The National Academies of SCIENCES ENGINEERING MEDICINE

Bringing Fusion to the U.S. Grid

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PUBLIC BRIEFING

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What is fusion, and why is it important?

Fusion occurs when two light elements combine to form heavier elements and release a large amount of energy.

- Powers the sun and other stars

Initiating a fusion reaction requires very high temperatures and confinement of the plasma.

Generating a self-sustaining plasma would enable electricity production from fusion.

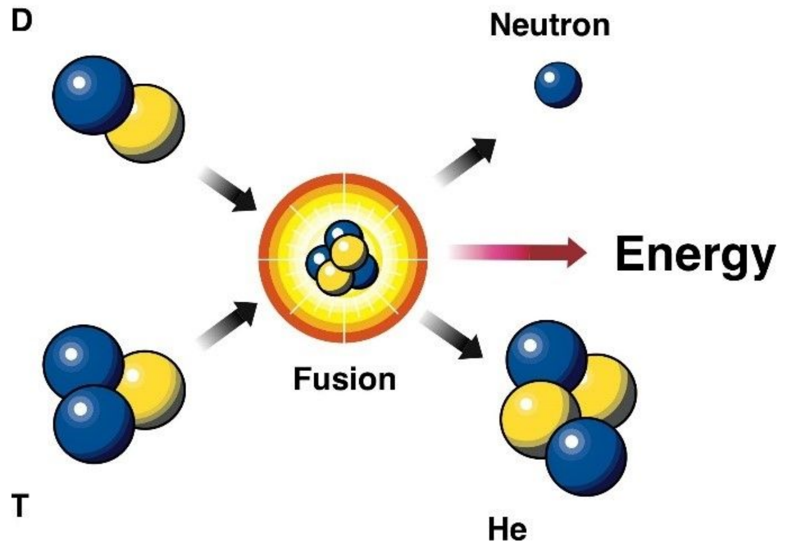
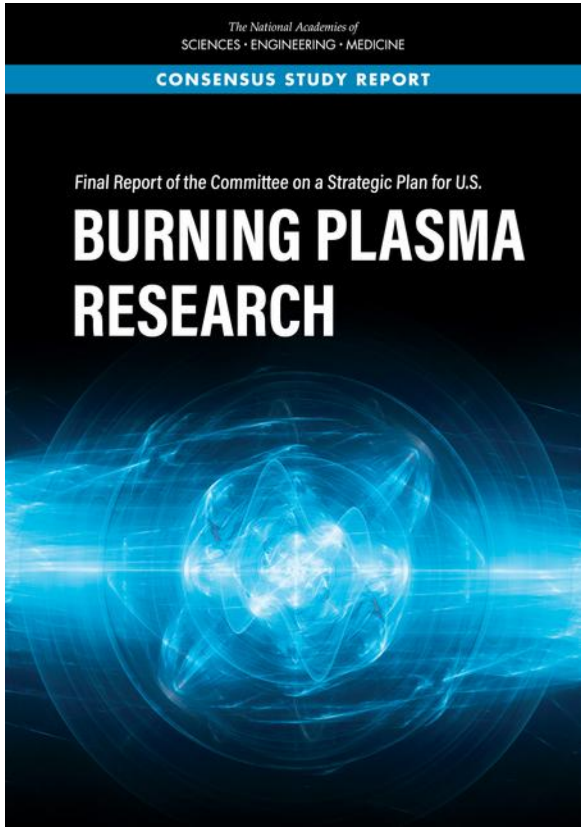


Image source: DOE

Benefits of Fusion:

- Non-carbon emitting source of electricity
- Dispatchable, firm energy generation
- Abundant fuel supplies and minimal long-lived radioactive waste

2019 REPORT: Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research.



Key Recommendations:

First, the United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant.

Second, the United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible capital cost.

The second recommendation motivated this study.

Statement of Task

The National Academies of Sciences, Engineering, and Medicine (NASEM) shall assemble a committee to provide guidance to the U.S. Department of Energy, and others, that are aligned with the objective of constructing a pilot plant in the United States that produces electricity from fusion at the lowest possible capital cost ("Pilot Plant").
The committee shall provide a concise report that addresses the following points:

- Establish key goals for all critical aspects of the Pilot Plant, independent of confinement concept and during each of the plant's anticipated phases of operation.
- Identify the principal innovations needed from both the private sector and government to meet those key goals.
- Seek input from potential "future owners" of power plants and potential manufacturers of fusion power plant components.
- Characterize the energy market for fusion and provide input on how a fusion pilot plant could contribute to national energy needs.

NOTE: TASK STATEMENT PARAPHRASED TO FIT ON SLIDE

Committee Composition

Richard J. Hawryluk (Chair)
Princeton Plasma Physics Laboratory

Brenda L. Garcia-Diaz
Savannah River National Laboratory

Gerald L. Kulcinski (NAE)
University of Wisconsin-Madison

Kathryn A. McCarthy (NAE)
Oak Ridge National Laboratory

Per F. Peterson (NAE)
University of California, Berkeley/ Kairos Power

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TechSource, Inc.

Wanda K. Reder (NAE)
Grid-X Partners

David W. Roop (NAE)
DWR Associates, LLC

Philip Snyder
General Atomics

Jennifer L. Uhle
Nuclear Energy Institute

Dennis G. Whyte
Massachusetts Institute of Technology

Brian D. Wirth
University of Tennessee, Knoxville

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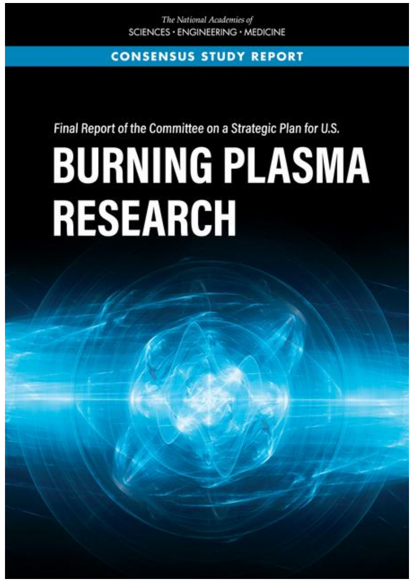
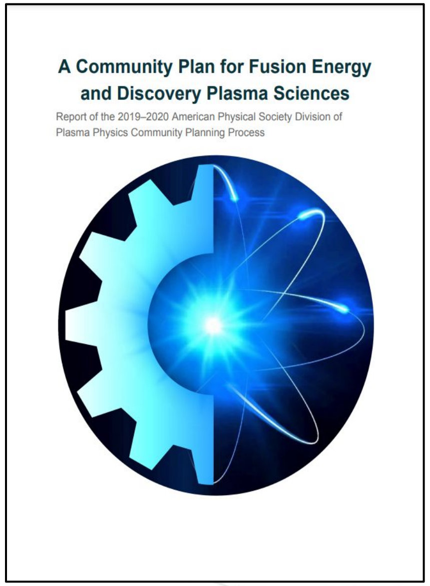
Study Input

- Technical input from NASEM Burning Plasma and APS Community Planning Process reports
  - Solicited additional input on website
  - Workforce issues from NASEM Diversity, Equity and Inclusion reports
- Presentations by DOE and Congressional staff
- Panel discussions with groups from
  - Power Plant Owners/Utilities
  - Developers of fusion power plants
  - National Laboratories
  - Universities
  - Manufacturers of components
  - Regulatory bodies





Key Takeaways

Recommendation: For the United States to be a leader in fusion and to make an impact on the transition to a low-carbon emission electrical system by 2050, the Department of Energy and the private sector should produce net electricity in a fusion pilot plant in the United States in the 2035—2040 timeframe.

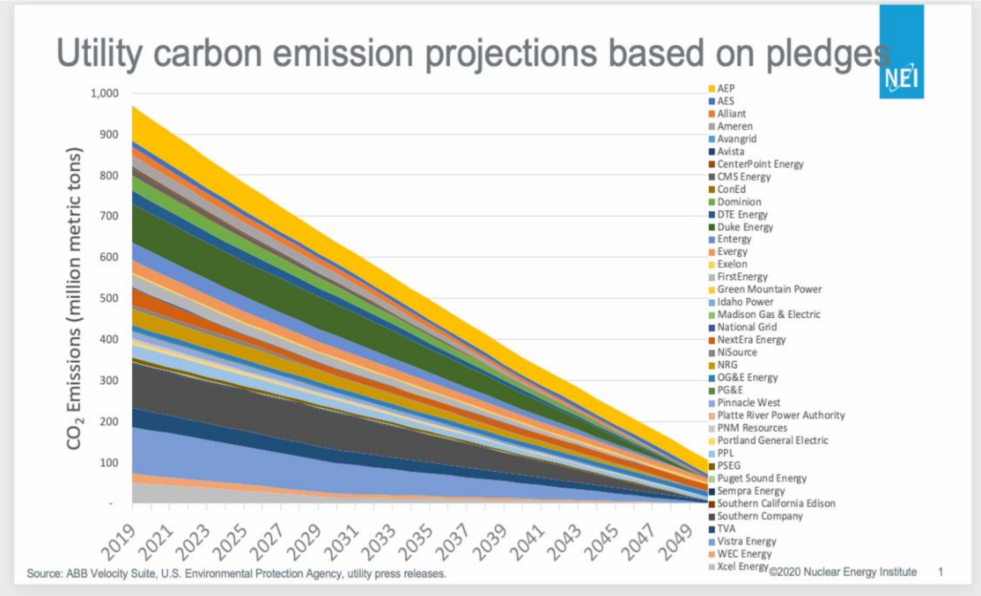
Recommendation: DOE should move forward now to foster the creation of national teams, including public-private partnerships, that will develop conceptual pilot plant designs and technology roadmaps that will lead to an engineering design of a pilot plant that will bring fusion to commercial viability.

Conclusion: Successful operation of a pilot plant in the 2035—2040 timeframe requires urgent investments by DOE and private industry — both to resolve the remaining technical and scientific issues, and to design, construct, and commission a pilot plant.

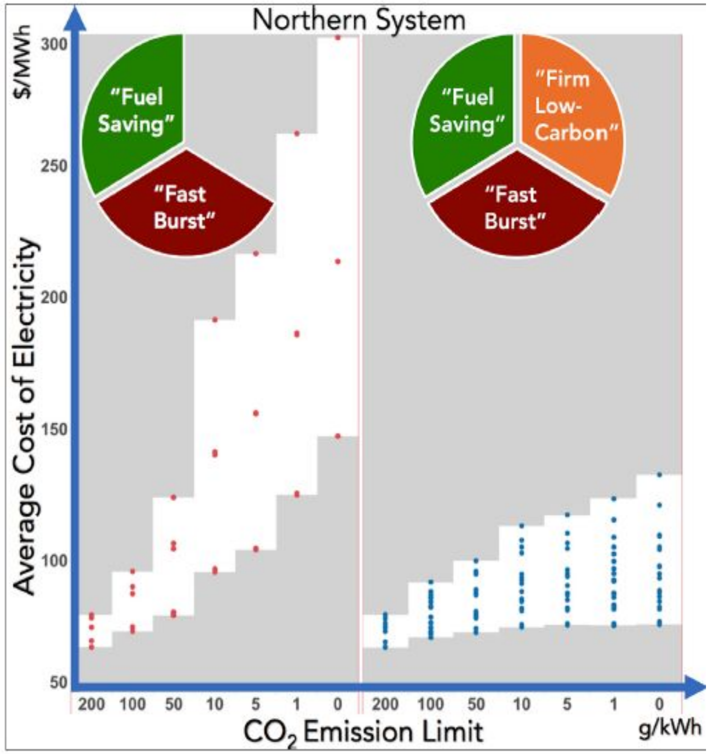
Report Outline

1. Introduction
2. Role of the pilot plant on the path to commercialization
3. Goals for a fusion pilot plant
4. Innovations and research needed to address key fusion pilot plant goals
5. Strategy and roadmap for a pilot plant

Role of the Pilot Plant:
Future Electricity Generation Market



Utilities foresee a transition to low-carbon electrical generation by 2050.



Firm low-carbon/non-carbon electrical energy generation will be needed to decrease the cost.

Role of the Pilot Plant:
Non-Carbon Emitting Baseload Energy

Finding: Dispatchable, firm low-carbon and non-carbon emission generation will be needed in the future for grid support functions and can enhance the movement to a lower carbon footprint at a lower cost.

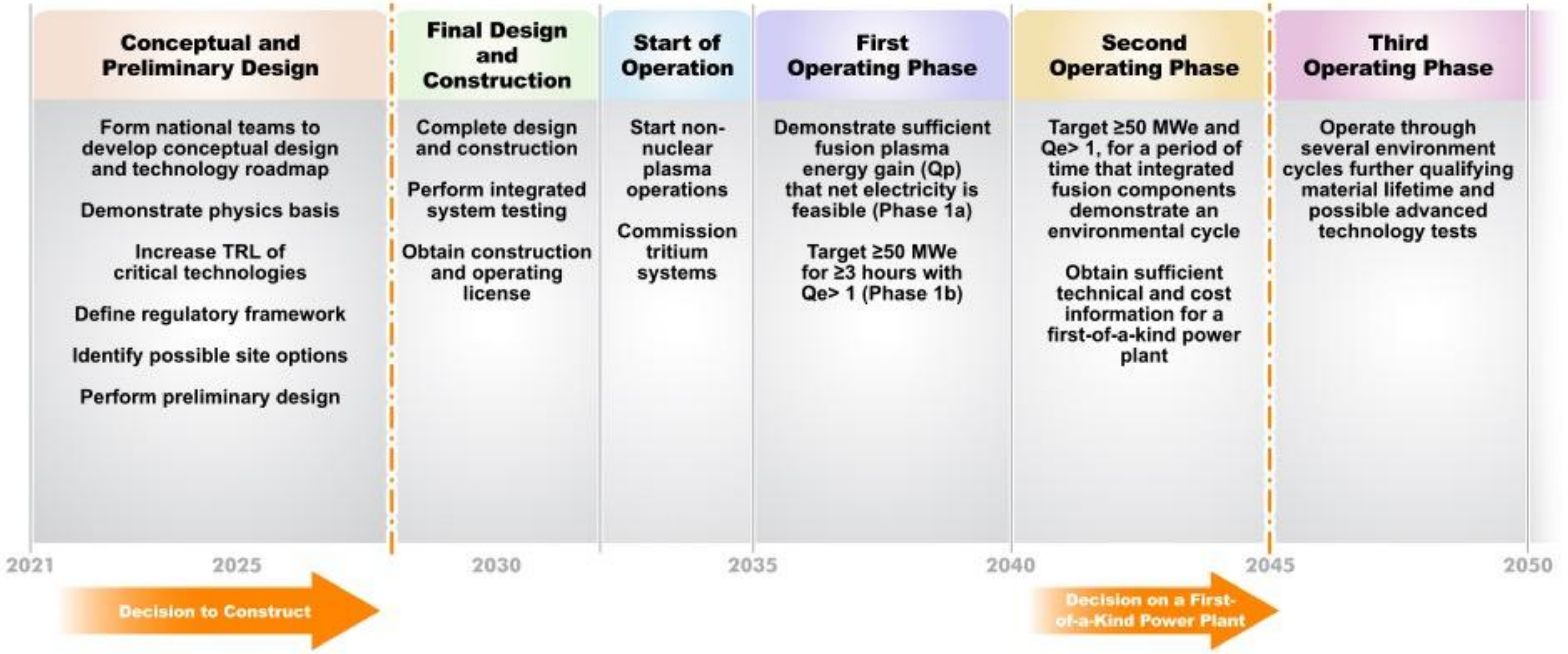
Recommendation: Electricity generation market policy and incentives should encourage a diversity of energy sources from various firm, low-carbon emission generation resources including non-carbon emission fusion, in the future for baseload as part of a national strategy to ensure national security and the lowest cost path to a low-carbon emission future.

Role of the Pilot Plant:
Provide Technical and Economic Information

Finding: A pilot plant must provide the technical and economic information needed for utilities to operate future plants. It must be a test to ensure public confidence in the technology and the success of the commercial plants that will follow.

Recommendation: Due to the evolving energy marketplace, the characteristics of a fusion power plant should be periodically reviewed by energy experts and updated to increase the likelihood that the fusion concept will successfully contribute to the needs of society.

Strategy and Roadmap



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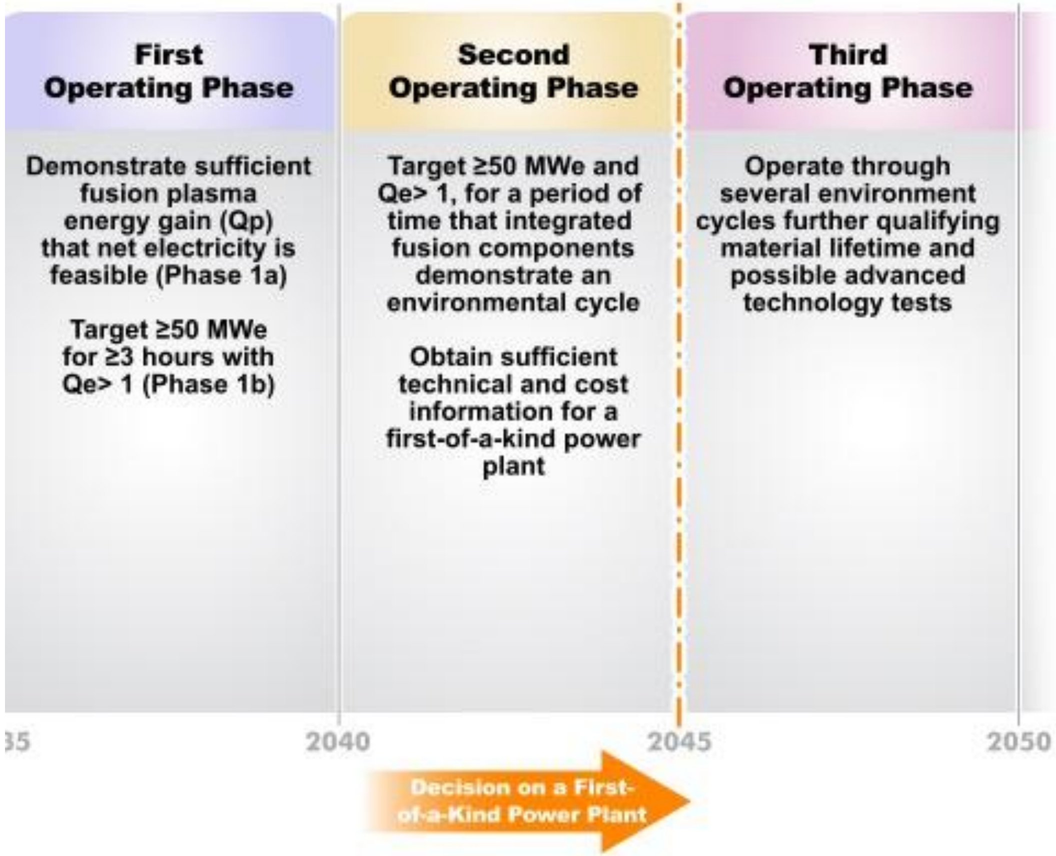
Goals for a Fusion Pilot Plant:
Overall Considerations for Operating Phases

Finding: The pilot plant design will need to be based on a vetted, well-established confinement physics basis for achieving net plasma gain well in excess of unity.

Conclusion: A pilot must produce an amount of fusion power and energy that is sufficiently representative of the market needs in order to meet the pilot's goal of demonstrated integrated performance and cost, while also demonstrating net electricity gain Qe > 1 and produce peak net electrical power ≥ 50 MWe.



Goals for a Fusion Pilot Plant:

Considerations for Phase 1

First Operating Phase

Demonstrate sufficient fusion plasma energy gain (Qp) that net electricity is feasible (Phase 1a)

Target ≥50 MWe for ≥3 hours with Qe> 1 (Phase 1b)

Phase 1a

- target 100-500 MW time-averaged thermal power for ≥100 s
- for pulsed concepts, operate at the design repetition rate for Phase 2

Phase 1b

- for D-T fusion, demonstrate production, extraction, and refueling of tritium on a timescale sufficient to maintain reasonable operations
- for pulsed concepts, these should be for a comparable time scale of ≥3 hours at the design repetition rate for Phase 2

Goals for a Fusion Pilot Plant:

Considerations for Phases 2 and 3

Second Operating Phase

Target ≥50 MWe and Qe> 1, for a period of time that integrated fusion components demonstrate an environmental cycle

Obtain sufficient technical and cost information for a first-of-a-kind power plant

Phase 2

- demonstrate operation for an environmental cycle including maintenance
- require operation on the order of one full power year

Phase 3

- demonstrate and improve average availability for commercial fusion
- provide additional data on the mean time to failure and replacement time for materials/components
- use for testing advanced materials and technology and novel deployment of fusion to the grid

Third Operating Phase

Operate through several environment cycles further qualifying material lifetime and possible advanced technology tests

Goals for a Fusion Pilot Plant:
Economic Considerations

Finding: On the basis of today's energy market and costs, the fusion First-of-a-Kind power plant will need to have a total overnight construction cost less than \$5 billion to \$6 billion in order to be viable in the present U.S. electrical marketplace with a projected operation life of at least 40 years for the plant.

Conclusion: A fusion pilot plant should have a generating power >50 MWe and total overnight construction cost <5-6 B\$.

Goals for a Fusion Pilot Plant:
Additional Topics Addressed

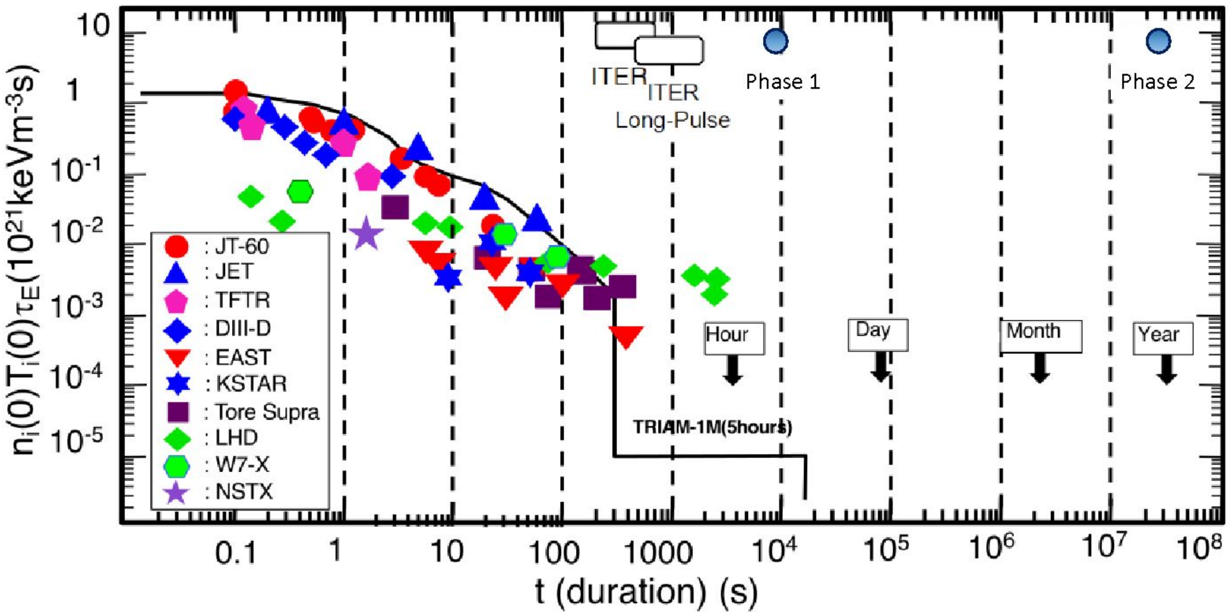
- Integrated fusion and electric power performance
- Materials and manufactured components
- Fuel and Ash
  - D-T fuel cycle – need for tritium breeding
  - Alternative fuel cycles to D-T
- Reliability and availability
- Environmental and safety consideration
- Regulatory process

Innovation and Research Needs:
Overall Innovation Strategy

Recommendation: To meet the challenge of having a viable design by 2028 and initial pilot plant operation in the 2035-2040, innovations in fusion confinement concepts and technology to extract fusion power and close the fusion fuel cycle should be developed in parallel. This will enable the engineering design of a pilot plant and the construction decisions to be accelerated by a combination of government and private funding.

Innovation and Research Needs:
Fusion Plasma Confinement and Pulse Duration

Fusion triple product vs. plasma duration



Conclusion: Before proceeding to the final pilot plant design phase, a DT fusion concept should simultaneously demonstrate temperatures of at least 100 million °C, and a triple product >2 (in units of 10^{21} keV s m^{-3}) corresponding to an DT equivalent plasma energy gain >1.

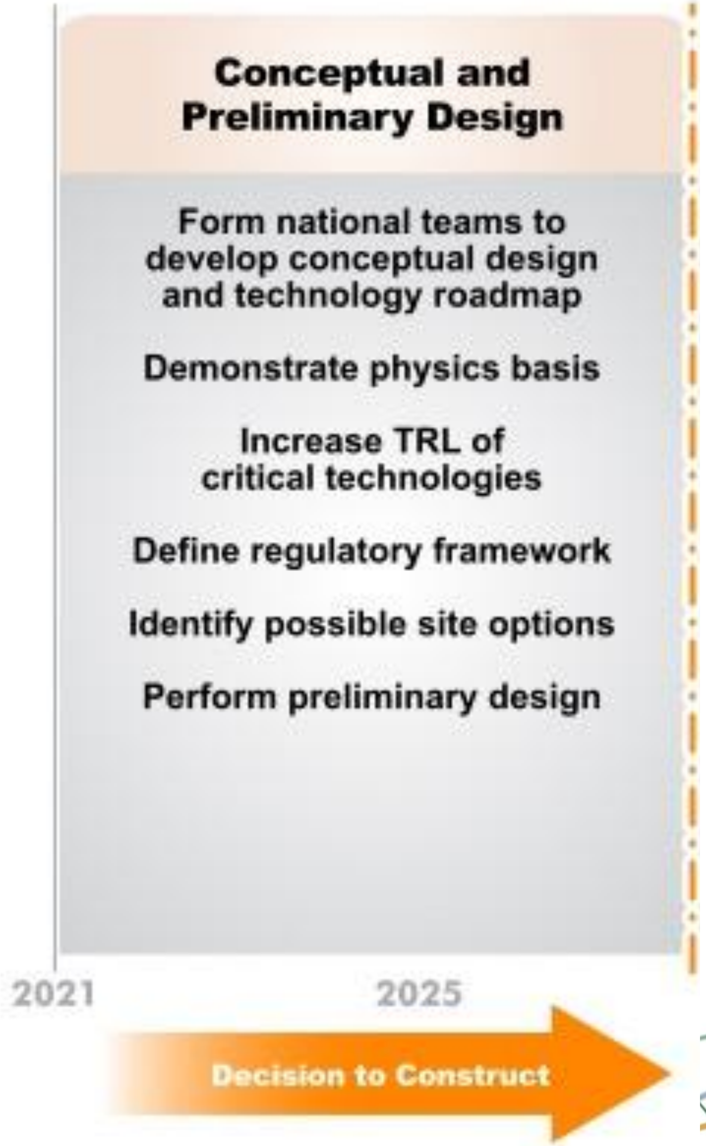
Conclusion: For alternate fuels, equivalent parameters needed for net plasma energy gain must be demonstrated.

Innovation and Research Needs:
Additional Topics Addressed

- Scientific and technical innovations and research advances
  - Fusion performance and plasma confinement
  - High heat flux challenge: plasma facing components
  - High temperature superconducting magnets
  - Structural and function materials: neutron degradation assessment
  - Closing the fuel cycle: tritium processing, developing a breeding blanket
- Many technological elements are at a low level of technical readiness
- Participants in developing a pilot plant
  - Workforce issues including Diversity, Equity and Inclusion
- Models for Public-Private Partnerships
- ITER contributions to a pilot plant

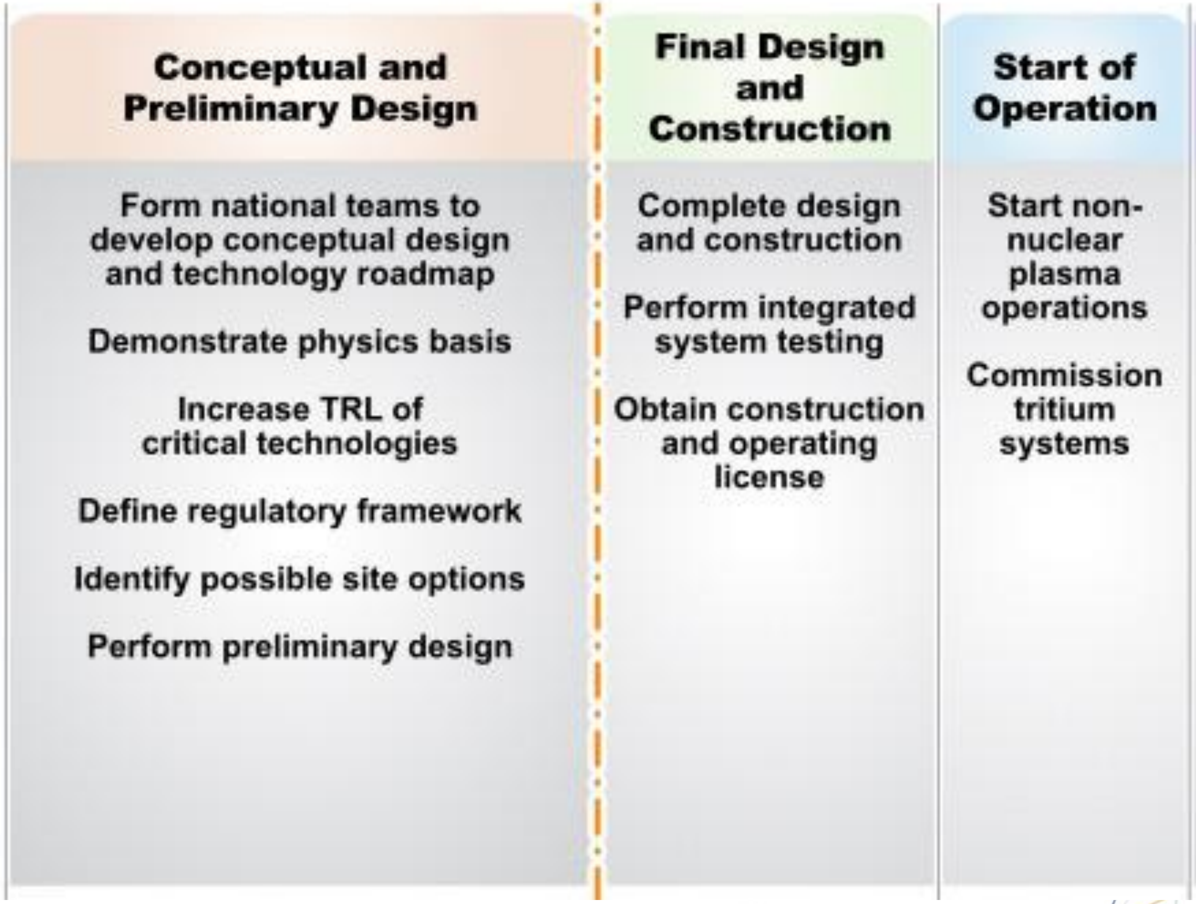
Strategy and Roadmap

Recommendation: The Department of Energy should move forward now to foster the creation of national teams, including public-private partnerships, that will develop conceptual pilot plant designs and technology roadmaps and lead to an engineering design of a pilot plant that will bring fusion to commercial viability.



Strategy and Roadmap

Conclusion: If the pilot plant cannot be built for less than the projected cost of the first-of-a-kind power plant or the concept does not have the potential for producing electricity at an economically competitive cost, then further innovations will be required to reduce the cost and improve the concept prior to proceeding to construction.



Strategic Risks and Opportunities

Risks

- Level of scientific and technological readiness resulting in schedule risk
- Schedule will not support the electricity transition
- U.K. or China will be first to put fusion on the grid
- Obtaining public and private funding

Opportunities

- Engagement of the private sector
- Impact the transition to low-carbon emission electricity
- Be a leader in the development of fusion energy

Mitigation

- Perform R&D in parallel with design
- Decision points to evaluate progress

Moving Forward for Fusion to Power the Grid

- Identified the goals, innovations and a timeline
- Plan is bold and achievable
- U.S. has played a major role in the development of fundamental science for fusion
  - U.S. can take the lead in this technology or
  - Let other countries take the lead

Key Takeaways

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Any Questions?

For more information, please visit the study website at

http://nas.edu/fusion