Key Goals and Innovations Needed for a U.S. Fusion Pilot Plant

Thoughts from DOE Fusion Energy Sciences perspective

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NASEM KGINUSFPP Committee Meeting
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CHARGE TO KGINUSFPP COMMITTEE

Introduction to Fusion Pilot Plant

- In the pursuit of nuclear fusion as a safe, carbon-free energy source with an almost unlimited supply of fuel, the construction and successful operation of a net-power-producing fusion facility that is prototypical of a power plant is considered the penultimate step before commercialization. Such a demonstration reactor, often called DEMO or Fusion Pilot Plant (FPP), is the goal of most publicly or privately funded fusion efforts around the world before the commercial energy-generation industry takes the lead.

- After decades of investments in research, the U.S. fusion community is ready to undertake the bold, critical step of developing a DEMO/FPP.
  - This is supported by the recent National Academy of Sciences (NAS) study on Burning Plasma Research, which recommended the construction of a compact pilot plant that produces electricity from fusion at the lowest possible cost.
  - It is also supported by the recently published Community Plan for Fusion Energy and Discovery Plasma Sciences report, which included the development of a fusion pilot plant as one of its top recommendations.
  - Both of these reports are currently under consideration by the Fusion Energy Sciences Advisory Committee as it develops a long-range plan for the U.S. fusion energy sciences program.

NASEM study: Statement of Task

The National Academies of Sciences, Engineering, and Medicine shall assemble a committee to provide guidance to DOE and others that are aligned with the objective of constructing a pilot plant in the U.S. that produces electricity from fusion at the lowest possible capital cost ("Pilot Plant"). In the study, to be completed within eight months of project initiation, the committee shall provide a concise report that addresses the following points:

- In developing and carrying out a plan for building a Pilot Plant, key goals need to be established for all critical aspects of the Pilot Plant. Identify those key goals, independent of confinement concept, which a Pilot Plant must demonstrate during each of its anticipated phases of operation.
- List the principal innovations needed for the private sector to address, perhaps in concert with efforts by DOE, to meet the key goals identified in the first bullet.

Further Committee Guidance

In addressing the first bullet in the statement of task, the committee should consider the key goals for each of the plant's anticipated phases of operation. Areas for key goals that the committee might consider include scientific (e.g., materials and systems performance and integration), technical (e.g., electrical output and availability), economic (e.g., capital costs and time frame, operating and maintenance costs), environmental (e.g., level of radioactive wastes), and safety-related (e.g., regulatory, tritium inventory).

In carrying out the statement of task, the committee is encouraged to seek input from potential "future owners" of power plants, such as electric utility companies, and potential manufacturers of fusion power plant components, to broadly characterize the energy market for fusion and to provide input on what they would look for in a fusion pilot plant and how such plants can contribute to national energy needs.

What is a Fusion Pilot Plant?

- The objective of the ITER international project, in which the U.S. is a member, is to demonstrate the scientific and technological feasibility of fusion energy. For what comes after ITER, there are different strategies and different ideas on what a fusion pilot plant is.

- One strategy is to build a Fusion Nuclear Science Facility, which does not need to produce electricity, but instead focuses on materials research and fusion nuclear science to develop materials and technology that can survive the harsh environment surrounding a fusion system, demonstrate the ability to be self-sustaining (i.e., closed fuel cycle with more tritium being produced than is consumed), and enable scientists to understand and control the operation of a burning plasma for many days. However, an FNSF would need to be followed by a second facility, a DEMO-type facility to demonstrate fusion electricity production.

- Another strategy is to pursue a large fusion DEMO capable of producing electricity, operating with a closed fuel cycle, which would be the single step between ITER and a commercial reactor. This definition of DEMO calls for a larger device with the mission to produce significant net electricity, establishing routine electricity production and maintenance in order to convince utility companies and other investors that all aspects of the power source are credible, reliable, safe, and economical.

- A third strategy, espoused by the 2019 NAS Burning Plasma Research report, is to target a Fusion Pilot Plant that produces power similar to the levels expected in ITER but in a device that is much smaller in size and cost and that employs design improvements that allow net electricity production. Furthermore, this FPP would be staged (as described in the charge letter).

Regulatory framework for fusion

- In 2009, the Nuclear Regulatory Commission determined that it has regulatory jurisdiction over commercial fusion energy devices
  - Directed NRC staff to conduct further evaluations of the technical and legal issues
  - Wait to do so until commercial deployment of fusion technology is more predictable
- Congress has expressed its interest on understanding the regulatory approach for Advanced Nuclear Reactors, including nuclear fusion reactors: *Nuclear Energy Innovation and Modernization Act*, S.512 (January 2018) & *Nuclear Energy Innovation Capabilities Act of 2017*, S.97 (January 2018)
- Currently, development work on a technology-neutral advanced reactor regulatory framework is in progress
  - It is likely that this framework would be modified (as necessary) to adapt to fusion technologies
- DOE-NRC Public Forum on Regulatory Framework for Fusion Energy is scheduled for October 6 (virtual meeting)
- Some arguments why fusion could possibly be regulated differently from fission energy:
  - Intrinsically safe (no chain-reaction is possible)
  - Environmentally responsible (with development of low-activation materials for the reaction chamber, for which radioactivity decays in a few tens of years and could either be disposed of in shallow land burial sites or possibly be recycled in a new reactor).
- FIA fusion regulatory white paper (https://www.fusionindustryassociation.org/post/fusion-regulatory-white-paper)

"Independent of confinement concept"

- "Independent of confinement concept" = not necessarily tied to mainline concepts (tokamak, stellarator, spherical torus)

- Fusion world is extensive (MFE, IFE, MIF, various fuel cycles, etc.), but your study is time-limited
  - Certain key FPP goals would be informed by the range of confinement concepts under consideration
  - However, a number of goals would be common across platforms and approaches

- The present study is understood as a follow-up to the NAS Burning Plasma Research report.
  - The Burning Plasma Research study was focused on magnetic confinement fusion energy (and U.S. participation in the ITER project); hence it concentrated on toroidal confinement using the DT fuel cycle.

- Suggestion: In order to accelerate the development of a DEMO/FPP and minimize risk, it might be prudent to initially adopt a confinement concept and fuel cycle that have the largest database.
  - From this point of view, the proposed DEMO/FPP would be a toroidal magnetic confinement device based on the tokamak configuration and the deuterium-tritium (D-T) fuel cycle.
  - Once the technology is demonstrated, future fusion power plants can be optimized through the consideration of other design configurations and/or fuel cycles that have the potential for higher performance or lower cost.

Community Planning Process report (1)

Fusion Pilot Plant

- Goal is to demonstrate capability that demonstrates technical feasibility while also projecting to commercial viability
- Three deliverables were considered to define an FPP
  – Produce net electricity from fusion
  – Establish the capability of high average power output
  – Demonstrate the safe production and handling of the tritium, as well as the feasibility of a closed fuel cycle
- Tokamak is the leading concept. However, optimized stellarators, inertial fusion, and other alternate concepts could ultimately lead to an attractive FPP.

Community Planning Process report (2)

(PR-C) Growing partnership with private industry

(PR-A) Multidisciplinary FPP design studies

Science Drivers

Control, sustain, and predict burning plasma
- (SO-D) Tokamak physics basis
- (SO-E) Stellarator physics basis
- (SO-F) Magnet, heating, and current drive science & technology
- (SO-H) IFE & alternative confinement approaches

Handle reactor relevant conditions
- (SO-A) PFC and PMI science & technology
- (SO-B) Structural and functional materials science & technology

Harness fusion power
- (SO-C) Blanket science & tech. and Tritium Processing
- (SO-G) Licensing, RAMI, balance of plant

(PR-B) Participation in ITER

(PR-D) Integrated Modeling

(PR-E) Diagnostic Development

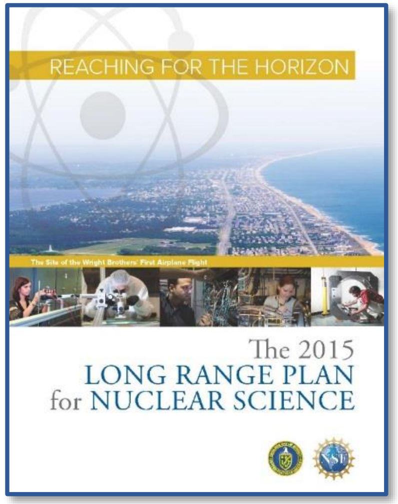
Design and construction of fusion pilot plant at lowest possible capital cost

Spherical Tokamak for Energy Production (STEP)

- Recently, the U.K. government launched the STEP program, whose mission is to design a commercially viable compact fusion reactor based on the spherical tokamak configuration and then collaborate with partners to build a prototype reactor by 2040. STEP consists of a partnership of UKAEA, industry, universities, national laboratories/institutes, and regulatory organizations. The program is targeting a preferred design by 2022, to take forward to Concept Design by 2024. Then an engineering design would be developed (2024-2032), after which a STEP Prototype Reactor would be constructed and commissioned (2032-2040).
- The first year of design was funded with £20M from the U.K. government. In October 2019, the British government announced a further £200M investment (US$248M). Subsequent phases of the facility’s development, after 2024, would involve both public and private investment.

U.S. has entered the second stage of a strategic planning activity to develop a long-range plan (LRP)

- The plan will be comprehensive, including all FES program areas
- Process is similar to that used by the Office of Science High Energy Physics (HEP) and Nuclear Physics (NP) programs for the development of the HEP-P5 report and NP-Long Range Plan



Phase 1: Community-organized activities

Community Awareness
Inform the community that a FESAC charge is coming

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Subfield community self-organization

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FESAC charge issued

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FES tasks APS-DPP to convene topical town hall meetings

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"Snowmass" meeting

Phase 2: FESAC federal advisory committee