Bringing Fusion to the U.S. Grid

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Presented to:

FESAC

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Committee Composition

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General Atomics

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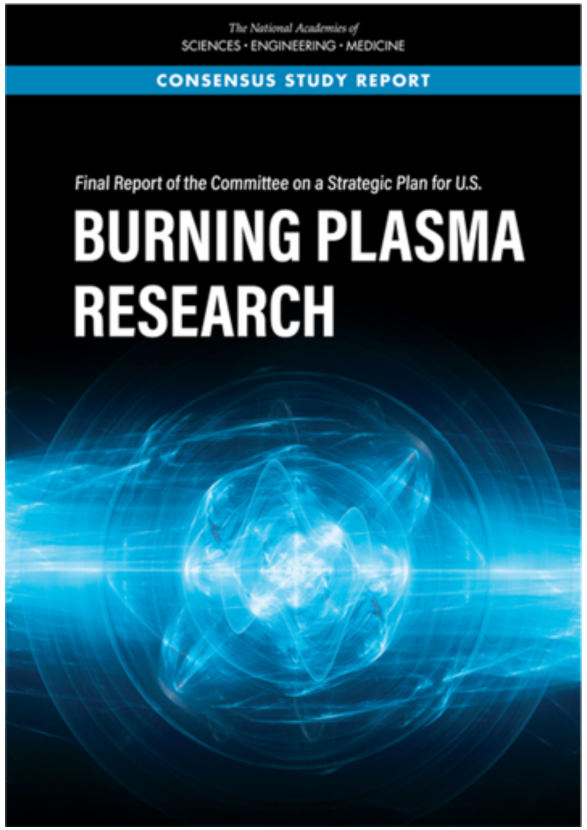
Briefings

- Briefings provided to Stakeholders:
  - DOE-FES,OMB,OSTP, DOE-ARPA-E
  - House E&W Approps, HSST (Authorizing Cmte), Fusion Caucus
  - NRC
- Briefings to Fusion Community:
  - Fusion Discussion Group, ORNL, PPPL, MIT-Commonwealth Fusion, GA
  - Burning Plasma Organization & University Fusion Association
  - Fusion Industry Association
  - Fusion Energy Council of Canada
- Future briefings:
  - AAPPS-DPP

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.

The National Academies of SCIENCES ENGINEERING MEDICINE

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

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.

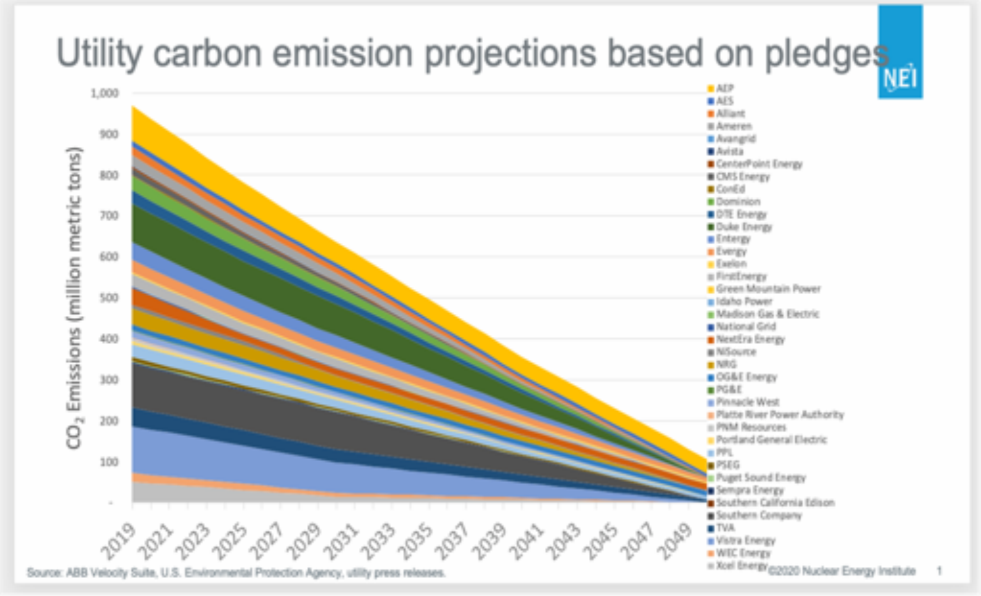
Report Outline

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

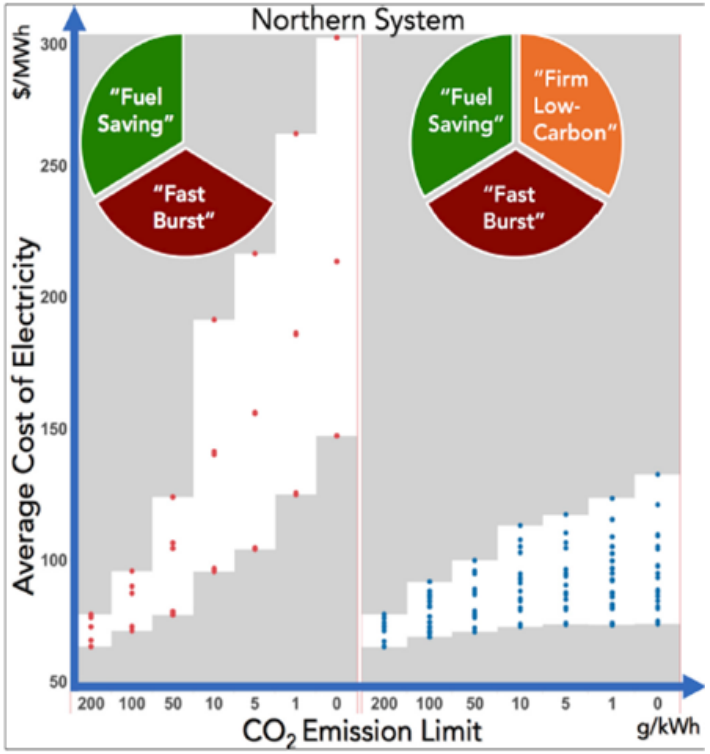
Role of the Pilot Plant on the Path to Commercialization

D. Roop

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.

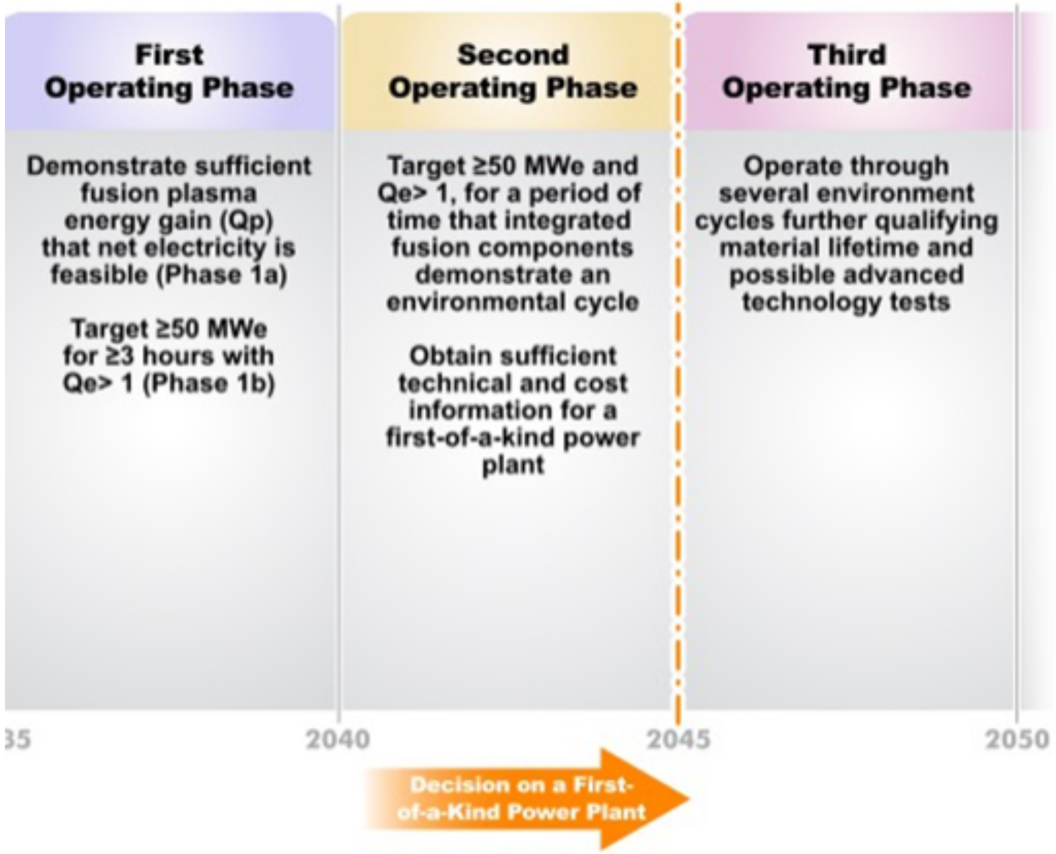
Goals for a Fusion Pilot Plant

D. Whyte

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:
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

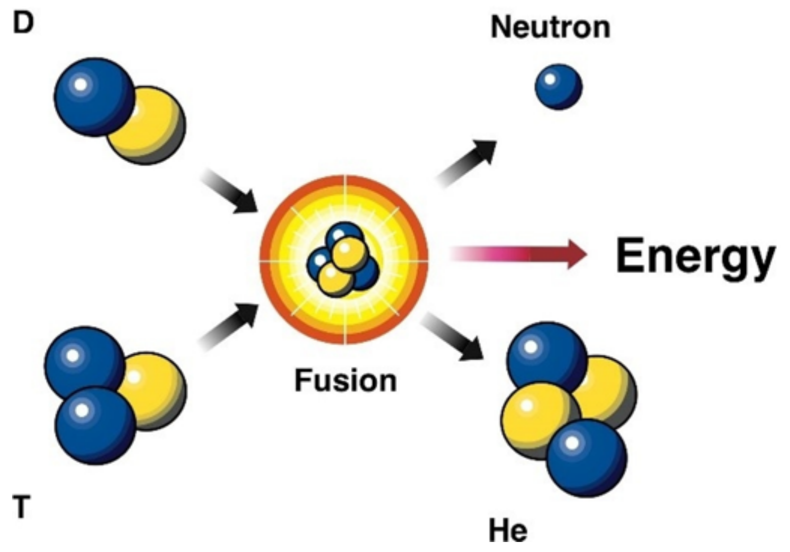


Image source: DOE

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$.

Innovations and Research Needed to Address Key Fusion Pilot Plant Goals

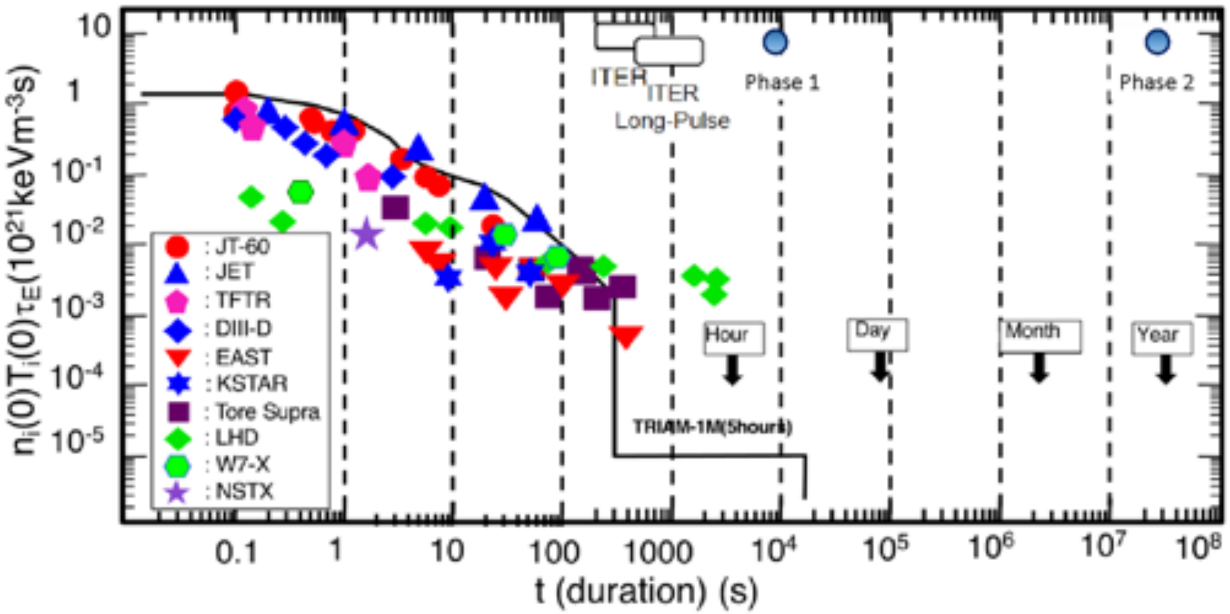
B. Wirth

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.

Integrated Simulation Is an Important Element Going Forward

- Modeling and simulation incorporating multiple physics and multiscale phenomena with increasing fidelity into simulations to evaluate and refine design options
  - High fidelity simulations will benefit from exascale computing and enable reduced models including via artificial intelligence.

- Physics, system and process models can be combined into comprehensive full device models which will likely contribute to evaluating the operations and maintenance of the pilot plant

- Engineering computer aided design, structural analysis and process and control modeling will provide an important opportunity to optimize the design and integration of the fusion pilot plant

High Heat Flux Challenge for Plasma Facing Components and First Wall Components

- ***Recommendation:*** The Department of Energy should support studies of the compatibility of innovative divertor designs in toroidal confinement concepts with divertor plasma detachment, which can significantly relax the radiated power requirement, and including the possibility of liquid metal PFCs.

- ***Recommendation:*** The Department of Energy should support a research program and new facilities, including linear devices for testing plasma facing components and non-plasma heat flux testing platforms, to identify, evaluate, and finalize a high-confidence, robust design for PFC and first wall armor materials, including both solid and liquid metal options, that are compatible with managing steady state and transient power loading.

Innovation and Research Needs:
Additional Topics Addressed

- Technical innovations and research advances are needed:
  - 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

Innovations and Research Needed to Address Key Fusion Pilot Plant Goals

Public-Private Partnerships

K. McCarthy

Participants in Developing a Pilot Plant

- **Recommendation:** The participants in the development of the pilot plant should execute the recommendation of the Community Planning Process to "Embrace diversity, equity, and inclusion, and develop the multidisciplinary workforce required to solve the challenges in fusion and plasma science."

- ***Finding:*** Teams made up of private industries, national labs, and universities bring together important strengths: industry brings the focus on deploying a usable product on a timeframe that will meet market needs, and national labs and universities bring innovation and deep technical expertise.

- ***Recommendation:*** The Department of Energy should further encourage access of private industry to the broad range of technical experts resident at the national laboratories and universities.

- ***Recommendation:*** The Department of Energy (DOE) should use and expand the new programs to partner with industry in support of the pilot plant design, and DOE should include all FES-funded researchers, including those at universities and private companies, in the INFUSE program.

Models for Public-Private Partnership

- ***Finding:*** The NASA COTS program achieved remarkable success in developing new commercially competitive space transportation capabilities at significantly less cost to the government and with an accelerated schedule using a payment-for-milestones public-private partnership.

- ***Finding:*** While the NASA COTS model holds promise, in general the TRL for space transportation systems is substantially higher than the TRL for major fusion energy systems. …

- ***Recommendation:*** The Department of Energy should evaluate and identify the best model for public-private partnerships to accelerate development and reduce government cost for a fusion pilot plant. Note that the different phases of the development, including conceptual design and technology roadmap, detailed engineering design, construction and operation, may involve different or incremental public private partnership models, including fixed-price payment for milestones.

ITER Contributions to a Pilot Plant

ITER activities that benefit U.S. industry include:

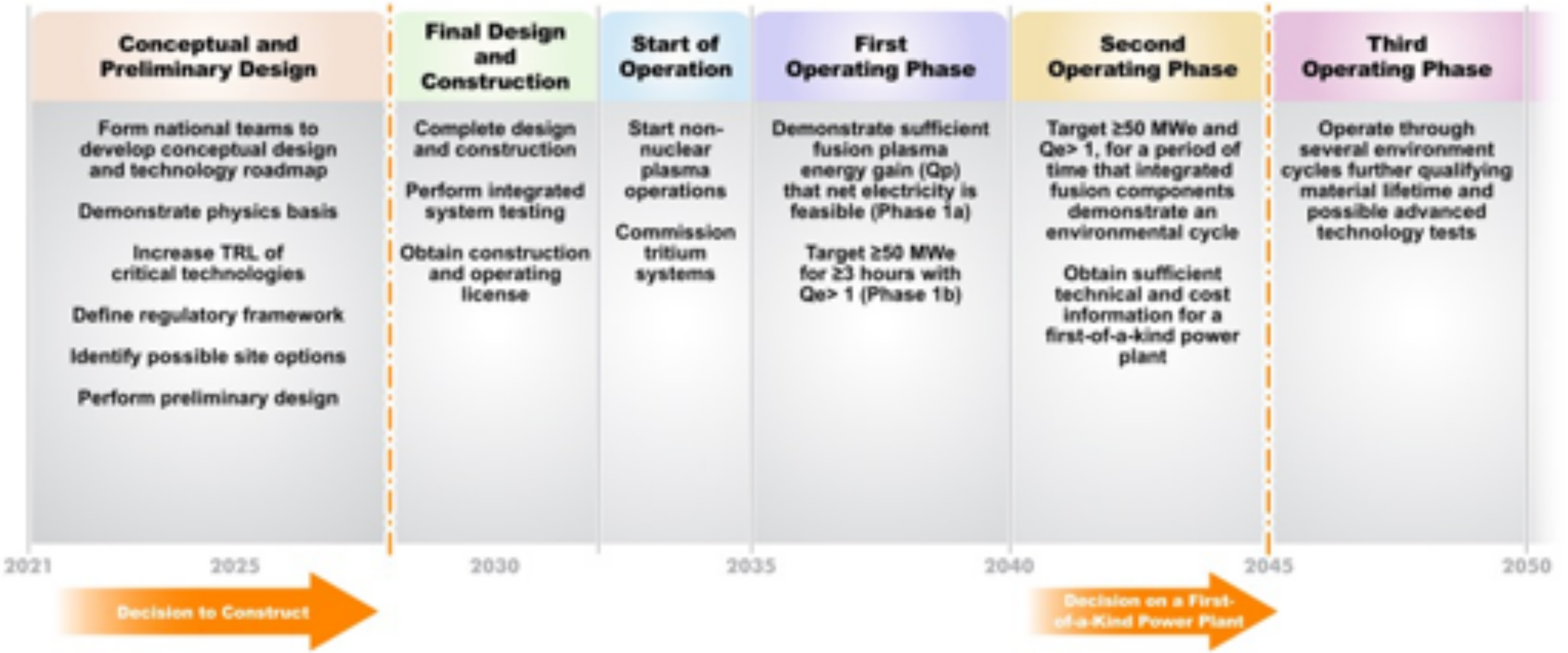
- Tools and strategies for plasma control and performance
- Superconducting magnet technologies
- Radiation transport analysis
- High-powered plasma heating
- D-T fuel cycle technologies
- Continuous plasma fueling
- Fusion materials
- Fusion power and particle handling
- Burning plasma science
  - Diagnostics

Recommendation: The Department of Energy should assure maximum possible access to ITER information for the members of the fusion pilot plant design teams.

Strategy and Roadmap

R. Hawryluk

Strategy and Roadmap



Strategy and Roadmap

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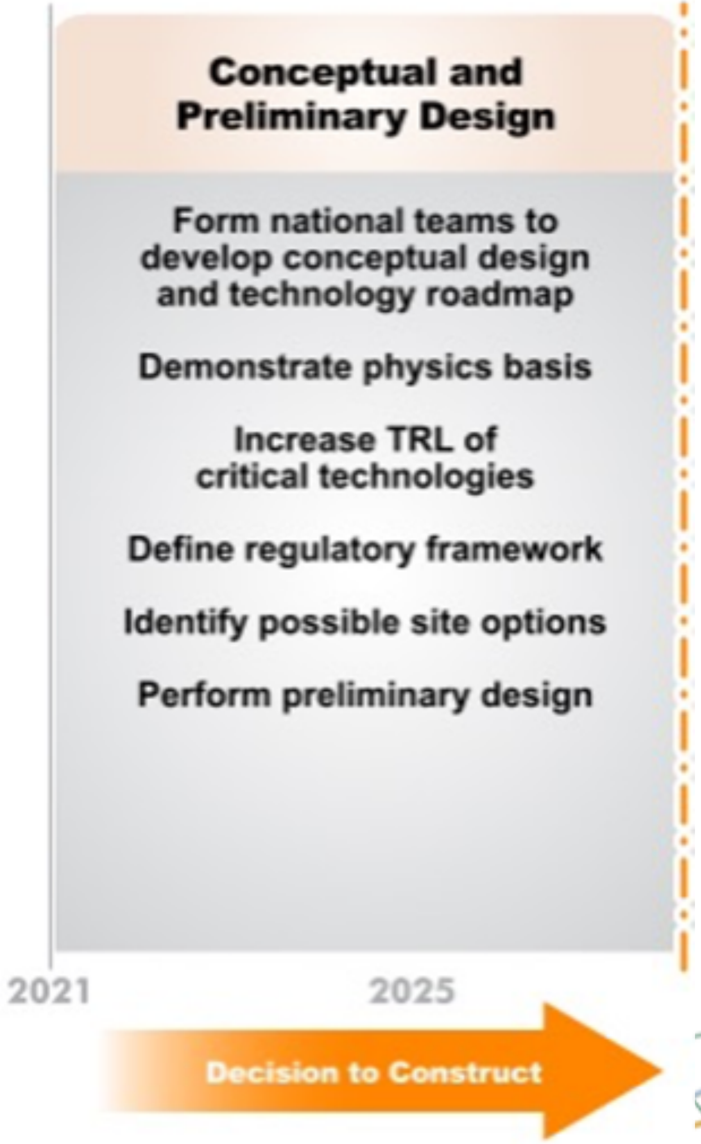
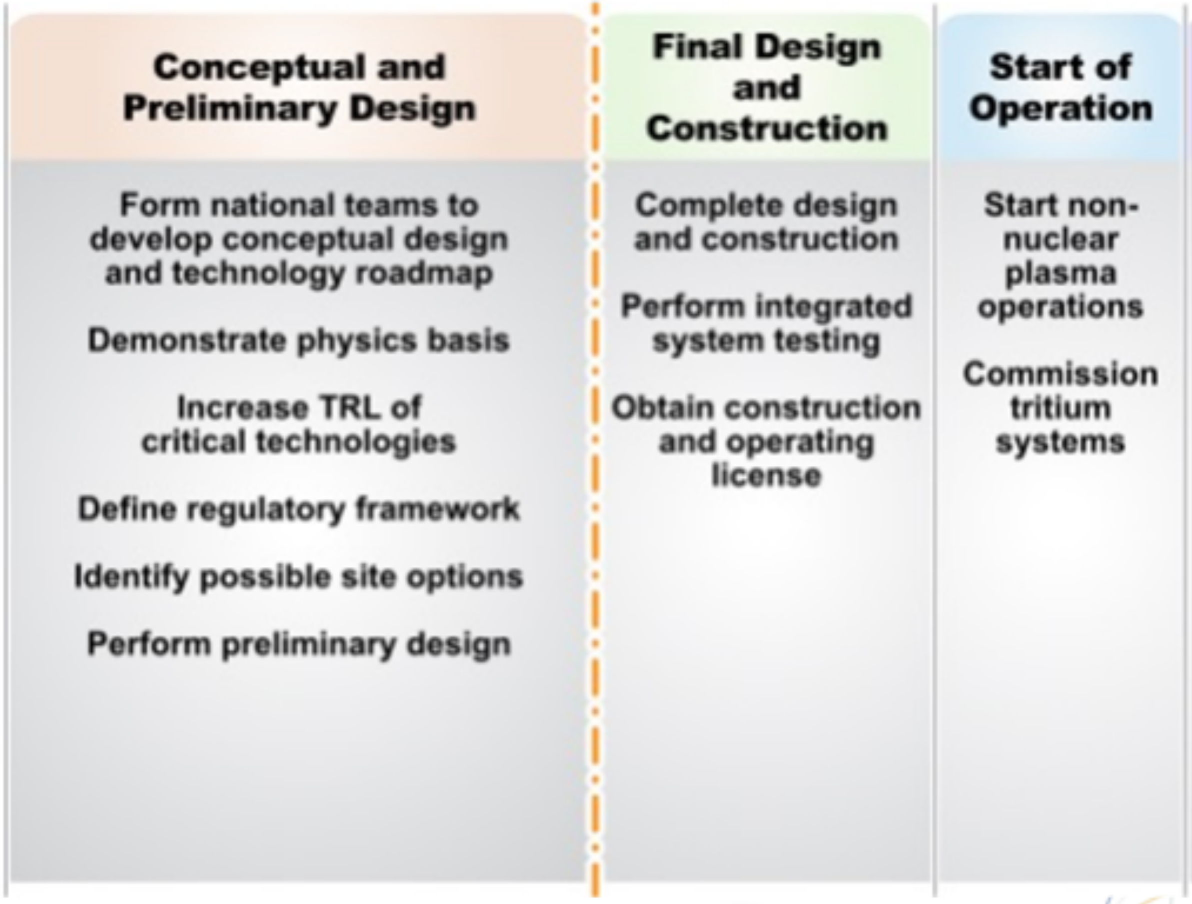


Strategy and Roadmap

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