RAPID™

Transforming Process Industries

2019 ANNUAL REPORT

ABOUT THE RAPID MANUFACTURING INSTITUTE™

For over 100 years, chemical engineers have been developing processes based on standard unit operations and scaling those processes to build large, centralized manufacturing facilities. These principles have served the process industries well, resulting in predictable methods for designing and building low cost, high volume operations. Over the last several decades, scientists and engineers have been advancing new technologies that are starting to shift this paradigm. Instead of achieving economies of scale by builder larger facilities, modular processes are built on standardized, smaller scale platforms and are scaled in number. Process Intensification (PI) enables new combined unit operations that are more energy and raw material efficient and safer to operate. While Modular Processing and PI, as concepts, stand on their own, combined into Modular Chemical Process Intensification (MCPI) these technologies allow manufacturers to reduce risk by building and operating smaller footprint systems designed to produce just the amount of product needed to satisfy demand at any time then scale in number to meet market needs. MCPI offers manufacturers the opportunity to build a more efficient, distributed supply chain that is both sustainable and resilient.

RAPID serves as a nexus between process innovation, economic development, and job creation. The technology innovations and educational programming we sponsor will increase energy and operational efficiencies, enhance productivity, and improve sustainability, making U.S. manufacturing in the chemical process industries (CPI) more competitive in the global market, driving domestic economic growth, and developing the next generation workforce for these industries.

RAPID TURNS 3! IN ITS THIRD YEAR (2019), RAPID HAS:

- Focused strongly on stewardship of its 37 projects, 100% of projects were reviewed at relevant Go/No Go milestones.
- Made significant EWD progress including the annualization of its signature RAPID Intern Program
- Grew membership with a focus on industrial partners.

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RAPID: MISSION, VISION & THE VALUE WE PROVIDE

Our Mission

- Lead a national effort to develop, demonstrate, and deploy high-impact process intensification and modular process technology solutions that reduce energy use, increase sustainability, and drive profitability for U.S. manufacturing.
- Bring together private and public organizations to co-invest in R&D, commercialization, and deployment of innovative technologies.
- Establish an infrastructure that enables access to resources, tools, expertise, and facilities.
- Establish a technical education and workforce development program.
- Leverage $70 million of federal funding and over $80 million in member cost share to fund the development of new technologies and educational offerings.

Our Industry-Led Vision

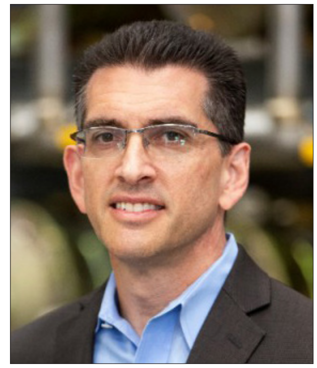
A dynamic network of partners who collectively build a sustainable ecosystem that:

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

The Value We Provide

BY PARTICIPATING IN RAPID, MEMBERS CAN:

- **De-risk** new technology development/deployment with R&D opportunities through projects or partnerships for new funding opportunities.
- **Accelerate** new process and/or product development through member connections and capabilities and the Test Network.
- **Explore** a shift toward resilient, sustainable, distributed manufacturing for the process industries with access to modular processing resources.
- **Educate** the current and future workforce with tools to re-think conventional processes and/or develop new innovative solutions through PI & MCPI training, free or discounted for members.
- **Receive** priority access to implementation software and modeling tools, strategy reports, tech assessments, and consulting services.
- **Contribute** to problem discovery workshops.



To Our Valued Members and Colleagues,

Thanks to the RAPID team and member community for helping us to complete a third very successful year. RAPID finished 2019 with 84 members, including 39 from industry, 33 from academia, and 12 from non-profits, national laboratories, and industry consortia. RAPID and its members continue to develop the technical and educational tools to allow process intensification (PI) and modular processing to reduce energy and water use, lower greenhouse gas emissions, decrease capital and operating costs, and enable resilient, sustainable, distributed manufacturing in the process industries. I could not be more pleased with the progress that we and our members are making together.

2019 marked an excellent year for technical progress on RAPID-funded projects. Member teams continued work on 33 research and development projects, authoring 187 publications, delivering 57 conference presentations, filing 8 patent applications and invention disclosures, and moving several technologies toward deployment at scale. In the IntraMicron led project on Modular Catalytic Desulfurization Units for Sour Gas Sweetening, the team deployed a modular processing unit to a wellhead in Texas and demonstrated cost-effective desulfurization of natural gas for over 1000 hours. Similarly, the University of Pittsburgh and Lubrizol led project on Intensified Commercial Scale Production of Dispersants piloted a modular, continuous manufacturing process that replaces a historically batch manufacturing operation; the continuous platform produced better quality product at lower capital and operating costs and moved toward commercial deployment much faster than anticipated.

This year the RAPID team focused strongly on outreach to the existing member community in several key ways. First, RAPID held several roadmapping and problem discovery sessions to better understand how PI and modular technologies might significantly alter the energy, water, and greenhouse gas footprint; cost structure, or deployment times for processes across several different industries. RAPID used the output from these discussions to inform a third call for technical projects which launched in December. The approach allowed prospective project teams to tailor R&D proposals to meet the cross-industry needs that the problem discovery sessions uncovered, also allowing those proposals to map to clearly defined market needs.

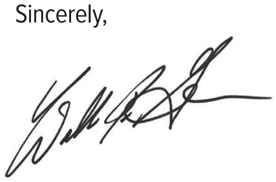
Second, RAPID added new community building offerings in 2019. Kicking off at the AIChE Spring Meeting in New Orleans, RAPID launched Technology Showcases during which members share details about their technical work or businesses. Members often discuss new product or service offerings, describe relevant research projects, or present problems with which they need help. The Showcases have catalyzed several new business and research collaborations among RAPID members, reinforcing the value of the member community that RAPID continues to build.

Third, at the AIChE Spring and Annual Meetings, RAPID focused on delivering high quality PI topical programming that featured presentations by RAPID-funded project teams. Also at the Annual meeting in Orlando, RAPID held our most successful poster session and mixer event at which all projects were represented, and DOE and RAPID hosted the annual two-day Peer Review during which a group of international experts in process development listened to detailed institute level and project presentations and provided feedback for improving institute operations and maximizing project impact.

RAPID also significantly grew Education and Workforce Development (EWD) efforts in 2019. We expanded virtual offerings by launching six new webinars and starting development on six eLearning courses, and the RAPID team collaborated with AIChE to author the 2019-2020 Student Design Competition with a focus on modular ammonia production. The impact of these efforts is compelling. By the end of 2019, over 5000 registrants viewed RAPID webinars, eLearning courses, or topical programming content. RAPID also successfully piloted the 4-day "Modular Chemical Process Intensification Boot Camp" developed by Oregon State University and plans are in place to offer the course again in the future. Three additional face-to-face courses are in development with project teams at the University of Arizona, Chemstations, Texas A&M University, and Worcester Polytechnic Institute.

The RAPID team takes great pride in the innovation, outreach, and education efforts that we and our members are doing. We have confidence that our community of innovators and transform the process industries and make U.S. manufacturing more sustainable, resilient, and competitive in the years to come.

Sincerely,



WILLIAM GRIECO
Chief Executive Officer,
The RAPID Manufacturing Institute

RAPID BY THE NUMBERS

MEMBERS YEAR END 2019
84

TOTAL PROJECT PORTFOLIO
37

R&D TECHNICAL PROJECTS
33

EDUCATION, WORKFORCE DEVELOPMENT PROJECTS
4

INTERN PROGRAM STUDENT PARTICIPANTS
40

TOTAL WEBINAR AND eLEARNING COURSE OFFERINGS
18

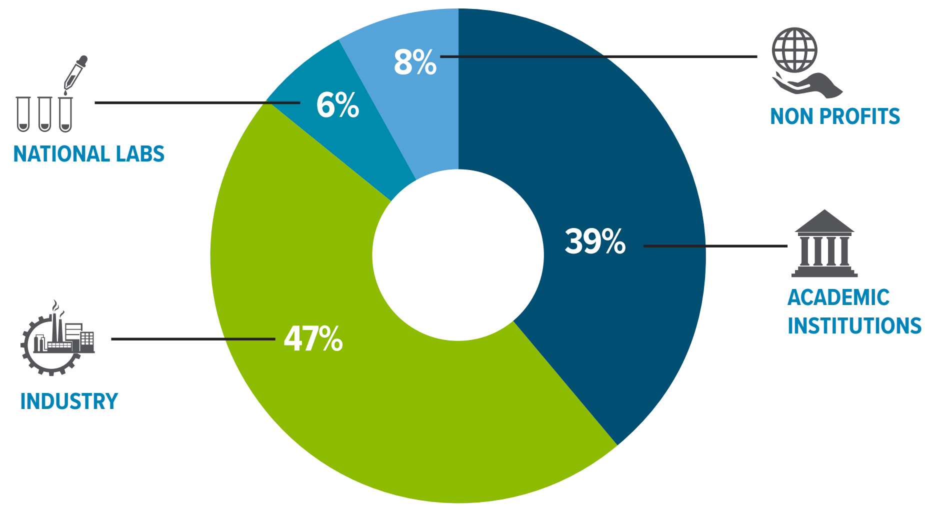
WEBINAR, CONFERENCE AND ELEARNING PARTICIPANTS
5,225

PATENT APPLICATIONS AND INVENTION DISCLOSURES
8

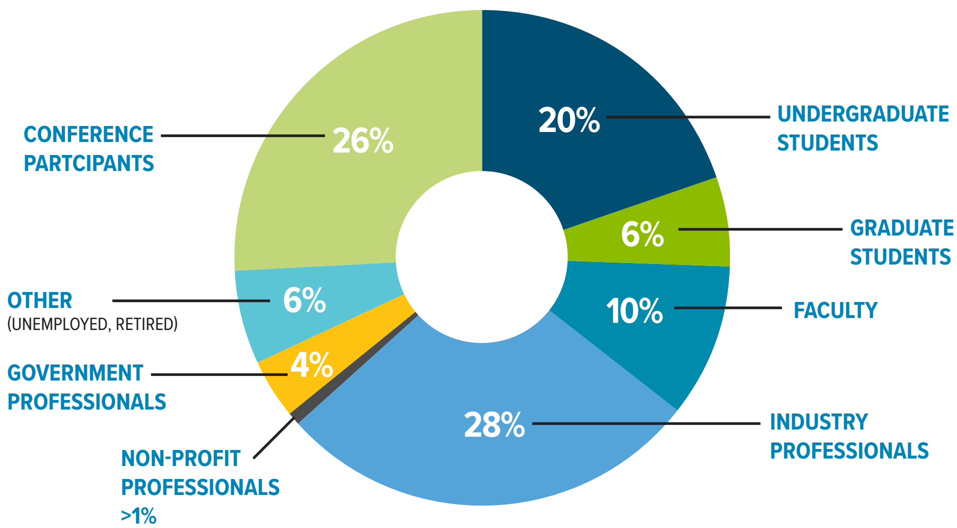
PUBLICATIONS FROM RAPID PROJECTS
187

TOPICAL CONFERENCE PRESENTATIONS IN 2019
57

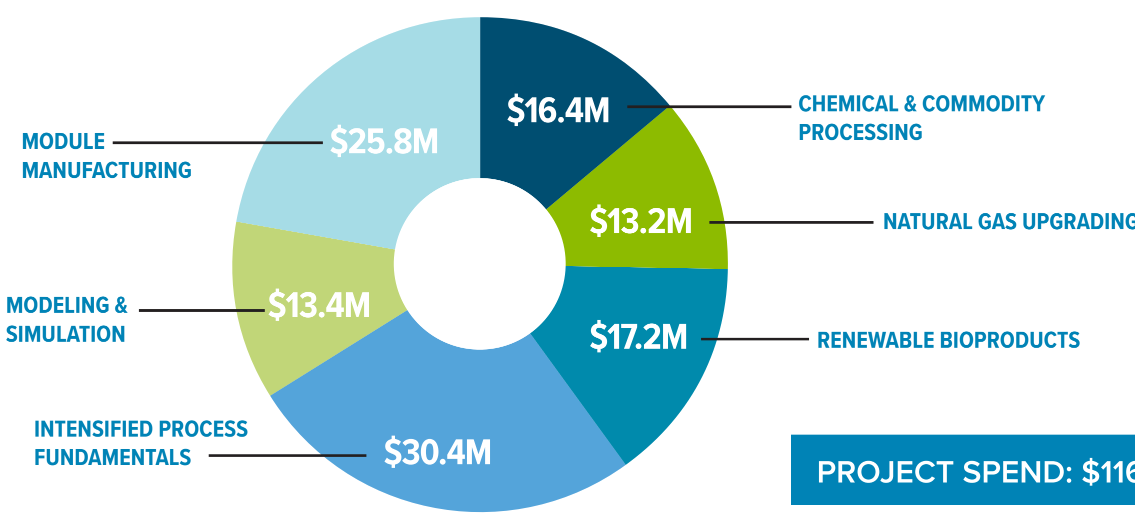
RAPID MEMBERS BY ORGANIZATION TYPE



EDUCATION, WORKFORCE DEVELOPMENT IMPACT BY ATTENDEE TYPE



RAPID R&D PROJECT BREAKDOWN BY FOCUS AREA



PROJECT SPEND: $116.4M

KEY ACCOMPLISHMENTS

Financial Sustainability

RAPID made substantial progress on implementing its plan for long term financial sustainability. The institute will operate as a member-focused consortium that (1) selects and manages technical development projects funded by members and supplemented with private and public sector support, (2) delivers content at meetings and via publications, (3) develops and distributes design guidelines and technical tools, including the RAPID Modeling Toolbox™ and RAPID Test Network, (4) tests and grows an engineering services practice to help clients benchmark their existing processes and understand how best to deploy PI and modular process technologies, and (5) deploys premium Education and Workforce Development content to inform the process community.

> “Lubrizol’s long-standing collaboration with the University of Pittsburgh led to a successful submission of a RAPID project. In turn, the RAPID/DOE funds allowed Lubrizol to greatly accelerate its efforts and install a fully functional production scale unit in our Spartanburg, South Carolina manufacturing plant early this year.”
>
> — Frank van Lier, Senior Director Global Process Technology at Lubrizol

Outreach

While significant progress was being made on technical projects and institute initiatives throughout the year among RAPID members and staff, there was also a considerable focus on sharing the vision, mission, and ongoing institute impact. In 2019, RAPID participated in multiple outreach events including:

- NYSTAR Innovation Summit, Rochester, NY
- Presented the “Business Case for PI”, SOCMA Executive Forum, Philadelphia, PA
- DVIRC Delaware Valley Manufacturing Summit, Oaks, PA
- Chem Show, New York, NY
- Engaged with the Tri-State Shale Coalition
- Presented at the UEF/AIChE Congressional Briefing titled “Workforce Development and Manufacturing Innovations to Enhance the Chemical Processing Industry”
- Water Use/Reuse Workshop, Orlando, FL
- STARTech Conference, Boston, MA
- 2019 Food Innovation Conference, Philadelphia, PA
- Solar Energy Systems Conference, Waco, TX
- Innovation Day at the Science History Institute

(Left to right) Montgomery Alger (AIChE President-Elect), Ashley Smith-Schoettker, (RAPID), Ignasi Palou-Rivera (RAPID), Bond Calloway (Savannah River National Lab), Hannah Murnen (Compact Membrane Systems), Dan Rozinski (Dow) present at the UEF/AIChE Congressional Briefing.

RAPID Project Highlight: Lubrizol Teams with Pitt to Intensify Production of Specialty Chemicals

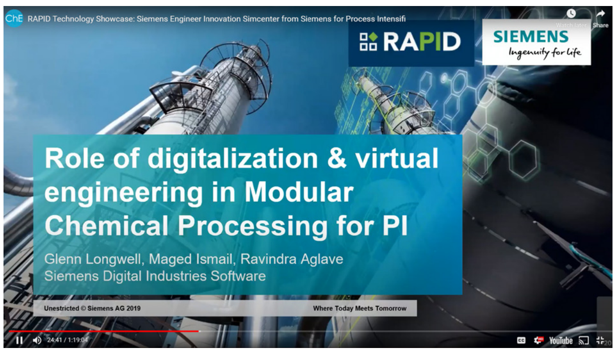
A research team comprising University of Pittsburgh and Lubrizol developed a continuous modular process to make an existing specialty chemical at **much lower operating and capital cost**. The new process has a smaller footprint in the manufacturing plant than the existing batch process and produces higher quality product with **virtually no waste generation and 30% lower energy use**. In particular, the project focuses on production of dispersants. This particular chemistry is challenging because of the wide range of viscosities involved, which requires special attention to the mixing. Pitt researchers performed measurements and modeling to understand the underlying reaction kinetics and mass transfer, which in turn allowed the Lubrizol engineers to design and build an intensified modular pilot skid. The initial pilot skid has recently entered service as a production asset, completing the batch-to-continuous process conversion in under 24 months. Now the team is designing a second-generation pilot skid and exploring alternative, intensified reactor designs.

RAPID Celebrates Manufacturing Day 2019 with M. Davis & Sons

RAPID participated in an exciting Manufacturing Day event at M. Davis & Sons in Newark, Delaware. M. Davis hosted a gathering of customers, suppliers, community leaders, educators, and government officials at their modular equipment manufacturing site. CEO Peggy Del Fabbro and President John Gooden shared details about their company's history and role in creating manufacturing jobs for the local economy. RAPID CEO Bill Grieco had a chance to talk about the work that RAPID is doing to advance process intensification and modular processing and how partnering with module manufacturers like M. Davis & Sons will accelerate deployment of new distributed manufacturing technologies in the process industries.

A COMMUNITY OF INNOVATORS

RAPID brings together recognized process technology experts from industry, academia, national laboratories, research institutes and other organizations to create a rich community that collaborates on R&D and education projects and provides thought leadership on PI and modular processing.



Siemens provides a virtual technology showcase to RAPID members.

In 2019, RAPID members convened quarterly to discuss institute progress and network. One example is the AIChE Annual Meeting in 2019 where RAPID hosted its second-annual signature Poster Session that provided unique networking opportunities between and among members while also providing opportunities to learn more about ongoing RAPID projects. During the AIChE Spring Meeting in April 2019, RAPID launched its Technology Showcase series, during which members highlight their research, product and service offerings, or problems to be solved. That event catalyzed interactions among several RAPID members, including a collaboration between Idaho National Laboratory and Starfire Energy. RAPID hosted Virtual Technology Showcases every six weeks, during which Idaho National Laboratory, Kebotix, the Manufacturing Extension Partnership, and Siemens continues to create new connections among the membership.

BENEFITS OF MEMBERSHIP IN RAPID INCLUDE:

- **Networking** with a diverse community of technical experts through in-person and virtual events as well as the online RAPID Member Directory.
- **Building** partnerships to access funding opportunities. When relevant funding opportunities are announced, RAPID not only notifies its members but actively works with them to make meaningful connections and build strong partnerships for winning project teams.
- **Developing**, licensing and commercializing valuable intellectual property.
- **Accessing** potential customers and supply chain partners.
- **Participating** in workshops and webinars on the latest developments in Process Intensification and Modular Processing.
- **Exclusive**, members-only access to RAPID updates and events, such as the RAPID Technology Showcases
- **Free** or discounted access to RAPID educational content.

RAPID Member Community at the 2019 AIChE RAPID Poster Session, Orlando, FL

2019 RAPID MEMBER ORGANIZATIONS

- ACS Green Chemistry Institute, Chemical Manufacturers Roundtable
- ACS, Chemical Manufacturers Roundtable
- American Chemistry Council
- Apache Corporation
- APPTI
- Argonne National Laboratory
- AspenTech
- Auburn University
- AVEVA
- B&P Littleford
- BayoTech
- Carnegie Mellon University
- Cerahelix
- Chemstations
- CISTAR (Purdue)
- City College of New York (CCNY)
- Clemson University
- Compact Membrane Systems
- Cornell University
- Dow
- DuPont
- EcoCatalytic Technologies
- ExxonMobil Research & Engineering Company
- Flint Hills Resources (FHR) Biofuels & Ingredients
- Fluor
- Georgia Institute of Technology
- Heat Transfer Research Inc. (HTRI)
- Idaho National Lab (INL)
- Induction Food Systems
- InnoSepra
- Institute of Gas Innovation and Technology at Stony Brook University
- IntraMicron
- Iowa State
- Kebotix
- Lubrizol
- M. Davis & Sons, Inc.
- Massachusetts Institute of Technology (MIT)
- MATRIC
- Michigan Technological University
- Missouri University of Science & Technology
- National Renewable Energy Lab
- North Carolina State University
- Optimation Technology, Inc.
- Oregon State University
- Owens Corning
- Pacific Northwest National Laboratory
- Praxair (Linde)
- Process Systems Enterprise
- Rensselaer Polytechnic Institute (RPI)
- Rutgers University
- Savannah River Nuclear Solutions
- Secat
- SHB Power Plant Engineering
- Shell
- Shepherd Chemical Company
- Siemens PLM Software Inc.
- Sironix Renewables
- Solvay
- Southern Research
- Starfire Energy
- StenCo LLC
- Texas A&M Engineering Experiment Station (TEES)
- Texas Tech
- United Technologies Research Center
- University of Alabama
- University of Arizona
- University of Arkansas
- University of Connecticut
- University of Delaware
- University of Houston
- University of Illinois - Urbana Champaign
- University of Kansas
- University of Michigan
- University of Minnesota
- University of New Hampshire
- University of Pittsburgh
- University of South Carolina
- University of. Texas – Austin
- US Clean Water Technology (USCWT)
- Via Separations
- W.L. Gore & Associates
- West Virginia University
- Worcester Polytechnic Institute (WPI)
- Zaiput Flow Technologies

“Being a RAPID member has allowed M. Davis to be at the forefront of innovative ideas and to be part of the solution to bring them to scale. By connecting members on the research side of the solution to those on the constructability and manufacturing side they have created a synergy that benefits everyone involved.”

— Sean Boston, M. Davis & Sons, Inc.

PREPARING THE WORKFORCE FOR A TRANSFORMATION IN THE PROCESS INDUSTRIES

RAPID's Education and Workforce Development mission is to establish a technical education and workforce development program to train and educate the current and future workforce, which can then research, develop, design, and operate processes that incorporate new PI technologies and modular process designs in the U.S.

In order to advance this mission, RAPID develops and deploys initiatives and content that bring awareness and education to target audiences including undergraduate students, graduate students, faculty as well as practicing engineers. In 2019, RAPID:

- Convened a diverse working group who developed the AIChE 2019-2020 Student Design Competition on the topic of modular ammonia production.
- Hosted six live webinars in addition to offering archived versions of webinars developed in 2018.
- Began development of six eLearning courses which will form the structure for a future RAPID Professional Certification
- Piloted two face-to-face hands-on courses through projects:
  - Modular Chemical Process Intensification, September 2019, Oregon State University
  - Emerging Membrane Processes for Water Purification, January 2020, University of Arizona
- Selected two additional EWD projects to develop face-to-face courses
  - COMPLETE - Computer-Aided, Model-based Process Intensification Learning, Training, and Education, Texas A&M University and Chemstations
  - Fundamentals of Batch to Continuous Process Conversion in Specialty and API Chemistries, Worcester Polytechnic Institute
- Developed train-the-trainer materials including lecture notes and homework problems

For a complete list of RAPID's educational offerings visit www.aiche.org/rapideducation

RAPID Pilots Modular Chemical Process Intensification MCPI Boot Camp

Through an EWD Project Call, RAPID developed a 4-day, face-to-face, course in partnership with Oregon State University's ATAMI Center and successfully piloted the course in September 2019. This face-to-face course is designed for professional engineers interested in advancing modular chemical process intensification in the processing industries, specifically through the use of "number-up" plant designs. RAPID plans to continue to offer this course in the future and is working with partners on three additional courses to be piloted in future years.

After attending the pilot course, Paul Yelvington, RAPID's CTO remarked, "What struck me most was how the Oregon State team took us on a journey from concept through to commissioning. We started by re-examining the fundamental chemistry and physics, moved on to learning about design and advanced manufacturing of intensified process equipment that exploits that fundamental understanding, and finished by learning how modular chemical plants are built using that intensified process equipment."

RAPID's Virtual Internship Program Develops Future Leaders

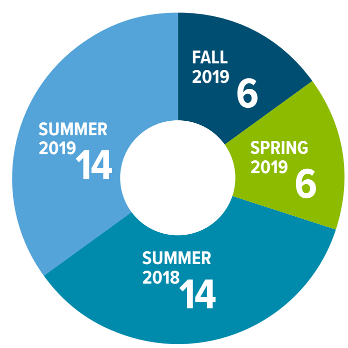
In this structured, 10-week virtual program, engineering student interns at RAPID member organizations join a virtual community and receive online safety, technical, and leadership training, as well as professional development and mentorship. The program helps smaller organizations by giving them access to interns nationwide and by allowing their student interns to become part of a broad virtual network across the U.S. Not only does this create a sense of shared learning and community, it also offers interns the chance to network with other students at peer organizations. The combination of technical know-how and professional development gives interns the diversity of skills necessary to be successful in the workforce. After successfully piloting the program in the summer of FY2018, RAPID now continues to offer Spring, Summer and Fall rotations on an annual basis.

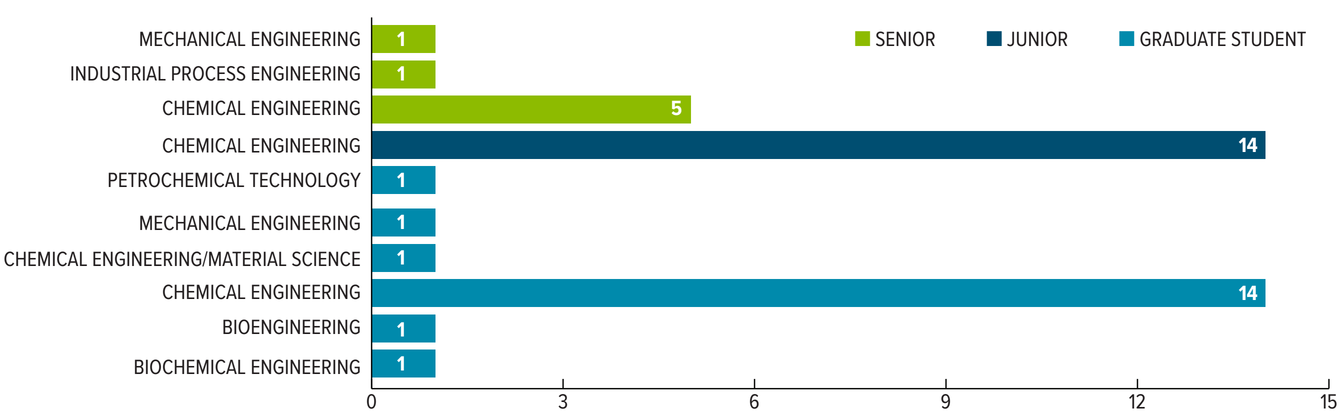
> "The RAPID Virtual Internship Program is an excellent way for students to learn about industrial research with a focus on Process Intensification. The student gains personal relationships within the industry while developing the skills required to be an attractive full-time employee. The company benefits from deeper connections to academic research and stronger relationships with the students and their respective universities. I cannot think of a better way to learn how the chemical industry is tackling global sustainability through process intensification."
>
> — Paul Witt, Dow

RAPID INTERNS TO-DATE **40**

AVERAGE RAPID INTERN GPA **3.59**

RAPID'S INTERNS COME FROM NUMEROUS INSTITUTIONS:
Stony Brook University, IntraMicon, Iowa State University, Oregon State University, University of Pittsburgh, Michigan Technological University, Missouri Science & Technology University





RESEARCH BREAKTHROUGHS PAVE THE WAY FOR MCPI TECHNOLOGIES

One of the ways that RAPID drives change in the U.S. process industries is through technology development. RAPID developed a portfolio of innovation projects that apply MCPI technologies to solve problems across different industries. Following RAPID's initial roadmapping work, the institute has developed a high-impact portfolio of R&D projects to prove out these new technologies and foster future demonstration, scale-up, deployment, and commercialization activities to promote competitiveness and job creation in the U.S. process industries. At the same time, RAPID's portfolio of R&D projects seeks to provide engineers with the simulation tools and critical data needed to design and evaluate potential MCPI solutions. These projects are challenging the "bigger is better" paradigm of equipment sizing and the "unit operations" paradigm of process design, which while having served the process industry well over the last 100 years, are not likely to serve us well into the next 100.

Always with an eye towards our institute technical metrics, projects have chipped away at these ambitious goals to reduce energy intensity while also reducing costs. Many project teams have demonstrated achieving these goals, as summarized in the graphic below, while more have them in their sights.

2019 also saw the release of our most recent call for research proposals. The areas of interest for this most recent call were selected based on feedback received from problem discovery sessions held throughout the year and analysis of gaps in our portfolio relative to our roadmap. These areas of interest included the fixed-nitrogen value chain, carbon capture and utilization, and post-use plastics valorization among others. New projects selected as a result of this call for proposals will begin in 2020, and we look forward to bringing you details of those in a future annual report.

Several project success stories within our existing portfolio are described here, while short summaries of the entire portfolio are presented in the appendix. These success stories highlight research breakthroughs, new measurement techniques, new analysis frameworks, and technology deployment & demonstration successes.

+20% Energy Efficiency

Metric#1

20% improvement in **energy efficiency**

17 projects achieved; 13 targeting

+2X Energy Productivity

Metric#2

Doubling (2X) in **energy productivity** ($/kWh)

6 projects achieved; 6 targeting

1,000hr Pilot Demonstration

Metric#3

1,000 hr **pilot demonstration** (with 20% improved energy efficiency, 10X reduced capacity cost, and 20% lower emissions/waste)

8 projects achieved; 13 targeting

-20% Module Cost

Metric#4

Experience (or learning) curve with 20% reduction in module cost for each doubling in the number of modules produced

17 projects achieved; 13 targeting

-50% Cost of Deployment

Metric#5

Module **deployment cost reduction** by 50% compared to current SOTA

17 projects achieved; 13 targeting

FEATURED RAPID PROJECTS

Dow Teams with Compact Membrane Systems to Seek Alternatives to Distillation (Project 5.7)

Throughout the petrochemical and refining industries, the separation of olefins and paraffins is generally performed via distillation, a costly and capital intensive method, particularly for light olefins. Recently, Compact Membrane Systems (CMS), a Delaware small business, developed a silver-incorporated custom amorphous fluoropolymer membrane for non-thermal separation of olefins and paraffins. Compared to previous attempts using facilitated transport membranes, this CMS membrane has been shown to have very good longevity in laboratory settings including exposure to expected process poisons. The objective of the project is to gain a better understanding of the membrane performance in realistic operating conditions through both real-world testing and fundamental modeling of the membrane system. The target case study for integration of the membrane module is the recovery of propylene from propane in a polymerization reactor purge stream, with the propylene recycled to the reactor. The techno-economic analysis predicts a 53% improvement in energy efficiency compared to a distillation baseline. CMS and Dow Chemical are gearing up for a field trial of the membrane skid at a Texas petrochemical plant; skid fabrication and site preparation/planning are now underway. At the successful completion of the project, the team will have field data at a large scale to demonstrate commercial feasibility of the application and fundamental understanding of fluid dynamics and membrane performance in a large membrane module.

WVU, U. Pitt, NETL, and Shell Explore Microwave Heating for Direct Natural Gas Conversion (Project 6.7)

U.S. natural gas production from shale exposed challenges linked to gas distribution and prompted renewed interest in better routes to liquid products. Indirect routes are generally energy and capital intensive. In contrast, direct non-oxidative natural gas conversion eliminates the syngas production step and required oxygen generation. However, these technologies have not been commercialized because of technical challenges such as low selectivity, coking, heat management, catalyst deactivation and catalyst regeneration. The goal of this project is to develop and demonstrate microwave catalysis for direct natural gas conversion, allowing simultaneous production of high value chemicals (e.g. aromatics) and hydrogen generation. West Virginia University (WVU) leads the project team which includes Pitt, Shell, and NETL—a powerhouse **combination of industry, academia, and the national labs**. The project is exploiting unique facilitates, including a first-of-a-kind 500 W variable frequency microwave reactor at NETL and unique capabilities to measure material properties important for microwave chemistry at reaction conditions. The team is engaged in microwave reactor design, identification of new microwave-susceptible zeolite catalysts, and techno-economic analysis. The non-traditional microwave heat addition enables selective heating of the catalyst reactive sites to temperatures several hundred degrees above the bulk temperature, thereby minimizing side reactions and providing opportunities for catalyst decoking and regeneration. The TEA has indicated **63% improvement in energy efficiency and 56% reduction in capital cost** compared to a baseline indirect syngas route.

Oregon State and the Construction Industry Institute Perform Four Case Studies Examining the Economics for Distributed, Modular Chemical Production (Project 10.9)

Developing cost models for modular chemical processes is challenging because the available capital cost estimation heuristics are strictly for stick-built plants rather than modular plants where some or all of the fabrication is done at a module yard rather than on site. The research objective of this project is to develop models for the total cost of ownership (TCO) for scaling up via modular chemical process intensification (MCPI) and to apply this model to at least four case studies taken from RAPID projects. The Construction Industry Institute (CII) brings a wealth of experience in plant construction through their industry advisory team, while Oregon State brings a unique manufacturing engineering perspective. This research is important for establishing a rationale for the numbering up approach to scaling and establishing cost drivers as compared to conventional stick-built plants. In particular, the project is illuminating some of the differentiators for modular numbered-up processes such as increased asset deployment flexibility, lower initial capital outlay/risk, and potential for economies of mass production. Initial work focused on development of cost models and methods for case study data collection. The current work centers on formal data collection and analysis to understand the TCO for the four selected case studies, which include distributed ammonia production and natural gas sweetening at the wellhead. The team plans to **release the bottoms-up OPEX and CAPEX cost model formulation and the first of the case studies** in the form of two upcoming journal publications.

RAPID PROJECT PORTFOLIO

PROJECT FINANCIALS

For 2019, total spending for RAPID increased to $32.29M ($14.65M federal share and $17.64M cost share), of which $25.45M supported 37 ongoing technical and education and workforce development projects. Funding of RAPID institute operations, including RAPID staff, meetings, content development, and support for Focus Area leadership, was $6.84M.

For comparison, in 2018, total project funding was $21.42M. Increased funding in 2019 reflected a ramp up in project work and several new projects started during the year.

The RAPID team and project investigators anticipate that project funding will increase to $40.77M in 2020 as work accelerates on most projects.

Formation of RAPID Center For Process Modeling

RAPID Project Number: 2.7

PARTNER ORGANIZATIONS

Texas Tech, SRNL, Dow, Clemson, AspenTech, Chemstations

PROJECT EXECUTIVE SUMMARY

RAPID aims to improve energy efficiency, reduce feedstock waste, and improve productivity by promoting modular chemical process intensification (PI) for processing industries in the U.S. manufacturing sector. To facilitate consistent and objective evaluation of performance metrics of various PI projects, RAPID has established this program to support and/or perform first principles-based process modeling for both baseline and intensified processes. Representing an alliance of academia, national laboratories, and industry, this project establishes a center for process modeling (CPM) responsible for process model-based metrics evaluation under RAPID sponsorship. The CPM objectives include 1) to standardize and advance process modeling methodology for evaluating DOE performance metrics; 2) to validate and capture PI insights for RAPID PI projects with process models; and 3) to serve as the repository for RAPID process models for distribution, education, and continual refinement.

POTENTIAL PROJECT IMPACT

CPM develops novel process modeling methodologies for non-traditional chemical processes that build off of existing process modeling tools. First-principles process modeling is the best way to capture PI insights and fundamentals, which further provide guidance to the intensification of other processes with similar process operations. In addition, novel process modeling methodology advances for non-traditional chemical processes will have a broad and lasting impact beyond the RAPID PI projects for the US industry.

CHEMICAL AND COMMODITY PROCESSING FOCUS AREA

Dynamic Intensification of Chemical Processes

RAPID Project Number: 5.4

PARTNER ORGANIZATIONS

University of Texas at Austin, Dow

PROJECT EXECUTIVE SUMMARY

A significant portion of commodity products are manufactured in large facilities that operate at steady state. In many ways, the traditional chemical industry has reached a plateau in terms of productivity and energy efficiency in such facilities. Improvements based on existing technologies and unit operations are mostly incremental and unable to address fundamental transport limitations that drive process efficiency. Process intensification, largely based on reducing transport and transfer limitations, has the potential to take bulk and specialty chemical production to new levels of economic efficiency. However, process intensification has thus far largely focused on the redesign of process hardware, requiring significant capital investments to realize benefits. This project looks to use modeling and optimization to define PI opportunities in existing hardware. In particular, it takes a general look at dynamically forcing a process to take advantage of non-linear systems responses. In certain cases, this mode of operation can deliver significant improvements in performance. The goal of the project is to provide a general theoretical framework for dynamic intensification, as well as using divided wall column operation as a test case to practice dynamic intensification at the pilot scale.

POTENTIAL PROJECT IMPACT

Changes in operating strategy can potentially lead to considerable energy savings. This can be achieved without substantial process hardware changes and thus with low capital expenditure. In the context of divided wall column application, the implementation of these ideas can be a true game-changer for energy consumption in the US chemical industry (there are around 40,000 distillation columns in operation, accounting for about 40% of the energy consumption for this industry). The technology transfer plan in this project will directly translate into industry application.

Para-Xylene Selective Membrane Reactor

RAPID Project Number: 5.5

PARTNER ORGANIZATIONS

University of Minnesota, ExxonMobil Research & Engineering

PROJECT EXECUTIVE SUMMARY

The current approach to p-xylene production includes an isomerization step that gives a near-equilibrium distribution of mixed xylenes, followed by a separate step to recover p-xylene, then recycling of p-xylene depleted product for further isomerization. This project aims to develop and validate para-xylene ultra-selective zeolite membranes and integrate them with an appropriately designed isomerization catalyst in a membrane reactor to accomplish selective para-xylene production. A successful membrane reactor will increase the yield of para-xylene beyond the limits of equilibrium by selectively removing para-xylene from the reactor as it is produced. Increased productivity and reduced separation energy, capital intensity, and greenhouse gas emissions are the key drivers for developing such an approach. Recent breakthroughs introduced by the University of Minnesota for the synthesis of zeolite membranes using ultrathin zeolite crystals (2-dimensional zeolites and zeolite nanosheets) enabled unprecedented mixture separation factors for para-xylene over its isomers (up to 10,000). This ultra-selective performance has been validated by measurements at ExxonMobil Research and Engineering Company and membranes are currently being tested at temperatures, compositions, and pressures relevant to membrane reactor operation.

POTENTIAL PROJECT IMPACT

Para-xylene is a key petrochemical intermediate with demand growing at an annual rate of ~7% and a market value of $35 billion in 2014 to $67 billion by 2022. The current state-of-the-art commercial separation technology is a Simulated Moving Bed (SMB) adsorption process, which produces 99.9 wt. % pure para-xylene and accounts for ~70% of the global share. Although significant improvements over the last 15 years in the SMB technology have brought down its energy requirements, it is still an energy-intensive process with an annual operating cost corresponding to $13/MT. As the global para-xylene demand grows and the world drives toward a low carbon economy, decreasing the energy demand associated with hydrocarbon separations will be increasingly important. This project not only provides significant economic benefits and energy savings for the specific process of para-xylene production (by reducing or eliminating separation costs) but it also serves as a test-bed for a novel membrane-reactor technology based on ultra-selective membranes that can be coupled with high-temperature and high-pressure catalytic reactors.

Modular Conversion Of Stranded Ethane to Liquid Fuels

RAPID Project Number: 5.6

PARTNER ORGANIZATIONS

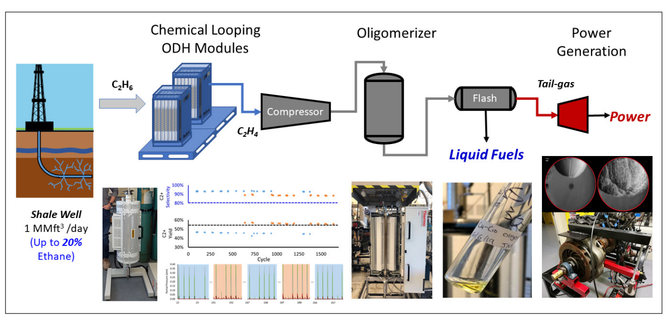
NC State University

PROJECT EXECUTIVE SUMMARY

Ethane can represent up to 20 vol.% of shale-gas, exceeding the 10 vol. % allowed in "pipeline-quality" natural gas. Each year, over 210 million barrels (liquid equivalent) of ethane are rejected in the lower 48 states. Upgrading low- to negative-value ethane to easily transportable liquid fuels is a promising solution to this supply glut. The key to this process is the development of modular systems that can operate economically at stranded sites. Conventional gas-to-liquids (GTL) technologies face significant challenges such as high capital cost and limited efficiency. This project will develop a fundamentally improved modular ethane-to-liquids (M-ETL) concept. The proposed M-ETL technology uses a modular Chemical Looping-Oxidative Dehydrogenation (CL-ODH) system to convert ethane and natural gas liquids (NGLs) efficiently into olefins (primarily ethylene) via cyclic redox reactions of highly-effective redox catalyst particles. The resulting olefins are converted to gasoline and mid-distillate products via oligomerization. The proposed project will also advance the M-ETL technology to make it ready for full-scale demonstration. A pilot-scale testbed will be designed and constructed for CL-ODH demonstration. The reactor channels of the testbed will be at a scale comparable to those of the proposed modular system.

POTENTIAL PROJECT IMPACT

The M-ETL technology can lead to 80% reduction in energy demand for ethane conversion. This will also result in corresponding reductions in carbon dioxide and NOx emissions. Due to the simplified process scheme compared to conventional GTL, 20+% savings in capital cost can be achieved. Therefore, significant improvements in energy productivity are expected from M-ETL. This modular system can be particularly suited for valorization of stranded ethane at shale gas production sites. Moreover, the CL-ODH component of M-ETL can also potentially used for polymer grade olefin production in centralized facilities with significantly reduced energy intensity and emissions compared to existing approaches.



Energy-Efficient Separation of Olefins and Paraffins Through A Membrane

RAPID Project Number: 5.7

PARTNER ORGANIZATIONS

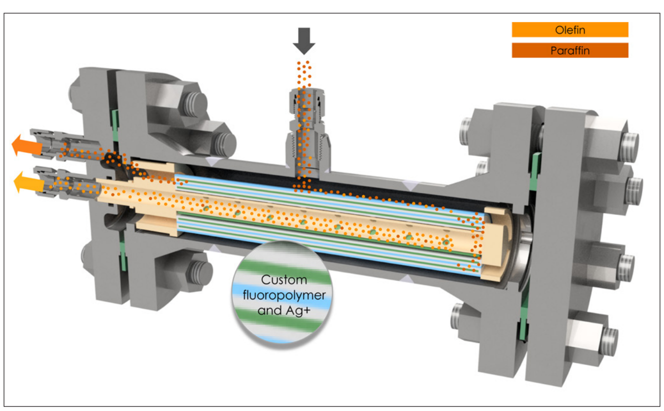
Compact Membrane Systems, Dow, University of Minnesota, ACS

PROJECT EXECUTIVE SUMMARY

Throughout the petrochemical and refining industry, the separation of olefins and paraffins is generally performed via distillation, a costly and capital intensive method, particularly for light olefins. This project uses a silver-incorporated custom amorphous fluoropolymer membrane to separate olefins and paraffins. Compared to previous attempts using facilitated transport membranes, this membrane has been shown to have very good longevity in laboratory settings and has been tested with reasonably-expected process poisons. The objective of this project is to gain a better understanding of the membrane performance in realistic operating conditions through both real-world testing and fundamental modeling of the membrane system. It targets the case of integrating a membrane module in a process to recover propylene from propane in a polymerization reactor purge stream, with the propylene recycled to the reactor.

POTENTIAL PROJECT IMPACT

The commercial benefit of a technology to separate olefins and paraffins through a membrane is potentially very large. Light olefins are one of the most important chemical markets globally, approaching 200 million metric tons of propylene and ethylene production in 2018. These molecules are extremely important due to their status as building blocks for numerous petrochemicals including polyethylene and polypropylene. Currently, these molecules are separated from each other using distillation, an energy-intensive process that is estimated to consume 0.3% of the world's energy. While many of the early applications will take place in cooperation with distillation, as the membrane technology developing under this project becomes more accepted and proven it may come in direct competition with distillation for new builds.



Intensified Commercial Scale Manufacture of Dispersants

RAPID Project Number: 5.8

PARTNER ORGANIZATIONS

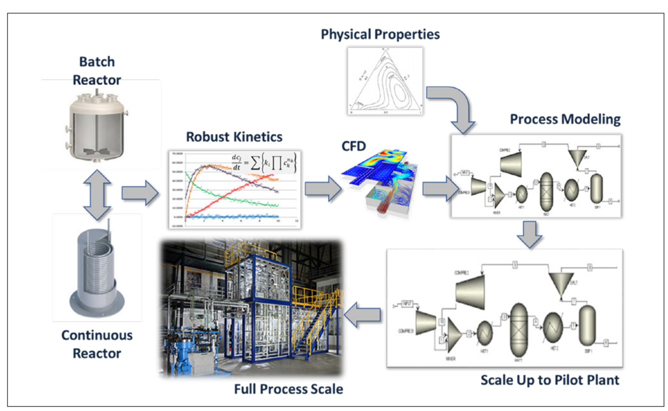
University of Pittsburgh, Lubrizol Corporation

PROJECT EXECUTIVE SUMMARY

This project will demonstrate conversion of a large-volume chemical commodities process from batch to continuous processing. It is focused to create an order of magnitude reduction in equipment size (and associated capital cost) by transitioning the traditionally batch production of dispersants, specifically succinimide dispersants, into a continuous process. Succinimide dispersants are a relatively large volume family of products that vary by molecular weight, and structure. Application and adoption of intensified, continuous processing principles offers the prospect of revolutionizing their manufacture. The project will look to establish a firm kinetic understanding of the proposed chemistry and to develop reactor modeling tools so that reaction and mass transfer requirements can be balanced while minimizing system volume, ultimately leading to construction and demonstration of an industrial pilot plant. Successful demonstration of a batch to continuous process at previously unrealized scales could open the door for a broader shift to continuous processing in the fine/specialty chemical industries.

POTENTIAL PROJECT IMPACT

The project will enable the first full-scale realization of an intensified, continuous process in the lubricants and dispersants market, and one of the first demonstrations of transition from batch to continuous processing in the US outside the pharmaceutical industry. As such, it could have a transformative impact on this industry. Successful demonstration is expected to quickly translate to other large-volume additives and to manufacture of similar specialty chemicals, such as various performance coatings and personal/home care products. By demonstrating value to a market and by validating both the technology and development process, the project will provide a model for others in the industry to emulate.



NATURAL GAS UPGRADING FOCUS AREA

Adsorptive Nitrogen from Natural Gas

RAPID Project Number: 6.4

PARTNER ORGANIZATIONS

Praxair, Georgia Tech

PROJECT EXECUTIVE SUMMARY

Low permeability natural gas reservoirs are being developed across the world using fracturing technologies. The most common approach for fracturing uses water with friction-reducing agents and thickening polymers. However, this approach requires approximately 400 tanker trucks to bring millions of gallons of water to a wellhead and results in millions of gallons of contaminated water that must be treated before going back into the natural water cycle. A second approach to fracturing uses high-pressure gases such as nitrogen or carbon dioxide. The use of energized fluids such as N_2 or CO_2 offers the potential to carry out fracturing without the negative aspects associated with water-based fracturing. This approach, however, often requires producers to divert initial gas production to a flare until N_2 / CO_2 gas concentrations in the "flow-back" drop below allowable limits for feeding into the natural gas pipeline network. This project aims to address the loss of hydrocarbon energy and the associated CO_2 emissions related to N_2 fracture operations by utilizing a new adsorbent developed by Praxair in a modular Pressure Swing Adsorption (PSA) system capable of recovering N_2 from produced gas at wellhead locations. Technology development in this area will address the specific problem described above and will shed light on the challenges of modular processing of distributed resources in general.

POTENTIAL PROJECT IMPACT

The adsorbent and pressure swing adsorption system described in this project provides an opportunity to significantly mitigate and even eliminate flaring associated with nitrogen fracturing. By rejecting the N_2 from the initial gas flowback streams, hydrocarbon can be recovered from flare and sold to customers. It is estimated that 50 – 80% of the hydrocarbon can be recovered from flare during the flow back operation. This would reduce or eliminate the estimated ~600 kilotons of CO_2 emitted annually the USA from current N_2 fracking operations. Additionally, this also saves ~20% of the water currently used in hydraulic fracturing by replacing 20% current water fracturing activities with N_2.

Efficient Chemicals Production via Chemical Looping

RAPID Project Number: 6.5

PARTNER ORGANIZATIONS

University of Delaware, Dow

PROJECT EXECUTIVE SUMMARY

This project will develop chemical looping technology (CLT) into a general process intensification (PI) strategy for modular upgrading of natural gas to commodity chemicals. Nonoxidative upgrading of methane, ethane, and propane to alkenes and aromatics is often limited by equilibrium. CLT is an effective PI strategy to circumvent such limitations by either reactive separation or selective oxidation of a subset of products from the reaction mixture to restore the thermodynamic driving force. CLT also allows for efficient heat utilization/management among different reaction steps, thus enhancing the overall energy efficiency of the process. The commercial potential of CLT is underexplored primarily because of the high cost in the design and prototyping of automated continuous systems. This project aims to demonstrate the generality of chemical looping technology (CLT) as a process intensification strategy by advancing chemical looping for methane dehydroaromatization (DHA) and alkane (ethane and propane) dehydrogenation (DH) at yields well in excess of one-pass thermodynamic limits. In each of these chemical looping processes, an increase in per pass conversion, a dramatic simplification of separation, and heat integration are all addressed in a single system, which makes them ideal for being deployed in standard reactor modules at remote natural gas extraction sites.

POTENTIAL PROJECT IMPACT

Chemical looping technology offers a unique and effective approach to overcome thermodynamic limitations in nonoxidative upgrading of natural gas to high-value aromatic products, e.g., benzene and toluene. It also has the potential to increase energy efficiency through more efficient heat management. Since natural gas extraction sites are often located in remote areas, the ability to produce easy-to-transport liquid aromatic products, rather than gaseous products, will drastically reduce the transportation cost. Further, the development of modular reactors, a customizable control mechanism, and a predictive computational model for materials screening will accelerate and reduce the cost of the prototyping of chemical looping processes for applications beyond natural gas. The successful implementation of this project could substantially improve the competitiveness of US chemical and energy industries.

Advanced Nanocomposite Membranes for Natural Gas Purification

RAPID Project Number: 6.6

PARTNER ORGANIZATIONS

University of Texas at Austin, Commonwealth Scientific and Industrial Research Organization (CSIRO)

PROJECT EXECUTIVE SUMMARY

Processing natural gas is the largest industrial application of gas separation membranes. Membranes occupy 10% of the ~$5 billion worldwide annual market for new natural gas separation equipment, with amine absorption accounting for most of the rest. While widely used, amine systems suffer from corrosion, complex process design, and equipment often unsuitable for offshore gas processing platforms. Amine systems are also less efficient than membranes at high CO_2 concentrations. Current membrane systems are most commonly based on asymmetric cellulose acetate polymers and suffer from lower CO_2/CH_4 selectivity and lower fluxes than are needed for more general adoption. Low selectivity means that such systems are often multi-stage, requiring expensive recompression of exhaust gas to extract more hydrocarbon product from it or resulting in greater losses of hydrocarbon product to waste streams. Low fluxes impact the overall size and cost of membrane equipment to treat a given quantify of natural gas. This project will prepare and characterize novel nanocomposite membranes based on recently discovered metal organic framework (MOF) materials and related nanoparticles having outstanding separation properties for removal of acid gases (e.g., CO_2) from natural gas. The project aims to demonstrate advanced nanocomposite membranes with much higher flux and selectivity than commercial state-of-the-art membranes when separating CO_2 from mixtures with CH_4 and mixtures containing aromatic contaminants. Membrane systems based on such membranes would be several times smaller than existing systems to process comparable amounts of gas and lower the hydrocarbon losses, thereby increasing energy efficiency and minimizing emissions/waste.

POTENTIAL PROJECT IMPACT

Relative to conventional cellulose acetate (CA) membranes, the proposed MOF membrane materials would have improved separation properties, excellent stability in process environments, and the ability to be manufactured as thin-film composite or asymmetric membranes. This would markedly reduce the size and weight of the systems. It will also eliminate the need for multi-stage processes, simplifying the process markedly, and decreasing emissions/waste and energy consumption per unit mass of pipeline-grade natural gas produced. The proposed nanocomposite membranes systems will have 10x higher flux and will be 10x smaller and lighter (important for offshore applications on platforms) with hydrocarbon waste/emissions reduction by 50%.

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

RAPID Project Number: 6.7

PARTNER ORGANIZATIONS

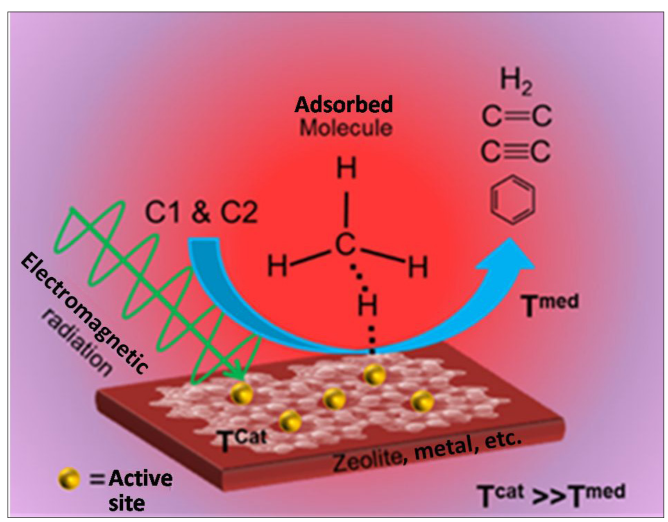
West Virginia University, University of Pittsburgh, Shell, NETL

PROJECT EXECUTIVE SUMMARY

The rise in US natural gas supplied, tied to challenges/costs associated with natural gas logistics, point to the value of converting natural gas to liquid products. Indirect routes are generally energy inefficient and capital intensive. In contrast, direct non-oxidative natural gas conversion eliminates the syngas production step and required oxygen generation. However, these technologies have not been commercialized because of technical challenges such as low selectivity, coking, heat management, catalyst deactivation and catalyst regeneration. The goal of this project is to develop and demonstrate an innovative modular system intensified with microwave (MW) catalysis, which allows simultaneous production of high-value chemicals (e.g. aromatics) and hydrogen generation via direct non-oxidative natural gas conversion. Specifically, the technical merits consist of synergistically integrating microwave reaction chemistry with novel zeolite catalysts that selectively activate natural gas. The microwave catalysis will enable direct, non-oxidative natural gas conversion under mild conditions with high product yield.

POTENTIAL PROJECT IMPACT

The conventional indirect conversion process via syngas is capital intensive and energy inefficient. Direct non-oxidative methane conversion to aromatics eliminates costly syngas production, resulting in capital savings and improvement in energy efficiency. 63% improvement in energy efficiency, 51% capital cost reduction due to the reduction in the number of unit operation and 4X improvements in energy productivity can be achieved due to the elimination of syngas production.



RENEWABLE BIOPRODCUTS FOCUS AREA

Autothermal Pyrolysis of Lignocellulosic Wastes to Sugars and Other Biobased Products

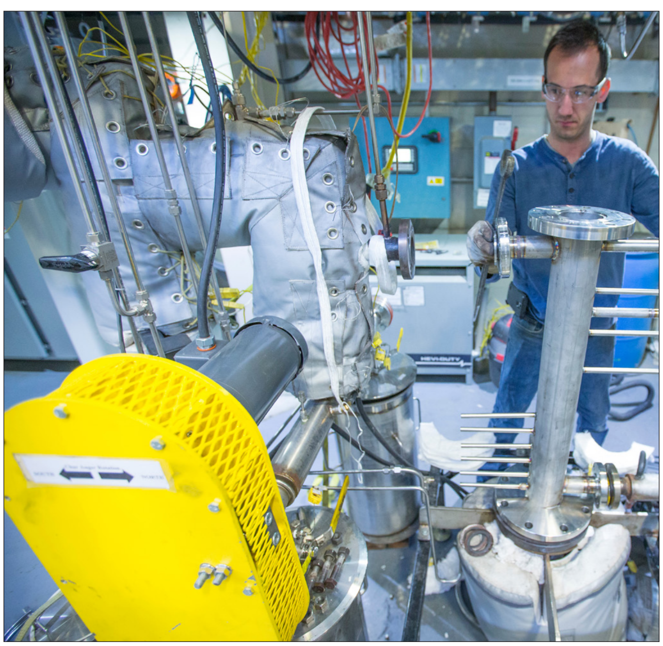
RAPID Project Number: 7.4

PARTNER ORGANIZATIONS

Iowa State University

PROJECT EXECUTIVE SUMMARY

Deconstruction of lignocellulosic biomass into fermentable sugars is among the major challenges in producing cellulosic biofuels and biobased products. Current pretreatment methods to liberate solid cellulose are expensive, accounting for as much as 30% of the cost of producing cellulosic biofuels. Most pretreatments do not completely fractionate cellulose and lignin, the latter of which interferes with enzymatic hydrolysis. The goal of this project is to develop a pyrolysis-based Modular Energy Production System (MEPS) for the thermal deconstruction of lignocellulosic biomass into cellulosic sugars and other value-added products. Thermal deconstruction uses thermal energy instead of enzymes or chemicals to fractionate lignocellulose into solubilized carbohydrate and phenolic oil. It has prospects for intensifying and modularizing biorefineries, especially through pyrolysis innovations including biomass pretreatments to increase cellulosic sugar production and autothermal pyrolysis to simplify design and increase feedstock throughput. MEPS configures unit operations as modules sized to fit in standard shipping containers, mass produced and integrated in the field to form fully operational biorefineries at a smaller and on-demand scale. Distributed processing with modular pyrolysis units deployed at multiple locations decreases logistical hurdles/costs for both feedstock and products.



POTENTIAL PROJECT IMPACT

The technologies proposed in this project are a transformative departure to traditional lignocellulosic processing systems which feature large, custom, “stick-built” plants. This project is based on MEPS, where unit operations are configured as modules sized to fit in standard shipping containers, mass produced and integrated in the field to form fully operational biorefineries at a smaller and on-demand scale. Distributed processing with modular pyrolysis units deployed at multiple locations decreases logistical costs/hurdles for both feedstock and products. Success in modular manufacturing is dependent on technologies that can achieve process intensification, thereby allowing enhanced output at reduced cost. If the thresholds for process intensification proposed here can be achieved, modular energy production systems can reduce carbon intensity in energy production and improve economic, environmental and social well-being.

Robust Membranes for Black Liquor Concentration

RAPID Project Number: 7.5

PARTNER ORGANIZATIONS

Georgia Tech, APPTI

PROJECT EXECUTIVE SUMMARY

Black liquor (BL), also known as “spent pulping liquor,” is a high-volume byproduct of lignocellulosic biomass pretreatment (i.e., wood pulping by the kraft process). BL is a corrosive, toxic, and complex mixture. About 500 million tons/yr of BL are produced in more than 200 kraft process units worldwide (including 99 in the US, with about 0.2 quads/yr energy spent for BL concentration by multi-effect evaporation). Currently, BL concentration is performed by multi-effect evaporators and is one of the most energy-intensive industrial separation processes. The development of a more efficient BL concentration technology is a high priority for the forest products industry, with membrane technology being a particularly feasible alternative. However, membrane technology has been elusive because of the lack of a long-lived/stable, low-cost, high-performance membrane. This project will develop and demonstrate a bench-scale modular graphene oxide (GO)-based membrane system that substantially improves the energy efficiency of concentrating kraft BL from 15 wt% solids (lignin, organic molecules, and inorganic salts) to 30 wt% solids by removing water (maximum 0.1 wt% solids). The key innovation is the development of BL-stable, scaled-up, GO-based nanofiltration, and reverse-osmosis membranes supported on macroporous polymeric (polyethersulfone, PES) supports for dewatering black liquor. The challenge is in developing and scaling up low-cost membranes that are long-lived in the corrosive conditions. The recent work on this project promises successful development and scale-up of BL-stable GO membranes. It would allow this technology to be quickly integrated into existing kraft processing facilities to leverage existing assets.

POTENTIAL PROJECT IMPACT

If successful, this project will make a critical leap in the path to industrializing a membrane-based process intensification technology for a key process in the renewable bioproducts industry. The capability to inexpensively purify components such as lignin and smaller organic molecules is also critical for valorizing lignocellulosic biomass. The work on BL-stable GO-based membranes will create a body of new knowledge on how these membranes can be engineered to deliver performance and stability in challenging applications once considered "out-of-bounds" for membranes. This approach uses a combination of low-cost macroporous supports and thin GO membrane coatings deposited by benign and low-cost vacuum filtration processes; and has substantive potential as a design approach allowing fabrication of customized modules for different applications and problems. The ultimate impact is to develop a membrane technology that can deliver high performance in much harsher environments than typical applications.

Sugars-to-Bioproducts Scalable Platform Technology

RAPID Project Number: 7.6

PARTNER ORGANIZATIONS

University of Delaware, Rutgers

PROJECT EXECUTIVE SUMMARY

While tremendous progress has been achieved on creating routes for the production of chemicals and fuels from lignocellulosic biomass, many of these processes are not economic due to the number of process steps required and the requirement for significant inter-stage separations. This project is developing a modularized chemical process intensification technology for the production of bio-para-xylene (biopX) from glucose. This process has received significant attention as a route to meet the high growth rate of pX (CAGR = 7%) and at the same time as we are seeing declining petroleum-based pX production in North America due to the reduction of naphtha cracking. This approach also meets the rising consumer demand for sustainable feedstocks to manufacture materials. This project focuses on the significant reduction of biopX production costs (>20%) using a novel, biphasic, multifunctional, continuous flow microreactor to carry out a cascade of four reactions combined with reactive extraction and potential in-situ generated H_2 – all in a single pot – followed by hydrophobicity-driven separation and a second multiphase microreactor. 'Smart' organic solvent selection as a common platform for all processes will also be explored to minimize separations. Fast and efficient microwave (MW)-based heating will also be implemented.

POTENTIAL PROJECT IMPACT

The success of this program can have a major impact on US economic development and sustainability. The proposed MCPI will enhance the reaction rate, minimize total reaction and heating time from hours to seconds, improve carbon efficiency, minimize separation complexity, and increase energy efficiency. These improvements enable >20% reduction in biopX minimum selling price—from the current estimated value of ~$1300/ton—and 20% energy savings, potentially making bioPX production commercially viable. Furthermore, the MCPI technology proposed herein can impact other bio-products' production, such as bio-acrylic acid, bio-jet fuels, bio-surfactants, and bio-lubricants.

Three-Way Catalytic Distillation to Renewable Surfactants via Triglycerides

RAPID Project Number: 7.7

PARTNER ORGANIZATIONS

University of Minnesota, Sironix Renewables, Univerisity of Delaware

PROJECT EXECUTIVE SUMMARY

Renewable feedstocks, including triglycerides and lignocellulose-derived sugars, can be converted to a new class of ionic surfactants, called "oleo-furan sulfonates" (OFS) by multi-step solid acid catalysis. The renewable OFS surfactant exhibits superior properties relative to conventional fossil-derived materials with higher micelle-forming efficiency, stability in cold water, and resistance to hard water. The sequential synthesis process includes catalytic hydrolysis of triglycerides, fatty acid dehydration to anhydrides, and furan acylation with anhydrides to form alkylfuran ketones, the key precursor to OFS surfactants. This technology has been demonstrated as a three-step process with independent reactors. This project aims to more efficiently prepare oleo-furan sulfonate (OFS) surfactants by combining all three chemistries (hydrolysis, dehydration, and furan acylation) into a single reactor-separator that permits integrated separation of byproduct water. All three reactions will be conducted in a vertical column containing packed trays to promote selective vaporization of light components (i.e., water). Spatially distributed throughout the column will be three catalytic zones containing hierarchical solid acid zeolite catalysts, each of which promote the chemistry specific to the composition of that zone. Water liberated from the acylation and dehydration steps at the bottom of the reactor flow upward to promote triglyceride hydrolysis, while fatty acids and anhydrides flow down to promote furan acylation. At the conclusion of this project, a detailed design of a reactive distillation system will be developed permitting tunable extents of each of the three chemistries, such that various grades of OFS surfactants can be manufactured. The project is also looking into advancing the lab-scale demonstration to the pilot-scale production.

POTENTIAL PROJECT IMPACT

Intensification of three process steps into a single device condenses three reactors and separation systems and has the potential to achieve single-step processing of natural oils to surfactant precursors, thereby eliminating as much as two-thirds of the processing costs. This approach also further enhances the capability for rapid design and deployment by advancing design techniques of process intensified catalytic systems.

High Purity Ethanol Without Distillation: Carbon Nanotube Enabled Ethanol Dewatering

RAPID Project Number: 7.8

PARTNER ORGANIZATIONS

University of Connecticut

PROJECT EXECUTIVE SUMMARY

Biofuels produced from fermentation processes have long been processed using decades-old distillation technology. Distilling a minor component of this broth to a high purity requires substantial amounts of energy that can lessen the net-energy and profitability of the fuel produced. This work will demonstrate a new technology concept developed by Mattershift, LLC that uses a carbon nanotube (CNT) membrane to selectively extract the biofuel, in this case ethanol, from a fermentation broth. Due to the unique chemical and structural features of the nanotubes, ethanol selectively permeates through the membrane, leaving water behind. Mattershift has developed the first-ever hollow fiber CNT membrane for this task, and this work will demonstrate its effectiveness at selectively removing ethanol directly from fermentation broths. These membranes are expected to take low concentration ethanol solutions (between 10 and 40%) and selectively extract it to above 80% ethanol in a single pass.

Use of Power Ultrasound for Nonthermal, Nonequilibrium Separation of Ethanol/Water Solutions

RAPID Project Number: 7.9

PARTNER ORGANIZATIONS

University of Illinois Urbana-Champaign,
Carnegie Mellon University

PROJECT EXECUTIVE SUMMARY

Separation of liquid mixtures, frequently by distillation, consumes large amounts of energy in the chemical and process industries. This project proposes to develop, test, and demonstrate a continuous-flow, scalable, nonthermal, nonequilibrium liquid separation for the test case of ethanol + water that uses ultrasound, and avoids the heat transfer losses and azeotropic bottleneck of distillation. The basis of the separation is straightforward. When ultrasound passes through a nominally quiescent liquid with a free surface above, droplets are produced and form a mist. Previous work in this area shows that in aqueous ethanol solutions, removal of these droplets using a carrier-gas flow provides a liquid in which ethanol is significantly enriched relative to the initial bulk solution. Successful deployment of this technology could result in significant savings in energy and capital costs for this high-volume separation, and will lay the groundwork for similar separations in a broad class of other binary (and probably multi-component) systems, including those forming azeotropes.

POTENTIAL PROJECT IMPACT

The process will yield large reductions in energy consumption, and provide significant savings in size and capital cost. The methodology will be applicable to methanol/water, butanol/water, and other systems.

INTENSIFIED PROCESS FUNDAMENTALS FOCUS AREA

Intensified Microwave Reactor Technology

RAPID Project Number: 8.3

PARTNER ORGANIZATIONS

University of Delaware, Rutgers University, United Technology Research Center

PROJECT EXECUTIVE SUMMARY

This project looks to develop both foundational hardware and modeling tools for microwaves as a non-conventional energy input source - a key theme in process intensification - for reactions across chemical conversions and materials synthesis. The project develops scalable microwave technology (MWT) across industries and RAPID focus areas (FAs) and demonstrates its diverse applications with different spatial, temporal, and phase characteristics, often combined with additional process intensification (PI) technologies. It develops software for optimization and design, followed by module fabrication and demonstration. It is expected that microwaves will be particularly useful in processes that are both high temperature and endothermic and for processes that may be difficult to scale down for modular applications using other approaches for heating.

POTENTIAL PROJECT IMPACT

This project promises to overcome today's most critical barrier for MW powered reactor technology by developing general scalable design techniques for improved energy efficiency, enhanced selectivity and reduced deactivation for energy intensive processes across industry sectors. The impact can range from food to commodity chemicals to shale gas. Given the revolution in shale gas in the US, on-demand small alkane conversion to alkenes is of tremendous interest. Success of this program will revolutionize modular and robust manufacturing of valuable liquids for transportation from shale gas and biogas in remote locations to improve rural economies.

Microfibrous Entrapped Sorbents for High Throughput Modular Process Intensified Gas Separation and Ion Exchange

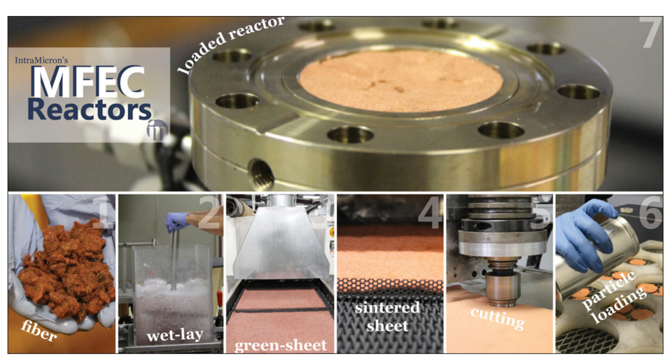
RAPID Project Number: 8.4

PARTNER ORGANIZATIONS

IntraMicron, SRNL, University of South Carolina, Auburn Univerisity, Oregon State University, BASF

PROJECT EXECUTIVE SUMMARY

This project will utilize microfibrous entrapment of small particulate sorbents or ion exchange (IX) resins to overcome physical barriers and identified technology gaps that currently prevent energy efficient and cost-effective wellhead CO_2/CH4 separations through pressure swing adsorption (PSA) and Cs_+ removal from nuclear fuel processing streams. Both commercial cyclic adsorption processes are currently limited by heat and mass transport restrictions occurring in large particle (1-4 mm diameter) packed beds. In this project, the use of smaller particles (10-150 µm diameter) eliminates previous intraparticle mass transport restrictions resulting in effectiveness factors near unity, while particulate entrapment within sinter-locked networks of micron-diameter metal fibers (microfibrous entrapped sorbent, MFES) provides packed bed thermal conductivities that are up to 250-fold higher than those of typical packed beds. Higher thermal conductivity allows for near-isothermal operation and results in more rapid and higher duty cycles, which reduces the required sorbent load and increases the overall output of the now smaller unit. The entrapment of particulates within a flexible fibrous structure eliminates shrink/swell problems and bed channeling while maintaining a low pressure drop. For IX processes, the reduction in particle size provides an order of magnitude enhancement in IX kinetics and allows new IX resin powders to be quickly adopted without having to undergo the lengthy, expensive, performance-limiting penalties associated with large bead formulations. For both applications, the process intensification and enhancement of fundamental rate phenomena decreases system size, increases energy efficiency, decreases cost, and promotes efficacy and modularity. This methodology is a transformative platform approach that is inherently modular and broadly applicable across a wide range of catalytic or sorbent-based processes.



POTENTIAL PROJECT IMPACT

The size, CAPEX, OPEX, energy consumption and performance of traditional IX and PSA systems are limited by the heat and mass transport and hydrodynamics associated with traditional designs. Implementing MFES technology to improve upon traditional packed beds will result in 50%-75% reductions in CAPEX and 65%-85% reductions in OPEX. With knowledge gained from this project, the reduced size and cost of MFES-based approaches will facilitate the further commercialization of intensified modular process units which are critical for purification and waste treatment applications. This MFES methodology enables many new IX formulations to be rapidly evaluated for facile transition to the commercial scale. For PSA-based natural gas treatment applications, the anticipated 10-fold throughput enhancement will enable the production of cost-effective modular units for gas purification that can be implemented at distributed production sites.

Thermoneutral Propane Dehydrogenation Via a Solid Oxide Membrane Reactor

RAPID Project Number: 8.5

PARTNER ORGANIZATIONS

University of Michigan, ExxonMobil Research & Engineering

PROJECT EXECUTIVE SUMMARY

This project is utilizing solid oxide membrane reactors for chemical transformations that are critical to the seamless integration of shale natural gas and liquids into the chemical industry supply chain. The project is particularly interested in the production of propylene from propane. Current propylene production occurs primarily via naphtha steam cracking, a highly energy-intensive process that is not amenable to distributed operations, which are highly desirable when shale natural gas and liquid is used as the carbon source. This technology can apply to centralized or distributed operation and can operate at dramatically lower temperatures than steam crackers. The technology will apply perovskite solid oxide membranes which can simultaneously conduct oxygen and hydrogen ions. On one side of the membrane reactor, air is used as an oxygen source to the perovskite. Oxygen anions are conducted across the membrane where they can react with propane at the interface of the perovskite and small Pt alloy catalysts in an exothermic partial oxidation process. In addition, the process of propane dehydrogenation takes place at the same side of the membrane yielding hydrogen ions, which are conducted by the same membrane to the other side. By adjusting the external conditions as well as the membrane and catalyst design, the flux of oxygen and hydrogen ions in the opposite directions of the membrane can be controlled. This control will allow to develop a highly selective thermo-neutral process operating at lower temperatures and drive equilibrium conversion forward while avoiding the deleterious further reaction to unselective combustion products.

POTENTIAL PROJECT IMPACT

Current propylene demand is growing at 4.6 % per year. Due to the abundance of cheap natural gas and the demands of the developing world for high performance plastics, growth is expected to further increase in the near term future. Given this anticipated growth in demand, new supply capacity must be built. A typical steam cracker unit may take 7-8 years for construction, so development and deployment of alternative technology is viable in this space. The energy footprint for operation of a typical steam cracker is 300 MW for a 1 Mta propylene plant to overcome the reaction endothermicity alone. Even mitigating a fraction of the energy costs would result in a more environmentally friendly sustainable process. The process intensified modular reactor design of this technology will allow significant improvements in energy efficiency compared to current state-of-the-art technologies.

Multiphase Microchannel Separator

RAPID Project Number: 8.6

PARTNER ORGANIZATIONS

Oregon State University

PROJECT EXECUTIVE SUMMARY

In conventional two-phase separation, mass transport between the two phases can be intensified via increased surface area, usually in the form of smaller droplets or bubbles. The increase in the interfacial surface area typically results in higher energy cost due to agitation or mixing and slower processing time as the smaller droplet phase requires more time to separate. One can increase processing speed in centrifugal extractors but this, in turn, increases energy requirements significantly. Often, microscale process intensification is at odds with macroscale energy efficiency in conventional systems. From a capital cost perspective, current separation methods are economically feasible at large scale due to the inherent cost scaling of hardware manufacturing for traditional unit operations. As a result, they can be prohibitively difficult to translate into smaller modular systems. This project is working on the development of a flexible yet standardized platform for multiphase separation utilizing microchannel processing technology (MPT). Multiphase Microchannel Separation in MPT systems directs flow of each phase by creating a capillary force gradient via size and spacing of micro-scale architectural features, thereby controlling interfacial curvatures and thus capillary forces.

With a proper choice of surface properties, the system is designed so that a selected phase cannot overcome capillary forces in one direction of the gradient with inertial and viscous forces, guiding the fluid towards a selected outlet stream. Additionally, a flat plate design can accommodate a larger processing throughput per layer of the device and reduce manufacturing complexity compared to single microchannel devices.

POTENTIAL PROJECT IMPACT

This technology has demonstrated three to four orders of magnitude reduction in power input per liquid volume compared to conventional technology and has shown a 500x increase in mass transfer coefficient, resulting in faster processing and higher throughput per unit. This will allow the hardware to be significantly smaller and less expensive to produce. Microchannel systems are scalable, making them highly suitable for modular chemical processing. This technology has significant potential to de-risk CapEx associated with downstream separations in small to medium chemical plant applications.

Energy Efficient Technology for Metals Separation

RAPID Project Number: 8.7

PARTNER ORGANIZATIONS

University of Alabama, Secat, Inc., AVEVA, Idaho National Lab

PROJECT EXECUTIVE SUMMARY

This project addresses the demonstration of a low-cost and low-energy pathway for the separation of metals from mixed scrap based on ionic liquids. The goal of the project is to develop and demonstrate a novel electrochemical process for the separation of metals from mixed scrap using ionic liquids (ILs) at low temperatures. For example, conventional separation of aluminum involves scrap melting at 800 °C resulting in high losses in metal values, high energy consumption and the generation of greenhouse gases including CO2 and fluorides that require post-combustion and flue gas cleaning processes. In the proposed electrochemical separation process, the separation will be carried out at low temperatures (<120°C), high metal recovery (>99%), low energy consumption, and no greenhouse gases generation. The electrolyte and residue of the process are recycled. This project will take the technology from bench to pilot scale.

POTENTIAL PROJECT IMPACT

Separation of aluminum from mixed scrap using ionic liquids will result in major energy saving. The new aluminum separation technology developed in this project will have an energy consumption of 9.5 kwh/kg of Al ($1.10/kg of Al) as compared to the industrial best process is 13.64 kwh/kg of Al ($1.64/kg of Al) which translate to 30.4% energy reduction in US industrial energy intensity. The energy savings of 38.1% and a carbon dioxide reduction of 56.1% are estimated from the commercialization of this project.

Modular Mechanical Vapor Compression Membrane Distillation (MVC-MD) for Treatment of High TDS Produced Water

RAPID Project Number: 8.8

PARTNER ORGANIZATIONS

Texas Tech University, University of Arkansas, Apache, AspenTech, W.L. Gore & Associates

PROJECT EXECUTIVE SUMMARY

This projects aims to integrate mechanical vapor compression with membrane distillation (MVC-MD) to intensify the treatment of produced water resulted from hydraulic fracturing of shale oil and gas. In particular, membrane distillation offers a viable pathway to treat concentrated brine streams with high salinity brines, and it has the potential to be utilized for near-zero liquid discharge. However, MD in its current state is handicapped by significant energy intensity due to loss of heat of evaporation, and scaling (fouling). This project is looking into the energy intensity issue by integrating MD with MVC to recycle the latent heat of evaporation. It also proposes a facile aluminum electrocoagulation (EC) pretreatment to remove up to 95% of total suspended solids and organic compounds. The proposed aluminum EC can effectively mitigate membrane scaling for long-term applications.

POTENTIAL PROJECT IMPACT

- Treating produced water for recycle and reuse is an untapped business. The oil & gas industry spends more than $40 billion for the PW treatment and disposal, annually. Less than 10% of PW is recycled or reused, while only 1% is treated.
- Small, modular MD-MVC can be used to treat the produced water at the well site. This technology has the potential to be utilized for near-zero liquid discharge.

Modular Catalytic Partial Oxidation Reactors Using Microstructured Catalyst Structures with Combined High Thermal Conductivity and Flame Extinction Capacity to Enhance Process Safety Margins and Enable High Per Pass Conversion and High Selectivity

RAPID Project Number: 8.9

PARTNER ORGANIZATIONS

Auburn University, University of South Carolina, IntraMicron

PROJECT EXECUTIVE SUMMARY

This project looks to use IntraMicron's platform technology of microfibrous entrapped catalysts (MFEC) to create a safer and more efficient process for the production of ethylene oxide (EO). Ethylene oxide is produced via the exothermic reaction of oxygen with ethylene. Because of the poor heat transfer and flow distribution in current packed bed reactors, hotspots form in the bed, resulting in poor selectivity. To mitigate these issues, EO processes are typically operated with sub-stoichiometric oxygen concentrations resulting in only a 10-12% ethylene conversion per pass. The use of thermal buffering inerts, such as CH_4, and operating at low per pass conversion results in significant downstream costs associated with separations, recycle, BOP, and OPEX. This project aims to apply microfibrous entrapped catalyst (MFEC) with high thermal conductivity and inherent flame arresting propensity to safely increase single-pass conversion of current ethylene epoxidation processes. MFEC is a structured catalyst with an effective thermal conductivity 250 times higher than a typical packed bed. Because of its high thermal conductivity and highly porous nature, MFEC provides a near-isothermal intrabed temperature profile and reduces risks of hotspot formation, autoignition, and explosions.

POTENTIAL PROJECT IMPACT

- Reduce or eliminate the level of inerts in the feed stream to reduce the amount of product recycle
- Reduce CAPEX
- Reduce OPEX
- Improve or maintain EO selectivity
- Modular capabilities

MODELING & SIMULATION FOCUS AREA

SYNOPSIS–Synthesis of Operable Process Intensification Systems

RAPID Project Number: 9.3

PARTNER ORGANIZATIONS

Texas A&M, Georgia Tech, Auburn University, Dow, Shell, Process Systems Enterprise, Inc.

PROJECT EXECUTIVE SUMMARY

This project looks to achieve the aggressive goal of discovering potential MCPI process configurations that are both safe and operable based on using existing modeling approaches. The team will link together and expand upon existing modeling tools that are in various stages of development to create an environment that can define potential MCPI solutions without needing to define potential process schemes. This approach to process synthesis is high risk, but could create unanticipated and highly valuable solutions. As a test chemistry, the team will look at hydrogen production approaches to define potential MCPI solutions that improve upon SMR.

POTENTIAL PROJECT IMPACT

There is no current commercial software available that allows for novel conceptual process designs without requesting equipment and flowsheet structures beforehand, and at the same time, provides a specialized PI model library. The tools developed in academia either disregard process intensification or are incapable of encompassing the whole roadmap required for an operable process design. Hence, the resultant design procedures, software prototype, and model library generated within this program will be unique with its holistic view on process intensification via integrating the process synthesis, design, optimization, and control tasks in a single software platform. The application showcase on thermal decomposition of methane will provide a commercially promising pathway for large-scale production of high-quality carbon materials. SYNOPSIS will contribute to bridging the gap between lab scale and commercial application of methane pyrolytic conversion by combining process synthesis, reaction engineering, and heat management. In doing so, it will demonstrate a generic process for employing PI for challenges across industry.

Optimization Modeling for Advanced Syngas to Olefin Reactive Systems

RAPID Project Number: 9.4

PARTNER ORGANIZATIONS
Dow, Carnegie Mellon University

PROJECT EXECUTIVE SUMMARY
Advanced reactor designs with multiple catalysts are game-changers for process intensification. These reactors transform large, complex processes with multiple reactors to one-shot reactors, where complex reaction mechanisms can be exploited within a single unit. Such designs lead to layered and mixed catalyst beds that overcome equilibrium limitations, manage heat effects and improve product selectivity. These graded bed reactors have been considered for a number of reactive systems, ranging from Fischer-Tropsch synthesis, benzene hydrogenation, oxidative coupling of methane and steam reforming. This project develops and applies a new approach for the optimization of graded bed systems, based on EO-based optimization of fully discretized DAE (differential-algebraic equations) and PDAE (partial differential-algebraic equations) models. Known as direct transcription, this approach has been widely applied to challenging dynamic optimization problems, adapted to large-scale optimization software and is generally much faster and more reliable than with standard commercial tools. In particular, for graded beds, this approach stabilizes exponential forward modes and applies specialized regularization strategies in order to handle singular problem characteristics. As the target application, this project is especially devoted to improving the design and optimization methodologies for syngas to olefin (STO) processes, with emphasis on producing light (<C5=) olefins. Here, the optimization process significantly advances the synergies between methanol synthesis catalysts for syngas reactions and zeolite catalysts that produce light olefins.

POTENTIAL PROJECT IMPACT
The simultaneous dynamic optimization approach, coupled with a bi-level formulation for singular control, forms the core technology to determine optimal catalyst and temperature distributions for graded beds. A study for partial oxidation reactors has shown that the graded bed optimization increases the yield up to 34%, merely through the design of optimal catalyst and temperature distributions profiles within the reactor, without capital expense. The impact is also significant for new plant designs, where traditionally multi-reactor beds can be simplified to a single vessel, offering potential capital and energy benefits, in addition to chemistry yield improvements.

RAPID Reaction Software Ecosystem

RAPID Project Number: 9.5

PARTNER ORGANIZATIONS
University of Delaware, Dow, Process Systems Enterprise Inc

PROJECT EXECUTIVE SUMMARY
Intensified processes are spatially and/or temporally coupled systems needing new modeling tools that go beyond systems analysis, and integrate reactor models with molecular scale models of chemical reactions. Current software at the quantum scale (density functional theory (DFT)) and the reactor scale (e.g., CFD) are widespread. In contrast, kinetics codes, especially for heterogeneous catalysis are at the proof-of-concept level due to outstanding technical barriers. This project will overcome these barriers by integrating existing software components and building missing ones from available prototypes. It will develop an open-source chemical kinetics software and data hub (OpenCK) as a transformative, cross cutting platform to address one of the most pressing gaps in process intensification (PI) and modular chemical process intensification (MCPI), namely the lack of a kinetics multiscale modeling software to plug and play (i.e., analyze, design, optimize, control), along with an associated hub of documented and validated models and data, a catalyst discovery 'engine', and toolkits for error analysis and assimilation of experimental data.

POTENTIAL PROJECT IMPACT
The proposed software and data-hub will fill in a critical gap across chemical industry. It will catalyze innovation cycles by replacing empiricism and shorten time to market, e.g., by potentially minimizing intermediate scale-up steps, and by accelerating catalyst development. These outcomes can in turn have significant economic benefit. Ten trillion dollars of the world's Gross National Product (GNP) are generated by petroleum, chemicals, energy, and food industries. Combined with the environmental sector, these sectors depend critically on catalysis. The project can, within a short time period, build the cyber-infrastructure-enabled data hub and software to accelerate these economically vital sectors of the US, including emerging distributed resources (e.g., shale gas, CO_2 reduction, biogas, bioproducts), with obvious ramifications for job creation.

An Experimentally Verified Physical Properties Database for Sorbent Selection

RAPID Project Number: 9.6

PARTNER ORGANIZATIONS

Georgia Tech, Dow, Praxair, AspenTech

PROJECT EXECUTIVE SUMMARY

This project works to close the gap seen in the intensified process fundamentals area around how to enable modeling tools through the presentation of useful data for phenomena such as adsorption in complex systems. It looks to use meta-analysis of available databases to determine what data can currently be used with statistical confidence in its accuracy. Additionally, the project will also look to perform selected experiments to enhance this data set, and it will carry out simulations (validated by the data set that has been established) to further enhance the availability of a broad class of input data for process models.

POTENTIAL PROJECT IMPACT

When successful, the project will provide publically available data that will strongly incentivize software providers to include widely accessible process design modules for adsorptive separations in their products. Basing these modules on real materials will greatly increase the motivation of users across the chemical industry to consider adsorptive separations in the early stages of process design as an alternative to distillation. Individual software providers will be able to create distinctive value for their products by the functionality and ease-of-use of their design tools for adsorptive processes, which require cyclic processes and typically offer many design alternatives.

MODULE MANUFACTURING FOCUS AREA

Manufacturing Supply Chain Development for the STARS Technology Modular Solar-Thermochemical Conversion Platform

RAPID Project Number: 10.4

PARTNER ORGANIZATIONS

Oregon State University, Pacific Northwest National Lab

PROJECT EXECUTIVE SUMMARY

This project is looking to address the primary challenge we see in the module manufacturing space – how we can significantly improve the Manufacturing Readiness Level (MRL) of a high Technical Readiness Level (TRL) technology to open the door for broad deployment. In particular, the team at PNNL and OSU is carrying out a cost/manufacturability study on the piloted STARS technology for solar steam methane reforming. The results of this study will define key economic break points in the production number of STARS process modules that point to "best" methods of mass manufacturing (such as additive manufacturing for production runs on the order of 100–1000). Within each of these target methods, a cost analysis is carried out to determine where the largest cost drivers exist (e.g. raw material costs) and then modified production approaches are proposed to address these issues and move toward desired production cost targets.

POTENTIAL PROJECT IMPACT

The STARS technology offers a new and unique means for converting solar energy into chemical energy. The STARS technology is inherently modular and relies on process intensification to channel point source solar heat into an onboard reactor. Scale up of STARS technology is achieved by "numbering up" since each STARS unit is based on a single parabolic dish concentrator with integrated reactor for conversion of solar to chemical energy stored in synthetic gas or liquid fuels. This approach addresses a key constraint with centralized processing, where upfront capital can be prohibitive (hundreds of millions of dollars for gas-to-liquids systems and similar processes). Indeed, numbering up allows production to be expanded as demand grows without a large upfront capital expense. The key benefit to STARS from the proposed project is the reduction of equipment capital cost and establishing a supply chain for sourcing components, such that commercial adoption can be accelerated.

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

RAPID Project Number: 10.5

PARTNER ORGANIZATIONS

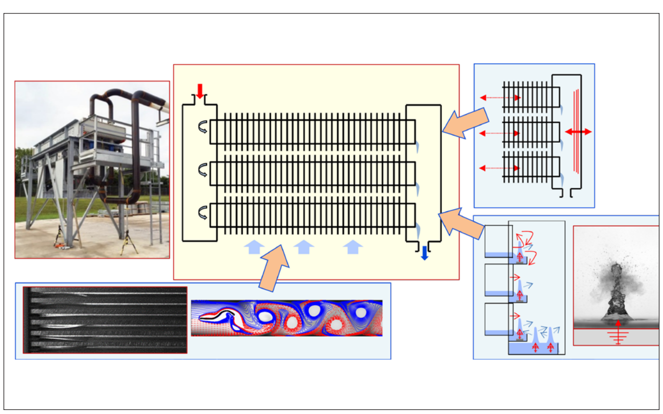
Georgia Tech, University of Illinois Urbana-Champaign, HTRI

PROJECT EXECUTIVE SUMMARY

Almost every process in the chemical and processing industries (CPI) involves heat transfer. Integrated functioning of a variety of heat exchangers with gas, liquid, and vapor/liquid flows of single- and multi-component working fluids, is critical in any processing plant. Improving air and/or process-side performance can significantly reduce energy consumption and capital costs. This project is looking at the novel geometries and mechanical actuation to enhance heat exchanger performance. The level of improvement, and approach to modification will facilitate the design of both "bolt on" process enhancement for existing equipment and the design of standardized modular heat exchangers. Significant effort in this proposal will focus on taking leads demonstrated in the lab and looking to establish cost effective and scalable manufacturing approaches.

POTENTIAL PROJECT IMPACT

The proposed novel heat transfer approaches have the potential to transformatively enhance performance of a broad class of heat exchangers currently used in a wide range of applications across the CPI. They also have the potential to enable new applications, including natural gas upgrading by cryogenic distillation, multifunctional modules, and utilization of renewable bioproducts, as well as for integration of multiple processes (e.g., separation and heat transfer for binary and multi-component liquids, for which ultrasound has already demonstrated the capability to produce an atomized mist enriched in one component). The higher energy efficiency and energy productivity will allow for new trade-offs between reduced size/volume/footprint (and hence lower capital cost), and higher throughput (allowing for de-bottlenecking). The potential for swap-in/swap-out retrofit is particularly attractive.



Modular Catalytic Desulfurization Units for Sour Gas Sweetening

RAPID Project Number: 10.6

PARTNER ORGANIZATIONS

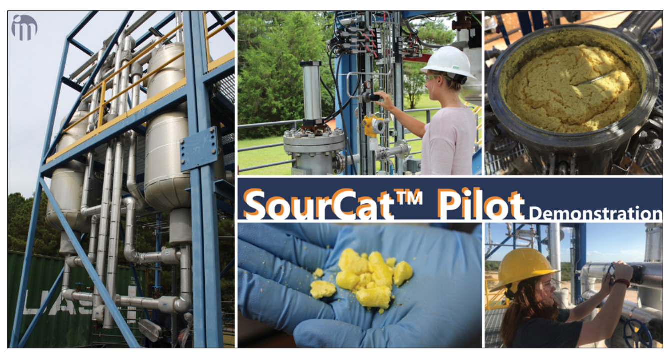
IntraMicron, Auburn University, Oregon State University

PROJECT EXECUTIVE SUMMARY

This project focuses on overcoming manufacturing and supply chain issues associated with a much needed modular technology solution in the gas processing sector. The team will look to take an existing technology for sour gas cleanup (processing scale on order of 1 T/day sulfur or 1 MMSCFD gas processed) and look to improve benefit vs. cost through pilot testing to improve performance and manufacturing design/analysis to determine highest leverage cost reduction steps. The resulting technology will be piloted in a field test to confirm economic assessments.

POTENTIAL PROJECT IMPACT

If successful, the project will profoundly affect the US energy sector. It directly offers an economical means to sweeten sour gas resources, especially those at small scales or with high sulfur contents. Because the intensified desulfurization process enables significant cost reductions in CAPEX (77%), OPEX (97%) and waste generation (60–95%) compared to current SOA processes at similar scales, sour wells that have previously been capped or neglected due to their high sulfur contents or low production rates can be turned into valuable resources. This will directly benefit the US O&G industry; it may experience a new booming period due to this technology.



On-Demand Treatment of Wastewater Using 3D-Printed Membranes

RAPID Project Number: 10.7

PARTNER ORGANIZATIONS

University of Pittsburgh, Siemens, Lubrizol

PROJECT EXECUTIVE SUMMARY

This project will demonstrate on-demand separation of multicomponent and multiphase water-oil mixtures using 3D-printed membranes. It is focused on wastewater treatment that is critical to the chemical industry. Application and adoption of intensified process design and 3D-printed membranes offers the prospect of revolutionizing the multicomponent and multiphase water-oil separation. While conventional membranes have been utilized in oil-water separation for some time, demonstration of 3D-printed membranes with well-controlled local structure, which renders the membrane to have multi-selectivity, is still lacking to-date. Moreover, wastewater treatment often involves many steps, and a more intensified process, which is enabled by a single multi-selectivity membrane, is highly desirable. The driving force for the proposed membrane is surface selectivity and topology rather than pressure and has been demonstrated in the laboratory. The present project aims to be a first-of-its-kind demonstration of the validity of the above-mentioned concept for the chemical industry.

POTENTIAL PROJECT IMPACT

The project will enable the first demonstrations of a 3D-printed membrane with multiple selectivity for multicomponent and multiphase oil-water separation, which is critical to wastewater treatment in the chemical industry. We anticipate that the proposed process intensification effort will demonstrate: 1) Strong improvement in energy efficiency by enabling an intensified membrane process by reducing pressure and physical size. 2) Significant reduction in capital cost and physical footprint through fabrication of 3D-printed membranes with multiple selectivity. 3) Substantial reduction in waste generation per unit as well as improved process safety due to improved wastewater treatment. This design approach can further translate beyond wastewater separation to include organic/organic systems as well.

Deploying Intensified, Automated, Mobile, Operable, and Novel Designs “DIAMOND” for Treating Shale Gas Wastewater

RAPID Project Number: 10.8

PARTNER ORGANIZATIONS

Texas A&M, University of Pittsburgh, University of Texas at Austin, US Clean Water Technology

PROJECT EXECUTIVE SUMMARY

One of the key technology gaps identified in the RAPID roadmap was to develop design tools and practices that would reduce the need for non-recurring engineering design costs in modular applications. This project is focused on developing integrated design and operating approaches for modular systems that can be deployed in the treatment of flowback and produced water resulting from shale gas production. Because of the highly distributed nature and variable characteristics of shale-gas wastewater (SGWW), there is a unique opportunity to deploy modular systems. There is also a major challenge in developing tailored designs for each source of wastewater. An integrated theoretical-experimental project is being executed to: (1) Assess, screen and integrate commercially-viable conventional and emerging technologies for wastewater treatment, (2) Develop computer-aided modeling, design, operation, scheduling, and costing approaches for non-recurring engineering needed to deploy the SGWW treatment systems, and (3) Demonstrate proof-of-concept via applications to a broad range of SGWW samples. A combination of systems engineering approaches and experimental/pilot-scale work will be used to generate commercially viable design and operational strategies with significant impact.

POTENTIAL PROJECT IMPACT

The majority of SGWW is disposed in underground injection control (UIC) wells. Development and application of novel treatment technologies to enable on-site water recycling and/or recovery for other applications is needed. These technologies will lead to a reduction in the overall cost, energy, and environmental impact for SGWW management.

Modeling the Total Cost of Ownership for Scaling-Up via Modular Chemical Process Intensification

RAPID Project Number: 10.9

PARTNER ORGANIZATIONS

Oregon State University, University of Texas at Austin, Construction Industry Institute

PROJECT EXECUTIVE SUMMARY

This project represents a collaboration between the RAPID Module Manufacturing Focus Area (MMFA) and the Construction Industry Institute, within the Cockrell School of Engineering at the University of Texas at Austin. The research objective is to model the total cost of ownership (TCO) for scaling up via modular chemical process intensification (MCPI) and apply this model to four RAPID projects over the remaining course of the effort. This research is important for capturing the lessons learned within module manufacturing activities ongoing within the RAPID Institute and providing a rationale for numbering up via MCPI. Further, this research will help RAPID to apply a consistent means for quantifying the costs involved in MCPI as well as helping the MMFA understand cost drivers as impediments to MCPI adoption. The work plan involves a first year in which the model is developed including literature review and interviews with companies currently engaging in MCPI to identify opportunities for case study development. The second year will involve execution of formal data collection and analysis to understand the TCO for individual MCPI implementations.

POTENTIAL PROJECT IMPACT

- Heightened awareness of key benefit and cost drivers in CAPEX and OPEX of MCPI plants
- Case studies providing clarity on the impact of MCPI on net present value

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