems would also be a prerequisite for broad adoption.

3. Design approaches that incorporate standardization in modular manufacturing in a manner that could lead to optimal cost/performance and broad acceptance of MCPI

Several groups pointed out the potential benefit that could result from mass manufacturing of modular technologies, but such benefits can only be realized if standard designs can be widely deployed. This gap needs to be addressed by determining what can be economically standardized based on market needs and technology requirements, and by focusing on modularization of both novel process components, as well as the balance of plant.

4. MCPI solutions in water processing, particularly in aqueous/organic separations

While not explicitly called out in RAPID's initial scope, water management was highlighted by several groups as an area with large potential impact. Applications range from product recovery and inhibitor removal in biological processing systems to process water purification and management across the chemical and commodity processing space, as well as wastewater management in unconventional gas production.

5. Lack of training and awareness of PI solutions

This gap is well aligned with RAPID's mandate to develop tools to advance education and workforce development associated with MCPI. The roadmap working groups called out educational needs that span heightened awareness of decision makers within industry to the need for both conceptual and detailed engineering design training for engineering students.

EDUCATION & WORKFORCE DEVELOPMENT

The RAPID Institute is focused on addressing barriers to MCPI deployment and enabling the development of breakthrough technologies to boost energy productivity and energy efficiency through manufacturing processes in industries such as oil and gas, pulp and paper, and chemical manufacturing. RAPID will leverage approaches to MCPI — such as combining multiple process steps including mixing, reaction, and separation into more complex and intensified processes — with the goal of improving productivity and efficiency, cutting operating costs and reducing waste.

Achieving this goal will require more than the development of new MCPI technologies — it will require a cultural change in how industrial processes are designed and implemented and for process intensification to become part of the engineer's standard toolset when designing processes. Also crucial is an understanding of when modular, de-centralized processes are most appropriate for reduction of risks and sustainable processes.

Key to achieving this cultural change is a workforce trained in PI & MCPI technologies, which aligns with RAPID's mission to:

> Establish a technical education and workforce development program that will leverage existing resources to train and educate the workforce, who can then research, develop, design and operate processes that incorporate new process intensification technologies and modular process designs widely within U.S. industry.

GAP IDENTIFIED: LACK OF TRAINING RESOURCES AND AWARENESS

One of the first activities taken on by RAPID was a detailed technology roadmapping activity. Over 100 subject matter experts from industry, academia and government were brought together to define the key gaps that stand in the way of broader deployment of MCPI technologies. During this roadmapping process, a lack of training resources and awareness of PI and MCPI solutions was specifically identified as an institute-wide gap. Education and training needs were ascertained for groups ranging from practicing engineers to students to management, and formed the structure of the EWD Roadmap.

This gap in education and training materials/opportunities is well-aligned with RAPID's mandate to develop tools to advance education and workforce development (EWD) associated with PI and MCPI. In particular, RAPID's two EWD-related institute targets are:

- Train at least fifty education/training professionals per year in modular chemical process intensification technologies for clean energy including energy management practices, by year 3.
- Train at least 500 students per year in modular chemical process intensification technologies and solutions, including energy management practices by year 3.

EDUCATION & WORKFORCE DEVELOPMENT (EWD) ROADMAP OVERVIEW

Building on the institute-wide gap identified in the technology roadmapping process, RAPID's Education & Workforce Development (EWD) Committee convened to develop a roadmap specifically focused on EWD efforts needed to fill this gap. The roadmap is outlined by six target audiences where there is both a gap in PI & MCPI educational content and a need for such content, in order to meet the emerging industrial requirements of new PI & MCPI opportunities and a workforce trained to execute these.

OVERVIEW OF EWD ROADMAPPING PROCESS

Phase 1: Survey of existing education and training content

RAPID surveyed individuals to identify the current state of training and education on the topics of PI and MCPI. Themes that emerged from this survey include:

- PI & MCPI content exists but it is limited in depth and scope
- Delivery methods of existing content is varied and includes comprehensive courses, senior design projects, lecture materials, computer-based training, condensed workshop format materials, hands-on learning methodology, informal presentations and examples
- Industrial applications most represented in existing content are Oil & Gas and Biofuels & Bioproducts followed by Specialty Chemicals
- A need exists for education content in PI & MCPI, with the FA of greatest need identified as Intensified Process Fundamentals followed by Modeling and Simulation

Phase 2: EWD Roadmapping Workshop & Body of Knowledge Development

A small face-to-face workshop was held in August 2017, which included the EWD Committee as well as select representatives from AIChE and CCPS. The group reviewed the results of the survey, reviewed an initial proposal for an EWD roadmap, created a PI & MCPI Body of Knowledge framework, and developed two course outlines.

Phase 3: Curriculum Development

Based on the high-priority topic areas identified in the PI & MCPI Body of Knowledge framework, curricula were developed for target audience groups. The purpose of the curriculum is to serve as a resource and guide for the audience members. With the curriculum as our guide, we plan to assess the potential of a PI & MCPI certification program offered through AIChE Academy.

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RAPID Roadmap

Chemical & Commodity Processing

- **Rxn/Separation**

Novel reaction/separation schemes that are scalable and drive process efficiencies (*e.g.*, membrane-,or sorption enhanced reactors). Applications include processing light paraffins to olefins, Increase p-xylene yield vs conventional processes, hydrogen production, managing oxygen supply to reactions, etc.

- **Non-Thermal Drivers**

Use of alternative, non-thermal driving forces to activate chemical systems at the appropriate (atomic/molecular) scales.

- **Batch Systems**

Intensification schemes for batch systems. Transferring concepts largely developed for continuous processes to the batch realm could result in increased productivity/lower cost for specialty/fine chemicals.

Natural Gas Upgrading

- **Selective Conversion**

Concepts that show dramatic increases in desired product yields via fundamental improvements in catalysis, heat and mass transfer, and process concepts. This could include include alternative energy inputs and/or the use of novel reaction systems.

- **Separations**

Energy efficient separations technology to purify the reaction product mix, condition the feed in preparation for conversion, and to generate co-reactants for participation in natural gas conversion gas.

- **Process Consolidation**

Process consolidation and modularity to reduce total installed cost by reducing the total number of unit operations and by reducing the amount of field fabrication.

Renewable Bioproducts

- **Primary Separation**

Technologies to reduce energy demand in primary separation process steps designed to recover organic molecules and biomass components from water.

- **Water Management**

Low capital and energy intensive solutions for dewatering and drying of biomass feedstocks, water removal and drying in pulp and paper process, and drying and removal of low levels of residual water from end products.

- **Couple Rxn/Spn/Hxt**

Use of novel chemistries and MCPI strategies to couple heat transfer and reaction in thermal processing of biomass and/or novel applications of reactive separation technologies in biological conversion technologies such as fermentation.

Intensified Process Fundamentals

- **Scale-Out Methods**

Scale out methodologies and models to predict performance of alternative energy input approaches for reactions and mixing and determine the suitable scale for modular manufacturing.

- **Fundamental Data Acquisition/Modeling**

Approaches to address key issues with lack of data on fluxes, adsorption, and catalyst kinetics for wide classes of materials, enabling model development and experimental testing of novel materials as adsorbents, membranes, catalysts and their integration.

- **Predictive Models**

Modeling capabilities to screen concepts and configurations of all types and predict optimal structures.

Modeling & Simulation

- **PI Software Tools**

Software tools for integrated reaction and/or separation processes and/or cyclic process such as pressure swing adsorption (PSA) or temperature swing adsorption (TSA). Such tools must be widely accessible and capable of integrating MCPI solutions with existing unit operations.

- **Data Availability**

Modeling approaches coupled with data generation and/or analysis to generate databases of physical parameters enabling design with mass separating agents.

- **PI Assessment Tools**

Tools to assess safety, sustainability, and control in PI and MCPI applications, including tools that address unique issues of uncertainty and reduced control variable options that are present in PI and MCPI applications.

Module Manufacturing

- **Intensified Components**

Intensified components that drive down the cost of module pre-assembly, transportation, and installation, while driving significant energy savings in chemical processes.

- **Standard Designs**

Design approaches that limit the amount of non-recurring engineering — during systems integration and installation — needed to support customized modules. This could include standard modules that enable economies of mass production and/or designs that enable incremental capacity additions.

- **Distributed Processing**

Module design and manufacturing approaches to enable distributed chemical processing. These will provide new paths to capital cost reduction and innovative techniques for maintenance and remote access and monitoring.

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RAPID: Education & Workforce Development Roadmap

OBJECTIVE: Establish a technical EWD program that will leverage existing resources to train and educate the workforce, who can then research, develop, design and operate processes that incorporate new PI technologies and modular process designs widely within U.S. industry.

Undergraduate Students

GOAL
Create PI & MCPI awareness in future generations of engineers by augmenting the standard (ABET accredited) engineering curriculum with modules and educational content introducing PI & MCPI topics relevant to industry.

WHAT SUCCESS LOOKS LIKE
500 students* trained in PI & MCPI per year by 2019.

METHOD
eLearning course modules, face-to-face courses in conjunction with major meeting, Intern program.

Graduate Students

GOAL
Generate PI & MCPI expertise so that graduate students can connect the relevance of PI & MCPI research to industrial applications and create new opportunities and applications for MCPI.

WHAT SUCCESS LOOKS LIKE
500 students* trained in PI & MCPI per year by 2019.

METHOD
eLearning course modules and face-to-face courses in conjunction with major meeting.

Faculty

GOAL
Update and educate university faculty on PI & MCPI concepts and introduce eLearning modules created by RAPID for integration into their curriculum.

WHAT SUCCESS LOOKS LIKE
50 education/training professionals per year in MCPI by 2019.

METHOD
Face-to-face course in conjunction with major meeting on the Fundamentals of PI & MCPI.

Technicians/Operators

GOAL
Introduce technicians and operators to PI & MCPI, provide awareness of new processes that include PI & MCPI as well as emphasizing process safety.

WHAT SUCCESS LOOKS LIKE
At least 50 professionals** per year in MCPI by 2019.

METHOD
eLearning course modules.

Professional Engineers R&D | Design | Production

GOAL:
Train the current generation of engineers on how to utilize and deploy PI & MCPI technology in order to improve process efficiency.

WHAT SUCCESS LOOKS LIKE:
At least 50 professionals** per year in MCPI by 2019.

METHOD
eLearning course modules, face-to-face courses in conjunction with major meeting, and promotion through Manufacturing Extension Partnerships (MEPs).

Management

GOAL
Create high level awareness of the benefits of PI & MCPI from a techno-economic analysis perspective.

METHOD
Presentation material (includes relevant case studies, sustainability, and safety); short videos aimed at executives.

PI & MCPI Body Knowledge Drives

Cross-Cutting areas identify content topics, levels of understanding for each audience member as well as high-priority topic areas. It includes four sub-sections:

- PI & MCPI Overview
- Modeling & Simulation
- Intensified Process Fundamentals
- Module Manufacturing

Content Development Topics and Priority

Application areas drive relevancy for content and provide industrial applications, examples and case studies within content and include the three sub-sections above.

* Students defined as undergraduate and graduate students.
** Professionals defined as technician, operator or engineer.

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