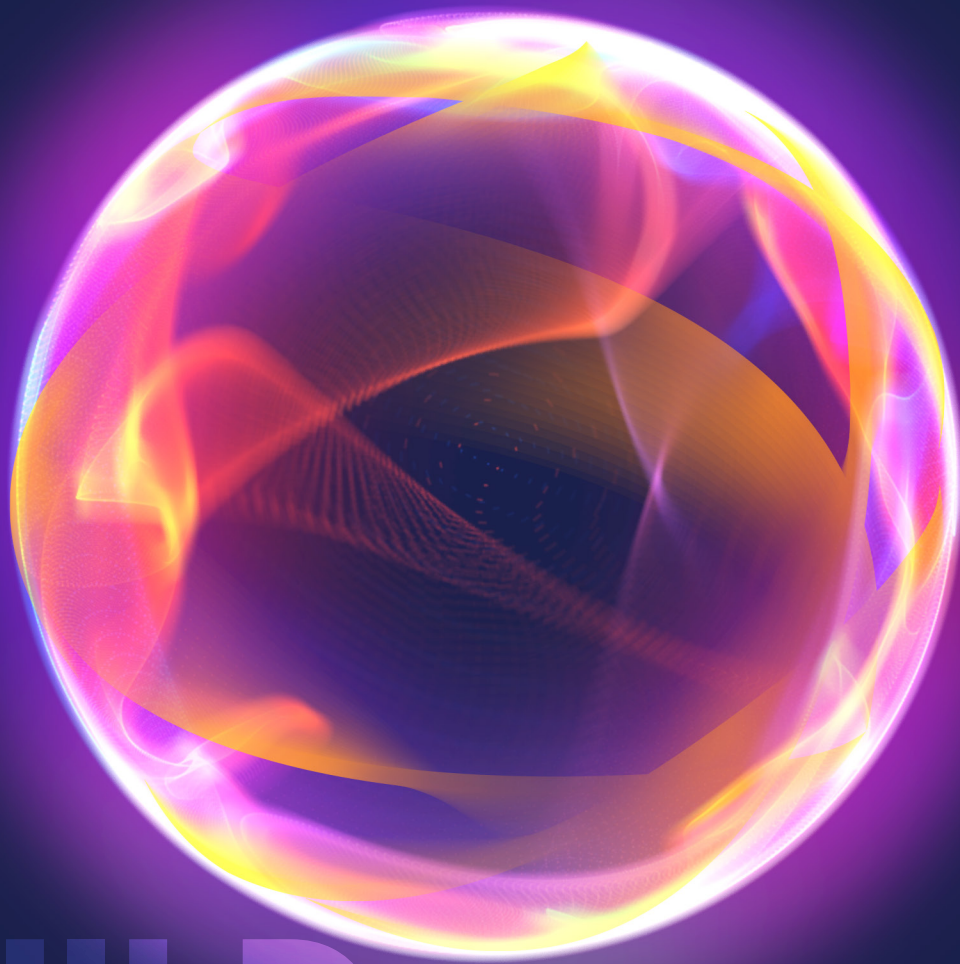




U.S. DEPARTMENT
of **ENERGY** | Office of
Science

Fusion Science & Technology Roadmap



**BUILD
INNOVATE
GROW**

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List of Acronyms

AEC	Atomic Energy Commission	GAO	Government Accountability Office
AI	Artificial Intelligence	H3AT	Hydrogen-3 Advanced Technology Facility
ALARA	As Low As Reasonably Achievable	HFT	High-Field Tokamak
AMPS DS	Affordable, Manageable, Practical and Scalable Demonstration System	HHF	High-Heat-Flux
AmSC	American Science Cloud	HPC	High-Performance Computing
APP-FPP	Advanced Profile Prediction for Fusion Pilot Plant Design	HTS	High-Temperature Superconducting
ArF	Argon Fluoride	HX	Heat Exchanger
ASCR	Advanced Scientific Computing Research	ICF	Inertial Confinement Fusion
ASME	American Society of Mechanical Engineers	ICRH	Ion Cyclotron Resonance Heating
ATLAS	Advanced Technology Lasers for Applications and Science Facility	IFE	Inertial Fusion Energy
BCTF	Blanket Component Test Facility	IFMIF-DONES	Inertial Fusion Energy
BES	Basic Energy Science	IMPACT	Integrated Materials Program to Accelerate Chamber Technologies
BOP	Balance of Plant	INFUSE	Innovation Network for Fusion Energy
BRN	Basic Research Needs	INL	Idaho National Lab
CAD	Computer-Aided Design	ITEP	Integrated Tokamak Exhaust and Performance
CPP	Community Planning Process	ITER	International Thermonuclear Experimental Reactor
CSU	Colorado State University	JET	Joint European Torus
CTC	Compact Toroidal Concepts	KIT	Karlsruhe Institute of Technology
DIII-D	DIII-D National Fusion Facility	KrF	Krypton Fluoride
DIR	Direct Internal Recycling	KSTAR	Korea Superconducting Tokamak Advanced Research
DOE	Department Of Energy	LANL	Los Alamos National Laboratory
DPSSL	Diode-Pumped Solid-State Laser	LCLS	Linac Coherent Light Source
DD	Deuterium-Deuterium	LEAPS	Leading-edge Advancement for Energy Power Solutions
DT	Deuterium-Tritium	LIBERTI	Lithium Breeding Tritium Innovation Facility
EBR II	Experimental Breeder Reactor 2	LLE	Laboratory for Laser Energetics
ECC	Emerging Confinement Concepts	LLNL	Lawrence Livermore National Laboratory
ECRH	Electron Cyclotron Resonance Heating	LMCE	Liquid Metal Core-Edge
ELM	Edge-Localized Mode	LPI	Laser-Plasma Interaction
FAIR	Finadable, Accessible, Interoperable and Reusable	LTX	Liquid Tokamak Experiment
FCP	Facilities Construction Projects	MAST-U	Mega Amp Spherical Tokamak Upgrade
FEDER	Fusion Energy Data Ecosystem and Repository	MEC	Matter in Extreme Conditions
FES	Fusion Energy Science	MFE	Magnetic Fusion Energy
FESAC LRP	Fusion Energy Sciences Advisory Committee Long-Range Plan	MHD	Magnetohydrodynamics
FIA	Fusion Industry Association	MIBL	Michigan Ion-Beam Laboratory
FIRE	Fusion Innovation Research Engine	ML	Machine Learning
FIRST	Fusion Integration Research and Science Test Facility	MPEX	Materials Plasma Exposure Experiment
FM&T	Fusion Materials and Technology	MTTF	Mean-Time-To-Failure
FNS	Fusion Nuclear Science	NASEM	National Academics of Sciences, Engineering and Medicine
FOAK	First-Of-A-Kind	NBI	Neutral-Beam Injection
FPNS	Fusion Prototypical Neutron Source	NDE	Non-Destructive Examination
FPP	Fusion Pilot Plant	NEAMS	Nuclear Energy Advanced Modeling and Simulation
FS&T	Fusion Science and Technology	NE	Nuclear Energy
FuRTH	Fusion Research and Technology Hub	NIF	National Ignition Facility
FuZE-Q	Fusion Z-pinch Experiment	NIFS	National Institute for Fusion Science (Japan)
GAIN	Gateway for Accelerated Innovation in Nuclear		

NNSA	National Nuclear Security Administration	SNL	Sandia National Laboratory
NRL	Naval Research Laboratory	SOL	Scrape Off Layer
NSF	National Science Foundation	SPARC	Smallest Possible Affordable, Robust, Compact Plant
NSTX-U	National Spherical Torus Experiment-Upgrade	ST	Spherical Tokamak
OFEI	Office Of Fusion Energy Innovation	SWIFT-PFCs	Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components
ORNL	Oak Ridge National Laboratory	TBR	Tritium Breeding Ratio
PFC	Plasma Facing Component	TEAMS	Theory, Engineering, AI, Modeling and Simulation
PFM	Plasma Facing Material	TEC	Transformative Enabling Capabilities
PFR	Private Facility Research	TFTR	Tokamak Fusion Test Reactor
PMI	Plasma-Material Interactions	TIMBL	Tennessee Ion Materials Beam Laboratory
PPCF	Public-Private Consortium Framework	TINEX	Target Injector Nexus for Development Research
PPPL	Princeton Plasma Physics Laboratory	TRL	Technology Readiness Level
PPP	Public-Private Partnership	TVA	Tennessee Valley Authority
QA	Quality Assurance	UKAEA	United Kingdom Atomic Energy Authority
RAFM	Reduced Activation Ferritic Martensitic	UQ	Uncertainty Quantification
RAMI	Reliability, Availability, Maintainability, Inspectability	UR	University of Rochester
REBCO	Rare-Earth Barium Copper Oxide	USG	U.S. Government
R&D	Research and Development	VNS	Volumetric Neutron Source
RD&D	Research, Development and Demonstration	VV	Verification and Validation
RRA	Risk Reduction Activity	W7-X	Wendelstein 7-X
S&T	Science and Technology	WEST	Tungsten (W) Environment in Steady-state Tokamak
SciDAC	Scientific Discovery Through Advanced Computing	XFEL	X-ray Free-Electron Laser
SCSP	Special Competitive Studies Project		
SLAC	Stanford Linear Accelerator Center		

Disclaimer

The activities outlined in the Fusion Science & Technology Roadmap are focused on prioritizing strategic directions for the Department of Energy to further collaborate with the U.S. Fusion Industry. The Department of Energy's ability to support this Roadmap's milestones and timelines of scaling up the domestic fusion private sector by the 2030s is contingent on the development of future public-private partnerships. This Roadmap is not committing the Department of Energy to specific funding levels, and future funding will be subject to Congressional appropriations.

Executive Summary

The U.S. Department of Energy's (DOE) Fusion Science & Technology (FS&T) Roadmap (hereafter "*the Roadmap*") aims to usher a burgeoning fusion private sector industry in the U.S. toward maturity on the most rapid timeline. By leveraging investments from both the public and private sectors with prudent and strategic processes, the Roadmap marshals the forces of the public and private sectors to close gaps on the critical path toward fusion energy. The Roadmap targets actions and milestones out to the mid-2030s, providing the scientific and technological foundation to support a competitive U.S. fusion energy industry.

The U.S. strategy for fusion energy development is enabled by three primary drivers to Build, Innovate and Grow a leading, competitive and robust American-driven fusion energy industry. While the U.S. private sector is investing > \$9B to demonstrate sustaining burning plasma on the path to fusion power plants¹, there remain critical science, materials and technology gaps, such as the breeding and handling of fusion fuels, that must be closed. These critical gaps require innovation and bridging of public and private sectors.

The goal of the Roadmap is to deliver the public infrastructure that supports the fusion private sector scale-up in the 2030s.

The U.S. will: **Build** key infrastructure to address critical fusion materials and technology (FM&T) gaps; **Innovate** and advance the science and engineering of fusion; and **Grow** the U.S. fusion ecosystem through domestic and international public-private

partnerships, fostering new regional consortia, building research FS&T infrastructure and supply chains and fusion manufacturing networks.

Build-Innovate-Grow is DOE's new strategy to support fusion energy commercialization in the U.S. and its tool is the Roadmap. The Roadmap is strongly aligned to the 2020 Fusion Energy Sciences Advisory Committee (FESAC) Long-Range Plan (LRP). The Roadmap combines the FESAC LRP critical science drivers with a revamped FES public program in the DOE Office of Science (SC) to define a new era of U.S. fusion energy leadership. This era is characterized by strong alignment between the public sector roadmap and the private sector's stated ambitions to deliver fusion power on an aggressive timeline and is increasingly enabled and accelerated by the revolutionary potential of Artificial Intelligence (AI)-Fusion convergence.

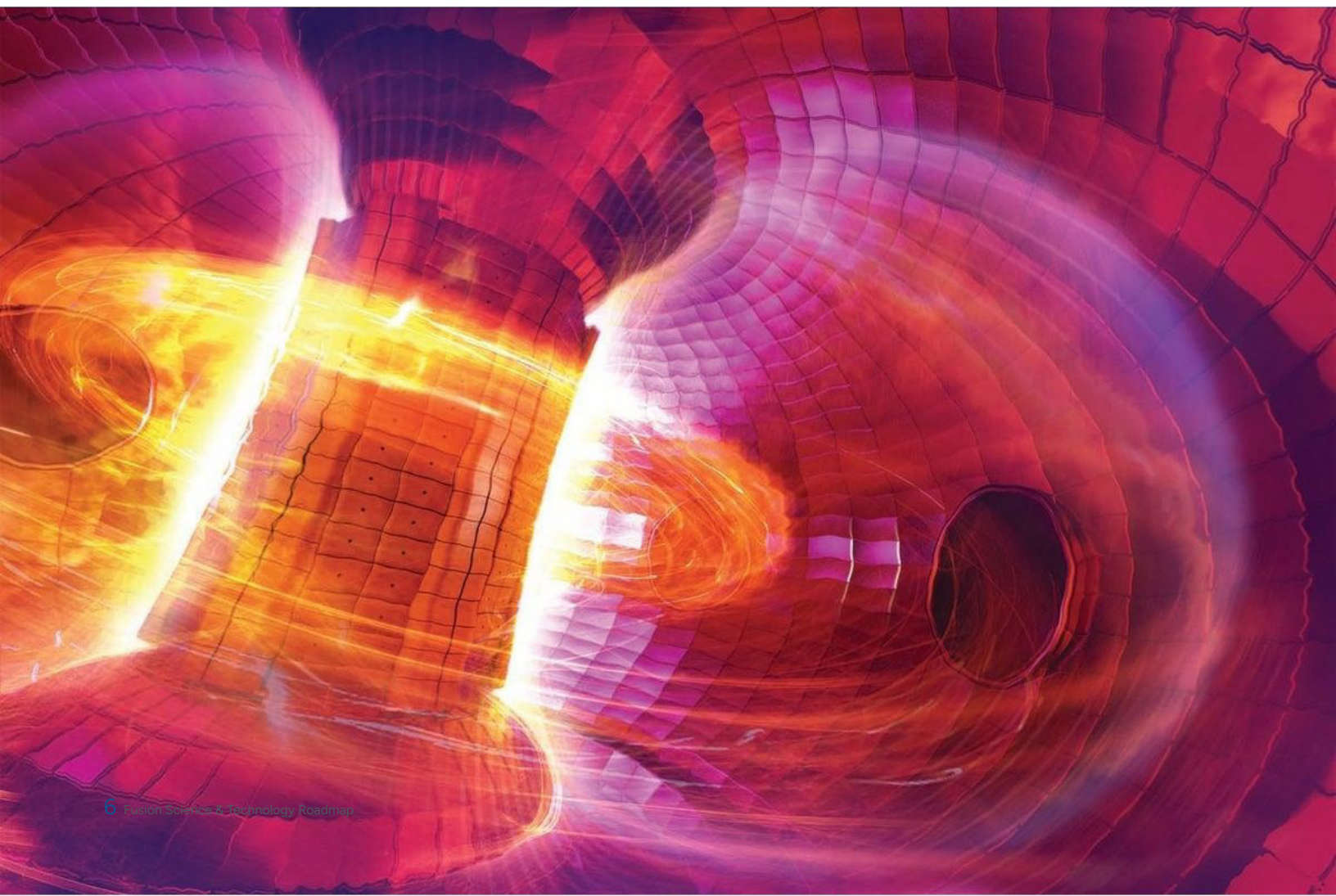
The Roadmap defines **Key Actions** to be executed in the near-term (next 2-3 years), mid-term (3-5 years) and long-term (5-10 years), aligned to the Build-Innovate-Grow strategy and to the LRP science drivers. DOE will build FS&T infrastructure and the AI-Fusion digital convergence platform. DOE will **innovate** through transformative research and advance toward cost competitive power plants. DOE will **grow** the U.S. fusion enterprise through public-private partnerships and by supporting development of supply chains, workforce pathways, synergies with advanced nuclear and enabling fusion energy adoption and commercialization. The roadmap also **maps the DOE plan for delivering FS&T infrastructure** along the same near-mid-long term schedule, that will be critical for the development of an FPP on industry timeline. Together the delivery of Key Actions and infrastructure will enable U.S. progress on closing S&T gaps on the critical path

1. Fusion Industry Association, 2025. The Global Fusion Industry in 2025, <https://www.fusionindustryassociation.org/fusion-industry-reports/>

to fusion energy across six core **challenge areas**, **tracked with technical milestones and metrics**: structural materials, plasma-facing components and plasma-material interactions, confinement approaches, the fuel cycle, blankets and fusion plant engineering and system integration.

The Roadmap sets the path for strategic actions and capability delivery necessary to support a world-leading U.S. fusion ecosystem, including clear metrics to track progress and to ensure these actions are aligned with closing critical scientific and technical challenges and rapidly progressing toward realizing abundant commercial fusion in the U.S. It is a dynamic tool for DOE that is designed to evolve with continual input from the public and private sector fusion community. **The goal of the Roadmap is to deliver the public infrastructure that supports the fusion private sector scale up in the 2030s.**

By leveraging investments from both the public and private sectors with prudent and strategic processes, the Roadmap marshals the forces of the public and private sectors to close gaps on the critical path toward fusion energy.



The Roadmap Strategy: Build-Innovate-Grow

The U.S. Department of Energy's (DOE) Fusion Science & Technology (FS&T) Roadmap (hereafter "*the Roadmap*") aims to usher a burgeoning fusion private sector industry in the U.S. toward maturity on the most rapid timeline. **Build-Innovate-Grow is the new U.S. strategy for DOE to support fusion energy commercialization in the U.S. and its tool is the Roadmap.** The mission of U.S. DOE Fusion Energy Sciences (FES) is to drive the scientific and technological foundation for a fusion energy source and support the development of a competitive U.S. fusion energy industry. The FES Building Bridges vision² is anchored on advancing the foundational research needed to close key science and technology (S&T) gaps towards the development of fusion power as an affordable and reliable energy source in the U.S. using multiple tools and strategic approaches. Core capabilities in foundational FS&T areas are complemented by alignment with the 2020 Fusion

Energy Sciences Advisory Committee (FESAC) Long-Range Plan (LRP)³ Fusion Materials and Technology (FM&T) gaps, which connects three science drivers: Sustain a Burning Plasma, Engineer for Extreme Conditions and Harness Fusion Power.

Foundational science is the engine to innovate and the U.S. strategy for fusion energy development is enabled by three primary drivers to Build, Innovate and Grow a leading, competitive and robust American-driven fusion energy industry (Figure 1). While the U.S. private sector is investing > \$9B to demonstrate sustaining burning plasma on the path to fusion power plants⁴, there remain critical science, materials and technology gaps, such as breeding and handling of fusion fuels, that must be closed to deliver fusion power to the grid. These critical gaps that remain require innovation and bridging of public and private sectors.

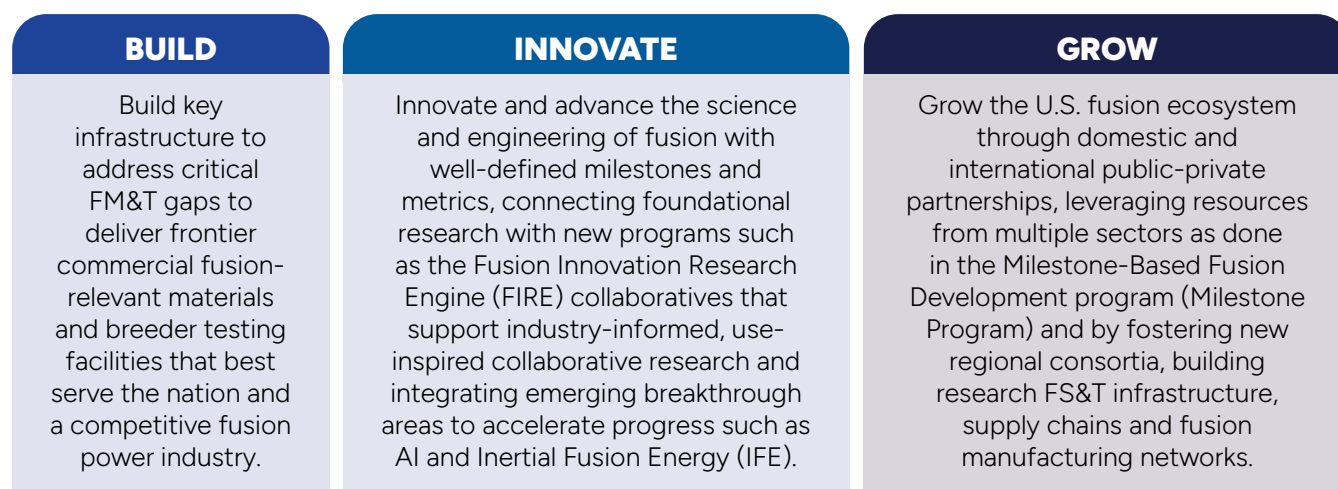


Figure 1. The U.S. Build-Innovate-Grow Strategy

2. U.S. Department of Energy, 2024. Building Bridges: A Vision for the Office of Fusion Energy Sciences, https://www.energy.gov/sites/default/files/2024-12/fes-building-bridges-vision_0.pdf
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4. Fusion Industry Association, 2025. The Global Fusion Industry in 2025, <https://www.fusionindustryassociation.org/fusion-industry-reports/>

Roadmap Introduction

Advancing the Mission of Supporting a Competitive Fusion Power Industry

Establishing a competitive fusion power industry requires more than the development, demonstration and deployment of fusion energy technologies. To sustain and scale fusion energy requires bridging both public and private sector talent, expertise and resources. This approach demands rethinking how DOE leverages its assets and prioritizes its investments for fusion energy development. A strategic and ambitious plan is needed to sustain momentum across a broad range of complex research lines.

Commercial fusion energy requires a spectrum of activities that include foundational research and development (R&D), bridging over to translational research that leverages demonstration platforms, to ultimately result in deployment of fusion energy. The Roadmap enables the public program to prioritize and adapt based on the successes (and failures) of the private sector. In the late 2020s, planned private sector demonstration platforms, such as SPARC (a compact, high field tokamak)⁵, Polaris (a magneto-inertial fusion device)⁶, Infinity One (a stellarator)⁷,

FuZE-Q (a Z-pinch fusion device)⁸, Anvil (a magnetic mirror device)⁹, Vulcan¹⁰ (a laser facility), ATLAS (a laser facility)¹¹, AMPS DS (a pulser driven IFE demonstrator)¹² and others, will help address key gaps of these approaches to realize fusion energy and electricity generation.

In parallel, the public program will complement the private sector-led activity with a focus on closing the most common and critical FM&T gaps to private sector developers into the early 2030s when the fusion industry will scale (Figure 2). Strategic partnerships between the public program, industry and international allies will help leverage assets and resources¹³. The DOE FES program has recently undergone a restructuring, forming two new divisions – the Fusion Energy Research Division and the Enabling Technology and Partnerships Division – to better align with and focus on, LRP science drivers. This restructure, along with the Roadmap, respond to recent recommendations from the GAO¹⁴ to address planning and execution of the FES mission. Details of the restructuring of DOE FES, along with a history of the program and mapping of the Roadmap to the National Academies of Science, Engineering and Medicine (NASEM) 2021 Report¹⁵ can be found in Appendix 1 of this document.

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5. Commonwealth Fusion Systems, 2025. Designing and Building Fusion Energy Systems to Power the World, <https://cfs.energy/technology/>
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 12. Pacific Fusion, 2025. Affordable, Manageable, Practical and Scalable (AMPS) High-yield and High-gain Inertial Fusion, <https://arxiv.org/pdf/2504.10680>
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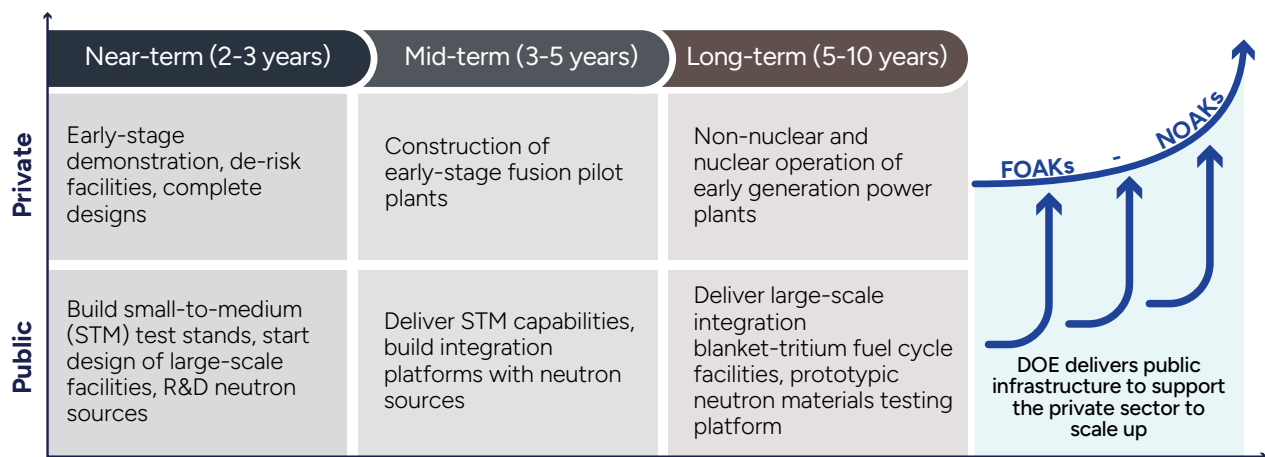


Figure 2. Roadmap sequence of public and private sector timelines over the near-, mid- and long-term, to support the scaling of private industry as it develops first-of-a-kind (FOAK) and nth-of-a-kind (NOAK) fusion power plants and continue to support innovation.



Figure 3. The roadmap builds upon a range of community planning reports, strategic documents, community workshop reports and roadmap forums.

Aligning Roadmap to the FESAC Long-Range Plan

The Roadmap represents the culmination of the FES Community Planning Process (CPP)/FESAC LRP consensus reports, augmented with over a dozen community and basic research needs (BRN) workshops, several principal investigator meetings, fusion roadmap forums and three FESAC activities (e.g. International Benchmarks, Fusion Construction Projects and the Decadal Plan) between 2023-2025 (Figure 3).

In total, over 600 scientists and engineers from both public and private sectors contributed to shaping this vision for America's pursuit of fusion energy as a viable source of energy. These scientists and engineers represented more than 15 private sector companies, over 10 national laboratories and over 72 universities. Contributions also came from allied nation organizations, including the UKAEA (UK), NIFS (Japan), Karlsruhe Institute of Technology (KIT) (Germany), Max Planck Institute for Plasma Physics

The Roadmap defines a path that balances alignment with the private sector and innovation grounded in foundational science, while closing near-term gaps with well-defined milestones and metrics to track progress.

(Germany), Fraunhofer Institute (Germany), CEA (France) and Canadian National Labs (Canada). These community-led efforts of the past half decade input to this Roadmap provide the plan for DOE to support the innovation required to close key FS&T gaps that remain and the path to translate fusion technologies to the market. The Roadmap defines a path that balances alignment with the private sector and innovation grounded in foundational science, while closing near-term gaps with well-defined milestones and metrics to track progress. This approach requires multiple bridges between public and private sectors and for both sectors to converge their interests for the benefit of the American taxpayer and the national security of the United States.

Roadmap Structure

The Roadmap as a Strategic Implementation Tool

To implement the fusion energy development strategy to Build, Innovate and Grow in America, DOE developed the Roadmap providing a structured framework for advancing fusion energy objectives. The Roadmap is primarily based on two key reports developed under President Trump's first administration. The first is the 2020 FESAC LRP anchored by the 2019-2020 CPP, based on a charge from the DOE Office of Science to its federal advisory committee to undertake a new long-range strategic planning activity for the FES program. The second is the 2021 National Academies of Sciences, Engineering and Medicine (NASEM) report *Bringing Fusion to the U.S. Grid*, based on a request from DOE to the National Academies' Committee on the key goals and innovations needed for a U.S. fusion pilot plant. Both reports are used to define scientific challenge areas, technology gaps and key milestones with defined metrics to chart a course for expanded U.S. leadership in fusion energy development.

The Roadmap translates high-level priorities into a coordinated set of actions and milestones, to enable DOE and FES to prioritize investments while measuring traction on addressing key science and technology gaps defined by the U.S. fusion community and informed by the private sector. The Roadmap includes a brief update to the FESAC LRP, including key factors that have impacted fusion energy development in the past half decade and therefore provides important context for the path forward. These key factors include the significant increase in private capital investment in fusion energy in the United States since the NASEM 2021 publication (see, for example, the Fusion Industry Association's (FIA) 2024¹⁶ and 2025 Global Fusion Industry Reports), the increased demand

for electricity generation driven by data-center infrastructure to support an exponentially growing AI industry and delays in key fusion infrastructure projects, such as the International Thermonuclear Experimental Reactor (ITER).

The Roadmap combines the FESAC LRP critical science drivers with a revamped FES public program in the DOE Office of Science (SC) to define a new era of U.S. fusion energy leadership. The Roadmap is structured in three parts: **Roadmap Key Actions (Part I)** are aligned to the FESAC LRP and chart the critical path to fusion energy by identifying actions that will enable closure of critical S&T gaps along six core Challenge Areas. These areas include Structural Materials, Plasma-Facing Components (PFCs), Advancing Confinement Approaches, Fuel Cycle and Tritium Processing, Blankets and Fusion Plant Engineering & System Integration. Technical **Roadmap Milestones and Metrics (Part II)** dive deeper with detailed metrics and milestones that address key S&T gaps defined by the U.S. fusion community (public and private) organized around the six major challenge areas listed above. **Internal Road mapping Tools (Part III)** for DOE use with detailed information, critical insights and knowledge requiring appropriate protection to further track progress and evaluate critical decision points.

The Roadmap utilizes a collaborative, structured and adaptive process. The Roadmap Key Actions in Part I

The Roadmap translates high-level priorities into a coordinated set of actions and milestones, to enable DOE and FES to prioritize investments while measuring traction on addressing key science and technology gaps defined by the U.S. fusion community and informed by the private sector.

16. Fusion Industry Association, 2024. The Global Fusion Industry in 2024, <https://www.fusionindustryassociation.org/wp-content/uploads/2024/07/2024-global-fusion-industry-report-FIA.pdf>

serve as a basis for engagement with the broader stakeholder community as the U.S. accelerates its pursuit of commercially deployable fusion power, while Technical Roadmap Milestones and Metrics in Part II track progress and serve to catalyze the fusion ecosystem and align efforts. The Roadmap will have a standing Task Force of experts to provide feedback to DOE representing the public and private sector fusion communities (including academia and National Laboratories) to maintain the Roadmap's relevance and responsiveness to a rapidly growing and changing U.S. fusion ecosystem.

Roadmap Key Actions and Timeline

The **Roadmap Key Actions (Part I)** describe how DOE will implement the Build-Innovate-Grow strategy to support a competitive U.S. fusion industry to realize commercial fusion energy. It defines how DOE will respond to FESAC LRP recommendations and maps to the FESAC LRP Science Drivers. Roadmap Key Actions are executed over a timeline of three stages: near-term (next 2-3 years), mid-term (3-5 years) and long-term (5-10 years). These key actions enable U.S. progress on closing S&T gaps on the critical path to fusion energy.

The ten Roadmap Key Actions are:

- **Deliver Fusion Science and Technology Infrastructure:** accelerate building fusion infrastructure to close critical gaps identified by the FESAC LRP science drivers.
- **Build the AI-Fusion Digital Convergence Platform:** to help accelerate sustaining burning plasmas and materials discovery to close the fusion fuel cycle and harnessing fusion power.
- **Pursue Innovative and Transformative Research:** across key innovative and transformative technologies that could help mitigate risks with conventional paths to commercial fusion.
- **Advance Toward Cost-Competitive Fusion Power Plants:** consider multiple and emerging concepts as a means of delivering an FPP at the lowest possible capital cost and at the earliest possible time.

- **Expand Public-Private Partnership Programs:** design public-private partnerships to help de-risk critical scientific and technical issues.
- **Seed Fusion Supply Chains:** leverage foundational and enabling science R&D combined with advanced testing platforms to establish supply chains relevant to fusion.
- **Foster Talent by Enabling Fusion Workforce Pathways:** establish partnerships for integrating the development of infrastructure with opportunities for training, education and integration of talent at all levels.
- **Leverage Advanced Nuclear R&D and Deployment:** strategic coordination with advanced nuclear research, development and deployment efforts.
- **Support a Practical Path to Fusion Energy Adoption:** expand measurement innovation and other R&D activities that enable widespread fusion energy deployment.
- **Provide a Path to Commercialization:** Develop a plan for a transition phase towards an applied office and track key indicators that signal readiness for the transition.

Roadmap Key Actions and Strategy

The following sections summarize how each Roadmap Key Action enables the implementation of the Build-Innovate-Grow Strategy. The *"build" section will provide timeline context developed in detail in Part II of the Roadmap release while "Innovate-Grow" sections will be explained more broadly and found threaded through the Roadmap timeline.* This is followed by an overview of the Challenge Areas that define the Technical Roadmap Metrics and Milestones framework that will be expanded in Part II of the Roadmap release and that includes an FS&T Infrastructure Map aligned to the Roadmap.

The background of the image is a deep blue color. It is decorated with numerous thin, wavy, yellow lines that flow diagonally from the top right towards the bottom left. These lines vary in thickness and spacing, creating a sense of movement and depth. In the upper left quadrant, the word "BUILD" is written in a bold, yellow, sans-serif font. The letters are thick and blocky, with a slight shadow effect that makes them stand out against the blue background.

BUILD

BUILD

1. Deliver Fusion Science & Technology (FS&T) Infrastructure

The FESAC LRP recommended to “move aggressively toward the deployment of fusion energy” and outlined and prioritized a series of key facilities needed to address critical FS&T gaps aligned with the three science drivers. In 2024, the FESAC sub-committee on Facilities Construction Projects (FCP) recommended a list of facilities that “best served” FES in closing many of these FS&T gaps. The assessment by the FESAC FCP only considered “large-scale” facilities defined by a notional estimate of their total project cost >\$100M USD. In addition to these large-scale facilities, the FESAC LRP indicated “Opportunities for developing small and midscale facilities aligned with the plan...” and the need for “separate effect test stands” to support closure of key FS&T gaps such as “tritium transport properties and phenomena in solid and liquid breeder materials, as well as associated modeling and model validation efforts.”

The Roadmap consists of a **FS&T Infrastructure Map designed to close S&T gaps** addressing Core Challenge Areas along the Roadmap timeline. Infrastructure in this context consists of a platform of tools such as large-scale facilities, small-to-mid scale capabilities and test stands, threaded by a National AI-Fusion Convergence Platform initiative (i.e. including high-performance computing, digital tools and computational model systems) that help close critical FS&T gaps and deliver the public infrastructure to support the U.S. fusion industry scale up in the 2030s. The Roadmap charts a path where the public and private sectors work in tandem, with the former focused on the most common and critical gaps for industry and the latter quickly deploying the first-

generation commercial fusion power plants and demonstration platforms. The Technical Roadmap Metrics and Milestones (Part II) includes the complete FS&T Infrastructure Map to chart the full path.

This framework organizes needs into clear timeframes: near-term (2-3 years), mid-term (3-5 years) and long-term (5-10 years). It breaks infrastructure into eight distinct streams critical for the development of an early-stage fusion power plant in the U.S. on industry timelines (Figure 4).

Given that the private sector is investing ~ 10 billion USD in developing technology roadmaps towards sustaining a burning plasma, the priority of new

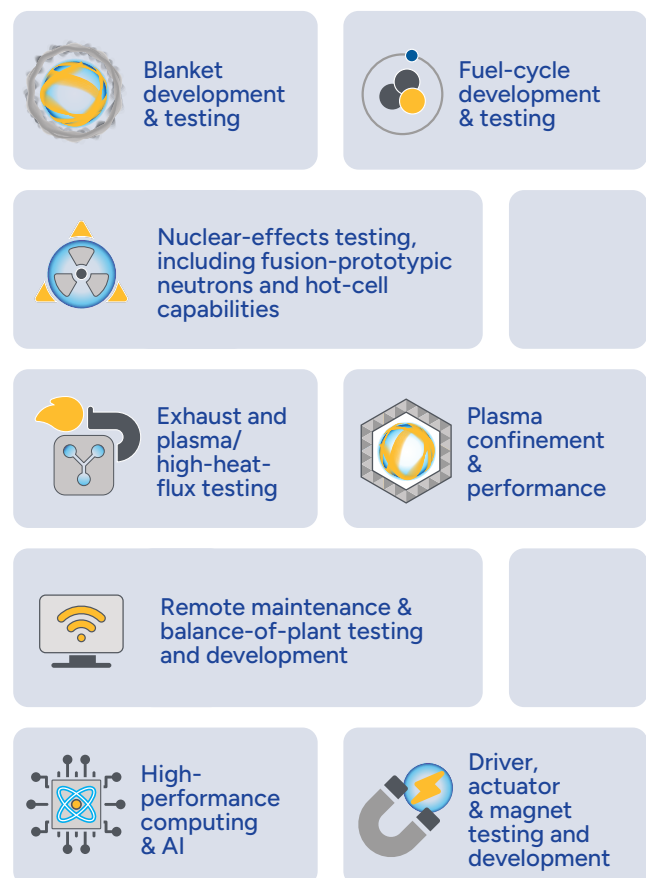


Figure 4. Eight distinct infrastructure streams critical for progress towards the development of fusion power plants have been identified.

infrastructure built by DOE will focus on the latter two FESAC LRP science drivers: engineering for extreme environments and harnessing fusion power.

Engineering for Extreme Environments Infrastructure

Fusion-specific extreme conditions, including neutron irradiation, heat and particle exhaust, stress and chemical reactivity, that drive significant changes in materials that make up most components in a fusion power plant. Innovations are required to deliver materials capable of operating safely and reliably under these conditions and must be designed and tested under prototypic fusion conditions, including exhaust, plasma and high-heat flux (HHF) and nuclear effects.

The exceptional materials degradation caused by large quantities of fusion neutrons is one of the single largest factors limiting the economics and safety of fusion energy. There are currently two critical knowledge gaps regarding the performance of materials exposed to fusion-relevant irradiation conditions:

1. Determination of whether existing material classes can survive irradiation damage levels expected in a fusion power plant.
2. Development of a robust understanding of materials performance and lifetime limits, along with the generation of an engineering materials database that is required to design and deploy a fusion power plant.

A. Exhaust, Plasma and High-Heat Flux Infrastructure: Currently, there are a number of existing single-effects, small test stands relevant to exhaust and plasma/HHF challenges as well as new planned test stands that help address S&T gaps across the Structural Materials S&T, PFC and Plasma-Material Interactions and Blanket S&T core Challenge Areas. These test stands provide surrogate systems that provide insights on materials irradiation damage and serve as an important bridge to future materials irradiation facilities such as a Fusion Prototypical Neutron Source (FPNS). A more exhaustive list of

facilities and critical gaps/metrics identified by the U.S. fusion materials community, is included in its Roadmap report.

In the next 2-3 years, DOE will deliver key facilities to address exhaust and plasma/HHF testing:

- The Materials Plasma Exposure Experiment (MPEX) at ORNL will enable testing of plasma-materials interaction (PMI) challenges. Research questions will broadly, include addressing challenges related to erosion, redeposition and co-deposition; gas implantation; surface morphology evolution; H-isotope retention; and effects of thermal transients. An additional strength of this facility is the ability to expose neutron-irradiated materials with their unique lattice and elemental compositions to high-flux, high-fluence plasmas.
- DOE will pursue public-private partnership modalities to deliver domestic HHF capabilities including prototypic fusion environmental testing to transition the U.S. from minimally capable to world-leading capabilities in power-density, exposure area, synergistic effects and cooling techniques to mimic conditions found in future fusion power plants.

B. Nuclear-Effects Testing Infrastructure:

An FPNS is the highest priority facility to help develop and engineer materials needed by the fusion industry under fusion-relevant testing environments:

- The NASEM 2021 report recommended that *“The Department of Energy should support a research program, including facilities to provide a limited volume prototypic neutron source for testing of advanced structural and functional materials and to assess neutron degradation limits of RAFM alloys beyond 5 MW-year m⁻².”*
- The FESAC LRP stated that FES should *“Immediately establish the mission need for an FPNS facility to support development of new materials suitable for use in the fusion nuclear environment and pursue design and construction as soon as possible.”*

- The 2024 FESAC sub-committee on FCP recommended an FPNS as a facility that best serves fusion.

In 2023, DOE conducted a risk reduction activity (RRA) to assess potential technological design approaches to an FPNS and ways to accelerate the construction and delivery of such a facility, including partnerships with the private sector and options for a reduced-cost FPNS.

In the next 3-5 years, DOE will aggressively pursue the closure of near-term R&D gaps of D-Li stripping approaches, spallation and true-fusion approaches. This strategy allows for simultaneous development of volumetric neutron sources (VNSs) and novel fusion neutron sources supporting a path for an FPNS. Cyclotron D-acceleration approaches will be targeted for R&D and analysis in the near term for their potential for schedule and cost savings. This path is complemented by robust nuclear-grade HHF and particle flux synergistic materials testing accompanied by some of the most advanced characterization techniques.

Until the U.S. has access to an FPNS (e.g., **long-term of 5-10 years**), the near-term, irradiation-effects strategy will be focused on multiscale modeling and surrogate techniques. Physics-based, multiscale modeling techniques which allow designers to simulate material evolution under complex loading, irradiation and tritium exposure histories will be established. Surrogate irradiation experiments will exploit over 40 years of U.S. leadership in the availability and operation of thermal fission test reactors for materials testing and will expand this leadership through world-first proton irradiation capabilities, targeting fusion materials gaps defined by the Roadmap. Together, multiscale modeling and surrogate irradiation will build the knowledge base necessary for material development towards power-plant-capable materials and ultimately prototypic neutron source materials irradiation facilities culminating in FPNS.

Harnessing Fusion Power Infrastructure

The FESAC LRP prioritized the need to develop a *“strategy for component-scale blanket testing in a nuclear environment” enabled by a combination of tools according to the FESAC LRP, such as “non-nuclear blanket component test facility (BCTF), fission irradiations, a volumetric neutron source and a fusion prototypical neutron source.”* The Roadmap outlines a strategic path with stepwise stages that includes the establishment of a domestic neutron source R&D activity (under the mission of the Fusion Nuclear Science program) supporting a path towards an integrated blanket-tritium fuel cycle facility and FPNS. This approach allows for sub-component materials testing, leveraging fusion neutrons at scale to support technology levels of single-effect and multi-effect synergistic phenomena.

The Roadmap includes an infrastructure timeline that leverages international test stands and facilities to address a spectrum of technology readiness in blanket system and fusion fuel cycle performance metrics. The strategy identifies technology readiness levels (TRLs) according to specific gaps associated with defined challenge areas in blanket and fusion fuel cycle. The relatively low TRLs of these technologies require a stepwise approach guided by the Roadmap that introduces small-, medium- and large-scale facilities and capabilities closing gaps in breeding blankets and the fusion fuel cycle. The 2020 FESAC LRP articulated that achieving a thriving and sustainable fusion energy industry of the future requires addressing key scientific and technology gaps with a diverse set of tools and strategic approaches¹.

*To achieve early stage fusion power plants by the 2030s requires increased investment in research and development of fusion materials and other critical technologies. Emphasis is needed on fusion materials science, plasma-facing components, **tritium-breeding blanket technology and the tritium fuel cycle**. Several key experimental facilities are recommended. The Fusion Prototypic Neutron Source (FPNS) will provide unique material irradiation capabilities, the Material Plasma Exposure eXperiment (MPEx) and high-heat-flux testing experiments will enable solutions for the plasma-facing materials. **Blanket research and associated integration blanket facilities will provide the scientific understanding and basis to qualify fusion fuel breeding systems for future power plants.***

- 2020 FESAC LRP

These systems must ultimately be integrated into prototypic nuclear environments that can study the performance of breeding blankets as they harness prototypic fusion neutron power, heat and irradiation-driven effects to a tritium processing system. However, although many blanket concepts are being considered to meet these simultaneous demands, no fusion blanket has yet been built and validated and current testing environments for components are limited. Therefore, a strategic approach towards a nuclear-grade tritium breeder blanket facility that supports the most common and critical gaps in industry is necessary. Inherently, the facility design would require versatility to serve a variety of blanket designs and approaches and ultimately for DOE to deliver the blanket/tritium fuel cycle infrastructure to support the scale up of the U.S. fusion industry in the 2030s.

In the next 2-3 years, DOE will engage with partners to access blanket and fuel cycle test stands and facilities including LIBERTI (UK), H3AT (UK), facilities

at KIT (Germany), UNITY-1 (Japan), UNITY-2 (Canada) and Chimera (UK). This will consist of programs that fund scientists to have access to facilities capable of addressing low-TRL gaps in tritium extraction, joint development models, materials compatibility testing and exhaust-gas processing at relatively low throughput scales. Design of small- and medium-scale test stands and capabilities that support the FNS mission would be complemented by non-nuclear blanket testing and tritium surrogate loops that support workforce training and development with innovative regional partnerships.

In the next 3-5 years, DOE will build and deliver small-to-medium scale test stands and capabilities including non-nuclear blanket component test facilities and the integration of neutron sources with versatile blanket systems. These systems would have a downstream series of innovative metrology that would be used to design FPP-relevant radiation-hardened sensors. In the mid-term will also see delivery of a midscale tritium processing test facility that can bring international partners and private sector entities to help build and manage these projects.

In the long-term 5-10 years, DOE will deliver a platform of small-to-midscale tritium fuel cycle and blanket system test stands and capabilities to address key science and technology gaps defined by the Roadmap and informed by industry. A coherent component-scale nuclear testing strategy and an integrated fuel cycle testbed to validate system-level tritium transport will be delivered and leveraged to build an integrated blanket and fuel cycle facility.

Sustaining a Burning Plasma Infrastructure

Magnetic Fusion Energy (MFE): Bridging the scientific gap between current confinement physics knowledge and a robust understanding of sustained burning plasma dynamics, which is crucial for high-confidence extrapolation to FPPs and beyond, will necessitate a combination of existing and future infrastructure investments. Prior to dedicated DT experimentation on SPARC (a private facility of

Commonwealth Fusion Systems, a Milestone Program company) and eventually ITER, existing confinement facilities will advance core confinement science, divertor heat flux management, core-edge integration for candidate plasma scenarios and FM&T testing to support future operation of plasma facilities.

In the next 2-3 years, DOE will pursue a portfolio of activities on public, private and international facilities, efficiently exploiting the unique characteristics of each platform to close urgent S&T gaps:

- DOE assets and small-scale facilities (existing): R&D on SC short-pulse toroidal facilities (e.g., DIII-D and National Spherical Torus Experiment-Upgrade (NSTX-U)) enable access to international long-pulse facilities abroad. These mature platforms support the convergence of AI and fusion R&D, advancement of core and edge confinement science, maturation of divertor heat flux management strategies and integration of core and edge plasma solutions for candidate plasma scenarios while also providing a testing platform for fusion materials and innovative fusion technology prototypes. Small-scale experiments across U.S. national laboratories and academia provide additional opportunities for training and specialized research.
- International collaborations (existing): Closure of S&T gaps continue across international experiments MAST-U and W7-X. Similarly, concurrent research to address aspects of core-edge integration toward closing the Integrated Tokamak Exhaust and Performance (ITEP) gap will be conducted across international facilities, including the Korea Superconducting Tokamak Advanced Research (KSTAR), WEST and JT-60SA superconducting long-pulse tokamaks.
- SPARC (under construction): SPARC is expected to begin operations in the near-term (2-3 years). Existing SPARC research collaborations will continue through initial plasma campaigns to deliver the world's first magnetically confined fusion gain experiments.

- Public-private partnership programs such as the Milestone Program enable the conceptual development and advancement of private-sector designs. The Private Facility Research (PFR), proposed in the 2026 financial year, is a key strategy that supports public research on privately-owned facilities. The PFR program will also be used to explore emergent confinement concepts that may offer compelling alternative configurations for delivering cost-competitive fusion energy.

In the next 3-5 years and long-term 5-10 years:

- In the mid/longer-term (3-10 years), SPARC will operate at higher fusion gain, at which time DOE will expand research efforts to realize and study the world's first burning plasmas ($Q > 5-10$). These research efforts will quickly close longstanding burning plasma scientific gaps to develop a cost-competitive, commercial-relevant fusion energy source. Additionally, this experimentation will generate vital data for the fusion engine needed to validate first principles models and AI convergence, allowing for extrapolation to first-generation fusion power plants and beyond.
- The long-term (5-10 year) goal will be sustained high-performance fusion engines operating compatibly with power and particle exhaust at power-plant demonstration conditions. Tokamak programs will focus on integrated demonstrations representing true solutions to the long-standing challenge of coupling high-performance cores with survivable boundaries at the edge. R&D activities would begin on ITER with nuclear operations expected near the mid- to late-2030s.
- Alternate or emerging confinement concepts (ECC) will be supported by the ECC program within DOE and leverage public-private partnerships (PPPs) and the PFR program to support advances in enabling technology.
- In the long-term (5-10 years), DOE will establish a validated projection capability for pulsed- and steady-state concepts, integrating lessons from SPARC, DIII-D, NSTX-U, ITER and next-generation

facilities that will inform the execution of next-generation pilot plant designs and higher nth-of-a-kind fusion power plants.

Inertial Fusion Energy (IFE): IFE has entered a groundbreaking era, marked by significant achievements at the National Ignition Facility (NIF). In 2022, NIF successfully achieved a burning plasma, a pivotal step towards harnessing fusion energy. Since this initial success, NIF has repeatedly demonstrated burning plasma conditions, with eight successful ignition experiments to date. The most recent of these experiments set a new energy yield record that delivered an impressive 8.6 MJ, more than four times the 2.08 MJ of energy input to the target¹⁷.

The IFE mission within DOE FES will coordinate with the National Nuclear Security Administration (NNSA) to strategically leverage inertial fusion burning plasma developments in NIF. This approach aligns with recommendations from the CPP and FESAC LRP, which advocated for “An IFE program that leverages U.S. leadership and current investments.” This will be accomplished through collaborative efforts with NNSA’s Inertial Confinement Fusion (ICF) program. The focus will be on shared areas of burning plasma physics and access to NIF via the discovery science mechanism. Furthermore, both the Z-machine at Sandia National Laboratories (SNL)¹⁸ and the Omega laser at the Laboratory for Laser Energetics (LLE)¹⁹ are vital NNSA resources, capable of conducting experiments of implosion physics directly relevant to IFE. Coordination and collaboration with NNSA and its labs will be essential in carrying out a DOE fusion energy strategy that supports a competitive fusion power industry in the U.S. while protecting our national security.

In the next 2-3 years, DOE is committed to advancing IFE through maintaining, upgrading and completing key facilities, all of which have been recommended by the IFE BRN workshop:

- **LaserNetUS & ZNetUS (existing):** These nationwide networks, supported by the Office of Science and NNSA respectively, encompass multiple midscale laser and pulsed-power facilities. They are crucial for conducting IFE-relevant experiments and for the development of a skilled fusion workforce.
- **The OMEGA laser at the LLE, University of Rochester (existing):** This facility is uniquely capable of performing sub-scale (i.e. at lower energy levels than NIF) implosion studies, within a symmetric, direct-drive geometry, alongside a broad spectrum of IFE-relevant physics experiments. A top priority for the IFE program is to secure dedicated access to the OMEGA laser by augmenting its operational capabilities to facilitate more experiments.
- **Matter in Extreme Conditions (MEC)²⁰ at the SLAC National Accelerator Laboratory (existing):** DOE plans to upgrade MEC’s long-pulse beam from its current 100 J (one shot every 7 minutes) to an enhanced 200 J (0.1 shots per second). This upgraded laser, when combined with the capabilities of the Linac Coherent Light Source (LCLS) x-rays, will establish a unique national resource for advancing IFE physics, particularly in achieving a profound spatio-temporal understanding of ablator materials dynamics essential for fusion capsules. Through coordination with the Basic Energy Sciences (BES) program, FES will provide targeted IFE-only access to the scientific community, accelerating IFE development consistent with the IFE BRN.
- **DOE-CSU-Marvel Fusion ATLAS laser facility (under construction):** For the exploration of advanced IFE fusion concepts and laser-driven

17. Lawrence Livermore National Laboratory, 2025. Achieving Fusion Ignition, <https://lasers.llnl.gov/science/achieving-fusion-ignition>

18. Sandia National Laboratories, 2025. Z Pulsed Power Facility, <https://www.sandia.gov/z-machine/>

19. University of Rochester, 2025. Omega Laser Facility, <https://www.lle.rochester.edu/omega-laser-facility-2/>

20. SLAC National Accelerator Laboratory, 2025. MEC (Matter in Extreme Conditions), <https://lcls.slac.stanford.edu/instruments/mec>

neutron sources, DOE intends to fully utilize the DOE-CSU-Marvel Fusion ATLAS laser facility, currently under construction in Colorado. This \$150M facility, anticipated to be operational in early 2027, will feature three synchronized laser beams delivering a cumulative power exceeding 4 petawatts. The ATLAS facility is a foundational component of the \$16M RISE IFE hub, of which Marvel Fusion is a key member.

In the next 3-5 years and consistent with the IFE BRN's recommendation to construct "integrated laser-system demonstrators," a strategy akin to the successful de-risking approach used for NIF will be implemented. This involved prototyping a single beamlet to validate the technology before proceeding with full facility construction. For laser fusion, two distinct demonstrator types focusing on specific laser technologies are prioritized:

- A demonstrator based on Diode-Pumped Solid-State Laser (DPSSL) technology: A single DPSSL prototype offering enhanced power capabilities with an electrical wall-plug efficiency exceeding 10% would substantially de-risk the laser driver for laser fusion applications. This demonstrator will advance the TRL for commercial IFE through the demonstration of high-efficiency, large-aperture amplification at a nominal frequency, by integrating advanced DPSSL technology from other sectors, such as defense and capitalizing on the capabilities of optics and photonics industries in the U.S.
- A demonstrator utilizing Krypton Fluoride (KrF) or Argon Fluoride (ArF) excimer laser technology: This approach is currently supported by DOE through the Milestone Program. This partnership includes Xcimer Energy, which has recently achieved a significant milestone by successfully completing the first private-sector electron-beam excimer laser.

These near-term projects are pursued through actions to build infrastructure and leverage public-private and strategic partnerships, including through DOE FIRE collaboratives and the Milestone Program.

Beyond de-risking the driver technology, DOE envisions each of these advanced beamlets to be integrated with a dedicated target chamber equipped with sophisticated diagnostics. This strategic coupling will directly address critical scientific gaps within IFE. The high repetition rates inherent in these proposed facilities are particularly advantageous, as they will enable the application of AI and Machine Learning (ML) techniques. This integration of AI/ML will significantly accelerate the understanding of physics gaps, while simultaneously validating and refining complex simulation models to enhance predictive capabilities for IFE system designs.

In the long-term 5-10 years, future infrastructure development, specifically the MEC-U upgrade and the IFE Fusion Integration Research and Science Test Facility (IFE-FIRST), hinges on strategic near-term and mid-term investments and partnerships. The proposed MEC-U upgrade, presently on hold, would couple efficient optical lasers to the LCLS XFEL at SLAC, thereby providing a national resource for both SC IFE and NNSA ICF programs. IFE-FIRST will enable the study of IFE burning plasma at high repetition rates and will be critical for investigating material degradation, activation and performance in the characteristic neutron flux and spectrum of IFE implosions, including their effects on chamber components, tritium breeding, heat management and the consequences of high-energy x-rays and debris.

2. Build the AI-Fusion Digital Convergence Platform

DOE and its national laboratories, together with academia, are advancing AI through world-class supercomputers, cutting-edge algorithms and software stacks through the Exascale Computing Program and high-quality scientific datasets. The FESAC Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy 2018 report during President Trump's first administration called out *"advanced algorithms used for feedback control of a burning fusion plasma"* as one of *"the most promising transformative enabling capabilities for the U.S. to pursue that could promote efficient*

advance toward fusion energy.” This capability has evolved into the convergence of AI and fusion development fueled by DOE investments in advanced computational modeling, with FES partnering with the Office of Science’s Advanced Scientific Computing Research (ASCR) program. AI has become a transformative tool for fusion energy and the U.S. ecosystem is harnessing the exponential growth of AI technology. This Roadmap Key Action will thread the AI-Fusion convergence as a national capability that will weave through all DOE fusion program elements.

For example, researchers have utilized AI/ML tools to rapidly predict the onset of disruptions on KSTAR and used automated control techniques to navigate a stable parameter regime to completely avoid these instabilities. Researchers at Lawrence Livermore National Laboratory (LLNL) have developed surrogate models of turbulence and transport in the plasma edge by applying AI/ML techniques to experimental and simulation databases, accelerating calculations by a factor of up to x100,000,000, from several hours to fractions of a millisecond. AI/ML projects require significant amounts of high-quality data to provide the most accurate predictions. A collaboration led by General Atomics has developed an Open Access Fusion Data Platform that hosts both DIII-D and MAST experimental data, applying automated curation techniques that account for uncertainty quantification (UQ). A Scientific Discovery Through Advanced Computing (SciDAC) Partnership led by Princeton Plasma Physics Laboratory (PPPL) is collating a database of fusion plasma discharges to train predictive models that can optimize device performance under these scenarios. Researchers at the University of Texas at Austin have utilized AI/ML techniques to close complex plasma physics gaps, which can advance predictive capabilities for stellarator devices.

The recent Theory, Engineering, AI, Modeling and Simulation (TEAMS) Workshop highlighted a set of critical priority research opportunities related to the use of AI for fusion energy applications that were incorporated into the metrics and milestones of the Roadmap. The Fusion Theory community recommended:

- Expanding the development of surrogate and reduced-order models with data from High Performance Computing (HPC) codes.
- Engaging with the American Science Cloud (AmSC) for data-driven activities including workflows, pipelines and metadata standards.
- Exploring the acceleration of HPC numerical algorithms with AI/ML methods.
- Developing AI-enabled digital twins that integrate physical device data with modular, integrated simulation tools.
- Exploring the use of AI/ML methods for optimizing the design of facilities and experiments.

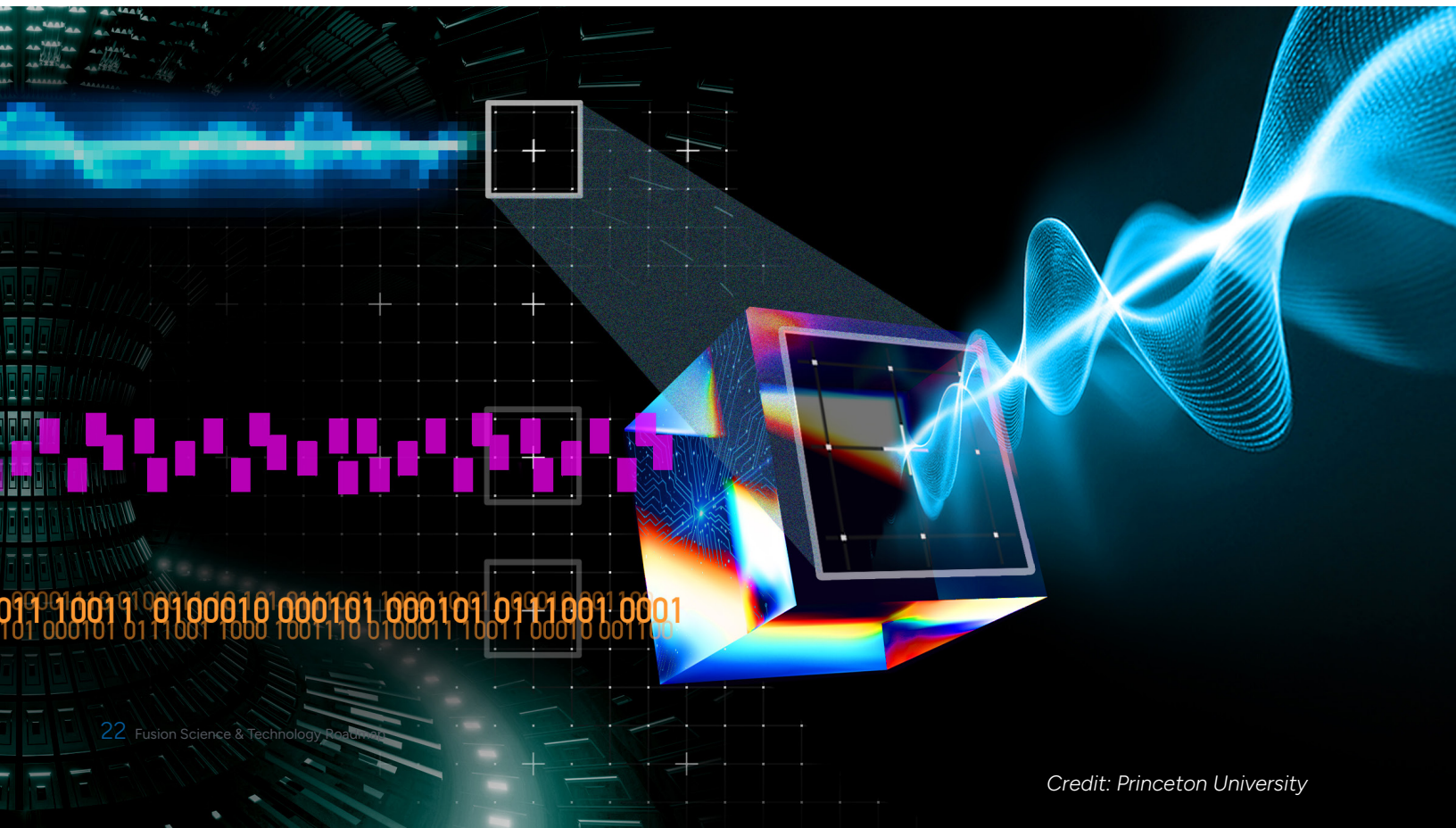
The AmSC program will deliver transformational AI models through advanced data sharing, computing infrastructure and foundation model development. FES researchers seek to deliver foundation models for materials, digital twins of DOE fusion facilities and private fusion experiments and applications of advanced reasoning models for HPC software development. The Theory, Simulation and AI/ML programs will work together to deliver advanced software suites for the design, engineering and scenario planning of fusion concepts that incorporate materials and fuel-cycle physics along with plasma stability. Comprehensive digital twins, constructed using AI-driven surrogate models, will accelerate the analysis of experimental facilities and greatly improve the productivity of fusion energy researchers.

PPPL, along with NVIDIA and IBM, is leading an effort to establish an AI-optimized fusion-centric supercomputing cluster known as Stellar-AI. This cluster will serve as a hub for fusion industry, university and DOE’s national laboratory collaboration, leveraging advancements in GPU architecture to train foundation models.

By learning from vast experimental and simulation data and from ever more powerful operating conditions, AI can deliver breakthroughs in some of the greatest challenges for fusion energy including materials discovery and design, fuel-cycle self-sufficiency and potentially one of the greatest challenges in realizing sustainable ignited fusion

plasmas: the loss of stable operation as the power and gain of the fusion engine reach controllability boundaries. Within a decade, AI could deliver digital twins of fusion engines that enable self-optimizing energy systems. AI will be embedded across design, operation and materials discovery and will speed innovations across all aspects of fusion plant system design. By building the AI-Fusion digital convergence, DOE is defining a path to this future, accelerating the commercialization of fusion power plant, to achieve U.S. energy dominance and provide the abundant power needed to drive the next generation of AI and computing.

This era is characterized by strong alignment between the public sector roadmap and the private sector's stated ambitions to deliver fusion power on an aggressive timeline and is increasingly enabled and accelerated by the revolutionary potential of AI-Fusion convergence.





INNOVATE

INNOVATE

3. Pursue Innovative and Transformative Research

The FESAC LRP² called out **four key innovative and transformative technologies** that could help mitigate risks with conventional paths to commercial fusion such as the application of a tokamak with solid PFCs. These areas included: stellarators, liquid-metal PFCs, IFE (discussed in previous section) and alternate magnetic-confined concepts. In addition, recent innovations in measurement technologies for fusion energy and the convergence of AI and fusion energy (discussed in the previous section) have become transformative tools enabling commercial fusion. Each of these technologies appear in the Technical Roadmap Metrics and Milestones (Part II), threaded through the six core Challenge Areas. Here in this Roadmap Key Action, we discuss how the Build-Innovate-Grow strategy is supporting innovation and transformative research around these technologies and their mapping to the Roadmap.

Stellarators

DOE has funded two U.S. based companies under the Milestone Program, Type One Energy and Thea Energy, the latter of which is a spin-off from PPPL. The stellarator approaches leverage U.S. leadership and outline a path towards potentially more economically attractive commercial fusion engines. Type One Energy selected the former Bull Run coal power plant operated by the Tennessee Valley Authority (TVA) in Eastern Tennessee Valley as its site for Infinity One, a midscale stellarator derisk facility that will bring regional investment in fusion technology development including tritium blanket and HHF materials test stands. Thea Energy

has introduced a paradigm shift in stellarator design with the use of high-temperature superconducting (HTS) planar magnet technology. Based in New Jersey, Thea Energy is leveraging expertise in the region including multiple universities and PPPL's long-standing collaboration with W7-X, the world's largest stellarator experimental facility (which recently broke world records in pulse lengths and triple product)²¹. W7-X is a key asset to the U.S.-Germany partnership and public-private partnership de-risk strategies with stellarator approaches in fusion energy. The stellarator expert community recently completed their community workshop, with guidance from DOE and priority research objectives formulated during this workshop are incorporated into the Technical Roadmap Metrics and Milestones (Part II).

Liquid-Metal PFCs

The use of liquid walls with a fusion engine could become a game-changing technology to address the significant heat exhaust challenges in commercial fusion power plants. The unmitigated parallel heat flux anticipated in a compact, high-field tokamak²² or spherical tokamak²³ based fusion power plant is estimated to be greater than 10 GW m^{-2} in the divertor, which is significantly more than the MW m^{-2} heat fluxes generated by a propane torch. Liquid-metals PFCs for fusion energy have been pioneered in the U.S. since the 1990s, culminating in fundamental testing of liquid-based PFCs on compact tokamak platforms including CDX-U and LTX (Liquid Tokamak Experiment)²⁴. In the 2010s pioneering work at the University of Illinois Urbana-Champaign and PPPL resulted in the development of the LIMITS facility and other de-risk small test stands. The next frontier of liquid metal development in the U.S. will address key gaps for liquid metal PFCs outlined in the U.S.

21. Max Planck Institute for Plasma Physics, 2025. Wendelstein 7-X Sets New Performance Records in Fusion Research, <https://www.ipp.mpg.de/5532945/w7x>

22. A. Q. Kuang et al., 2020. Divertor Heat Flux Challenge and Mitigation in SPARC. *Journal of Plasma Physics* 86

23. J. E. Menard et al., 2022. Fusion Pilot Plant Performance and the Role of a Sustained High Power Density Tokamak. *Nuclear Fusion* 62

24. Fusion Energy Sciences Advisory Committee, 2018. Transforming Enabling Capabilities for Efficient Advance Towards Fusion Energy, https://science.osti.gov/-/media/fes/fesac/pdf/2018/TEC_Report_1Feb20181.pdf

Fusion Materials Roadmap²⁵ consistent with the Fusion Nuclear Science and Materials sub-elements in FES that will leverage innovation from experts in the U.S. ecosystem. Innovations such as diverterlets²⁶,²⁷, vapor box^{28, 29} and porous media to deliver liquid metal as PFCs^{30, 31} will be explored. De-risking of these novel PFC concepts in compact toroidal confinement environments (e.g., ST-40 (LEAPS)) and test-stands is necessary prior to the examination of an integrated Liquid Metal Core-Edge (LMCE) solution on NSTX-U under FPP prototypic conditions.

Alternate Fusion Concepts

In the area of alternate fusion concepts, DOE supports innovation through exploration of emergent confinement concepts through public-private partnerships, as the U.S. industry is a leader in this innovation space. The Milestone Program selected two alternate concept companies – Realta Fusion (using HTS magnets in a magnetic mirror configuration) and Zap Energy (pursuing sheared-flow-stabilized Z-pinch fusion) – that will deliver conceptual designs and technology roadmaps as part of the program.

Measurement Innovation

Deployment to public and private sector fusion demonstration platforms will enable validation/verification (VV) of design modeling codes for components/materials under extreme prototypical fusion environmental conditions. DOE will expand programs supporting innovations in measurement technologies to address outstanding metrology gaps. These gaps must be closed in both magnetically and

inertially confined fusion power plants, including the needs identified through a Measurement Innovations BRN workshop held in 2024:

- For a magnetically confined fusion power plant, measurements will focus on plasma control and performance verification. These diagnostics must withstand high levels of radiation and be compatible with long-pulse operation. Testing these diagnostics will require prototypic conditions that may necessitate deployment to public- and private-sector fusion facility platforms.
- For an inertially confined FPP, measurements must be developed for monitoring the implosion, the health of the driver and innovative target tracking and metrology schemes. These diagnostics will need to function at high repetition rates (~10 Hz) and withstand high levels of radiation. Although some existing technologies used in research facilities like NIF, OMEGA and Z could be further developed and adapted to support progress toward fusion power plants, innovations beyond these existing techniques are expected to be required.

4. Advance Towards Cost-Competitive Fusion Power Plants

Historically, fusion energy research has progressed from studying a variety of confinement concepts to a near-exclusive focus on tokamaks. The focus was a result of tokamaks achieving scientific breakthroughs in plasma confinement. Experimental platforms such as the ITER tokamak remain a path in most global roadmaps towards fusion demonstration and large-

25. U.S. Fusion Materials Coordinating Committee, 2025. U.S. Fusion Materials: Community Roadmap (RD2), <https://www.epri.com/research/programs/065093/events/0b97781d-e3eb-470a-ab11-97800fb84638>

26. J. Saenz et al., 2025. Challenges of Long-Distance Liquid Metal Flow for Divertors: Improved Design for Divertorlets, <https://control.princeton.edu/assets/data/publications/pdfs/Wynne%20for%20Saenz%20US-Japan%202025%20PDF.pdf>

27. Princeton Plasma Physics Laboratory, 2024. Creating loops of liquid lithium for fusion temperature control, <https://www.pppl.gov/news/2024/creating-loops-liquid-lithium-fusion-temperature-control>

28. M. Parsons, et al., 2025. Thermal Response of a Lithium Vapor Divertor to Cyclical Operation. *Journal of Fusion Energy* 44 45

29. G. Romano et al., 2024. Lithium vapour-box divertor module design for investigating vapour shielding on Magnum-PSI. *Fusion Engineering and Design* 208

30. A. Khodak, et al., 2021. Modeling of liquid lithium flow in porous plasma-facing material. *Nuclear Materials and Energy* 26

31. A. de Castro, et al., 2023. Physics and Technology Research for Liquid-Metal Divertor Plasma-Facing Components. *Journal of Fusion Energy* 42 122

scale (e.g. 1 GWe) power plants. These large-scale approaches are challenging given the complexity of their projects, large budgets, large FOAK builds and the inability to de-risk multiple fusion engine concepts in a short timescale.

Uniquely, this Roadmap supports an accelerated path to fusion energy that considers commercialization factors, highly leverages private fusion sector R&D infrastructure investments and involves close collaboration with both international and private-sector strategic partners. This U.S. strategy requires innovation towards cost-competitive fusion power plant demonstration and deployment. The program considers compact toroidal concepts (CTC) (i.e., high-field tokamaks and spherical tokamaks), as well as non-tokamak concepts, as a means of delivering a fusion power plant at the lowest possible capital cost and at the earliest possible time. This includes inertial confinement approaches that could leverage advances in IFE-centric technologies leveraging modular design de-risk strategies, potentially reducing costs for both the development and deployment of a fusion power plant.

Critical to the realization of a low-cost fusion power plant is the closure of key outstanding S&T gaps. A subset of the FESAC LRP² S&T gaps addressed in this Roadmap to deliver a low-cost fusion power plant include advancing the understanding of the following: energetic particle and burning plasma physics relevant to a high-fusion-gain fusion power plant; plasma-material interactions and material choices for exhaust solutions; transport and stability physics for sustaining disruption-free, high-average power-output operation; and low aspect ratio physics. Targeted research efforts across the CTC and Private Facility Research (PFR) programs, mentioned below, will address these gaps.

The objective of the CTC program is to support research necessary to develop a compact, lower-cost FPP in a toroidal geometry. Two of the most promising concepts in this program are the spherical tokamak (ST) and the high-field tokamak (HFT). These devices offer complementary strategies for achieving compactness: STs leverage enhanced plasma physics properties (e.g. energy confinement time, normalized plasma pressure and high self-driven bootstrap current), while HFTs rely on advanced high-field magnets. Both STs and HFTs are

expected to challenge first-wall materials, requiring a strong connection to the “*Pursue innovative and transformative research*” area of the roadmap where novel PFC solutions (e.g., liquid metals) will be developed.

For reasons related to confinement physics and engineering, the lowest-cost fusion power plant may not be a tokamak. For instance, the intrinsic steady-state plasma properties of the stellarator could provide economic advantages by eliminating the need for auxiliary plasma current drive sources and their associated recirculating power costs. The cylindrical geometry inherent in concepts such as magnetic mirrors, field-reversed configurations and Z-pinches offers substantial engineering and manufacturing simplifications compared to the tokamak, which could significantly reduce the cost of fusion power. Perhaps the greatest cost savings may come from confinement strategies that burn aneutronic fuels. Given the potential of these concepts to provide the most cost-effective fusion power, advancing the physics basis of non-tokamak devices to a level comparable to or exceeding that of the tokamak is crucial.

The promise of these concepts has motivated private companies to pursue a variety of non-tokamak designs³. Along the path to designing and building their fusion power plants, many private fusion companies are constructing interim small-to-large scale research facilities to establish the scientific and/or technological basis for their chosen fusion concepts. Because the research on most of these interim facilities is largely foundational in nature, the mission overlap between the public and private sectors is large. The PFR program serves as a bridge between boldly delivered private sector hardware and foundational research expertise residing in the public sector. Through the PFR program, public researchers will conduct open, peer-reviewed science at private facilities, to enhance the scientific rigor and breadth of the existing private efforts for the mutual benefit of all involved. This research will accelerate progress through foundational, game-changing insights that extend beyond the minimum viable product focus of private company objectives. As with all thriving high-tech industries, a strong connection to foundational research is essential to delivering better, faster and cheaper products.

GROW



GROW

5. Expand Private-Public Partnership Programs

PPPs are awards that feature resource sharing (generally in the form of cost-share or non-federal share from private-sector awardees) between public and private sector partners. PPPs in fusion leverage decades of public support for fusion R&D as well as existing activities. Greater resources can be applied to specific problems and risk- and cost-sharing ensure all stakeholders are committed and aligned. Research and innovation are also pursued, guided by the Roadmap, relevant and valuable for commercialization. As private investment grows, topping \$2.6B in the 12-month period ending in 2025^{32,33}, working together with the private sector allows greater resources to support development of a competitive domestic fusion power industry.

Even as venture capitalists deploy investment to achieve key near-term fusion milestones, the pace of fusion technology development in the U.S. remains capital constrained. PPPs leverage public investment, fusion S&T talent and deep technical due diligence processes to create additional risk-appropriate opportunities for a wide range of current and emerging stakeholder groups to invest in creating a competitive U.S. fusion industry. Importantly, expanding the range of risk-appropriate opportunities for private capital to fund fusion technology RD&D also supports rapid execution of scope that could otherwise be delayed by public processes. To date, fusion PPPs have had an outsized impact on accelerating the timeline to a competitive fusion industry. They have done so by nudging investment risk downward, catalyzing investments and collaborations that lead to faster solutions and increasing awareness of the vast near-

term opportunity for increased prosperity that fusion energy presents. These impacts suggest that we act with urgency to expand the scale and scope of PPP programs.

Currently, DOE supports two PPP programs in fusion.

- The Innovation Network for Fusion Energy (INFUSE) began in 2019. As of August 2025, the INFUSE program made 127 awards, totaling \$30.3M, to support 38 private companies partnering with 10 DOE national laboratories and 15 U.S. Universities. The INFUSE program is modeled after the DOE Nuclear Energy (NE) program, the Gateway for Accelerated Innovation in Nuclear (GAIN).
- Milestone-Based Fusion Energy Development Program (Milestone Program) is designed to support private sector companies to develop their technological roadmaps towards viable early-stage fusion power plant designs. The commercialization path for all eight Milestone Program³⁴ companies can vary quite dramatically and evolve rapidly. These eight companies include Commonwealth Fusion Systems (CFS), Tokamak Energy, Type One Energy, Excimer Energy, Zap Energy, Thea Energy, Realta Fusion, and Focused Energy. This requires a public-sector Roadmap that is agile and nimble to adapt to changes in the private sector while maintaining a steady investment in the S&T gaps not being addressed by the private sector in a substantial way.

In the near-term (next 2-3 years), PPPs in FES have substantial opportunities to grow and better support the domestic fusion ecosystem. Toward this end, DOE is implementing the PFR program and the Fusion Fostering Regional Investments to Develop and Grow

32. Fusion Industry Association, 2025. Over \$2.5 Billion Invested in Fusion Industry in Past Year, <https://www.fusionindustryassociation.org/over-2-5-billion-invested-in-fusion-industry-in-past-year/>

33. Fusion Energy Base, 2025. July 2025 Fusion Equity Investment Update, <https://www.fusionenergybase.com/articles/july-2025-fusion-equity-investment-update>

34. U.S. Department of Energy, 2025. U.S. Department of Energy Announces Selectees for \$107 Million Fusion Innovation Research Engine Collaboratives, and Progress in Milestone Program Inspired by NASA, <https://www.energy.gov/articles/us-department-energy-announces-selectees-107-million-fusion-innovation-research-engine>

a U.S. Fusion Engine (Fusion BRIDGE) PPPs in the 2026 financial year.

- The PFR program supports public research utilizing world-leading S&T experimental capabilities owned by private companies³⁵. Along the path to constructing fusion power plants, many private fusion companies are constructing interim small-to-large scale research facilities to establish the scientific and/or technological basis for their chosen fusion concepts. Because the research on these interim facilities is largely foundational in nature, the mission overlap between the public and private sectors is significant. Through the program, public researchers will conduct open, peer-reviewed science at private facilities to enhance the scientific rigor and breadth of the existing private efforts for the mutual benefit of all involved.

- The Fusion BRIDGE program (a modality of the Public-Private Consortium Framework) extends beyond collaborative research at private facilities by co-sponsoring the construction of new experimental capabilities with the private sector and other stakeholders³⁶. The network of small-to large-scale facilities established through this program will accelerate the de-risking of crucial fusion technologies. The objective is to assemble a broad consortium of partners, including state and local governments, philanthropies, international government agencies and private industry, to support these essential fusion infrastructure projects. In addition to experimental facilities, Fusion BRIDGE also seeks to grow the American fusion supply chain, with an emphasis on manufacturing and digital engineering.

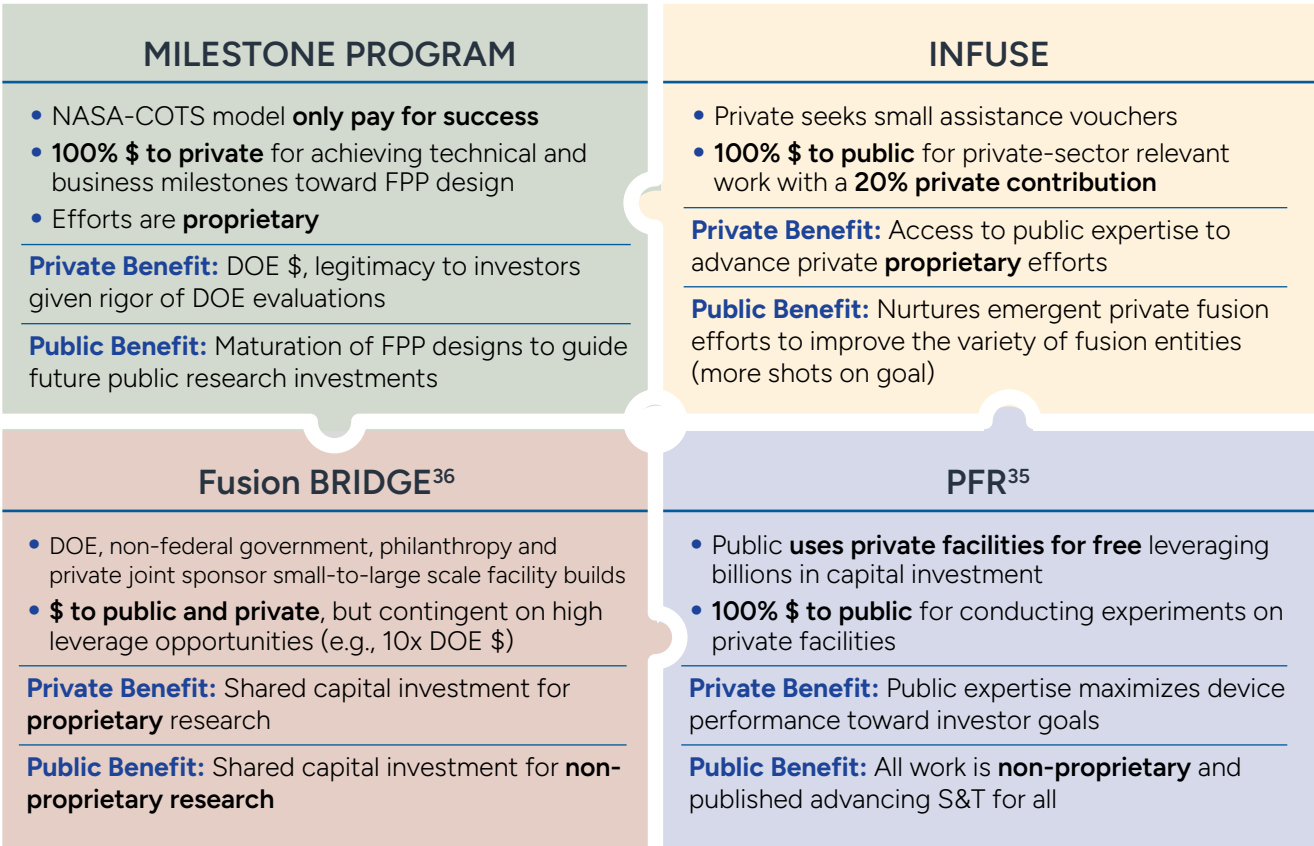


Figure 5. Summary of PPP Modalities

35. PFR is only a pilot program pending a FY2026 appropriated budget
36. Fusion BRIDGE is only a pilot program pending a FY2026 appropriated budget

6. Seed Fusion Supply Chains

Establishing a competitive fusion energy industry in the U.S. requires the establishment of supply chains relevant to fusion power plants. The long-term strategy to link innovation in DOE research to fusion supply-chain development must leverage foundational and enabling science R&D combined with advanced testing platforms, such as those with prototypic fusion environment test stands of components and materials. For example, fusion power plants will require robust, radiation-tolerant internal components that can be manufactured at scale. Discovery of new materials that are developed through an understanding of process-property-performance attributes will be a key challenge for components exposed to the extreme environments expected in fusion energy systems. Further, manufacturing of high-temperature refractory metal-based components will require a combination of robust advanced manufacturing methods (e.g. laser-based additive/subtractive approaches) and testing with a combination of infrastructure (e.g. small test stands, mid-scale demonstration platforms and large-scale facilities) that enable full qualification under realistic environmental fusion conditions lowering the risk and cost.

In addition to internal fusion energy systems, environmental testing of the external systems supporting the fusion energy plant is required. For example, innovations are needed for high-power capacitor switches, optical and diode components in high-intensity laser systems for IFE and robust tritium-breeder blanket components. To realize these innovations, R&D will be required to enable advances that support the scale-up of a robust fusion supply chain. This includes the development and diversification of other fusion equipment manufacturers which could provide systems such as tritium blanket systems for fuel resiliency, gyrotron systems for heating, pellet injection systems for fueling and advanced diagnostics systems compatible with fusion power plants.

7. Foster Talent by Enabling Fusion Workforce Pathways

Realizing fusion energy will require talent at all levels including trades, engineering, science and advanced degrees, as well as robust programs that bridge talent at each level. To support a competitive fusion power industry the public program must partner with other USG entities (e.g. NSF) and provide cost-share to enable fusion workforce pathways such as training and education in fusion engineering. Recently, a NSF-sponsored workshop that included members of the fusion academic community defined the critical challenges and opportunities required to secure talent for scientific, industrial and national laboratory ecosystems in fusion energy. The Roadmap provides opportunities to enable fusion workforce pathways by integrating the development of infrastructure with opportunities for training, education and incorporating talent at all levels linking universities to national laboratories and the private sector under the strategic programs outlined in the Roadmap.

DOE will pursue a strategy for activities supporting fusion workforce pathways that has three main goals: 1) partnerships with public and private universities at regional hubs collaborating with local/state governments to foster education and training, 2) linking universities with DOE national laboratories through FIRE Collaboratives and other program elements (e.g. Theory & Simulation, Fusion Materials and Fusion Nuclear Science, among others) and 3) linking universities with private sector via INFUSE, PFR and Fusion BRIDGE activities. These programmatic activities can also include opportunities for early-career faculty and students to engage with international partners at unique facilities in allied nations. This enables a strategic approach to fusion energy development by bridging talent to the mission of the public program, accelerating traction and progress guided by the Roadmap. Given the inherent timescales with student training and degrees, programs must be designed to transcend

public-private partnerships with shorter project time cycles, budget cycle uncertainty and bridging between program grants or pivots due to Roadmap priorities.

8. Leverage Advanced Nuclear R&D and Deployment

DOE seeks to further accelerate the timeline to a competitive fusion energy industry through strategic coordination with advanced nuclear RD&D efforts. Opportunities exist to jointly develop mutually needed enabling technologies, for example advanced manufacturing of high-temperature radiation-tolerant alloys, stress corrosion cracking measurement methodologies and durable, corrosion-resistant molten metal and molten salt system components. Additional areas of overlap exist in developing test stands for these materials and components as well as in developing codes for simulating and optimizing physics performance. Where common areas of interest between fusion energy and advanced nuclear exist, there could be opportunities for DOE equities to co-invest in specific projects with well-defined outcomes guided by this Roadmap. A recent example of leveraging advanced nuclear R&D to accelerate the fusion timeline is Kairos Power, a more experienced user of FLiBe coolant, supporting Commonwealth Fusion Systems' efforts to develop a FLiBe-based tritium breeding blanket. Fusion ecosystem benchmarks of NE efforts to accelerate advanced nuclear R&D have yielded the DOE INFUSE program, modeled after GAIN, efforts targeting a fusion code repository similar to NEAMS and PPPL investigation of the FuRTH facility as a potential site that could support private fusion companies in shrinking their timelines to deploy and test next-generation devices, similar to Idaho National Laboratory's (INL) use of the

EBR II dome to site advanced reactors developed by industry. Opportunities for collaboration will multiply as networks between fusion and advanced nuclear ecosystems strengthen.

9. Support a Practical Path to Fusion Energy Adoption

The freedom to iterate fusion technology rapidly toward broadly deployable, affordable, reliable power plants of this extreme energy density will provide an unprecedented pathway toward the prosperity that comes from abundant, affordable energy. There are many factors that impact fusion energy adoption. These factors include innovation in measurement for tritium accountancy, increased lifetime of fusion components, regulatory frameworks^{37, 38} with proportional risk defined for fusion energy (see recent 2024 Advance Act) and by-product material minimization. In a recent paper by S. Desai et al. Atlantic Council, 2025 titled: Building a path toward global deployment of fusion: Nonproliferation and export considerations, the authors outlined a compelling argument for keeping fusion energy out of the context of nuclear fission frameworks for regulatory and non-proliferation policy. One key advantage for fusion energy adoption is its unique operational features that do not involve special nuclear material such as Plutonium, high-level waste, or the possibility of chain reactions that lead to meltdown. Although passive advanced fission systems have certainly improved the reliability and

The freedom to iterate fusion technology rapidly toward broadly deployable, affordable, reliable power plants of this extreme energy density will provide an unprecedented pathway toward the prosperity that comes from abundant, affordable energy.

37. U.S. Nuclear Regulatory Commission, 2025. About the ADVANCE Act, <https://www.nrc.gov/about-nrc/governing-laws/advance-act/about-advance-act>

38. U.S. Nuclear Regulatory Commission, 2020. Part 30 – Rules of General Applicability to Domestic Licensing of Byproduct Material, <https://www.nrc.gov/reading-rm/doc-collections/cfr/part030/index>

safety of nuclear fission systems, fusion energy provides a complementary pathway towards energy abundance that can be arguably adopted by parts of the market that nuclear fission systems cannot. Furthermore, with the right-sizing of regulatory and licensing processes, fusion energy can innovate through multiple iterations of prototype platforms at a speed unprecedented for technology offering similar magnitudes of energy density. On a per reaction basis, both nuclear fission and fusion offer one million times the energy density of fossil fuels. The relationship between regulatory burden and innovation speed means that thoughtfully adopting regulatory and nonproliferation regimes that accurately assess and appropriately mitigate fusion-specific risks carries outsized societal value.

To support the development of right-sized fusion energy regulatory and nonproliferation regime, DOE will expand the Measurement Innovation program and prioritize the development of tritium measurement and accountancy technologies that can further reduce the innovation speed penalty required to ensure nonproliferation.

DOE will also make investments targeted at shortening the timeline to widespread fusion energy deployment through innovation addressing fusion waste streams. Large volumes of low-level radioactive (e.g. Class C) waste may be inherent in early-stage fusion power plants due to the limited lifetime of internal components such as PFCs, divertor cassettes, coils, actuators and other systems. Innovating new advanced materials and protection strategies can increase mean-time-to-failure (MTTF) mechanisms that minimize fusion energy by-product material and extend component lifetimes.

10. Provide a Path to Commercialization

To enable execution of a successful path to fusion energy commercialization, a new “*Fusion Energy and Innovation (FEI)*” Plan will be implemented as part of the Build-Innovate-Grow Roadmap Strategy and a transition phase towards an applied Office of Fusion Energy and Innovation (OFEI) within DOE. The Plan will be developed in conjunction with the execution

of the Roadmap with key indicators that signal readiness for an OFEI:

1. Demonstration of a reliable and scalable burning plasma platform in the private sector to pivot the DOE FES program and enable engineering science for sustaining a burning plasma at $Q > 1$ (based on the NASEM Bringing Fusion to U.S. Energy Grid report)¹⁵.
2. The establishment of a platform of small-, medium- and large-scale test stands and capabilities to support TRL 0-4 R&D complementing a strong AI and HPC fusion capability.
3. Development of large-scale FM&T facilities supported by a PPP effort in advancing TRL 4-7 of FPP-relevant fusion S&T R&D.

The FEI implementation plan will be focused on all aspects of fusion energy development and translation established within the DOE. The FEI implementation plan will also have an interagency activity to ensure other equities such as the White House, Commerce, Intelligence and others, are engaged as needed. An aggressive and staged approach to realize fusion energy on the grid will align resources to bridge both public and private sectors enabling partnerships that are nimble, versatile and agile. The plan will examine how DOE assets and program elements will support fusion energy development and commercialization. The FEI implementation plan will be executed in conjunction to the Roadmap strategy to Build-Innovate-Grow. The Roadmap will enable a transition to a future Office of Fusion Energy and Innovation (OFEI) when above indicators are met. The FEI plan will support a path to commercialization and define missions for fusion energy science and development. The strategy will enable coordination between existing assets, R&D program activities in SC FES and a PPCF for fusion energy development positioning the U.S. for fusion energy deployment in the 2030s. The next half-decade will be instrumental to focus RD&D activities that close both science and technology gaps leveraging the existing ecosystem supported by SC FES and introducing a new transition plan in DOE in support of fusion energy guided by Technical Roadmap Metrics and Milestones along the six core Challenge Areas.

Technical Metrics and Milestones (Part II)

The **Technical Roadmap Metrics and Milestones** (Part II) will provide more detailed timelines on the infrastructure capabilities that are needed and the scientific metrics and key milestones that will be tracked toward closing gaps across the six core Challenge Areas (Figure 6). The milestones and metrics help both the program and fusion ecosystem assess progress in closing the gaps. In this section we provide a preview to the Roadmap Part II describing the core Challenge Areas and how they will be organized over the Roadmap timeline phases of near, midterm and long-term periods. Each period has a set of milestones and metrics derived from gaps identified by the expert community along the six core Challenge Areas.

Part II of the Roadmap will:

- **Map FS&T Infrastructure:** identity infrastructure across eight distinct Infrastructure Streams critical for the development of a fusion power plant on industry timelines: Blanket development & testing, Fuel-cycle development & testing, Exhaust and plasma/HHF testing, Nuclear-effects testing (including fusion-prototypic neutrons and hot-cell capabilities), Plasma confinement & performance, Driver, actuator & magnet testing and development, High-performance computing & AI and Remote maintenance & balance-of-plant testing and development.
- **Innovate Across Six Core Challenge Areas:** identify metrics and milestones to meet critical priorities and assess actions and progress across six core Challenge Areas: Structural Materials, Plasma-Facing Components and Plasma-Material Interactions, Advancing Confinement Approaches, Fuel Cycle Science and Technology, Blanket Science and Technology and Fusion Plant Engineering and System Integration.

Delivering fusion energy to the grid requires targeted innovation across the highest-priority science and technology gaps. The National Academies' 2021 report¹³, concluded that successfully delivering on the vision of a fusion pilot plant, or early-stage power plant demonstration, will depend on solving a set of enabling challenges: developing structural and plasma-facing materials that survive fusion conditions, optimizing plasma performance, creating blankets to both breed tritium and extract power, establishing a closed fuel cycle and advancing plant-level engineering. The FESAC LRP² also highlighted these challenges through three science drivers: sustaining a burning plasma, engineering for extreme conditions and harnessing fusion power. These documents, combined with a wide range of community reports and a dedicated forum process engaging the U.S. fusion community, have defined a set of cross-cutting challenges that must be addressed in parallel to make fusion power plants viable.

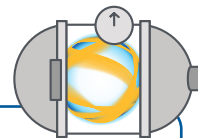
Each Challenge Area in the Technical Roadmap is structured around science and technology gaps identified by the fusion community as key barriers to fusion power plant deployment. Closing these gaps requires achieving a sequence of milestones, each tied to quantitative metrics that provide evidence of progress and technology readiness.

The Roadmap is designed to be an adaptive tool. As new discoveries emerge, private-sector advances accelerate, or international collaborations expand, the challenge areas and milestones can and will evolve. Maintaining flexibility will ensure the U.S. fusion program remains nimble and able to pivot strategically while maintaining a clear trajectory toward U.S.-led delivery of commercial fusion power plants.

Core Challenge Areas

	Structural Materials Science & Technology	The design, development and qualification of materials, structures and systems that can withstand the high neutron flux, thermal loads and environmental stresses of a fusion power plant. It includes research on physical and mechanical properties, manufacturing and qualification of materials that form the core vessel, support structures and in-vessel components.
	Plasma-Facing Components and Plasma-Materials Interactions	The design and testing of materials, structures and systems that can withstand the high neutron flux, thermal loads and environmental stresses of a fusion power plant. It includes research on physical and mechanical properties, manufacturing and qualification of materials that directly interact with the plasma. It includes solid and liquid metal walls, advanced composites, chamber and divertor design and technology along with the understanding of plasma-material interactions needed to manage challenges such as erosion, fuel retention and dust.
	Advancing Confinement Approaches	The physics and engineering of creating, sustaining and controlling high-performance burning plasmas. It includes turbulence and transport, stability, coupling, core-edge integration and disruption avoidance, with the goal of achieving fusion-relevant confinement regimes and sustained energy output.
	Fuel Cycle and Tritium Processing	The technologies and processes needed to produce, handle and recycle fusion fuels in a closed loop. It includes exhaust and separation systems, storage and inventory control, accountancy and development of supporting technologies like permeation barriers and detritiation systems.
	Blanket Science & Technology	The development of blanket concepts (e.g., solid, liquid, molten salt), materials compatibility studies, thermal hydraulics, tritium transport modeling and integrated testing to validate performance and maintainability.
	Fusion Plant Engineering & System Integration	The design and integration of the entire plant system, beyond the fusion engine. It includes balance-of-plant technologies such as power conversion and plant-wide control systems, as well as remote maintenance and robotics. It also includes the codes, models, tools and platforms for fully integrated power plant modelling.

Figure 6. The core Challenge Areas



Structural Materials Science & Technology

Backbone of a Fusion Power Plant

Structural materials form the backbone of a fusion power plant, forming the vessel, internal supports and blanket structures that must operate reliably in one of the harshest engineered environments. These materials endure sustained high thermal loads, intense neutron irradiation, corrosive coolants and strong mechanical stresses while retaining strength and toughness over long service lifetimes.

Structural materials underpin nearly every major subsystem. The vacuum vessel and in-vessel supports must provide a robust containment boundary and preserve geometric integrity while absorbing electromagnetic forces during disruptions. The first wall and blanket structures support components that directly face the plasma, transferring heat for power conversion and enclosing tritium-breeding materials. Alloys and composites must also support magnets, cooling channels and maintenance interfaces, all while being manufacturable at scale, compatible with joining and repair techniques and meeting Non-Destructive Examination (NDE)/ Quality Assurance (QA) criteria.

The operating conditions are extreme. High-energy neutrons displace atoms and transmute elements, causing swelling, embrittlement and changes in chemistry; cyclic thermal and mechanical loading drives creep-fatigue damage in welds and joints; and exposure to coolants or liquid-phase functional materials accelerates corrosion and erosion, often exacerbated by irradiation. Hydrogen and tritium can also permeate and accumulate within materials, posing additional safety and lifetime risks.

Developing and qualifying structural materials such as Reduced Activation Ferritic Martensitic (RAFM) steels, Vanadium alloys (V-alloys) and alternative/emergent materials able to endure the extreme environment of synergistic effects in stress, pressure, temperature and radiation is essential for safe, reliable and affordable fusion power-plant operation.

Relevant FIRE Collaboratives

- *Integrated Materials Program to Accelerate Chamber Technologies*
- *Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems*
- *Fusion Energy Data Ecosystem and Repository*
- *Blanket Collaborative on Test Facilities*
- *Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design*

Science & Technology Gaps



Require qualified materials for vacuum vessels & in-vessel supports. Including fusion-relevant irradiation data for swelling, transmutation and embrittlement and resolution of joint toughness, creep-fatigue and coolant compatibility. Emerging/ alternative material options require exploration.



Require qualified materials for blanket and first wall structural components. Closure of dose-temperature design windows and a qualified joining/repair methods for RAFM steels. V-alloys require developed tritium permeation/ embrittlement datasets. Emerging/ alternative material options require exploration.



Require predictive, multiscale modeling capabilities and open databases. Need to link atomistic damage and evolving chemistries to engineering performance. Includes validated inter-atomic potentials; mesoscale defect-evolution, tritium transport models; and developing open, code-ready datasets.



Require a path to codes and standards. Fusion-specific design rules and acceptance of small-specimen methods are not yet in place, preventing code allowables and consistent "rules of the road" for qualification.



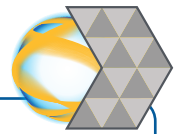
Industrial manufacturing, joining and quality assurance are required at scale. Multi-ton "nuclear-grade" heats with controlled impurities and repeatable properties require demonstration, along with thick-section product forms, dissimilar joints and repair welds. NDE/QA criteria remain immature.



Integrated environment compatibility testing for blanket/first-wall structures is required. Long-duration coolant compatibility, tritium transport/retention and magnetohydrodynamics (MHD)/ electrical insulation effects are not adequately quantified under thermal, mechanical, magnetic and irradiation loads.



Fusion-spectrum neutron effects testing is required. Lack validated data on fusion-prototypic neutron damage-including He/H transmutation and its coupling to swelling, embrittlement, creep-fatigue and weld/joint performance.



Plasma-Facing Components and Plasma-Materials Interactions

Materials at the Edge of Fusion

PFCs form the critical interface between the plasma and the engineered systems of a fusion power plant. They include the first wall, which shields the vacuum vessel and blankets; the divertor, which exhausts most of the heat and particles; and HHF cooling structures that transfer energy to the power conversion chain.

The PFC environment is extreme. In compact tokamak pilot plants, for example, unmitigated divertor heat fluxes are projected to exceed 10 GW m^{-2} ; even with mitigation, surfaces must endure $10\text{-}20 \text{ MW m}^{-2}$ steady loads and transient spikes far higher. Continuous bombardment by neutrons, ions and neutrals particles drives erosion, surface chemistry variation, microstructural damage and transmutation. Thermal cycling induces fatigue, cracking and recrystallization, particularly in tungsten, while copper-based heat sinks can suffer creep and embrittlement under stress and irradiation.

Divertors must dissipate exhaust power, remove helium ash and impurities, and maintain plasma detachment without degrading confinement. Divertor geometry and magnetic configuration define operating limits. Advanced designs, such as long-leg, snowflake, and liquid-metal divertors, aim to expand this space.

Plasma-material interactions (PMI) govern not only component survival but also fuel retention, impurity control and overall plasma performance, making mastery of PMI central to sustaining efficient, safe power plant operation.

Relevant FIRE Collaboratives

- *Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components*
- *Advancing Maturity of Liquid Metal Plasma-facing Materials and First Wall Concepts*
- *Integrated Materials Program to Accelerate Chamber Technologies*
- *Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems*
- *Advanced Profile Prediction for Fusion Pilot Plant Design*
- *Target Injector Nexus for Development Research*
- *Fuel Cycle FIRE*
- *Mitigating risks from abrupt confinement loss*
- *Fusion Energy Data Ecosystem and Repository*

Science & Technology Gaps



Design-quality, predictive PMI basis

must be developed. Lack physics-based, validated models that reliably connect near-surface evolution (erosion, morphology, retention) to component life and core compatibility.



No divertor solution is validated for pilot-plant power exhaust.

Need a scalable divertor concept that survives continuous $>10 \text{ MW m}^{-2}$ loading with transients. Detachment/impurity-seeding physics and core-edge coupling remain uncertain.



Solid PFCs and first wall armor candidates need further development.

Need to prevent/mitigate the effects of simultaneous transmutation, lattice damage, thermal cycling, HHF, erosion/redeposition, tritium retention/permeation and transients. Emerging/alternative materials require exploration.



Liquid metal PFC viability at the plant scale is unproven.

Core uncertainties span plasma-liquid interface physics, MHD/flow/wetting control in strong B-fields, corrosion/compatibility with substrates and tritium/impurity extraction at rate and scale.



Heat-sink and joint reliability under combined loads is unqualified.

Creep-fatigue-irradiation limits for Cu-alloy heat sinks, hydrogen/helium embrittlement thresholds and robust joints lack quantified life rules and accepted QA/NDE standards.



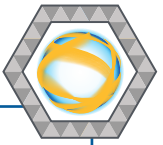
U.S. combined-effects test infrastructure and boundary diagnostics are insufficient.

Underdeveloped domestic capability for simultaneous HHF and plasma flux and neutron pre-damage from the coupon to the sub-component scale. Need to resolve key scrape-off layer (SOL)/divertor diagnostic gaps.



Require predictive, multiscale modeling capabilities and open databases.

Need to link atomistic damage and evolving chemistries to engineering performance. Includes validated inter-atomic potentials; mesoscale defect-evolution, tritium transport models; and developing open, code-ready datasets.



Advancing Confinement Approaches

Linking Plasma Physics to Sustained Fusion Performance

Advancing confinement spans both magnetic and inertial concepts, with a common performance objective: achieve fusion-relevant gain and sustain it reliably. Net electricity will require temperatures and pressures that deliver high fusion power density, with energy confinement sufficient to maintain these conditions for long duty cycles. Three practical target metrics: fusion triple product/ gain (Q), pressure (power density) and bootstrap current fraction (to limit recirculating power) are key anchors for progress.

Confinement is an integrated physics problem. In magnetic confinement systems, the core must retain heat and self-heat efficiently despite turbulence and fast-particle-driven modes, while the divertor must exhaust heat and helium ash without eroding core performance (i.e., credible core-edge integration at required power density). For inertial fusion, hydrodynamic instabilities and laser/ beam-plasma interaction (LPI) challenge symmetry and gain. Across concepts, credible design requires validated, predictive modeling spanning micro-to-macro physics and coordinated experiments that resolve boundary heat loads, transient suppression and impurity control in compact, high-power-density regimes.

Delivering fusion-relevant confinement also depends on the tools that shape the plasma. High-efficiency actuators such as gyrotrons, neutral beams, fueling and feedback systems, set profiles, sustain current and suppress instabilities; their electrical efficiency and durability directly impact Q_{eng} and plant availability in magnetic concepts and repetition-rate inertial systems. HTS magnets enable higher fields for all magnetic concepts, improving power density and bootstrap fraction, but must demonstrate quench-robust performance and functional materials with tolerance to fusion-prototypic neutron exposure. For IFE designs, drivers must deliver high repetition rates at low cost per joule with reliable target coupling—central determinants of plant-scale gain. Together, these technologies are the levers that translate physics headroom into sustained, controllable performance.

Relevant FIRE Collaboratives

- *Advanced Profile Prediction for Fusion Pilot Plant Design*
- *Mitigating risks from abrupt confinement loss*
- *Neutron-irradiation-tolerant REBCO tapes for Compact Fusion*
- *Target Injector Nexus for Development Research*
- *Advancing Maturity of Liquid Metal Plasma-facing Materials and First Wall Concepts*
- *Accelerating Fusion Blanket Development through Nuclear Testing*

Science & Technology Gaps



Require design-grade predictive capabilities for confinement and transport.

Require validated, uncertainty-quantified models that couple micro- and macro-physics across core, pedestal, SOL, PMI and materials; and compression/ burn (IFE).



Need to demonstrate efficient actuators for the sustainment of plasma energy.

Raise plasma heating and non-inductive current-drive efficiency and availability. For IFE, deliver high-rep-rate, reliable driver and target systems at low cost.



Need to achieve high-efficiency particle delivery/coupling.

Continuous core plasma fueling required (MFE). Overcome laser-plasma interaction limits and optics/debris constraints and close end-to-end coupling to high-gain targets, with precise, high-rate target injection (IFE).



Require demonstration of a sustained burning plasma and core performance.

Need a coupled understanding of α -particle physics, transport, stability and boundary compatibility in fusion-relevant regimes across concepts and show uninterrupted operation at high triple product and net gain (Q).



Integrated core-edge solutions at relevant power density have not been demonstrated.

Require simultaneous sustainment of a high-performance core and a dissipative boundary that exhausts heat/ He “ash” without degrading confinement.



Need to demonstrate stability and controllability for reliable plant operation.

Require disruption/ instability avoidance and mitigation and certifiable AI/ML supervisory control. Demonstrate management of symmetry and hydrodynamic instability tolerances and laser/ beam-plasma instabilities (IFE).



Diagnostics require progress and facilities are required to validate relevant scenarios.

Require minimal sets of radiation-hard, control-grade diagnostics for alphas, impurities, boundary state and fast transients. Need shared platforms to validate confinement with exhaust at scale and IFE coupling/LPI.



Fuel Cycle and Tritium Processing

Closing the Loop on Fusion Fuels

A fusion power plant must continuously supply, recover and recycle its fuel while minimizing radioactive inventory. The most common fuel cycle, based on deuterium (D) and tritium (T), poses unique challenges. Tritium is scarce and radioactive, requiring careful production and handling. Securing sufficient tritium supplies and producing excess tritium is critical to fusion's future growth path. A robust fuel cycle integrates fueling, exhaust processing, isotope separation, storage, tritium breeding and byproduct material management into a tightly controlled system.

Fueling and exhaust systems inject DT mixtures via cryogenic pellets, gas, neutral beams, or in the case of IFE systems, targets, while high-throughput vacuum pumping and exhaust processing recover fusion products (i.e., He), unburned fuel and impurities. Concepts such as direct internal recycling (DIR) aim to minimize system inventories by recirculating hydrogen isotopes directly back to the plasma. Once recovered, isotopes undergo separation and rebalancing to achieve the correct DT ratio. This requires technologies for isotope separation, permeation membranes and barriers, getter materials and high-integrity storage systems, all designed for continuous operation in tritium-compatible environments. The tritium breeding system, typically based on lithium-containing blankets, generates new tritium that must be extracted, purified and transferred into the cycle. This process depends on functional and structural materials that can withstand harsh environments with many challenges such as corrosion, static and fluctuating thermal and mechanical stresses, high neutron energies, fluxes and fluences and oxidation; all while maximizing tritium recovery efficiency and minimizing limiting tritium permeation losses.

Because tritium is mobile in solids, liquids and gases, comprehensive accountancy and detritiation systems are essential. These include real-time sensors, modeling frameworks for tritium migration and facilities for recovering tritium from air, water, gloveboxes and solid components. Advanced detritiation reduces both environmental releases and the volume of long-lived radioactive byproduct materials. Additionally, strategies for byproduct materials treatment, maintenance and storage—including tritiated water and materials—are integral to regulatory compliance and long-term sustainability.

Taken together, fuel cycle and tritium processing represent the circulatory system of a fusion plant, ensuring that fuel is delivered efficiently, recovered safely and recycled reliably. Progress in this area is critical for enabling sustained D-T operation, meeting safety standards and demonstrating the viability of fusion as a large-scale energy source.

Relevant FIRE Collaboratives

- *Fuel Cycle FIRE*
- *Target Injector Nexus for Development Research*
- *Advancing Maturity of Liquid Metal Plasma-facing Materials and First Wall Concepts*
- *Fusion Energy Data Ecosystem and Repository*

Science & Technology Gaps



Tritium self-sufficiency and accountancy as first-order design drivers remain unresolved.

Fuel systems need to self-produce tritium with clear accountability requirements and validated analytical methods/accountancy and measurement technologies; efficient tritium processing at relevant rates requires demonstration.



Plant-throughput fueling-exhaust-processing integration is unproven.

End-to-end operation that couples fueling/targets, tritium-compatible vacuum pumping trains, impurity removal, exhaust processing and DIR has not been demonstrated at pilot cadence and fuel ratio control. IFE requires target to fuel-cycle co-design to constrain isotopic/chemical impurities.



Design-grade, end-to-end modeling with UQ and online sensing is missing.

Validated plant-wide dynamic models of tritium inventories, retention, permeation and losses, tied to near-real-time, radiation-hard analytics, are needed to support operations, licensing and safeguards.



Isotope supply, separation/rebalancing and storage are not mature.

High-throughput isotope separation and rebalancing, compact safe storage and materials downselection all require maturation. Planning must address fuel cycle supply risks and by-design minimization of inventory.



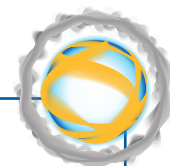
Industrial-scale detritiation and by-product-material management frameworks are immature.

Facility-level water/air/material detritiation remains largely lab-scale; fusion-specific classification, recycling and ALARA release modeling must be defined and validated for power plant operations.



Integrated nuclear testbeds for system validation are lacking.

The U.S. lacks a coherent, component-to-system fuel-cycle testbed that couples blankets, extraction, pumping, processing, accountancy and transport under nuclear conditions.



Blanket Science & Technology

Tritium Breeding and Power Extraction

In a DT fusion power plant, the blanket is the central nuclear system that connects plasma physics to power production. It performs three indispensable functions: converting neutron energy into heat for the power cycle, breeding tritium to close the fuel loop and shielding magnets and other sensitive components from radiation damage. Advancing blanket technology readiness is essential in order to select and optimize a concept for a first-generation fusion power plants or early fusion power plant demonstration platforms. Without a validated blanket solution, neither tritium self-sufficiency nor efficient energy conversion can be assured.

Blanket designs employ lithium-bearing breeders in either liquid form (e.g., PbLi), molten salt (e.g., FLiBe), or solid ceramics. Achieving tritium self-sufficiency requires that these systems provide a breeding ratio above unity, while enabling efficient tritium extraction and minimizing permeation that would otherwise increase inventory and safety risks. Neutron multipliers, typically beryllium or lead, are integrated into many designs to ensure adequate neutron economy. Accurately modeling and measuring neutron transport, multiplication and spectra is essential to predict tritium breeding, optimize shielding, minimize activation and validate that blanket designs can deliver both self-sufficiency and reliable energy conversion.

The environment within the blanket drives severe challenges. Structural materials must withstand high temperatures, intense neutron irradiation and corrosive coolants, while avoiding neutron absorbers that would reduce breeding. In liquid-metal and molten-salt concepts, magnetohydrodynamic (MHD) effects (conducting fluids flowing in strong magnetic fields) alter pressure drops, turbulence and heat transfer, demanding specialized coatings, insulators and channel geometries. Thermal management must couple these breeder systems to power cycles using helium, water/steam, CO₂, or dual-coolant schemes, all while handling chemically aggressive, radioactive fluids and preventing tritium crossover.

In essence, the blanket is the plant's energy engine and fuel supply. Its successful development will set the pace for tritium self-sufficiency, thermal efficiency and the overall practicality of operating fusion systems at scale.

Relevant FIRE Collaboratives

- Blanket Collaborative on Test Facilities
- Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design
- Accelerating Fusion Blanket Development through Nuclear Testing
- Advancing Maturity of Liquid Metal Plasma-facing Materials and First Wall Concepts
- Fusion Energy Data Ecosystem and Repository

Science & Technology Gaps



Functional and structural material performance in relevant environments is uncertain.

Corrosion/compatibility for PbLi/ FLiBe and steels/ceramics, long-term irradiation effects and tritium thermophysics remain poorly quantified for lifetime predictions and maintainability.



Mechanistic understanding of tritium-material interactions and durable barriers is incomplete.

Models for retention, trapping and permeation in irradiated materials and across interfaces are immature. Functional coatings/permeation barriers require qualification in FPP-relevant conditions.



Liquid-breeder MHD behavior and insulating technologies are not validated.

Fundamental and transient/turbulent MHD physics in strong fields, reliable insulators/coatings and scalable channel/manifold designs lack validated models and benchmark databases.



Tritium management within blankets is not FPP-ready.

Uncertainties persist in breeder-specific tritium extraction architectures, permeation control, impurity control and coupling to efficient coolant cycles. Continuous tritium extraction for both solid and liquid breeders remains at low maturity.



Diagnostics and qualification infrastructure are inadequate.

No defined, radiation-hard minimum diagnostic suite for in-situ monitoring (e.g., tritium concentration, corrosion, local temperatures). Integrated, multi-effect blanket testbeds are required.



No validated, integrated blanket design at FPP conditions.

No end-to-end blanket concept proven to meet tritium self-sufficiency and heat removal simultaneously, with clear down-selection/qualification rules.



Design-quality, multiphysics prediction and data standards are missing.

Usable, validated tools that couple neutronics, MHD, thermofluids, tritium transport and structural response are not yet available. Consistent neutronics-informed workflows and shared, qualified data repositories are absent.

Fusion Plant Engineering & System Integration

Designing and Integrating the Whole

For fusion to move from scientific demonstration to commercial deployment, the system-level aspects of plant design must advance in parallel with plasma and materials research. It is not enough to confine a plasma or breed tritium—the entire facility must operate as an integrated power plant, capable of sustained electricity generation, safe operation and efficient maintenance. This requires a shift from focusing on isolated components to engineering the connections between them, where reliability, availability, maintainability and inspectability (RAMI) become primary design principles rather than afterthoughts.

At the center of this integration is the balance of plant (BOP): the loops of coolants, pumps, heat exchangers (HX), turbines and controls that convert neutron energy into usable power. These systems cannot simply be “bolted on” after the fusion engine is designed; their thermal and chemical requirements feedback directly into choices of blanket design, coolant chemistry, tritium control and structural materials. In practice, this means co-optimizing the fusion engine and BOP so that efficiency, safety and serviceability are considered together from the outset.

Keeping such a complex system online requires advanced plantwide diagnostics and controls. Beyond plasma regulation, the plant must continuously monitor structural health, coolant conditions, tritium inventories and radiation levels, using sensors and feedback systems that can survive harsh environments. These diagnostics underpin condition-based maintenance and automated protection, ensuring that downtime is minimized and interventions are predictable.

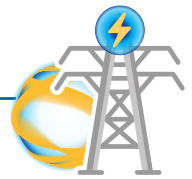
All of these decisions are guided by whole-of-system modeling and integration frameworks. Multi-physics simulations link plasma behavior to neutronics, thermal fluids, materials and plant controls, allowing designers to explore how changes in one subsystem cascade through the rest of the facility. Verification and validation (VV) and UQ are essential so that model predictions can be trusted for design and licensing. Increasingly, AI and ML play a role by providing fast surrogates for complex physics, integrating diverse data streams and enabling adaptive control strategies in real time.

Fusion plant engineering is therefore about closing the loop across scales and subsystems: aligning RAMI with maintainable designs, embedding the BOP into nuclear-core decisions, instrumenting the facility for resilience and anchoring choices in predictive, validated models. Progress in this area will determine whether fusion technologies can be assembled into a coherent, grid-ready power plant.

Relevant FIRE Collaboratives

- Blanket Collaborative on Test Facilities
- Fusion Energy Data Ecosystem and Repository

Science & Technology Gaps



No validated end-to-end plant model.

Subsystem tools remain siloed. Lack whole-plant model with data standards and UQ to support design choices, plant optimization and licensing.



RAMI/availability is not yet a first-class, quantitative design driver.

Need plant-level RAMI frameworks: failure modes, inspection intervals, maintainability budgets and availability accounting tied to design. Need to demonstrate target availability.



Remote maintenance in a fusion environment is unproven at plant cadence.

Need efficient, certifiable remote replacement schemes that account for activation, tritium retention and dose/ALARA, validated on representative mockups with time-to-repair KPIs and tooling qualification.



Modular, quickly replaceable component architecture is under-specified.

Interfaces, envelopes and service paths for “swap-and-go” blankets, divertors, first-wall/PFCs and in-vessel systems are immature.



Plant-wide diagnostics, sensing and automated protection are not validated.

Radiation-tolerant, maintainable instrumentation for structural health, coolant chemistry, tritium inventories, activation fields and in-vessel states remain underdeveloped.



Fusion engine-BOP co-design and interface definition are immature.

Co-optimization tools for thermal, chemical and availability requirements in the power-conversion chain and blanket/coolant/tritium system choices are required.



Controls/automation and remote operations are not qualified for service.

End-to-end control architecture (from plasma to plant), autonomous operations, data pipelines and cyber-secure digital twins need qualification in nuclear-relevant environments and demonstration of safe operation to meet availability goals.

Summary of key milestones across all challenge areas

Challenge area	Near-term (2 – 3 years)	Mid-term (3 – 5 years)	Long-term (5 – 10 years)
Structural Materials Science & Technology	- Develop accelerated qualification pathways for RAFM steels and V-alloys; target full datasets within four years. - Launch centralized materials data strategy using AI, HPC and fission partner facilities. - Establish domestic industrial heat capability for multi-ton RAFM and 500 kg V-alloy heats. - Deliver corrosion loops and HHF facility; leverage IMPACT and BCTF FIRE collaboratives.	- Complete irradiation campaigns and PIEs defining allowables up to ~10 dpa for RAFM and V-alloys. - Quantify helium-assisted embrittlement thresholds and high-T creep-fatigue limits. - Generate integrated tritium retention and permeation datasets across key alloys. - Leverage spallation/ fission sources and FIRE collaboratives to accelerate dataset integration.	- Demonstrate component-relevant performance under fusion-prototypic neutron, heat and tritium loads. - Codify fusion-specific allowables into ASME-based standards using validated small-specimen methods. - Deploy predictive multiscale modeling and design tools. - Qualify domestic manufacturing of thick-section heats and additive builds. - Validate performance via FPNS, VNS, IFMIF-DONES and expanded domestic test infrastructure.
Plasma-Facing Components & Plasma-Materials Interactions	- Commission MPEX to deliver plasma exposure testing and launch complementary domestic HHF testing. - Build database of W / Cu-class material PFC behavior under cyclic, transient and ELM-like loads. - Quantify erosion-redeposition, cracking and thermal-shock limits for PFC candidates. - Develop coupled physics-to-CAD divertor design tools; advance early IFE liquid-wall modeling.	- Demonstrate integrated divertor operation with detached exhaust and preserved confinement. - Advance liquid-metal systems: assess flow stability, MHD effects and tritium recovery. - Test tungsten and Cu-alloy mockups for fatigue, creep and thermomechanical durability. - Use AI-guided screening to down-select emerging low-erosion, low-retention materials.	- Validate tungsten-based and liquid-metal PFCs under fusion-prototypic neutron, heat and plasma flux. - Demonstrate component-scale endurance: recrystallization resistance, crack thresholds and transmutation effects. - Codify performance standards linking irradiation, PMI and mechanical data. - Operate continuous-flow liquid walls proving stability, impurity control and tritium recovery for power-plant readiness.
Advancing Confinement Approaches	- Expand access to IFE platforms (Omega, NIF, Z machine) for validating driver–target coupling and mitigating laser-plasma instabilities. - Validate divertor and exhaust concepts at FPP-relevant power fluxes in tokamaks and stellarators. - Conduct REBCO irradiation campaigns to define magnet performance and standards. - Strengthen integration across FIRE collaboratives (APP-FPP, TINEX, NIT-REBCO) and support DIII-D, NSTX-U and stellarator capabilities.	- Expand SPARC efforts to demonstrate sustained fusion gain ($Q > 1$) and progress toward $Q > 5$ with alpha-dominated plasmas. - Advance high-rep-rate IFE drivers, develop domestic single-beamline demonstrators and establish access to multi-PW laser facility. - Achieve real-time 3-D control of stellarator topology and extend low-A tokamak confinement scaling. - Qualify HTS magnet cables/ coils and radiation-hard diagnostics; deploy digital twins for scenario modeling and predictive control.	- Deliver predictive, uncertainty-quantified transport models linking turbulence, pedestal and fast-ion physics. - Demonstrate sustained high-performance cores with detached divertors and stable confinement in tokamaks and stellarators. - Operate steady-state actuator suites (including ECRH/ ICRH, NBI) at full duty and high efficiency. - Realize plant-ready IFE target systems and establish validated projection tools integrating lessons from ITER, SPARC, DIII-D, NSTX-U and early-stage pilot plants.

Challenge area	Near-term (2 – 3 years)	Mid-term (3 – 5 years)	Long-term (5 – 10 years)
Fuel Cycle and Tritium Processing	- Establish FPP-scale fuel-cycle targets: TBR > 1.1, continuous subsystem operation and impurity-limited designs. - Advance detritiation materials and chemistries for solids and water; integrate with vacuum-pump and impurity-control systems. - Develop byproduct material management frameworks, updated classification guidance and plant-level tritium accountability and analytics standards. - Expand domestic D/H loops and non-nuclear testbeds and enable access to tritium-capable facilities (UNITY-2, H3AT) for subsystem validation.	- Mature tritium-compatible vacuum pumping and impurity-tolerant systems for pilot-scale throughput. - Demonstrate isotope separation and rebalancing with low inventory, high protium removal and clear accountability. - Validate direct internal recycle (DIR) of tritium-rich exhaust streams with stable, efficient operation. - Deploy computational fueling models linking experiments to plasma control for responsive fueling strategies. - Establish domestic fuel cycle test facility (nuclear)	- Demonstrate integrated, tritium-self-sufficient fuel cycle sustaining continuous early-stage power-plant duty. - Validate real-time measurement, sensing and accountancy for tritium inventories and effluents. - Qualify advanced isotope storage and fueling systems (pellets, targets) with closed-loop control and digital-twin modeling. - Establish integrated blanket-fuel-cycle test facility coupling tritium breeding, extraction and fueling under fusion-relevant conditions.
Blanket Science & Technology	- Build an open, standardized database for thermophysical, corrosion, tritium and mechanical properties. - Define minimum diagnostic architecture for radiation-hardened temperature, heat-flux, flow and tritium sensing. - Operate PbLi/ FLiBe corrosion rigs and down-select permeation-barrier coatings. - Launch high-field MHD test loops linking materials, flow and magnet design data via BCTF, BNT and FEDER FIRE collaboratives.	- Advance blanket concepts to TRL 4-5, validating MHD mitigation, flow-channel inserts/ insulators and manifold/channel designs. - Close neutronics data gaps for activation, shielding and tritium breeding; integrate into multiscale models. - Demonstrate loop-scale tritium extraction with real-time monitoring and mass-balance validation. - Curate functional-material datasets for breeders and multipliers. - Establish domestic blanket cycle test facility (nuclear)	- Deliver validated first-principles models for tritium retention, permeation and recovery under fusion conditions. - Integrate plasma-blanket-fuel-cycle simulations for design, performance and maintenance with quantified uncertainty. - Establish fusion-spectrum irradiation testbeds producing qualification datasets for functional materials and components. - Demonstrate TRL-7 integrated blanket with TBR > 1.1, reliable heat removal, embedded diagnostics and maintainability for power plant readiness.
Fusion Plant Engineering & Whole System Integration	- Launch a centralized, standards-based data repository implementing FAIR principles and tiered access for experiments and simulations. - Publish a common V&V/ UQ framework enabling interoperable, traceable whole-plant modeling. - Connect AI and HPC pipelines to key facilities (DIII-D, NSTX-U, MPEX) to advance real-time digital-twin capabilities. - Establish initial RAMI handbook with metrics, availability targets and design-for-maintainability guidance.	- Qualify joining & cutting methods for irradiated materials to enable modular in-vessel replacement. - Demonstrate remote handling & sensing prototypes for activated blankets / PFCs in corrosive, hazardous environments. - Expand RAMI analysis to top failure-mode studies and pilot-relevant reliability targets. - Validate mock-up maintenance workflows and collect reliability data for predictive maintenance models.	- Qualify plant-wide diagnostics & protection systems with radiation-hardened sensors. - Demonstrate automated controls & remote operations in steady-state & high-rep-rate facilities. - Validate closed Brayton / Rankine power cycles. - Deploy modular digital-twin platforms coupling live data, simulations and predictive diagnostics for licensed power plant design.

Table 1. Summary of key milestones across all challenge areas over the near-, mid- and long-term.

Summary

Taken together, the Roadmap Key Actions described here set the course for strategic actions and capability delivery necessary to support a world-leading U.S. fusion ecosystem, while the Technical Roadmap Metrics and Milestones will track progress and ensure these actions are aligned with closing critical scientific and technical challenges progressing toward fusion commercialization. This approach enables the public program to remain nimble and prioritize resources with decisions that may require pivoting as fusion developers accelerate towards their technology roadmaps and viable fusion power plant designs, while suppliers advance their innovations,

supporting a growing fusion power industry in the U.S. The Roadmap also enables options and risk mitigation strategies for the public program for those approaches in the private sector that do not mature or translate due to technology challenges or market forces. This Roadmap is a dynamic tool used by the program and is continually updated with input from the public and private sector fusion community. The goal of the Roadmap is to deliver the public infrastructure that supports the fusion private sector scale up in the 2030s.



Concept art showing a potential IFE-FIRST or IFE FPP. (Credit: Eric Smith)

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Appendix 1

A New Era of U.S. Fusion Energy Leadership

The U.S. has led innovation in nuclear fusion since the 1940s^{39, 40} with significant fusion research carried out during the Manhattan Project, including measurements of the fusion deuterium-tritium (DT) cross section. In the 1950s, the U.S. launched Project Matterhorn under the Atomic Energy Commission (AEC) to pursue stellarator-based magnetic-confined thermonuclear fusion research led by Lyman Spitzer, an effort that later became part of the Department of Energy's (DOE) fusion program after the AEC's reorganization in the 1970s. The theoretical framework for compressing and heating fusion fuel using powerful energy drivers, the foundational concept for inertial confinement fusion, was also established through early work in the 1960s and 1970s, prominently by John Nuckolls and his colleagues.

In the 1970s, the U.S. led in multiple fusion energy efforts, including the Princeton Large Torus at the Princeton Plasma Physics Laboratory (PPPL), which demonstrated record electron temperature with neutral beam heating in a magnetically confined plasma and experimental successes in inertial confinement, including those at KMS Fusion and Lawrence Livermore National Laboratory (LLNL), confirmed the viability of producing thermonuclear neutrons with lasers. The U.S. deployed advanced diagnostic systems across the world, including instruments on magnetically-confined tokamak devices such as TEXTOR in FZ Juelich (Germany) and the Joint European Torus (JET) in the UK. The following decades were characterized by a

focused development of increasingly powerful laser systems across institutions, such as LLNL, Los Alamos National Laboratory (LANL), Naval Research Laboratory (NRL) and the University of Rochester (UR), allowing detailed investigation of target physics and precise control of implosion dynamics for inertial confinement, while investments in large-scale tokamak facilities, such as the Tokamak Fusion Test Reactor (TFTR), enabled the U.S. program to reach near break-even conditions culminating in the operation of DT plasmas enabled by lithium vapor wall conditioning technology⁴¹.

Since the early 1990s, building on decades of fusion energy R&D, the U.S. developed some of the world's most sophisticated multi-physics computational codes validated with world-leading diagnostic tools^{42, 43} on world-class domestic facilities such as DIII-D (a joint U.S.-Japan collaboration), NIF⁴⁴ and many others across the world. These computational codes supported the study of magnetically-confined plasma physics and the development of extrapolation tools that would enable confinement performance prediction of DT plasmas from experimentation on DD plasma devices.

In the 2000s, fusion technology activity began to grow modestly in the U.S. under the APEX and ALPS programs that seeded pioneering work in advanced liquid-based blanket and first wall/divertor research, including the first results of the use of lithium- and tin-based liquid plasma-facing wall materials. The operation of a national spherical tokamak at PPPL began campaigns to study the advent of low collisional regimes in compact tokamaks began in earnest.

39. S.O. Dean, 2013. Search for the Ultimate Energy Source: A History of the U.S. Fusion Energy Program, https://www.researchgate.net/publication/288374848_Search_for_the_Ultimate_Energy_Source_A_History_of_the_US_Fusion_Energy_Program

40. M. B. Chadwick, et al, 2024. Introduction to Special Issue on the Early History of Nuclear Fusion. Fusion Science and Technology 80

41. H.W. Kugel et al., 1997. Development of Lithium Deposition Techniques for TFTR

42. J. Candy et al., 2003. An Eulerian gyrokinetic-Maxwell solver. Journal of Computational Physics 186

43. J. Candy et al., 2009. Tokamak Profile Prediction Using Direct Gyrokinetic and Neoclassical Simulation. Physics of Plasmas 16

44. M.M. Marinak, 2024. How Numerical Simulations Helped to Achieve Breakeven on the NIF. Physics of Plasmas 31

In the 2010s the advent of high-performance computing (HPC) as a driver for computational tools to help guide R&D and the understanding of burning plasma physics ushered in a predictive capability that in the past decade has brought forth confidence in a path forward to the commercialization of fusion energy. Notably, fusion entered a new era in 2022 when LLNL's National Ignition Facility (NIF) achieved scientific breakeven and became the first controlled fusion experiment in history to produce a net energy gain.

Today, the U.S. boasts the fastest growing fusion energy private sector in the world. Led by private capital from both the U.S. and abroad, the U.S. has received over \$9B in private equity investment. According to the Fusion Industry Association's (FIA) 2025 Global Fusion Industry report³, the U.S. is home to the largest number of fusion companies (29) in the world, including the only three companies to have over \$1B investment each.

The Roadmap forges a path forward for the public program to support a robust private sector in the U.S. as it rapidly moves towards commercial fusion power in the early to mid-2030s. It recognizes that the early-stage fusion power plants and fusion power plant integrators will be supported by a public program that progresses along an aggressive commercialization path.

A restructured public program in DOE guided by this Roadmap will help support a competitive fusion power industry by leveraging public-private partnerships and consortia while anchoring in decades of innovation and scientific know-how to help usher in a new era of U.S. fusion energy leadership.

Mapping Build-Innovate-Grow Strategy to the NASEM 2021 Report

The NASEM 2021 report on *"Bringing Fusion to the U.S. Grid"* outlined a roadmap for a fusion pilot plant, structured around a three-stage approach to de-risk key aspects of a fusion system by meeting

quantitative performance metrics, thereby retiring technical risks and enabling a path towards adoption by electricity markets. The report also referred to innovation and technology necessary to meet these specifications and projects needed to close science gaps of a burning fusion plasma at the scale of a power plant. Since 2021, significant progress has been made towards defining a public-private partnership pathway to fusion energy. Collaboration in the U.S. among the U.S. Government (USG), FIA and other entities such as the Special Competitive Studies Project (SCSP) are helping drive momentum towards mechanisms that enable significant investment in key science and technology challenge areas as outlined in this Roadmap. Two key points made in the NASEM 2021 Report have outlived their premise:

1. The NASEM 2021 report stated: *"... 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."*
2. 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"*

DOE supports U.S. participation in ITER to provide U.S. scientists access to an industrial scale burning plasma experimental facility supporting the American fusion energy supply chain. While ITER remains a part of the U.S. fusion energy development strategy, a fast-evolving private sector requires prioritization amongst multiple projects and programs. Progress made towards a fusion power plant in the early 2030s, supported by both DOE investments, including FIRE Collaboratives, the Milestone program, INFUSE, the overall FES base research program and private sector investment (with cumulatively close to 10 billion USD invested as of September 2025), is gathering critical traction. With the 2024 announcement of a delay in ITER first plasma until mid-2030s and DT operations until end of 2030s, the assumptions underpinning both the FESAC LRP and NASEM 2021 reports, along with the accelerated timelines pursued by the private sector, necessitate

a re-assessment of priorities to be reflected in the Roadmap. Priorities include leveraging public-private partnerships that enable a path towards a fusion power plant in the U.S. at a timescale commensurate with the investments made from the private sector. The major technology de-risking paths are outlined in the Roadmap Challenge Areas and accompanied with well-defined gaps, milestones and metrics in three timelines: near-term (2-3 years), mid-term (3-5 years) and long-term (5-10 years). The longest timeline would result in actions by the mid-2030s to deliver key infrastructure in the U.S. to support industry scale up.

In addition, the concept of a national program where the public program would lead an effort to design and construct an FPP has been replaced by a Milestone-Based Fusion Energy Development program led by the private sector and enabled by the public program. The accelerated path of the private sector, even with the risks involved, requires the public program to align and invest resources towards directly addressing the most common and critical gaps that the private sector will not be able to de-risk.



Gyrotron (Source: Kyoto Fusioneering)

Appendix 2

Fusion Innovation Research Engine Collaborative Ecosystems

The second strategic action is to establish innovation research engine ecosystems that enable the bridge between foundational science activities (TRL ~ 1-2) to more mature development (TRL ~ 3-4) and enabling a bridge between science and early-stage technology development defined and inspired by the growing fusion industry (e.g., the technology roadmaps of the Milestone Program awardees). The “Engine” ecosystem bridges incubation activities within the base program in SC FES and acceleration of fusion technologies supporting translation to industry. The FIRE Collaborative acts as a bridge between incubation of ideas in foundational fusion science and public-private partnership activities that help link to user-defined FM&T gaps.

A significant distinction between FIRE Collaboratives and existing foundational science programs lies in their approach to research. While foundational science programs typically follow a basic research model, experimental or theoretical work is undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts. FES expects the FIRE Collaboratives to function as accelerated, results-driven research projects utilizing real-time results to inform research direction, allowing for agile adjustments and potentially discontinuing projects if deemed necessary based on outcomes or a pivot in priorities. This dynamic approach ensures that FIRE Collaboratives remain focused on achieving tangible advancements in de-risking FS&T within specified timelines and metrics. The existing FIRE Collaboratives are shown below⁴⁵.



The Integrated Materials Program to Accelerate Chamber Technologies

Accelerated alloy design, scale-up and testing to establish the first mature structural materials for fusion plants. Enables two U.S. materials (steel and vanadium alloys) to be produced by U.S. suppliers.

Rapid High-Fidelity Bulk Irradiated Materials Data Generation to Accelerate Solutions for Commercial Fusion Energy Systems

Establish new bulk material irradiation techniques with cyclotron-based proton beams. Accelerates U.S. leadership in rapid materials modeling, development and assessment to support the commercial fusion industry.



45. Selection for award negotiations is not a commitment by DOE to issue an award or provide funding. Before funding is issued, DOE and the applicants will undergo a negotiation process, and DOE may cancel negotiations and rescind the selection for any reason during that time.



Accelerating Fusion Blanket Development through Nuclear Testing

Provide relevant nuclear testing and data on blanket technologies using existing fission irradiation facilities and establish nuclear infrastructure necessary to test blanket components.

Fuel Cycle FIRE

Integrate modeling, materials and processing R&D to de-risk DT fuel cycles, reduce tritium inventory and releases, validate direct internal recycle and align designs with industry for fusion power plants.



Target Injector Nexus for Development Research

Comprehensively tackles key elements of the inertial fusion energy target lifecycle: target manufacturing, injection, survival, engagement and debris mitigation, enabling progress toward practical fusion energy

Advanced Profile Prediction for Fusion Pilot Plant Design

High-fidelity whole-device predictions of density, temperature & impurity profiles for tokamak and stellarator fusion power plants, including gyrokinetic turbulence and plasma-wall interactions via high-performance computing and AI/ML techniques.



Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components

Existing materials are incapable of withstanding extreme fusion environments. Develop an integrated design loop for composite architectures of materials in reactor-relevant scenarios.

Blanket Collaborative on Test Facilities

Building U.S. infrastructure for the integrated testing and validation of fluid flow, heat transfer, magnetic effects, hydrogen isotope transport and material compatibility in blanket subcomponents relevant to the private sector.



Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design

Lithium breeder blankets require extensive experimental tests that this project will perform in prototypic environments at the SHINE FLARE and UW WHAM facilities. Additionally, develop cooling components with additive manufacturing.

Neutron-Irradiation-Tolerant REBCO Tapes for Compact Fusion

Fusion concepts require HTS magnets to withstand high neutron fluence without degradation. This project will probe neutron irradiation effects in HTS via modeling, structural optimization and testing at world-class facilities.



Advancing the Maturity of Liquid Metal (LM) Plasma Facing Materials and First Wall Concepts

Flowing liquid metals used as wall materials hold the promise of higher exhaust power than solids. This project seeks to advance technical readiness of liquid metal PFCs for their consideration in fusion reactor designs.

Mitigating Risks from Abrupt Confinement Loss

Create advanced simulation and engineering workflows to quantify potential damage due to the abrupt loss of plasma confinement and partner with industry to develop solutions for mitigating these risks.



Fusion Energy Data Ecosystem and Repository

Standardized, accessible data will be necessary for the development of AI/ML predictive models and interoperable software workflows. This FIRE collaborative will provide the critical infrastructure enabling accessibility, interoperability and standardization of datasets, models and workflows across the fusion community.

