U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0002131
on
Enabling Technologies for a Commercially Viable Fusion Power Plant

Introduction:

ARPA-E is seeking information from diverse R&D communities, from both within and especially outside the fusion R&D community, about technological solutions and innovations that can enable commercially viable fusion power plants. While it is impossible to predict precisely what is needed for fusion to be commercially viable over the next few decades, fusion's market entry may require that both the nameplate generation capacity and total construction cost be well below the assumed 1-GWe and >$5B (2019 dollars) scales described in prior fusion-power-plant studies.[1] As discussed further below, this RFI focuses specifically on the enabling technologies for potential fusion power plants at reduced nameplate capacity and cost. ARPA-E is particularly interested in transformational R&D opportunities that are not already being pursued by or included in the roadmaps of ongoing DOE fusion programs.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, 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 NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Background:

Over several decades, the magnetic-fusion-energy (MFE) and inertial-fusion-energy (IFE) R&D communities have predominantly assessed research gaps and needs for fusion power plants at the 1-GWe scale. This scale has been driven by economics constrained by relatively conservative physics in order to limit the levelized cost-of-electricity (LCOE) and cost-per-Watt ($/W) of generation. Many expert panel reports[2,3,4,5,6] have identified enabling-technology gaps and needs for both "conventional" MFE and IFE at the 1-GWe scale. A modestly funded DOE program[7] supports R&D that emphasizes the enabling technologies required for an MFE power plant at the 1-GWe scale based on a tokamak using conventional,

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[1] See, e.g., F. Najmabadi et al., *Fus. Eng. Des.* **38**, 3 (1997); F. Najmabadi et al., *ibid* **80**, 3 (2006).

[2] National Academies of Sciences, Engineering, and Medicine, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research* (National Academies Press, Washington, DC, 2018).

[3] *Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy*, Report of the Fusion Energy Sciences Advisory Committee (FESAC), 2018.

[4] National Research Council, *An Assessment of the Prospects for Inertial Fusion Energy* (National Academies Press, Washington, DC, 2013).

[5] *Tritium*, Report of the JASON advisory group, JSR-11-345, 2011.

[6] *Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy*, Report to FESAC, 2007.

[7] https://vlt.ornl.gov.

low-temperature superconducting magnets, although there is increasing attention paid to the enabling-technology requirements for reduced-size, higher-field tokamaks using demountable, high-temperature superconducting (HTS) magnets.[8]

Realities in the energy marketplace, especially in the U.S. but also in many other global markets, point toward a growing need for flexible, carbon-free, and highly dispatchable power generation at much less than 1-GWe scale. For example, in 2016, power plants larger than 1 GWe were responsible for just 8% of U.S. electricity-generation capacity, and of the 17,000 power plants with >1-MWe capacity, only 76 were >1 GWe.[9] The desired smaller capacity is driven both by the characteristics of the evolving energy marketplace,[10] as well as the need to limit construction time and capital cost of a power plant to remain economically competitive, as the nuclear industry has learned.[11] Thus, total capital cost is likely to be of equal or greater importance than LCOE and $/W of generation in determining the likelihood of whether fusion will be developed and eventually impact the energy marketplace. Recognizing these factors, a growing number of efforts, especially privately funded ones, are pursuing higher-risk development paths toward fusion power plants with lower nameplate capacity and development/construction costs.[12] Imposing a market-aware constraint now, while recognizing that there is uncertainty in what will be economically competitive in the future, will improve the prospect that fusion energy, when it becomes available, will have market impact. Thus, consistent with its mission, ARPA-E fusion programs focus on higher-risk R&D to realize fusion power plants with reduced size, complexity, nameplate power capacity, and cost compared to conventional MFE or IFE.

Potential fusion power plants at reduced scale and total cost are likely to have both similar and different enabling-technology requirements, characteristics, and solutions compared to conventional MFE and IFE fusion power plants at the 1-GWe scale. This RFI focuses on the differences, including but not limited to:

Greater emphasis on:

- Use of thick liquid blankets (e.g., liquid metals or molten salts) for shielding outer structural components from 14.1-MeV fusion neutrons, breeding tritium via nuclear transmutation of lithium in the blanket, and serving as the medium for heat exchange in producing electricity
- Smaller tritium-processing plants that use a liquid medium with potentially low tritium solubility and that could potentially benefit from process intensification
- Lower-cost and longer-lifetime repetitive pulsed-power technologies required to repetitively assemble and heat the plasma core in pulsed fusion approaches, e.g., IFE or magneto-inertial fusion (MIF)[13]
- Use and challenges of advanced fusion fuels, e.g., DD, D^3He or $p^{11}B$, where most or all of the fusion products are charged particles rather than neutrons

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[8] B. N. Sorbom et al., *Fus. Eng. Des*. **100**, 378 (2015); Commonwealth Fusion Systems.

[9] Data from Form EIA-860.

[10] See, e.g., *Revolution Now, The Future Arrives for Five Clean Energy Technologies – 2016 Update*, Report of the DOE Office of Energy Efficiency and Renewable Energy, 2016.

[11] *Future of Nuclear Energy in a Carbon-Constrained World, An Interdisciplinary MIT Study*, MIT Energy Initiative (2018).

[12] See the member companies of the Fusion Industry Association and projects of the ARPA-E ALPHA program.

[13] See, e.g., G. A. Wurden et al., *J. Fusion Energy* **35**, 69 (2016) and a recent JASON report, and references therein. Magneto-inertial fusion (MIF) (aka magnetized target fusion) is a class of pulsed fusion approaches combining the compressional heating of IFE with the magnetically reduced thermal transport of MFE.

Reduced emphasis on:

- Structural materials that must last the life of the power plant and survive neutron-bombardment damage up to 150+ displacements per atom (dpa)
- Solid-material divertors that must withstand direct steady-state contact with plasma and overcome issues related to plasma-materials interactions (PMI).

Purpose and Need for Information:

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

REQUEST FOR INFORMATION GUIDELINES:

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 should not include any information in the response to this RFI that might 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 June 5th, 2019**. Emails should conform to the following guidelines:

- Please insert "Responses for Enabling Technologies for a Commercially Viable Fusion Power Plant" in the subject line of your email, and 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), etc.), email address, telephone number, and area of expertise in the body of your email.
- Responses to this RFI are limited to no more than 5 pages in length (12 point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential methodologies.

Questions:

Please provide evidence-based answers and/or commentary, with citations to the published literature wherever possible, about any of the following. ARPA-E does not expect any one respondent to address all or even many of the questions. Specific questions are in *italics* below:

1. Engaging communities outside the mainstream fusion R&D community: *If you are not familiar with the fusion-energy space, what information and/or tools would help facilitate your substantive engagement in applying the knowledge, solutions, techniques, and innovations from outside mainstream fusion R&D to develop the enabling technologies for a commercially viable fusion power plant?*

2. Containment of the fusion plasma core: a fusion power plant must have a transition from the fusion plasma core of at least 100 million degrees Kelvin to the rest of the power plant that converts fusion energy into electricity delivered to the grid. Somewhere within this transition, an interface will see a large average flux of 14.1-MeV neutrons (for DT fusion power plants), x-rays, and plasma constituents.
    a. If the interface is a thick (e.g., 50 cm or more) layer of flowing liquid, it could face the plasma directly or it could be separated from the plasma with a thinner solid-material layer that is intended to be "sacrificial," i.e., it does not need to last the life of the plant provided it can be replaced periodically and economically with minimal downtime for the fusion power plant. On the outside of the thick, liquid layer will be a solid, structural material that contains the liquid layer. The liquid could be, for example, lead-lithium or a molten salt containing lithium.
        i. *How can we overcome anticipated issues of corrosion and/or liquid-metal embrittlement at the solid/liquid interfaces of such a fusion containment configuration? What other industries deal with, and may have found solutions, to these problems?*
        ii. *Are there alloy additions to liquid metals or molten salts that could enhance absorption of 14.1-MeV neutrons (so as to further reduce activation of the outer structural materials) or provide other benefits to the overall system properties?*
        iii. *For pulsed concepts with direct plasma contact with a thick liquid blanket, how can we manage the response of the thick liquid blanket to repetitive intense fusion pulses?*
        iv. *Can we control, manipulate, and/or exploit temperature gradients and flow fields of the liquid blanket to enhance tritium breeding, recovery, and/or reduce corrosion/embrittlement effects?*
    b. If a first-generation fusion power plant is based on an unspecified magnetically confined fusion plasma core, a "divertor" plate is likely needed to take the brunt of the plasma exhaust. Conventional pursuit of divertor solutions focuses on the use of a solid material, e.g., a tungsten alloy, that can survive being in steady-state contact with plasma exhaust at a good fraction of 1 million degrees K and occasional extreme transient heat and particle loads due to instabilities of the fusion plasma core or edge. These phenomena cause significant erosion, surface modification, and re-deposition of the divertor material surface, all of which feed back on the edge-plasma characteristics. This field of study is known as plasma-materials interactions (PMI).[14]
        i. *What are viable alternatives (and their challenges) to a solid-material divertor surface, for which there could turn out to be no possible solution?*
    c. Even if most of the structural components of a fusion power plant are shielded by a thick liquid blanket, it is likely unavoidable to produce at least some stream of activated metals requiring disposal that must satisfy regulatory requirements.
        i. *What are ways beyond the ongoing efforts to develop low-activation metals to reduce the volume and classification of low-grade activated waste?*
    d. Plasma-facing and possibly structural materials in pulsed fusion concepts will experience repetitive thermal and mechanical loading, leading to fatigue.
        i. *What tools are available to study this problem, and what techniques from other industries can contribute to a solution for this problem for fusion?*

3. Fuel cycle and power cycle: A fusion power plant must have a sustainable fuel cycle that is well matched to an efficient power cycle. While deuterium is abundant in seawater, a deuterium-tritium (DT) fusion reactor must breed tritium (from the nuclear transmutation of lithium bombarded by 14.1-

[14] *Report on Science Challenges and Research Opportunities in Plasma Materials Interactions*, DOE Fusion Energy Sciences Workshop on Plasma Materials Interactions, R. Maingi (chair), 2015.

MeV fusion neutrons), recover the unburned tritium, provide a self-sufficient supply back to the fusion plasma core, all while minimizing the total tritium loss and inventory. A D^3He fusion power plant must have a self-sufficient supply of ^3He. Most present fusion-development efforts focus on DT fusion because it occurs at by far the lowest and most-achievable temperatures compared to the known alternatives.

   a. *Are there corrosion- and embrittlement-resistant materials and/or coating solutions for primary loop materials, heat exchangers, and pumps in contact with liquid metal or molten salt at very high temperatures (e.g., up to 1200 K) with relatively high tritium concentrations?*
   b. *How can the overall tritium inventory and reprocessing times of a DT fusion power plant be minimized through a combination of technological innovations in, e.g., fast separation/extraction of tritium from both the plasma exhaust and breeding medium (liquid metal or molten salt[15]), cleanup techniques, and low-permeability loop materials and heat exchangers to minimize tritium losses?[16]*
   c. *What are candidate working fluids and tritium separation techniques for the secondary loop? Is there an approach that allows a single heat exchange to steam or other working fluid, e.g., helium or supercritical CO_2, of an advanced power cycle?*
   d. *Can process intensification techniques,[17] used successfully in other industries, help enable faster tritium-processing times and smaller tritium-plant designs that are well matched to fusion power plants with reduced tritium inventories?*
   e. *What are the critical (non-plasma-physics) fuel-cycle-related challenges and potential solutions for fusion approaches using advanced fuels, e.g., DD, D^3He, or $p^{11}B$, including R&D needs for direct conversion systems?*
   f. *How should the containment and fuel-cycle aspects of a fusion power plant be optimized to better utilize advanced power cycles?*
   g. *Can there be "multi-conversion" systems to easily switch between electricity and high-grade heat as the output of the fusion plant, and how much can we further reduce the cost/size of a fusion plant if high-grade heat is the primary initial product?*

4. Driver technology:
   a. Any pulsed fusion-energy approach will require repetitive (e.g., at 1 Hz) pulsed-power technology that will be enabled by advances in solid-state power electronics, specifically low-cost, long-lifetime (>100 million pulses), high-current (e.g., multiple ~100-kA units in parallel), high-voltage (~100 kV), and fast rise time (<10 μs) switches, as well as higher-energy-density capacitors.
      i. *How can we significantly push the state-of-the-art in solid-state switches and high-energy-density capacitors to eventually meet the above specifications?*
   b. *Can advances in power electronics substantially improve overall plant economics via maximizing the efficiency and robustness of power supplies for magnets, heating systems, etc.?*
   c. *How can we substantially bring down the cost and improve the efficiency, modularity, and thermal management of laser drivers (from the pulsed power to the optics) to enable a*

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[15] See, e.g., C. W. Forsberg et al., *Nucl. Tech.* **197**, 119 (2017).
[16] To provide a scale for the tritium challenge, a 200-MWe commercial fusion power plant burning DT may consume 30 kg of T per year and have an instantaneous system inventory of 3 kg undergoing continuous reprocessing. In this case, a plausible allowable annual release (e.g., 1 g of T) must be at most 3×10^{-5} of the burnt tritium. See footnote 5 for the basis of these numbers.
[17] See, e.g., F. J. Keil, *Rev. Chem. Eng.* **34**, 135 (2018) and *Process Intensification Workshop Report*, DOE Advanced Manufacturing Office, Alexandria, VA, 2015.

commercially viable IFE power plant? How can we overcome significant gaps in lowering IFE target cost and driver-target coupling in a very high-repetition-rate system (e.g., 10–20 Hz)?

5. Accelerating and/or lowering the cost of the development of enabling technologies:
    a. To experimentally investigate and develop all the required enabling technologies in the full environment relevant to that of a fusion power plant will itself require $B-scale facilities.[18,19]
        i. *Are there existing facilities, or can we design sub-scale facilities, that can isolate and/or test relevant effects, on which we can make meaningful, near-term progress in developing the enabling technologies without waiting for $B-scale facilities?*
        ii. *What capabilities or sub-scale facilities can accelerate HTS magnet development and testing?*
        iii. *What are specific ways in which additive manufacturing and other techniques from throughout industry might enable transformative solutions to any of the problems outlined in this RFI?*

6. Other: *Are there other ideas/suggestions not captured in the above questions that can potentially provide transformational solutions for the required enabling technologies for commercially viable fusion power plants?*

[18] e.g., International Fusion Materials Irradiation Facility (IFMIF), J. Knaster et al., *Nucl. Fusion* **57**, 102016 (2017).
[19] e.g., Fusion Nuclear Science Facility (FNSF), C. E. Kessel et al., *Fus. Eng. Des.* **135B**, 236 (2018).