RAPID
Transforming Process Industries

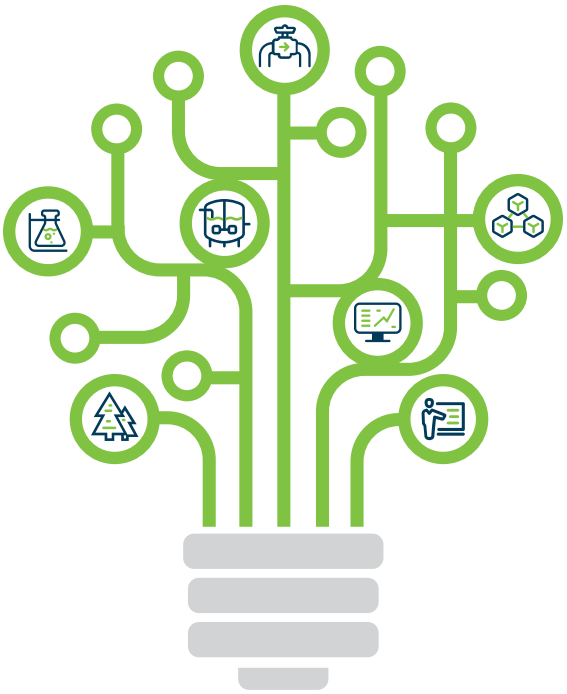
WORKING TOGETHER TO GROW STRONGER

2017 FIRST ANNUAL REPORT

Transforming Process Industries

RAPID

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



Our Mission

- Lead a national effort to research and develop high-impact modular chemical process intensification solutions for U.S. manufacturing.
- Operate the Institute to benefit a wide range of stakeholders.
- Establish an infrastructure that enables access to resources, tools, expertise, and facilities.
- Bring together private and public organizations to co-invest in R&D and deploy innovative technologies by leveraging $70 million of federal funding.
- Establish a technical education and workforce development program.

Our Industry-Led Vision

A dynamic network of partners who collectively build a sustainable ecosystem that:

- Researches, develops, and advances new technologies for modular chemical process intensification.
- Builds a strong portfolio of R&D projects and educational tools.
- Delivers dramatic reductions in energy, environmental footprint, capital, and operating cost.
- Makes U.S. manufacturing and our workforce more competitive.

Our Values

INNOVATION
Fostering new solutions and approaches using chemical engineering expertise and cutting-edge technologies.

INTEGRITY
Being honest, open, responsive, and fair.

ACHIEVEMENT
Empowering teams to take action; driving to achieve goals and meet commitments.

COLLABORATION
Building relationships for knowledge-sharing, innovation, and successful outcomes.

Message from the Interim Chief Executive Officer

As I look back on all that the RAPID Manufacturing Institute and its members have accomplished in the first year of operation, I am awed by the prospect for our future—which remains bright and bold.

In late 2016, as talks were underway to launch our institute—the 10th out of 14 under the Manufacturing USA banner—we knew that we had a daunting task ahead of us. According to the Bureau of Labor Statistics, since 2000 more than five million jobs in the U.S. have been lost and over 56,000 factories closed. The first decade of our new millennium was characterized by massive technological, societal, and economic change. What's more, Europe had established a lead in harnessing the power of process intensification and many believed we might never catch up. Pundits everywhere proclaimed that American manufacturing was dead and would never be revived!

But we knew differently.

Despite the many challenges, RAPID continues to grow and prosper, largely due to a disciplined execution of our strategic plan, a cultural mindset to foster change, and a steadfast commitment to provide direction and value to our members—leaders in industry, academia, government labs, and nonprofits.

Thanks to the support and financial funding of the U.S. Department of Energy (DOE) and guidance of our parent, AIChE, the RAPID Manufacturing Institute is well-positioned to create the paradigm shift in manufacturing that we initially aspired to but now are bringing to fruition.

In our first year, we welcomed 56 members and established technology roadmaps for six key focus areas, initiated four jump start projects and committed to an additional 21 projects representing over $30 million in funding.

During this remarkable year, we also created actionable plans to educate and train a workforce capable of operating new technologies and equipment that will drive the process industries forward.

We anticipate that these projects will not only transform the process industries but also change the face of manufacturing to ensure American leadership in a sustainable future. I now look ahead with great confidence to the opportunities that will arise to allow us to work side by side with our members to grow ever stronger.

Sincerely,

THOMAS WALSH
Interim Chief Executive Officer, RAPID Manufacturing Institute

RAPID:
EVOLVING + EMPOWERING

Traditional manufacturing must evolve if it is to survive and thrive. The process industries in particular are facing fierce global competition and are in need of innovation and investment. Only those who can understand the convergence of multiple new technologies, shifts in global value chains, and the imperative of continued investment in research, development, and improved manufacturing assets will succeed in the decades ahead.

Until now, progress has remained stagnant in these industries due to prohibitive capital costs, the high complexity of intensified modular systems, insufficient software, design tools, and data—as well as a multitude of other factors.

The Rapid Advancement in Process Intensification Deployment (RAPID) Manufacturing Institute of the American Institute of Chemical Engineers (AIChE) is the 10th member of the nation's network of Manufacturing USA Institutes and leads a national effort focused on the research, development, and implementation of high impact technologies and/or hardware equipment solutions that enable advances in the process industries—such as, Chemicals, Oil and Gas, Pulp and Paper.

Broadening the standard definition of process intensification, which is often defined by leading experts as chemical engineering developments that lead to a substantially smaller, cleaner, and more energy-efficient technology, RAPID is also focused on the development of standardized modular components and other hardware prototypes that can increase efficiencies.

The Institute's key technical focus areas are: Chemical and Commodity Processing, Renewable Bioproducts, Natural Gas Upgrading, Module Manufacturing, Intensified Process Fundamentals, and Modeling and Simulation.

The potential benefits of Modular Chemical Process Intensification (MCPI) to industry and society are many: lowered capital and operating costs, improved process and energy efficiencies, reduced waste, and a decreased carbon footprint. Equally important, RAPID's work will also result in enhanced global competitiveness and a better educated American workforce capable of operating these new technologies and cutting-edge equipment.

Chemical and Commodity Processing

Natural Gas Upgrading

Renewable Bioproducts

Intensified Process Fundamentals

Modeling and Simulation

Module Manufacturing

Education and Workforce Development

Message from the Chief Technology Officer

When molecules collide and transfer energy, it is called conduction. When manufacturing, technology, and business objectives are mixed together creating dynamic combinations—it is called the RAPID Manufacturing Institute.

As Chief Technology Officer for RAPID, I can say unequivocally, that this year has been exciting, fast-paced, intellectually stimulating, and personally very rewarding. I am proud and honored to be part of RAPID, our parent organization AIChE and the Manufacturing USA network.

But it is our members that I am most proud of: they are challenging us with their ideas, research, and commitment to drive real change in the process industries.

Many of the member projects we are sponsoring have enormous potential in developing technology and equipment for wider adoption. These projects can help reduce costs, improve performance, and increase energy efficiency and productivity. Our jump start projects clearly illustrate the potential for the changes we are advocating.

For example, RAPID members Praxair and Georgia Tech are using proprietary nitrogen-selective adsorbent to scale down a pressure swing adsorption systems that enables the use of nitrogen in place of water for fracturing in unconventional natural gas production. This technology, along with other projects that are starting up in 2018, can change the environmental impact and further enhance the economic attractiveness of unconventional natural gas resources.

Two other RAPID members, Easy Energy and the Bioeconomy Institute at Iowa State University are looking at applying novel process technologies to tackle another challenge in distributed resources—the conversion of lignocellulose wastes to sugars and other bio-based products. They are experimenting with novel reactor design and novel process chemistry to modularize sugar production from biomass by increasing the production of sugars per unit volume by several orders of magnitude and greatly improving the process' energy efficiency. We are hopeful this project will provide the understanding needed to design a commercial scale modular system.

RAPID members Oregon State University and Pacific Northwest National Lab, and the STARS Corporation are using a modular solar thermal conversion technology for H_2 production from natural gas to explore how we can rethink our approach to technology deployment. The group is using novel manufacturing technologies that are effective at small scales to shift from a conventional process scale up approach to number up approach that will allow broad commercial deployment at the same time as process refinement.

And finally, RAPID members Dow and the University of Texas are using advances in modeling and process control to challenge the paradigm of steady state process operation. They are exploring the use of non-steady process forcing to improve efficiency in separation processes. The team is applying the approach to theoretical design and experimental validation in a divided wall column system. Such unconventional thinking is a great example of the type of exciting work that we believe can change the process industries as a whole.

We hope that the information in this annual report provides greater insight into the transformational work we are fostering among our community of members. Our first year provided a solid foundation for the breakthroughs we are sure will come.

Sincerely,

JAMES BIELENBERG
Chief Technology Officer, RAPID Manufacturing Institute

2017 RAPID JUMP STARTS

Four projects that exemplify the Institute's mandate of creating paradigm shifts in manufacturing have been selected as jump starts.

1 Energy efficient separations technology to purify products/feeds/recycle streams and/or schemes to generate co-reactants such as adsorptive nitrogen rejection from natural gas.

SNAPSHOT

Innovation: Utilize breakthrough rate dependent adsorbent to modularize conventional pressure swing absorption (PSA) process.

Anticipated Project Outcome: Industrial validation of a portable, modular PSA system.

IN-DEPTH VIEW

RAPID members Praxair and Georgia Tech are using a proprietary nitrogen-selective adsorbent to scale down a pressure swing adsorption (PSA) system—making it suitable for removing nitrogen from natural gas at the wellhead. Such a technology would allow broader application of the use of nitrogen-energized compressed gas to stimulate flow and production of shale reservoirs, replacing the more common use of water with thickening polymers and other additives and the associated potential environment issues. By rejecting N_2 used in the fracturing process, hydrocarbon can be recovered immediately upon production and sold to customers instead of being flared—avoiding losses of saleable hydrocarbons and reducing CO_2 emissions.

2 Autothermal pyrolysis of lignocellulose wastes to sugars and other biobased products.

SNAPSHOT

Innovation: Couple intensified reaction and heat transfer in a novel reactor design and novel process chemistry to modularize sugar production from biomass.

Anticipated Project Outcome: Establish Modular Chemical Process Intensification (MCPI) benefits of autothermal pyrolysis to enable design of a commercial scale modular system.

IN-DEPTH VIEW

The Bioeconomy Institute (BEI) at Iowa State University and Easy Energy Systems are developing a modular system to convert biomass into sugars, which can be converted into ethanol and other fuels, as well as Lignocol, which can be co-fired with coal in electric generating plants. Other potential products include a fuel oil substitute and bio-asphalt, a mixture of asphalt and pyrolysis products. The project team aims to replace the common enzyme-based process with a thermal biomass conversion system.

At the core of this system is a technology called autothermal pyrolysis. Pyrolysis, the use of heat in the near absence of oxygen, is a tried-and-true method of converting biomass into fuels and chemicals. In the autothermal approach developed by Iowa State, air is co-fed into the reactor with the biomass. The incoming air selectively burns biomass components to generate heat without oxidizing the desired sugar products. Since the desired product from pyrolysis is a liquid, air (rather than purified oxygen) can be used as the oxidizing agent without adding significant costs to the downstream separation. This use of an intensified process that combines reaction and heat transfer into a single vessel along with the approach of utilizing thermal energy to generate sugars from biomass creates the potential for a truly disruptive modular technology.

The project can potentially benefit several industries. It can provide new markets for module manufacturers, as well as new uses for agricultural residues such as corn stover. This technology is capable of reducing the use of petroleum products in the transportation fuel and electric generation industries.

The team plans to design and build Modular Energy Production Systems based on Iowa State's pyrolysis technology. The modules are being built in size of standard shipping containers so they can be easily delivered and installed close to the source of biomass.

The RAPID Institute ensures that American manufacturing remains vital and robust by fostering an intellectually diverse and engaged community focused on a shared goal: **Modular Chemical Process Intensification**. The days of large-scale industrial behemoths is giving way to leaner, cleaner, greener, and safer factories that are more compact and modular to allow for greater mobility, productivity, and profitability.
(See page 11 for the Current RAPID Project Portfolio.)

3 Module design and manufacturing approaches that provide new paths to capital cost reduction and innovative techniques for maintenance and remote access/monitoring. This can be applied to Manufacturing Supply Chain Development for the Solar Thermochemical Advanced Reactor System (STARS) Technology Modular Solar-Thermochemical Conversion Platform.

SNAPSHOT

Innovation: Developing and demonstrating new manufacturing approaches in process intensification particularly for modular applications.

Anticipated Project Outcome: Establish a design approach and technology supply chain that spans the initial stages of applications to full commercial deployment.

IN-DEPTH VIEW

RAPID members Oregon State University and Pacific Northwest National Lab, and the STARS Corporation are taking a novel technology for the solar thermal conversion of natural gas to H_2 and defining a manufacturing plan that will allow for broad commercial deployment.

The PI technology for this project employs a mirrored parabolic dish to concentrate sunlight onto an array of meso-/micro-channel tubes for reaction and heat exchange. The concentrated sunlight heats natural gas as it flows through the catalyst-packed reactor channels and reacts with steam to produce synthesis gas (hydrogen and CO). The use of micro-/meso-sized tubes drastically improves heat and mass transfer, reduces thermal losses, and increases efficiency. STARS has set a world record of 69% conversion of solar energy to chemical energy.

The current RAPID project will define the most cost-effective manufacturing supply chain and approach for this technology for solar thermal methane reforming. This includes redesigning process equipment and materials of construction to reduce cost and to be amenable to lower-volume fabrication routes such as additive manufacturing. Although the project focuses on developing a manufacturing supply chain for a specific technology, the general approach and many of the capabilities that are being developed should be applicable more broadly to modular manufacturing in general.

4 Dynamic intensification of the operation of chemical processes of dividing wall columns.

SNAPSHOT

Innovation: Develop a dynamically controlled, non-steady chemical separation process for improved efficiency

Anticipated Project Outcome: Develop theoretical basis for defining a periodic operation in intensified chemical separation processes and experimentally confirm these benefits in a dividing wall column

IN-DEPTH VIEW

This project championed by RAPID members Dow and the University of Texas employs modeling and optimization to define process intensification opportunities in existing hardware systems. In particular, the team is taking a general look at dynamically controlled processes to see when this mode of operation can deliver significant improvements in performance. The goal is to provide a general theoretical framework to show when a generic process could see benefit, as well as using dividing wall column operation as a test case to reduce dynamic intensification to practice at pilot scale.

RAPID FIRST YEAR HIGHLIGHTS

After our establishment, the RAPID Manufacturing Institute in conjunction with the U.S. Department of Energy (DOE) and AIChE, drafted action plans allowing us to serve members in a more comprehensive and strategic way.

From day one, RAPID established a solid infrastructure with effective governance including a Governing Board, a Technical Advisory Board, and governing by-laws. RAPID also established legal, intellectual property, and membership documentation bolstered by effective communications to ensure that members were informed about important issues every step of the way. Finally, RAPID developed roadmaps for six critical technical focus areas and workforce development. Four jump start projects were selected for 2017 and 21 additional projects were identified for funding set to begin in 2018.

2017 Members

56

2017 Members: Industry / Forbes Global 2000

22/7

MEMBERSHIP

RAPID methodically seeks to create a balance of public and private organizations that can enrich the community as a whole and American manufacturing in particular. By bringing together recognized thought leaders from within industry, academia, and other sectors, greater synergies have been captured and leveraged.

At the end of our first year, RAPID membership consisted of 22 industry partners, 24 academic partners, four government labs, and six nonprofit institutions.

Benefits of Membership in RAPID include but are not limited to:

- Networking with a diverse community of subject matter experts
- Accessing potential customers and suppliers
- Competing for federal funding to move concepts from ideation to reality
- Developing, licensing, and commercializing valuable intellectual property
- Accessing workshops and webinars on the latest developments in Process Intensification
- Utilizing AIChE's valuable resources such as conferences and publications

2017 Members: Academia

24

2017 Members: Government Labs and Nonprofits

10

> "For too long, American process industries could not surmount the capital investment barriers, scientific gaps, and equipment design hurdles that have limited progress in MCPI technologies. It's been RAPID's mandate to help our members overcome these challenges."

James Bielenberg, Chief technology Officer, RAPID Manufacturing Institute

> "RAPID enables R&D collaborations with partners by helping to simplify a process that can be daunting to a small company. It's a significant benefit for a small business like ours."

Dr. Hannah Murnen, VP Business Development, Compact Membrane Systems

> "I have been impressed with the level of engagement and intellectual stimulation between academic institutions like Iowa State University and RAPID industry partners. We've been able to put theory into practice and develop commercial applications from our research based on the substantive feedback and input we have received through our involvement with RAPID."

Professor Robert C. Brown, Director, Bioeconomy Institute, Anson Marston Distinguished Professor of Engineering, Iowa State University

2017 Project Call Submissions

73

2017 Project Jump Starts

4

2018 Project Selections

21

ROADMAPPING

To ensure the creation of a high impact project portfolio, RAPID undertook a structured roadmapping process.

Workshops were formed attracting 125 participants from more than 30 companies, 28 universities, and 11 federal agencies to reach the following goals:

- Define gaps within each of the six focus areas that are large enough to have a significant impact if addressed and which could be bridged to make a significant contribution to modular chemical process intensification,
- Identify which of these gaps span focus areas and have the potential to create the broadest benefit if addressed, and
- Align RAPID members on which gaps are the most relevant to allow for prioritization.
- The roadmap end product is a set of gaps and/or areas designated for improvement that was used to guide project selection in the fall of 2017.

Professor Krista Walton, PhD, and Michael Dutzer, PhD, in the lab at Georgia Tech in 2017.

EDUCATION AND WORKFORCE DEVELOPMENT

Education is crucial to American competitiveness and RAPID recognizes the importance of establishing a technical education and workforce development program that will leverage existing resources to develop a well-trained and knowledgeable workforce, capable of researching, developing, and operating new PI and MCPI solutions widely within U.S. industry.

Traditionally, manufacturing plants are designed using the concept of economies of scale and a scale-up approach. To fully implement RAPID's advances in PI requires a paradigm shift in how industry processes are designed and implemented with smaller footprints, higher efficiencies, and modular designs.

In 2017, RAPID:

- Established a Body of Knowledge framework in Chemical Process Intensification and Modular Equipment Design,
- Developed two course outlines as part of the framework along with curricula for target audiences, and
- Partnered strategically with Manufacturing USA Institute (Education and Workforce Development) counterparts to share best practices.

And RAPID will continue to develop by:

- Offering a Process Intensification Boot Camp training for educators and trainers,
- Providing courses through AIChE Academy, such as:
  - eLearning modules for undergraduate and graduate students
  - Professional development courses for professionals and operators, and
- Promoting education through Manufacturing Extension Partnerships (MEP).

Looking ahead to 2018, RAPID will build upon our successes to offer:

- 10-part Process Intensification Webinar Series
- Fundamentals of PI eLearning Course
- Fundamentals of PI Faculty Workshop at the AIChE Annual Meeting
- Challenges of EWD in PI and MCPI Panel Session at the AIChE Spring Meeting
- Pilot Summer Intern Program
- EWD Project Call to fund development of a face-to-face course targeting advanced PI concepts for graduate students and professional engineers

> "We must find ways to engage talented young people who can contribute to innovation within the manufacturing sector of the Chemical Process Industries. RAPID's focus on educating and training this next generation of PI leaders through webinars, workshops, and other activities is critical in making that happen."

Paul Dimick, General Manager, IntraMicron Inc.

> "RAPID seeks to address a complicated set of challenges by advancing MCPI (on multiple technical fronts) and by moving our focus beyond just technology development and commercialization to include education, training, and tools creation, all while fostering a public-private network that can address the issues of complexity and standardization."

Thomas Walsh, Chief Executive Officer, RAPID Manufacturing Institute

Jordan Funkhouser, Assistant Manager at BioCentury Research Farm, Iowa State University. (Photo by Christopher Gannon.)

Current RAPID Project Portfolio

Chemical and Commodity Processing

Reaction/Separation Schemes that are Scalable and Drive Process Efficiencies

1. Paraxylene Selective Membrane Reactor
2. Modular Conversion of Stranded Ethane to Liquid Fuels

Alternative, Non-thermal Driving Forces to Impact Chemical Systems at the Appropriate (Atomic/Molecular) Scales

3. Energy Efficient Separations of Olefins and Paraffins through a Membrane

Intensification Schemes for Batch Systems—Transferring Concepts Largely Developed for Continuous Processes to the Batch Realm

4. Intensified Commercial Scale Manufacture of Dispersants

Natural Gas Upgrading

Concepts That Dramatically Increase Desired Product Yields via Fundamental Improvements in Catalysis, Heat and Mass Transfer, and Reactor Design

5. Efficient Chemicals Production via Chemical Looping

Energy Efficient Separations Technology to Purify Products/Feeds/Recycle Streams and/or Schemes to Generate Co-Reactants (e.g., O_2)

6. Advanced Nanocomposite Membrane for Natural Gas Purification
7. Jump Start: Adsorptive Nitrogen Rejection from Natural Gas

Process Consolidation and Modularity to Reduce Total Installed Cost By Reducing the Number of Unit Operations and By Reducing Field Fabrication

8. Microwave Catalysis for Process Intensified Modular Production of Value Added Chemicals from Natural Gas

Renewable Bioproducts

Technologies to Reduce Energy Demand in Primary Separation Process Steps to Recover Organic Molecules and Biomass Components from Water

(Project opportunity open)

Low Capital and Energy Intensive Solutions for Dewatering and Drying Across Biomass Feedstocks, Products, and Within the in Pulp and Paper Process

9. Robust Membranes for Black Liquor Concentration

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

10. Jump Start: Autothermal Pyrolysis of Lignocellulose Wastes to Sugars and Other Biobased Products
11. Sugars to Bioproducts Scalable Platform Technology
12. Three-way Catalytic Distillation to Renewable Surfactants via Triglycerides

Intensified Process Fundamentals

Scale Out Methodologies and Models to Predict Performance of Alternative Energy Inputs Approaches for Reactions and Mixing

13. Intensified Microwave Reactor Technology
14. Microfibrous Entrapped Sorbents for High Throughput Modular Process Intensified Gas Separation and Ion Exchange
15. Thermoneutral Propane Dehydrogenation via a Solid Oxide Membrane Reactor
16. Multiphase Microchannel Separator
17. RAPID MCPI Energy Efficient Technology for Metals Separation

Approaches to Address Lack of Data on Fluxes, Adsorption, and Catalyst Kinetics Which Retards the Use of Novel Materials as Adsorbents, Membranes, Catalysts and Their Integration

(Addressed in M&S Focus Area Project "RAPID Reaction Software Ecosystem," Project #20)

Modeling Capabilities to Screen Concepts and Configurations of All Types and Predict Optimal Structures

(Addressed in M&S Focus Area Project "Synthesis of Operable Process Intensification Systems," Project #18)

Modeling and Simulation

Software Tools for Integrated Reaction and/or Separation Processes and/or Cyclic Process such as Pressure Swing Adsorption or Temperature Swing Adsorption

18. Synthesis of Operable Process Intensification Systems
19. Optimization Modeling for Advanced Syngas to Olefins Reactive Systems
20. RAPID Reaction Software Ecosystem

Modeling Approaches Coupled With Data Generation and/or Analysis to Create Databases of Physical Parameters Enabling MCPI Designs

21. An Experimentally Verified Physical Properties Database for Sorbent Selection

Tools to Assess Safety, Sustainability, and Control in PI and MCPI Applications

22. Jump Start: Dynamic Intensification of the Operation of Chemical Processes

Module Manufacturing

Intensified Components That Reduce the Cost of Module Pre-Assembly, Transportation, and Installation, While Driving Significant Energy Savings

23. Development and Demonstration of Novel Thermal Technologies for Enhanced Air-Side and Two-Phase Performance of CPI-Relevant Heat Exchangers

Design Approaches That Limit the Amount of Non-Recurring Engineering—During Integration and Installation—for Customized Modules

(Project opportunity open)

Module Design and Manufacturing Approaches That Provide New Paths to Capital Cost Reduction and Innovative Techniques for Maintenance and Remote Access/Monitoring

24. Modular Catalytic Desulfurization Units for Sour Gas Sweetening
25. Jump Start: Manufacturing Supply Chain Development for the STARS Technology Modular Solar-Thermochemical Conversion Platform

RAPID Transforming Process Industries

AIChE The Global Home of Chemical Engineers

www.aiche.org/rapid

For information on RAPID membership, contact us at rapid@aiche.org or visit our website at www.aiche.org/rapid