U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0003534
on Nuclear Heat for Modular Process Intensification in Refineries and Petrochemical Plants

Introduction:

The purpose of this RFI is to solicit input for a potential future ARPA-E program focused on improving the performance and efficiency of unit operations in refining and petrochemical plants by leveraging heat input from nuclear heat transfer fluids rather than from combustion. ARPA-E seeks information regarding transformative and implementable technologies to facilitate this integration. ARPA-E previously issued an RFI on Nuclear Hybrid and Non-Electricity Energy Systems, DE-FOA-0003011, in February 2023.[1] Questions in this RFI reflect the refined scope of the potential program.

Technical Background:

Refining and petrochemical processing accounts for 37% of U.S. industrial emissions (roughly 8% of total U.S. emissions), primarily due to combustion for process heating (Figure 1).[2] Industrial furnaces,

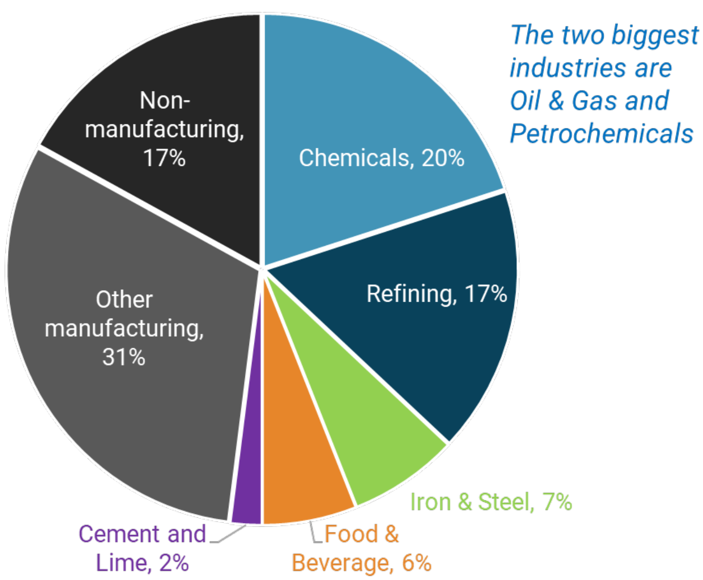

Figure 1. Contributions to Total U.S. Industry Emissions by Industry (adapted from Ref. 2).

[1] Previous RFI: https://arpa-e-foa.energy.gov/Default.aspx?foaId=d2e90f99-1878-4a34-b0a7-5255ee92ac81

[2] *Industrial Decarbonization Roadmap*, (U.S. Department of Energy DOE/EE-2635, 2022), https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.

however, are inefficient (less than 60% heating efficiency) and deliver insufficient heat transfer to highly endothermic reactions, limiting the performance of chemical reactors.[3,4,5]

One way to improve the heat transfer to process unit operations is to replace combustion with heat exchangers. Highly endothermic unit operations such as steam reforming, cracking, pyrolysis, and catalytic reforming operate at non-uniform temperatures due to the inability of combustion to provide dense, localized heat to the catalyst surface. Most endothermic unit operations heat and convert the process fluid in separate units (Figure 2), leading to large reactor volumes and low catalyst utilization (less than 5%).[6] When endothermic chemical reactors are actively heated, as in a steam methane reformer, the furnace accounts for 98-99% of the volume, with just 1-2% dedicated for catalytically coated process tubes.[7] Furnace efficiency (40%) is also sacrificed for higher heat fluxes. Combined with heat augmentation technologies (e.g., resistive, microwave, inductive), process intensification with heat exchangers can provide larger heat fluxes and targeted heating for endothermic chemistries. This would result in a more uniform temperature distribution, higher heating efficiency, and higher catalyst utilization, leading to decreased reactor size and ultimately lower costs.

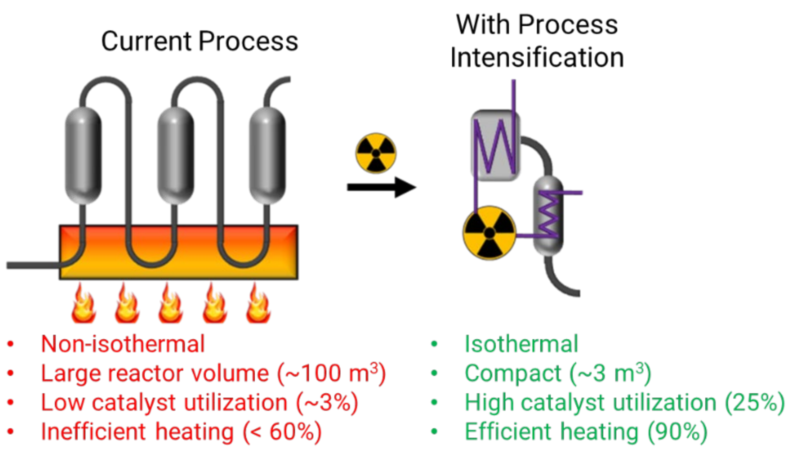

Figure 2. Process Intensification Using Nuclear Heat.

ARPA-E has identified modular advanced nuclear reactors as the most appealing source of heat for heat exchanger process intensification because of the process temperatures, geographical flexibility, low cost, and low emissions associated with nuclear. Most heating demands in refineries and petrochemical plants are less than 550 °C, which can be met by advanced reactor technologies. <u>The focus of this RFI is on using nuclear heat, not on developing advanced micro and small modular reactors.</u>

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[3] Wismann, Sebastian T., Engbæk, Jakob S., Vendelbo, Søren B., et. al. "Electrified Methane Reforming: A Compact Approach to Greener Industrial Hydrogen Production" *Science*, **364**, (2019). https://doi.org/10.1126/science.aaw8775.

[4] Balakotaiah, Vemuri., Ratnakar, Ram R, "Modular reactors with electrical resistance heating for hydrocarbon cracking and other endothermic reactions" *AIChE Journal,* **68** (2022). https://doi.org/10.1002/aic.17542

[5] *Technology Series: Hydrogen Energy Technologies*, (U.N. Industrial Development Organization, 1998), https://downloads.unido.org/ot/48/08/4808760/20001-_21974.PDF.

[6] J. Rostrub-Nielsen, L.J. Christiansen, *Concepts in Syngas Manufacture* (Imperial College Press, 2011).

[7] Latham, Dean A., McAuley, Kimberley B., Peppley, Brant A., Raybold, Troy M., "Mathematical modeling of an industrial steam-methane reformer for on-line deployment", *Fuel Processing Technology*, **92**, (2011). https://doi.org/10.1016/j.fuproc.2011.04.001

There are existing projects in development to decarbonize industry with nuclear energy, but these have been limited to steam and/or electricity generation; there are no current demonstrations of using nuclear energy to directly heat industrial processes. Developing nuclear as a clean source of heat also addresses the U.S. Department of Energy's Industrial Heat Shot, a goal to develop cost-competitive industrial heating technologies with 85% fewer emissions than combustion.[8] Integrating nuclear heat into industrial processes offers a pathway to not only improve the performance and economics of refineries and petrochemical plants, but also to decarbonize them.

ARPA-E has identified three areas of interest for using nuclear energy to decarbonize process heating demands in refineries and petrochemical plants:

1. Development of process-intensified reactors for endothermic processes;
2. Novel heat transfer and heat augmentation technologies; and
3. Process dynamics of incorporating a traditionally firm (nuclear) heat source with volatile demands.

Coupling nuclear with oil and gas operations will require both technical and commercial innovation in areas such as process co-design and co-optimization, sensors, controls, and thermal buffering interface-component development while meeting reliability, availability, and durability metrics cost effectively.

This RFI aims to gather information from interested and relevant stakeholders about opportunities and challenges in the technical, technology-to-market, and safety aspects of coupling of nuclear heat and/or power to industrial processes beyond pure power and/or steam production. The questions posed in the section below are based on the following program-level assumptions:

- Nuclear heat or combined heat and power (CHP) is a viable route to decarbonizing industrial processes;
- Regulatory approvals can be obtained on a predictable basis;
- The associated nuclear fuel cycle (including waste processing and geologic disposal) can be reliably and economically defined and implemented; and
- Warranty protection and insurability can be established.

<u>RFI Guidelines:</u>

CAREFULLY REVIEW ALL RFI GUIDELINES BELOW.

Note that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS RFI DOES NOT CONSTITUTE A FUNDING OPPORTUNITY. NO FUNDING OPPORTUNITY EXISTS AT THIS TIME.**

The purpose of this RFI is solely to solicit input for ARPA-E's consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use

[8] "Industrial Heat Shot", U.S. Department of Energy, accessed November 26, 2024, https://www.energy.gov/eere/industrial-heat-shot.

information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential**.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on ~~January 15, 2025~~ February 12, 2025.**

Emails should conform to the following guidelines:

- Insert "<your organization name> - Response to Nuclear Heat for Modular Process Intensification in Refineries and Petrochemical Plants RFI" in the email subject line.
- In the body of your email, include your name, title, organization, type of organization (e.g., university, non-governmental organization, small business, large business, federally funded research and development center [FFRDC], government-owned/government-operated [GOGO]), email address, telephone number, and area of expertise.
- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential materials, designs, or processes.

Areas Not of Interest for Responses to this RFI:

A potential ARPA-E program would focus on enabling technologies and approaches that could decarbonize high-emission industrial processes at refineries and petrochemical plants. Approaches not of interest include:

- Nuclear reactor design without integration with industrial processes;
- Uses of nuclear heat below 300°C;
- Use of nuclear reactors solely for production of electricity or steam;
- Catalyst development without consideration of nuclear heat integration;
- Design of heat exchangers for applications other than integration of nuclear heat with industrial processes; and
- Stand-alone heat exchangers with typical nuclear heat transfer fluids, such as molten salts.

RFI Questions:

The questions posed in this section are organized into several different groups. Respondents may provide responses and information about any of the following questions. **ARPA-E does not expect any one respondent to answer all, or even many, of the questions in this RFI.** In your response, indicate the question number (e.g., Response to RFI Question A.3). Appropriate citations are highly encouraged. Respondents are also welcome to address other relevant avenues or technologies that are not outlined below, except for those that fall under the "Areas Not of Interest for Responses to this RFI" described above.

A. Process Intensification

1. Which current industrial process unit operations utilize heat (steam or direct heat) with high energy requirements and/or high emissions? Please specify whether these unit operations are endothermic or exothermic. What are the associated estimates on energy required, efficiencies, and/or emissions of these process units?
2. For "refineries of the future," which future industrial process unit operations would utilize heat (steam or direct heat) with high energy requirements and/or high emissions? Please specify whether these unit operations are endothermic or exothermic. What are the associated estimates on energy required, efficiencies, and/or emissions of these units?
3. How do current plant and unit operation designs limit the performance and heat transfer for high-temperature and highly endothermic processes?
4. How would the substitution of furnaces with nuclear heat-driven chemical reactors impact the temperature profile and performance of chemical processes?
5. What types of heat transfer working fluids could work for process intensification from both a state-of-the-art and advanced research perspective?
6. What are ways in which process intensification can best take advantage of nuclear heat?
7. Are there any examples of heat exchangers replacing direct combustion in other industries? For example, are there any functional heat exchangers that are acting as both a heat exchanger and a catalytic reactor?
8. Why do some processes operate at high temperatures (greater than 750 °C), such as steam methane reforming? Could these high-temperature processes operate at lower temperatures if supplied with a lower temperature but denser form of heat? Why or why not?

B. Innovative Design Opportunities for Heat Exchangers and Heat Augmentation

1. What range of operating conditions (e.g., temperature, heat duty, volumetric flow rate, pressure drop, size) do furnaces require for major process operations at refineries, chemical plants, and petrochemical plants?
2. What are the main challenges to consider when replacing combustion/furnaces with heat exchangers? For example, are combustion dynamics more favorable than heat exchanger dynamics?
3. Assuming no change in the required process temperature, what potential upstream and downstream effects on process conditions and operations could be caused by replacing furnaces with heat exchangers?
4. What would be the acceptable cost of a heat exchanger for a given application in dollars per kilowatt-thermal ($/kW-th)?
5. Assuming currently proposed nuclear-based heat transfer fluids are limited to ≤850 °C, how would heat augmentation technologies (e.g., resistive, inductive, microwave) integrate into process intensification designs? How might they impact chemical reactor performance and heating efficiency?
6. What are potential opportunities and risks of implementing innovative heat transfer approaches such as using particle-based working fluids with heat exchangers and thermochemical thermal energy storage and buffering?

C. Interface Modeling, Process Dynamics, Control Co-Design, and Automation to Enable Integration of Nuclear Heat with Industrial Processes

1. What technology de-risking steps (non-nuclear) are necessary to adapt and couple nuclear reactors to industrial processes?
2. What are the current digital modeling software used for industrial processes or for nuclear reactors, and what software requirements are needed to enable integration of chemical reactor and nuclear reactor software?
3. What potential control co-design methodologies or control-engineering principles applied at the start of the design process would enable concurrent development of integrated nuclear heat and industrial processes?
4. What is the current state-of-the-art for process controls and automation for the nuclear industry and for industrial processes? What types of heat transfer experiments and controls need to be validated at scale?
5. How do you manage nuclear heat dynamics? What are the opportunities and challenges associated with using state-of-the-art and emerging high-temperature thermal heat management strategies for nuclear heat, such as thermal buffering and thermal energy storage?

D. General Considerations for Coupling Nuclear Heat with Industrial Processes

1. What temperatures and load ranges (power and/or heat) are of interest for coupling industrial processes to nuclear heat?
2. Maintenance cycles for nuclear heat sources should ideally align with the process plant to ensure economically acceptable availability. What are the minor and major service intervals for industrial process plants?
3. What type of process and operational flexibility do industrial processes and nuclear reactors have regarding uptime, heat duty, etc.? What process research and development could support decreasing the temperature of industrial processes to facilitate the utilization of lower temperature heat?
4. What are cost targets for heat and electricity input? What is an acceptable price premium relative to fossil heat?
5. What should the inside battery limits and outside battery limits be for a coupled nuclear plant and industrial process facility from a safety, technical, and operational perspective?