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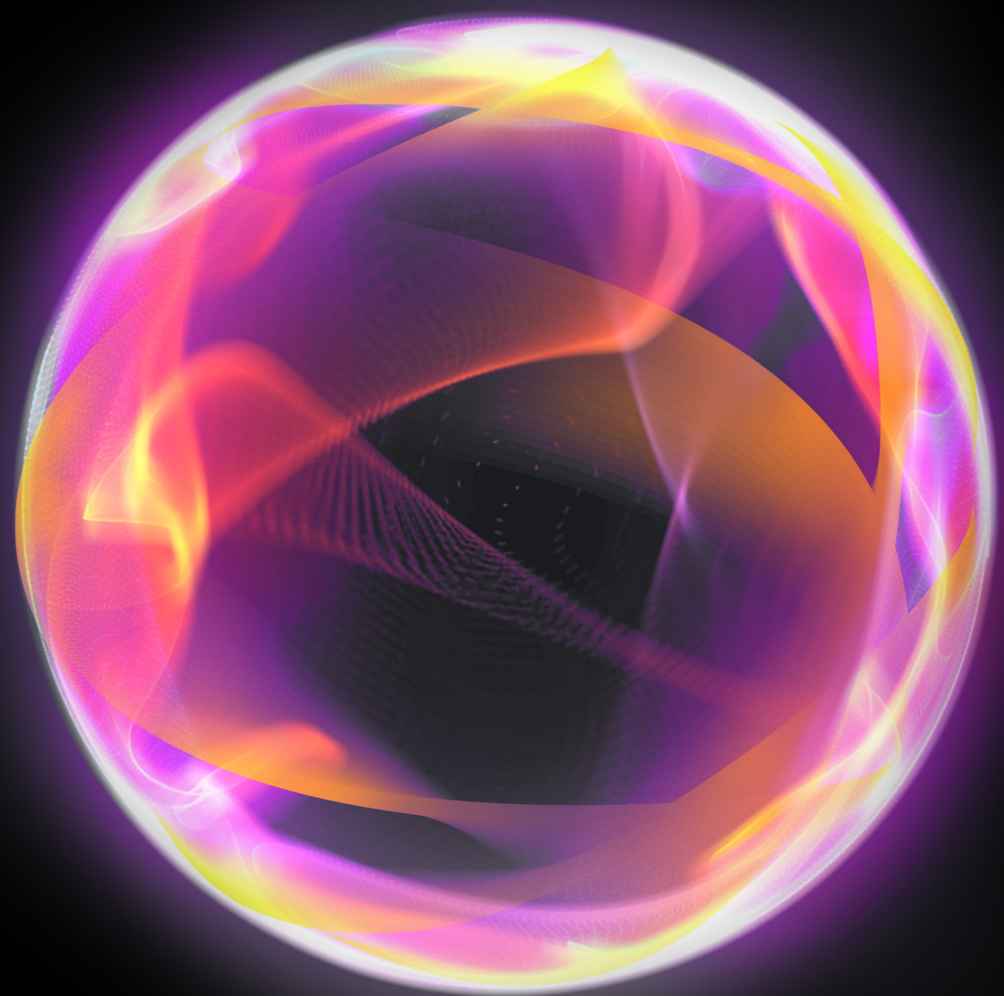
U.S. DEPARTMENT of ENERGY

Fusion Science and Technology Roadmap



Disclaimer → The activities outlined in the Fusion Science and Technology Roadmap are focused on prioritizing strategic directions for the United States (U.S.) Department of Energy to further collaborate with the U.S. Fusion Industry. This Roadmap does not commit the Department of Energy to specific funding levels. Future funding is subject to Congressional appropriations.

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List of Acronyms

AC	Alternating Current
AEC	Atomic Energy Commission
AI	Artificial Intelligence
ALPS	Advanced Limiter-divertor Plasma-facing Systems
AMPS DS	Affordable, Manageable, Practical and Scalable Demonstration System
AmSC	American Science Cloud
APEX	Advanced Power Extraction
APP-FPP	Advanced Profile Prediction for Fusion Pilot Plant Design
ArF	Argon Fluoride
ASCR	Advanced Scientific Computing Research
ASME	American Society of Mechanical Engineers
ATLAS	Advanced Technology Lasers for Applications and Science Facility
BCTF	Blanket Collaboration on Test Facilities
BES	Basic Energy Sciences
BNT	Accelerating Fusion Blanket Development through Nuclear Testing
BOP	Balance of Plant
BRN	Basic Research Needs
CAD	Computer-Aided Design
CDX-U	Current Drive Experiment-Upgrade
CEA	Commissariat à l'énergie atomique et aux énergies alternatives / French Alternative Energies and Atomic Energy Commission
CFS	Commonwealth Fusion Systems
CHIMERA	Combined Heating and Magnetic Research Apparatus
CPP	Community Planning Process
CSU	Colorado State University
CTC	Compact Toroidal Concepts
DBTT	Ductile-to-Brittle Transition Temperature
DCP	Digital Convergence Platform
DIII-D	DIII-D National Fusion Facility
DIR	Direct Internal Recycling
DOE	Department of Energy
DD	Deuterium-Deuterium
DPSSL	Diode-Pumped Solid-State Laser
DT	Deuterium-Tritium
EBR-II	Experimental Breeder Reactor-II
ECC	Emerging Confinement Concepts
ECRH	Electron Cyclotron Resonance Heating
ELM	Edge-Localized Mode
EMI	Electromagnetic Interference
FAIR	Findable, Accessible, Interoperable, and Reusable
FCP	Facilities Construction Projects
FEDER	Fusion Energy Data Ecosystem and Repository
FEI	Fusion Energy Innovation
FES	Fusion Energy Sciences
FESAC LRP	Fusion Energy Sciences Advisory Committee Long-Range Plan
FIA	Fusion Industry Association
FIRE	Fusion Innovation Research Engine
FIRST	Fusion Integration Research and Science Test Facility
FLiBe	Lithium Fluoride-Beryllium Fluoride
FM&T	Fusion Materials and Technology
FMEA	Failure Modes and Effects Analysis
FNS	Fusion Nuclear Science
FOAK	First-of-a-Kind
FPNS	Fusion Prototypical Neutron Source
FPP	Fusion Pilot Plant
FS&T	Fusion Science and Technology
FuRTH	Fusion Research and Technology Hub
GAIN	Gateway for Accelerated Innovation in Nuclear
GAO	Government Accountability Office
GPU	Graphics Processing Unit
H&CD	Heating and Current Drive
H3AT	Hydrogen-3 Advanced Technology Facility
HFT	High-Field Tokamak
HHF	High-Heat-Flux
HPC	High-Performance Computing
HTS	High-Temperature Superconducting
IB-FCTF	Integrated Blanket-Fuel Cycle Test Facility
IBML	Ion Beam Materials Laboratory
ICF	Inertial Confinement Fusion
ICRH	Ion Cyclotron Resonance Heating
IFE	Inertial Fusion Energy
IMPACT	Integrated Materials Program to Accelerate Chamber Technologies
IFE-FIRST	Inertial Fusion Energy Fusion Integration Research and Science Test Facility
INFUSE	Innovation Network for Fusion Energy
INL	Idaho National Laboratory
ITEP	Integrated Tokamak Exhaust and Performance
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
JT-60SA	Japan Torus-60 Super Advanced
KIT	Karlsruhe Institute of Technology
KrF	Krypton Fluoride
KSTAR	Korea Superconducting Tokamak Advanced Research
LANL	Los Alamos National Laboratory
LCLS	Linac Coherent Light Source
LEAPS	Lithium Evaporations to Advance PFCs in ST40

List of Acronyms

LIBRTI	Lithium Breeding Tritium Innovation Programme
LLE	Laboratory for Laser Energetics
LLNL	Lawrence Livermore National Laboratory
LMCE	Liquid-Metal Core-Edge
LPI	Laser-Plasma Interaction
LTX	Liquid Tokamak Experiment
MAST-U	Mega Amp Spherical Tokamak Upgrade
MBSE	Model-Based Systems Engineering
MEC	Matter in Extreme Conditions
MFE	Magnetic Fusion Energy
MHD	Magnetohydrodynamic
MIT	Massachusetts Institute of Technology
MITLs	Magnetically Insulated Transmission Lines
ML	Machine Learning
MPEX	Materials Plasma Exposure eXperiment
MTTF	Mean-Time-To-Failure
NASEM	National Academies of Sciences, Engineering, and Medicine
NBI	Neutral-Beam Injection
NDE	Non-Destructive Examination
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NE	Office of Nuclear Energy
NIF	National Ignition Facility
NIFS	National Institute for Fusion Science (Japan)
NIT-REBCO	Neutron-Irradiation-Tolerant REBCO Tapes for Compact Fusion
NNSA	National Nuclear Security Administration
NOAK	Nth-of-a-Kind
NP	Office of Nuclear Physics
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSTX-U	National Spherical Torus Experiment Upgrade
OF	Office of Fusion
ORNL	Oak Ridge National Laboratory
PFC	Plasma-Facing Component
PFM	Plasma-Facing Material
PFR	Private Facility Research
PIE	Post-Irradiation Examination
PMF	Pulsed Magnetic Fusion
PMI	Plasma-Material Interactions
PPCF	Public-Private Consortium Framework
PPPL	Princeton Plasma Physics Laboratory
PPP	Public-Private Partnership
PSFC	Plasma Science and Fusion Center
QA	Quality Assurance
RAFM	Reduced-Activation Ferritic-Martensitic
RAMI	Reliability, Availability, Maintainability, Inspectability
R&D	Research and Development
REBCO	Rare-Earth Barium Copper Oxide
RD&D	Research, Development, and Demonstration
RRA	Risk Reduction Activity
S&T	Science and Technology
SC	Office of Science
SciDAC	Scientific Discovery Through Advanced Computing
SCSP	Special Competitive Studies Project
SNL	Sandia National Laboratory
SOL	Scrape-off Layer
SRNL	Savannah River National Laboratory
ST	Spherical Tokamak
STM	Small-to-Medium
SWIFT-PFCs	Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components
TBDP	Tritium-Blanket technology Development Platform
TBM	Test Blanket Module
TBR	Tritium Breeding Ratio
TEAMS	Theory, Engineering, AI, Modeling, and Simulation
TFTR	Tokamak Fusion Test Reactor
TGAP	Tritium Gas Absorption/Permeation
TINEX	Target Injector Nexus for Development Research
TPE	Tritium Plasma Experiment
TRL	Technology Readiness Level
TVA	Tennessee Valley Authority
UCSD	University of California San Diego
UKAEA	United Kingdom Atomic Energy Authority
UNITY-1	Unique Integrated Testing Facility 1
UNITY-2	Unique Integrated Testing Facility 2
UQ	Uncertainty Quantification
UR	University of Rochester
USG	United States Government
UTK	University of Tennessee, Knoxville
UW	Madison University of Wisconsin-Madison
VNS	Volumetric Neutron Source
VV	Verification and Validation
W7-X	Wendelstein 7-X
WEST	Tungsten (W) Environment in Steady-state Tokamak
WHAM	Wisconsin HTS Axisymmetric Mirror
XFEL	X-ray Free-Electron Laser
ZFS	Z Fundamental Science

Executive Summary

The U.S. Department of Energy's (DOE) Fusion Science and Technology (FS&T) Roadmap aims to usher a burgeoning U.S. fusion industry toward maturity on the most rapid, credible timeline. By leveraging public and private sector investments through prudent, strategic processes, the Roadmap marshals these forces to close gaps on the critical path to 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. The U.S. private sector has attracted >$10 billion in cumulative private investment to commercialize fusion technology and deliver fusion energy to the grid. There remain critical science, materials, and technology gaps, such as the breeding and handling of fusion fuels, developing materials that can withstand fusion conditions, and increasing plasma performance, all of which must be closed. These critical gaps require innovation and bridging of the public and private sectors.

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 energy; and Grow the U.S. fusion ecosystem. Growth strategies include expanding domestic and international public-private partnerships (PPPs) and regional consortia, and building critical research infrastructure, supply chains, and fusion manufacturing networks.

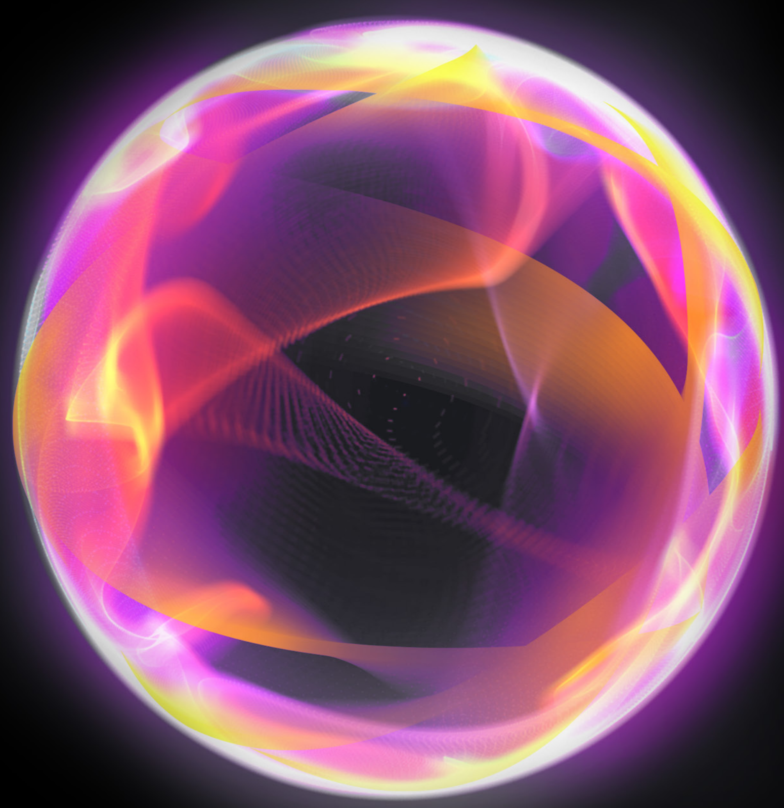
Build-Innovate-Grow is DOE's strategy to support fusion energy commercialization in the U.S., and the Roadmap is the tool to achieve it. The Roadmap is strongly aligned to the 2020 Fusion Energy Sciences Advisory Committee (FESAC) Long-Range Plan (LRP). The Roadmap combines the FESAC LRP critical science drivers with a revamped DOE public program 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 ambitious timeline. Progress is increasingly enabled and accelerated by the revolutionary potential of the convergence of artificial intelligence (AI) and fusion research.

The Roadmap defines Key Actions to be executed in the near term (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. The Roadmap outlines the DOE pathway for delivering FS&T infrastructure and the AI-Fusion Digital Convergence Platform (DCP) along the same near-, mid-, and long-term schedule that will be critical for the development of a Fusion Pilot Plant (FPP) in the 2030s. The delivery of key actions and infrastructure will enable U.S. progress on closing science and technology (S&T) gaps along the critical path to fusion energy across six core Challenge Areas: structural materials; plasma-facing components and plasma-material interactions; confinement approaches; the fuel cycle; blankets; and fusion plant engineering and system integration. Each Challenge Area is tracked with technical milestones and metrics.

The Roadmap sets the path for the strategic actions and capability delivery necessary to support a world-leading U.S. fusion ecosystem. This includes defining clear metrics to track progress, ensuring that these actions close critical S&T challenges and rapidly advance commercial fusion in the U.S. It is a dynamic tool for DOE, designed to evolve with continual input from the public and private sector fusion communities. The goal of the Roadmap is to deliver the public infrastructure that supports the fusion private sector scale-up in the 2030s. ■

"The Fusion Science & Technology Roadmap is a comprehensive national strategy to accelerate the development and commercialization of fusion energy by the mid-2030s. It charts a clear path for federal support to the growing fusion energy industry, identifying critical science and technology gaps and defining the milestones needed to bring commercial fusion power to the grid. By leveraging public and private sector investments through prudent, strategic processes, the Roadmap marshals these forces to close gaps on the critical path to fusion energy."

– Darío Gil, Under Secretary for Science
U.S. Department of Energy



Roadmap → Strategy

The U.S. DOE 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 DOE's strategy to support fusion energy commercialization in the U.S.; the Roadmap is the tool to deliver it.

The mission of the U.S. DOE's Office of Fusion (OF) and Fusion Energy Sciences (FES) is to support the scientific and technological foundations for a fusion energy source and the development of a competitive U.S. fusion energy industry. The FES Building Bridges vision[1] is anchored on advancing the foundational research needed to close key S&T gaps toward the development of fusion power as an affordable and reliable energy source. Core capabilities in foundational FS&T areas are aligned with the priorities identified in the 2020 Community Plan for Fusion Energy and Discovery Plasma Sciences[2], and the FESAC LRP[3]. The LRP identifies critical FM&T gaps that connect three science drivers: Sustain a Burning Plasma, Engineer for Extreme Conditions, and Harness Fusion Energy. The U.S. strategy for fusion energy is focused on innovation, built on foundational science, and enabled by three primary drivers – Build, Innovate, and Grow – to deliver a leading, competitive, and robust American fusion energy industry (Figure 1). While the U.S. private sector is investing >$10 billion to commercialize fusion energy technologies[4], there remain critical science, materials, and technology gaps, such as materials damage and the breeding and handling of fusion fuels, that must be closed to deliver fusion power to the grid. These remaining gaps require innovation and the bridging of the public and private sectors. ■

1. 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
2. American Physical Society Division of Plasma Physics, 2020. A Community Plan for Fusion Energy and Discovery Plasma Sciences, https://firefusionpower.org/CPP%20Strategic%20Plan%20Final_2020_03_11.pdf
3. Fusion Energy Sciences Advisory Committee, 2020. Powering the Future Fusion and Plasmas: A long-range plan to deliver fusion energy and to advance plasma science, https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf
4. Fusion Industry Association, 2025. The Global Fusion Industry in 2025, https://www.fusionindustryassociation.org/fusion-industry-reports

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

Build →	Innovate →	Grow
Build key infrastructure to address critical Fusion Materials and Technology (FM&T) gaps to deliver frontier commercial fusion relevant materials and breeder testing facilities that best serve the nation and a competitive fusion power industry.	Innovate and advance the science and engineering of fusion with well-defined milestones and metrics, connecting foundational research with new programs such as the Fusion Innovation Research Engine (FIRE) collaboratives that support industry-informed, use-inspired collaborative research, and integrating emerging breakthrough areas to accelerate progress such as AI and Inertial Fusion Energy (IFE).	Grow the U.S. fusion ecosystem through domestic and international public-private partnerships, leveraging resources from multiple sectors as done in the Milestone-Based Fusion Development program (Milestone Program) and by fostering new regional consortia, building research FS&T infrastructure, supply chains, and fusion manufacturing networks.

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, bridging public and private sector talent, expertise, and resources is required. This approach demands a rethinking of how DOE leverages assets and prioritizes investments in support of fusion energy development. This Roadmap provides the strategic and ambitious plan to sustain momentum across a broad range of complex research lines.

Commercializing 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 the deployment of fusion energy. The Roadmap enables the public program to prioritize and adapt based on the successes (and lessons learned) of the private sector. In the late 2020s, planned private sector demonstration platforms (Figure 2), such as SPARC (a compact, high-field tokamak),[5] Polaris (a field-reversed-configuration device),[6] Infinity One (a stellarator),[7] Millennium (a Z-pinch fusion device),[8] Eos (a stellarator),[9] Anvil (a magnetic-mirror device),[10] Vulcan (a laser IFE demonstrator),[11] Argo-1 (a laser 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 private sector-led activities with a focus on closing the most common and critical FM&T gaps for private sector developers into the mid-2030s, when the fusion industry will scale (Figure 3). Strategic partnerships between the public program, industry, and international allies will help leverage assets and resources.[13]

To better support these strategies, DOE recently established the Office of Fusion (OF) as part of its November 2025 reorganization. A stand-alone Office reporting to the Under Secretary of Science, OF has primary responsibility for coordinating all fusion-related activities across DOE and with key partners, including oversight for development and implementation of this Roadmap. FES continues to support the staff, research program, and the budget appropriated to execute the foundational science, enabling technologies, and facilities that close the gaps identified by the Roadmap. FES is also undergoing a restructuring, forming two new divisions – the Fusion Energy Research Division and the Enabling Technologies and Partnerships Division – to better align with and focus on LRP science drivers. This restructuring, along with the Roadmap, responds to recent recommendations from the Government Accountability Office (GAO)[14] to address planning and execution of the FES mission. The history of the program and mapping of the Roadmap to the National Academies of Sciences, Engineering, and Medicine (NASEM) 2021 Report [15] can be found in Appendix 1 of this document. ■

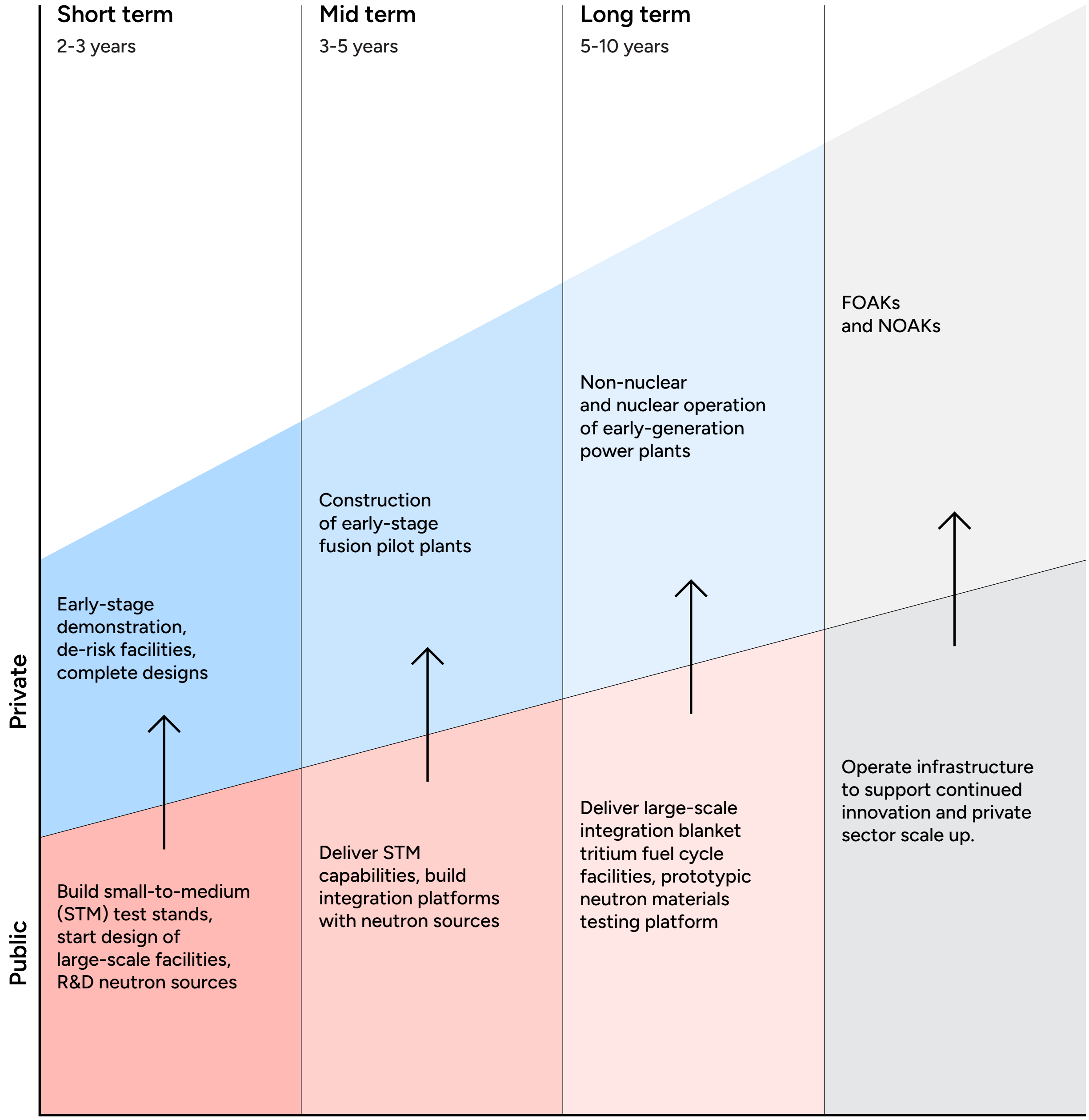
Figure 2.
Private company infrastructure timelines for early-stage demonstrations, scientific breakeven machines, and early-generation power plants.

Company (approach)	Existing	Near term 2-3 years	Mid term 3-5 years	Long term 5-10 years
CFS (Magnetic Confinement)		SPARC		ARC
Inertia Enterprises (Inertial Confinement)			Thunderwall	Argo-1
Marvel Fusion (Inertial Confinement)		ATLAS	TITAN	
OpenStar (Magnetic Confinement)	Junior	Tahi	Māui	Tama Nui
Pacific Fusion (Inertial Confinement)		GigaPulse/ Terapulse Foundry	Demonstration System	Commercial System
Realta Fusion (Magnetic Confinement)	WHAM	Hammir-DD		Hammir-DT
Starlight Engine (Magnetic Confinement)				FAST
TAE Technologies (Magnetic Confinement)	Norm		Da Vinci	
Thea Energy (Magnetic Confinement)			Eos	Helios
Tokamak Energy (Magnetic Confinement)	ST40			
Type One (Magnetic Confinement)		Infinity One		Infinity Two
Xcimer Energy (Inertial Confinement)	Phoenix	Anvil	Vulcan	Athena
Zap Energy (Magnetic Confinement)	FuZE-3 / Century	Millennium	Demo	Pilot

- ⬜ Early-stage demonstrations
- 🟦 Scientific breakeven machines
- 🟥 Early-generation power plants

This graphic is not exhaustive and only represents those companies that replied to a call to be included in the Roadmap. Other companies have also announced plans to build demonstration facilities, scientific breakeven machines, and early-generation plants within the timeframes listed here.

Figure 3.
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 continues to support innovation.



Aligning the Roadmap to the Fusion Energy Sciences Advisory Committee Long-Range Plan (FESAC LRP)

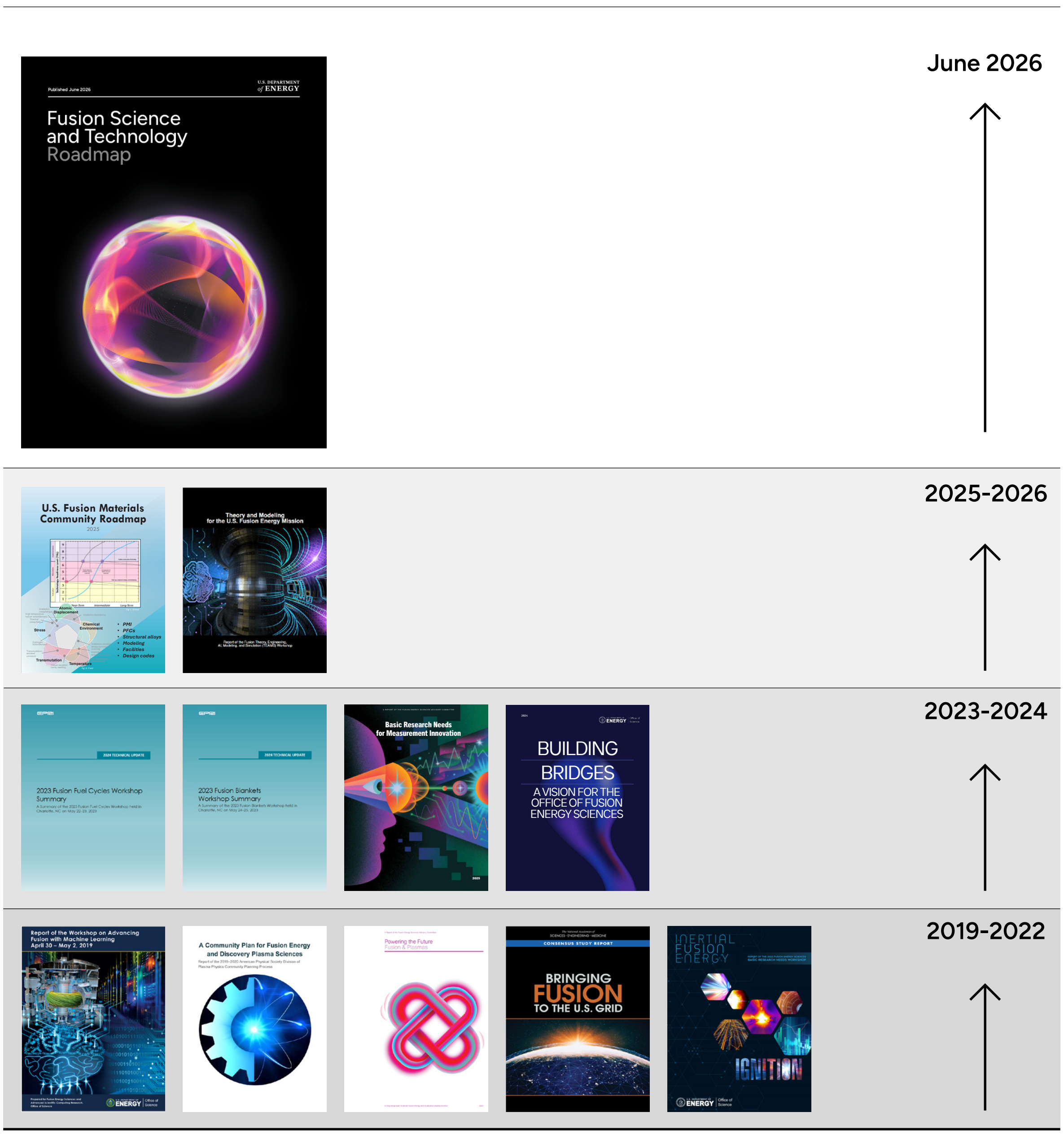
The Roadmap represents the culmination of the FES Community Planning Process (CPP) / FESAC LRP consensus reports, augmented with over a dozen community and Basic Research Needs (BRN) workshops, several principal investigator meetings, fusion roadmap forums, industry roundtables, and three FESAC activities (e.g., International Benchmarks, Fusion Construction Projects, and the Decadal Plan) between 2023 and 2025 (Figure 4).

In total, over 800 scientists and engineers from both the 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 United Kingdom Atomic Energy Authority (UKAEA) (United Kingdom, UK), National Institute for Fusion Science (NIFS) (Japan), Karlsruhe Institute of Technology (KIT) (Germany), Max Planck Institute for Plasma Physics (Germany), Fraunhofer Institute (Germany), French Alternative Energies and Atomic Energy Commission (CEA) (France), and Canadian Nuclear Laboratories (Canada). 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 the public and private sectors and strategic international collaborations to align interests for the benefit of the American taxpayer and the national security of the U.S. ▪

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.

5. Commonwealth Fusion Systems, 2025. Designing and Building Fusion Energy Systems to Power the World, https://cfs.energy/technology/
6. Helion Energy, 2025. Helion's Fusion Technology, https://www.helionenergy.com/technology/
7. Type One Energy, 2025. Our Technology, https://typeoneenergy.com/our-technology/
8. Zap Energy, 2025. Fusion Power No Magnets Required, https://www.zapenergy.com/
9. Thea Energy, 2026. Eos: a simpler way to build the stellarator, https://thea.energy/eos/
10. Realta Fusion, 2025. Decarbonizing Industrial Heat and Power with Compact, Scalable, Modular – CoSMo Fusion – Energy Systems, https://realtafusion.com/
11. Xcimer, 2025. Xcimer Energy Corporation, https://xcimer.energy/company/
12. Inertia Enterprises, 2026. Proven Fusion Science Meets a Proven Fusion Team with a Clear Plan, https://inertia.com/
13. Fusion Energy Sciences Advisory Committee, 2024. Report on International Collaboration Opportunities, Modes and Workforce Impacts for Advancement of US Fusion Energy, https://science.osti.gov/-/media/fes/fesac/pdf/2024/2311-16425-Humphreys-IB-Report_240513.pdf U.S.
14. Government Accountability Office, 2025. Fusion Energy: Additional Planning Would Strengthen DOE's Efforts to Facilitate Commercialization, https://www.gao.gov/assets/gao-25-107037.pdf
15. National Academies of Sciences, Engineering, and Medicine, 2021. Bringing Fusion to the U.S. Grid, https://nap.nationalacademies.org/catalog/25991/bringing-fusion-to-the-us-grid

Figure 4.
As shown in this illustration, the Roadmap builds upon a range of community planning reports, strategic documents, community workshop reports, and roadmap forums. Not all reports are shown in this figure.



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Roadmap → Structure

DOE developed the Roadmap to provide a structured framework for advancing fusion energy objectives and to implement the fusion energy development strategy to Build, Innovate, and Grow in America.

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 (SC) to its federal advisory committee to undertake a new long-range strategic planning activity for the FES program. The second is the 2021 NASEM report *Bringing Fusion to the U.S. Grid*, based on a request from DOE to the NASEM Committee on the key goals and innovations needed for a U.S. FPP. 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.

To enable DOE and FES to prioritize investments while measuring traction on addressing key S&T gaps defined by the U.S. fusion community and the private sector, the Roadmap translates high-level priorities into a coordinated set of actions and milestones. It includes a brief update to the FESAC LRP, including key factors that have shaped 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 U.S. since the NASEM 2021 publication (see, for example, the Fusion Industry Association's (FIA) 2024[16] and 2025 Global Fusion Industry Reports), the rapid deployment of data centers and AI infrastructure, and delays to large-scale, international fusion experiments such as the International Thermonuclear Experimental Reactor (ITER).[17]

The Roadmap is structured in two parts. The **Roadmap Key Actions and Timeline (Part I)** are aligned to the FESAC LRP and implementing the Build-Innovate-Grow strategy. These actions chart the path to fusion energy and to closing key S&T gaps in six core Challenge Areas (defined below). The **Gaps, Technical Milestones, and Infrastructure Pathway (Part II)** dives deeper with detailed metrics and milestones that address key S&T gaps defined by the U.S. fusion community (public and private). It is organized around the six core Challenge Areas and charts an infrastructure pathway aligned with private-sector timelines.

The activities outlined in the Fusion Science and Technology Roadmap are focused on prioritizing strategic directions for the United States (U.S.) Department of Energy to further collaborate with the U.S. Fusion Industry. This Roadmap does not commit the Department of Energy to specific funding levels. Future funding is subject to Congressional appropriations.

A pragmatic, structured, and adaptive process is utilized in this Roadmap. Part I serves as a basis for engagement with the broader stakeholder community as the U.S. accelerates its pursuit of commercially deployable fusion power, while Part II tracks progress and serves to catalyze the fusion ecosystem and align efforts. DOE will track implementation and progress of the actions, metrics, and milestones associated with the Roadmap and will use this information to evaluate critical decision points. The Roadmap is a living document that will be regularly updated with input from experts from 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. This will include tracking and reporting progress on the metrics and milestones of this Roadmap on at least an annual basis. ■

> The Roadmap translates high-level priorities into a coordinated set of actions and milestones to enable DOE 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
17. ITER, 2026. ITER In a Few Lines, https://www.iter.org/few-lines

Part I
Roadmap Key Actions and Timeline

The Roadmap Key Actions (Part I) describe how DOE will implement the Build-Innovate-Grow strategy to support the realization of a competitive U.S. fusion industry capable of delivering commercial fusion energy. It is organized under the three strategic areas, as follows:

→ Build

1. **Deliver FS&T Infrastructure:** accelerate fusion infrastructure to close critical gaps identified by the FESAC LRP science drivers.
2. **Build the AI-Fusion Digital Convergence Platform**: accelerate digital infrastructure to advance burning plasmas and materials discovery, close the fusion fuel cycle, and harness fusion energy.

→ Innovate

3. **Pursue Innovative and Transformative Research:** advance key innovative and transformative technologies that could help mitigate risks with conventional paths to commercial fusion.
4. **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.

→ Grow

5. **Support Public-Private Partnership Programs:** design PPPs to help de-risk critical scientific and technical issues.
6. **Seed Fusion Supply Chains:** leverage foundational and enabling science R&D combined with advanced testing platforms to establish supply chains relevant to fusion.
7. **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.
8. **Leverage Advanced Nuclear R&D and Deployment:** strategically coordinate with advanced nuclear research, development, and deployment efforts.
9. **Support a Practical Path to Fusion Energy Adoption:** expand measurement innovation and other R&D activities that enable widespread fusion energy deployment.
10. **Provide a Path to Commercialization:** develop a plan for a transition phase toward an applied office and track key indicators that signal readiness for the transition.

Part II
Gaps, Technical Milestones, and Infrastructure Pathway

The Gaps, Technical Milestones, and Infrastructure Pathway (Part II) sections include the following:

→ Gaps

Describe key S&T gaps identified by the fusion community across six core Challenge Areas: Structural Materials Science and Technology, Plasma-Facing Components (PFC) and Plasma-Material Interactions (PMI), Advancing Confinement Approaches, Fuel Cycle and Tritium Processing, Blanket Science and Technology, and Fusion Plant Engineering and System Integration.

→ Metrics and Milestones

Identify the milestones that address the S&T gaps and act as tools to track progress across the core Challenge Areas.

→ Infrastructure Pathway

Chart a pathway for FS&T infrastructure across eight distinct Infrastructure Streams critical for the development of a fusion power plant on industry timelines: Plasma confinement and performance; Enabling technologies development and testing; Exhaust and plasma/high-heat-flux (HHF) testing; Nuclear-effects testing (including fusion-prototypic neutrons and hot-cell capabilities); Remote maintenance and balance-of-plant (BOP) development and testing; Blanket development and testing; Fuel cycle development and testing; and High-performance computing (HPC), advanced manufacturing, and AI.

Part I.

Roadmap Key Actions and Timeline

Build →
Innovate
Grow

1. Deliver FS&T Infrastructure
2. Build the AI-Fusion Digital Convergence Platform
3. Pursue Innovative and Transformative Research
4. Advance Toward Cost-Competitive Fusion Power Plants
5. Support Public-Private Partnership Programs
6. Seed Fusion Supply Chains
7. Foster Talent by Enabling Fusion Workforce Pathways
8. Leverage Advanced Nuclear R&D and Deployment
9. Support a Practical Path to Fusion Energy Adoption
10. Provide a Path to Commercialization

1. Deliver 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 subcommittee 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 of >$100 million each. In addition to these large-scale facilities, the FESAC LRP indicated "Opportunities for developing small and mid-scale 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 infrastructure strategy is designed to close critical FS&T gaps and deliver the public infrastructure to support the U.S. fusion industry scale-up in the 2030s. Infrastructure in this context consists of a platform of tools, such as large-scale facilities, small-to-medium scale capabilities, and test stands, complemented by a National AI-Fusion DCP. The infrastructure strategy includes the Tritium-Blanket technology Development Platform (TBDP), the LRP FM&T large-scale facilities, including the Integrated Blanket-Fuel Cycle Test Facility (IB-FCTF), Fusion Prototypical Neutron Source (FPNS), as well as the AI-Fusion DCP. The TBDP includes all domestic and participating international small-to-medium scale infrastructure that supports development toward the IB-FCTF and neutron R&D toward an FPNS. TBDP is a resource-alignment strategy with close allies in fusion technology development and provides a de-risking path for the FM&T systems most critical and common to industry fusion developers.

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 demonstration platforms and first-generation commercial fusion power plants.

This framework organizes infrastructure needs into clear timeframes: near-term (2-3 years), mid-term (3-5 years), and long-term (5-10 years) with the aim of supporting the development of an early-stage fusion power plant in the U.S. on industry timelines.

Engineering for Extreme Conditions Infrastructure

Fusion-specific extreme conditions, including neutron irradiation, heat and particle exhaust, stress, and chemical reactivity, drive significant changes in materials that make up most components in a fusion power plant during its operational lifetime. 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 (a) exhaust, plasma, HHF, and (b) 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:

- Determination of whether existing material classes can survive irradiation damage levels expected in a fusion power plant.
- 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 HHF 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, Plasma-Facing Components and Plasma-Material Interactions, and Blanket S&T core Challenge Areas. These test stands provide surrogate systems that provide insights into materials irradiation damage and serve as an important bridge to future materials irradiation facilities, such as an FPNS. A more exhaustive list of facilities and critical gaps/metrics identified by the U.S. fusion materials community is included in the U.S. Fusion Materials Roadmap.[18]

In the next 2-3 years, DOE plans to deliver key facilities to address exhaust and plasma/high-heat-flux testing. The Material Plasma Exposure eXperiment (MPEX) at Oak Ridge National Laboratory (ORNL) will enable testing of 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. In addition, DOE will pursue PPP 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.

> Achieving early-stage fusion power plants by the 2030s requires increased investment into R&D 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 FPNS will provide unique material irradiation capabilities, while the MPEX and high-heat-flux testing experiments will enable solutions for plasma-facing materials (PFMs). Blanket research and associated integration blanket facilities will provide the scientific understanding and basis to qualify fusion fuel breeding systems [to perform at a tritium breeding ratio (TBR) > 1] for future power plants.
>
> – 2020 FESAC LRP

B. Nuclear-Effects Testing Infrastructure:
An FPNS is a high-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 Reduced-Activation Ferritic-Martensitic (RAFM) alloys beyond 5 MW·yr·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, spallation, and true-fusion approaches. This strategy allows for the simultaneous development of volumetric neutron sources (VNS) 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, synergistic nuclear-grade HHF and particle flux 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 focus on multiscale modeling and surrogate techniques. Physics-based, multiscale modeling techniques will be established that allow designers to simulate material evolution under complex loading, irradiation, and tritium exposure histories. 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. These experiments will expand U.S. leadership through the addition of world-leading 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 toward power-plant-capable materials and ultimately prototypic neutron source materials irradiation facilities, culminating in FPNS.

Harnessing Fusion Energy 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, 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 include the establishment of a domestic neutron source R&D activity (under the mission of the Fusion Nuclear Science program) supporting a path toward an IB-FCTF 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 pathway that leverages international test stands and facilities to address a spectrum of technology readiness in blanket systems and fusion fuel-cycle performance metrics. The strategy identifies technology readiness levels (TRLs) according to specific gaps within defined challenge areas. The relatively low TRLs of these technologies requires 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.

These systems must ultimately be integrated into prototypic nuclear environments to study the performance of breeding blankets as they harness prototypic fusion neutron power, heat, and irradiation-driven effects to a tritium processing system. 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 toward 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 linked to developer fusion machine designs and ultimately for DOE to deliver the blanket/tritium fuel-cycle infrastructure (e.g., IB-FCTF) to support the scale-up of the U.S. fusion industry in the 2030s.

In the next 2-3 years, DOE plans to engage with partners to access blanket and fuel-cycle test stands and facilities, including the Lithium Breeding Tritium Innovation (LIBRTI) Programme (UK), the Hydrogen-3 Advanced Technology (H3AT) Facility (UK), facilities at KIT (Germany), Unique Integrated Testing Facility (UNITY)-1 (Japan), UNITY-2 (Canada), and the Combined Heating and Magnetic Research Apparatus (CHIMERA) (UK) as part of its TBDP strategy. 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 Fusion Nuclear Science (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 plans to 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, a mid-scale tritium processing test facility could bring together international partners and private sector entities to help build and manage these projects.

In the long term of 5-10 years, DOE plans to deliver a platform of small-to-medium scale 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 should be leveraged to build an IB-FCTF.

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 deuterium-tritium (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 plans to 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 short-pulse toroidal facilities, e.g., DIII-D and National Spherical Torus Experiment Upgrade (NSTX-U), enables 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 continues across international experiments MAST-U (Mega Amp Spherical Tokamak Upgrade) and W7-X (Wendelstein 7-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), Tungsten (W) Environment in Steady-state Tokamak (WEST), and the Japan Torus-60 Super Advanced (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 leveraging DT fuels.

- **PPPs:** Programs, such as the Milestone Program, enable the conceptual development and advancement of private sector designs. The Innovation Network for Fusion Energy (INFUSE) program will continue to support the fusion industry, leveraging public sector infrastructure and assets at our national laboratories and universities. In addition, PPPs will be leveraged for creative de-risking collaborations addressing burning plasma physics R&D, such as the development of a PPP supporting a mid-scale stellarator facility.

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

- **In the mid/longer-term (3-10 years):** SPARC will operate at higher fusion gain, at which time, DOE will direct research efforts to realize and study the world's first burning plasmas (Q > 5-10). These research efforts are expected to quickly close longstanding burning plasma scientific gaps to develop a cost-competitive, commercially-relevant fusion energy source. Additionally, this experimentation will generate vital data for the fusion engine, the core system that generates fusion power, 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 years):** The 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 core plasmas with survivable boundaries at the edge. R&D activities would begin on ITER with nuclear operations expected near the mid- to late-2030s and DT plasmas to start by 2039.

- **Alternate or emerging confinement concepts (ECC):** Will be supported by the ECC program within DOE and leverage PPPs to support advances in enabling technology.

- **In the long term (5-10 years):** DOE plans to 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 FPP designs and further NOAK fusion power plants.

Inertial Fusion Energy

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 toward 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 target.[19]

The IFE mission within FES will coordinate with the National Nuclear Security Administration (NNSA) to strategically leverage inertial fusion burning plasma developments at NIF. This approach aligns with recommendations from the CPP and FESAC LRP, which advocate 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)[20] and the Omega laser at the Laboratory for Laser Energetics (LLE)[21] are vital NNSA resources, capable of conducting experiments of implosion physics directly relevant to IFE. Coordination and collaboration with NNSA and its laboratories 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 plans to advance IFE, including support for key facilities, all of which have been recommended by the IFE BRN workshop:

- **LaserNetUS:** Supported by SC, this network encompasses multiple mid-scale laser facilities that are crucial for conducting IFE-relevant experiments and for the development of a skilled fusion workforce. Enhancing the capabilities of this network, including but not limited to implementing AI and machine learning (ML) to enable real-time optimization and autonomous control of lasers and diagnostics, will benefit IFE. Furthermore, access to the OMEGA laser at LLE will advance IFE as it is uniquely capable of performing sub-scale (i.e., at lower energy levels than NIF) implosion studies.

- **Matter in Extreme Conditions (MEC)[22] at the SLAC National Accelerator Laboratory (existing):**
  DOE plans to enhance MEC's long-pulse beam from its current 100 J (one shot every seven minutes) to an enhanced 250 J (one shot per minute). This improved 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 spatiotemporal understanding of ablator material's dynamics essential for fusion capsules. Through coordination with the SC 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-Colorado State University (CSU)-Marvel Fusion Advanced Technology Lasers for Applications and Science (ATLAS) facility (under construction):**
  For the exploration of advanced IFE fusion concepts and laser-driven neutron sources, DOE intends to fully utilize the ATLAS facility, currently under construction at CSU. This facility, anticipated to be operational in early 2027, will feature three synchronized laser beams delivering a cumulative power exceeding four petawatts. The ATLAS facility is a foundational component of the DOE-supported RISE IFE hub.

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 involves 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:** An integrated KrF beamline demonstrator and testbed featuring two 100 kJ beam lines that utilize pulsed compression techniques would validate the at-scale laser architecture for IFE. It will advance the TRL for commercial IFE by demonstrating high-energy target illumination from solid angles required by thick-liquid-wall chambers. The demonstrator should also facilitate two-sided target implosions and serve as a testbed for future capabilities in this architecture, including target injection and tracking.

These near-term projects are pursued through actions to build infrastructure and leverage public-private and strategic partnerships, including through DOE FIRE Collaboratives, IFE Hubs, 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 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 enhancement and the IFE Fusion Integration Research and Science Test (IFE-FIRST) Facility, hinges on strategic near- and mid-term investments and partnerships. The proposed MEC enhancement would couple efficient optical lasers to the LCLS X-ray Free-Electron Laser (XFEL) at SLAC, thereby providing a national resource for both the SC IFE and NNSA ICF programs. IFE-FIRST will enable the study of IFE burning plasmas 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.

Pulsed Magnetic Fusion (PMF)

PMF concepts, such as magnetized-liner inertial fusion and staged Z-Pinch, have been explored through both computational and experimental efforts, and are the focus of several private sector efforts. Innovation to close critical scientific and technical gaps in PMF approaches is addressed in this Roadmap's Key Action to support innovative and transformative research in alternate confinement concepts.

Similar to the laser fusion roadmap, a coordinated effort that includes existing facilities and PPPs will help address these PMF S&T gaps. For example, the ZNetUS network, which brings together research scientists from academia and national laboratories across the country to support collaborative research in pulsed magnetic science and technology, can address some scientific and technological questions and contribute to the workforce development needed for PMF. Furthermore, leveraging the Z machine at SNL through the Z Fundamental Science (ZFS) Program to conduct large-scale experiments is crucial. Additionally, a PPP focused on developing a PMF module, analogous to a laser beamlet, for technology de-risking and integration, represents a logical step to advance this concept. ■

Burning plasma, ignition, and gain

The realization of a sustained burning, high-fusion-gain plasma is vital to determining if fusion can serve as a viable source of electricity. Within scientific literature, numerous definitions of fusion gain exist that depend on the chosen method of energy accountancy. For clarity, the Roadmap includes only two distinct definitions of fusion gain for magnetically confined fusion and distinguishes between the critical metrics around gain for magnetic and inertial fusion energy.

Magnetic Fusion Energy

The first definition for fusion gain (Q) is the ratio of fusion power produced to the total input power injected into the vacuum vessel of the device. The second definition for fusion gain is engineering gain (Q_{eng}), which is defined as the ratio of electrical power produced to electrical power consumed.

For magnetic confinement, realizing scientific breakeven ($Q_{sc} = 1$) will be a heartening accomplishment that marks the beginning of the next phase of magnetic fusion energy research. Much work will remain, as achieving $Q_{sc} = 1$ will still provide physics insights similar to those obtained from sub-breakeven plasmas from Tokamak Fusion Test Reactor (TFTR) and Joint European Torus (JET). To confidently develop an FPP, a sustained burning plasma primarily heated by fusion reactions (>50%) is required. For a DT fuel cycle, this burning plasma condition corresponds to a $Q_{sc} > 5$. Research efforts are underway, both in the U.S. and internationally, to surpass this threshold and conduct the vital work of studying burning plasmas. A key unresolved question is whether the fusion α particles remain confined long enough to transfer their energy to the plasma, a process known as α heating. To address this, SPARC and ITER have been designed to produce well-diagnosed burning plasmas operating at approximately $Q_{sc} \approx 10$.

Fusion studies in the U.S. have explored FPP facilities that slightly exceed net electrical energy breakeven (i.e., $Q_{eng} > 1$) and allow for fusion fuel cycle and materials testing. Q_{eng} depends on a combination of technological and physics performance metrics. FPP designs targeting a fusion power output exceeding 50 MWe, as outlined in the NASEM report, are expected to require a $Q_{sc} > 10$, depending on the approach. Moreover, for power levels comparable to baseload power plant installations in the U.S. (approximately 300 MWe), the requisite Q_{sc} may exceed 25 or more.

The ultimate objective of fusion science research is to reach sustained fusion ignition conditions ($Q_{sc} = \infty$). Ignition occurs when the plasma temperature can be maintained against energy losses solely through fusion α heating. To date, α heating of approximately 10% for a few seconds has been obtained in magnetic confinement experiments. Sustaining ignited plasmas could significantly simplify the fusion engine, thereby reducing costs. Although magnetically confined FOAK power plants will likely operate in sub-ignited conditions, it is imperative that the public program vigorously pursue this foundational scientific goal alongside, and in collaboration with, the fusion private sector to deliver the most economical form of fusion possible.

Inertial Fusion Energy

In inertial confinement fusion, scientific breakeven ($Q_{sc} = 1$), defined as the ratio of fusion energy output to IFE driver energy incident on the target, has been exceeded multiple times at the National Ignition Facility using the indirect-drive approach. Since the first demonstration in 2022 ($Q_{sc} \approx 1.5$), continued improvements in target design and implosion symmetry have led to repeated ignition events. This yielded a record gain of $Q_{sc} \approx 4.13$ (8.6 MJ output from 2.08 MJ input) reported in 2025.

For an inertial FPP, the product of the driver's wall-plug efficiency and the target gain (ηG) is a key parameter. This product reflects the need to limit recirculating power and compensate for thermal conversion and balance-of-plant losses. Multiple system studies suggest that ηG~10 is necessary for low recirculating power.

2. Build the AI-Fusion Digital Convergence Platform

DOE and its national laboratories, in partnership with other Departments and agencies, academia, industry, and philanthropy, are advancing AI through world-class supercomputers, cutting-edge algorithms, and software stacks as part of the Genesis Mission.[23] Launched in November 2025 by Executive Order from President Trump,[24] the Genesis Mission represents a historic national effort to transform American science and innovation through the power of AI, strengthening the nation's technological leadership and global competitiveness, particularly in the realm of fusion energy. As part of the 26 science and technology AI challenges identified in February 2026,[25] the mission specifically targets "Accelerating Delivery of Fusion Energy".

> AI has become a transformative enabling capability for fusion energy, and the Genesis Mission will harness 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.

This national initiative builds on the foundation laid by the 2018 FESAC "Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy" report,[26] which identified "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." The report marked a pivotal starting point for integrating advanced computation into fusion science, sparking the convergence of AI and fusion research and development.

Since then, DOE investments and strategic partnerships, such as those between FES and SC's Advanced Scientific Computing Research (ASCR) program, have propelled rapid advancements in this area (e.g., advanced computational modeling). Researchers have used AI/ML tools to rapidly predict the onset of disruptions on KSTAR and applied automated control techniques to navigate a stable parameter regime that avoids these instabilities. Researchers at Lawrence Livermore National Laboratory (LLNL) have developed surrogate models of turbulence and transport at 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 DOE SC Scientific Discovery Through Advanced Computing

(SciDAC) Partnership project 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 AI-Fusion DCP is furthering the Genesis Mission through advancements in research across the Roadmap's six core Challenge Areas. The DCP will integrate novel algorithms in HPC codes, foundation models for plasma and materials science, neural networks, surrogate models, and digital twins for whole-facility modeling and real-time control. These capabilities would allow performance and engineering trade-offs, failure modes, and design margins to be evaluated consistently in simulation and experiment. This investment is key to accelerating infrastructure development, shortening innovation cycles, and supporting a competitive U.S. fusion ecosystem.

The DOE is uniquely positioned to lead this effort, leveraging fusion facilities, national laboratories, leadership-class computing, data stewardship, and PPPs. This trusted, national-scale Genesis Mission platform will integrate data, models, and experiments across the fusion ecosystem, drawing on large-scale domestic and international experimental facilities, alongside fusion technology development and testing infrastructure. These resources include HHF testbeds, tritium and blanket test stands and loops, irradiation facilities, and in situ and in operando materials characterization capabilities across both the public and private sectors. By enabling rapid progress in fusion energy development, the Genesis Mission will help the U.S. meet the Roadmap milestones and position the nation as a global leader in fusion energy innovation.

> 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.

A Theory, Engineering, AI, Modeling, and Simulation (TEAMS) Workshop, held in late 2025, 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 the following steps:

- Expanding the development of surrogate and reduced-order models with data from 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.

These recommendations will inform the overarching scope of the AI-Fusion DCP. The AI-Fusion DCP will deliver transformational AI models through advanced data sharing, computing infrastructure, and foundation model development through the American Science Cloud project and Genesis Mission. 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 as directed by the Genesis Mission.

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 national laboratory collaboration, leveraging advancements in GPU (graphics processing unit) architecture to train foundation models.

By learning from vast experimental and simulation data, AI can deliver breakthroughs in some of the greatest challenges for fusion energy including materials discovery and design, and fuel cycle self-sufficiency, potentially solving the greatest challenges in realizing sustainable, ignited fusion. ■

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Build
Innovate →
Grow

3. Pursue Innovative and Transformative Research

The FESAC LRP 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 the previous section), and alternate 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 appears in the Technical Metrics and Milestones (Part II), threaded through the six core Challenge Areas. This Roadmap Key Action supports innovation and transformative research around these technologies.

Stellarators

DOE has funded two U.S.-based companies under the Milestone Program pursuing stellarator approaches: Type One Energy and Thea Energy, the latter of which is a spin-off from PPPL. Type One Energy selected the site of the former Bull Run coal power plant operated by the Tennessee Valley Authority (TVA) in East Tennessee for Infinity One, a mid-scale stellarator de-risking 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 longstanding collaboration with W7-X, the world's largest stellarator experimental facility (which recently broke world records in pulse lengths and triple product).[27] W7-X is a key asset to the U.S.-German partnership and PPP de-risking strategies with stellarator approaches in fusion energy. The stellarator expert community recently completed a community workshop, with guidance from DOE and priority research objectives formulated during this workshop are incorporated into the Technical Metrics and Milestones (Part II).

Liquid-Metal PFCs

The use of liquid walls with a fusion engine could become a transformative technology to address the significant heat exhaust challenges in commercial fusion power plants. The unmitigated parallel heat flux anticipated in a compact, high-field tokamak, or spherical tokamak-based[28] fusion power plant is estimated to be greater than 10 $GW{\cdot}m^{-2}$ in the divertor, which is significantly more than the $MW{\cdot}m^{-2}$ heat fluxes generated by a propane torch. Liquid metal 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 (Current Drive Experiment-Upgrade) and LTX (Liquid Tokamak Experiment).[26] 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-risking 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. Fusion Materials Roadmap, 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 divertorlets,[29,30] vapor boxes,[31,32] and porous media to deliver liquid metal as PFCs,[33, 34] will be explored. De-risking these novel PFC concepts in compact toroidal confinement environments (e.g., through collaboration at the UK ST-40 experimental facility) 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

DOE supports innovation through the exploration of emergent confinement concepts through PPPs, 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

The deployment of public and private sector fusion demonstration platforms will enable verification and validation (VV) of design modeling codes for components and 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 are used in research facilities like NIF, OMEGA, and Z machine, they could be further developed and adapted to support progress toward fusion power plants. Innovations beyond these existing techniques are expected to be required. ■

> The commercialization path for individual companies pursuing different concepts can vary quite dramatically and evolve rapidly. 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 common S&T gaps that are difficult for individual private sector companies to address on their own.

4. Advance Toward 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 toward fusion demonstration and large-scale (e.g., 1 GWe) power plants. This approach presents challenges including the complexity of the 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 toward cost-competitive fusion power-plant demonstration and deployment. This includes considering Compact Toroidal Concepts (CTC), such as high-field tokamaks (HFT) and spherical tokamaks (ST), 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. Additionally, this includes inertial confinement approaches that could leverage advances in IFE-centric technologies and leveraging modular design de-risking strategies, potentially reducing costs for both the development and deployment of a fusion power plant.

The commercialization path for individual companies pursuing different concepts can vary quite dramatically and evolve rapidly. 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 common S&T gaps that are difficult for individual private sector companies to address on their own.

A subset of the FESAC LRP S&T gaps is addressed in this Roadmap, with the aim of delivering a low-cost fusion power plant. These gaps include advancing the understanding of 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.

The objective of the CTC program is to support the research necessary to develop a compact, lower-cost FPP in a toroidal geometry. ST and HFT are two of the most promising concepts in this program. 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-drive 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. ■

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Build
Innovate
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1. Deliver FS&T Infrastructure
2. Build the AI-Fusion Digital Convergence Platform
3. Pursue Innovative and Transformative Research
4. Advance Toward Cost-Competitive Fusion Power Plants
5. Support Public-Private Partnership Programs
6. Seed Fusion Supply Chains
7. Foster Talent by Enabling Fusion Workforce Pathways
8. Leverage Advanced Nuclear R&D and Deployment
9. Support a Practical Path to Fusion Energy Adoption
10. Provide a Path to Commercialization

5. Support Public-Private Partnership Programs

PPPs 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 that all stakeholders are committed and aligned. Research and innovation that is relevant and valuable for commercialization is also pursued, guided by the Roadmap. As private investment grows, topping $2.6 billion in the 12-month period ending in 2025[35,36], working together with the private sector allows greater resources to support the development of a competitive domestic fusion power industry.

Even as investors deploy capital to support 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 Research, Development, and Demonstration (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 opportunity for increased prosperity that fusion energy presents. These impacts suggest that there is a need to act with urgency to expand the scale and scope of PPP programs.

Currently, DOE supports two PPP programs in fusion:

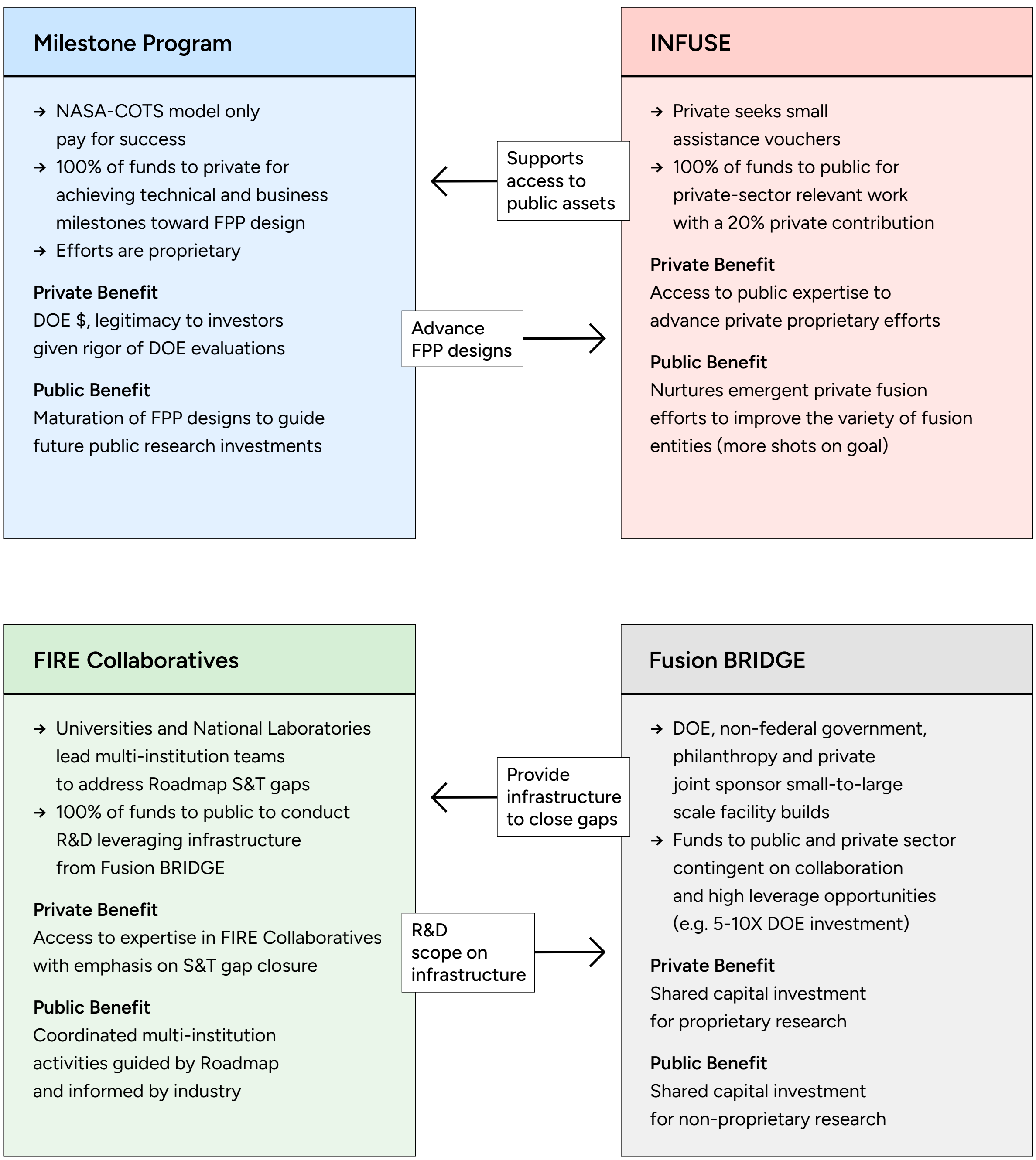
- The INFUSE program began in 2019, and as of August 2025, it has made 127 awards, totaling $30.3 million, to support 38 private companies partnering with 10 DOE national laboratories and 15 U.S. universities. The INFUSE program is modeled after the DOE Office of Nuclear Energy (NE) program, the Gateway for Accelerated Innovation in Nuclear (GAIN).

- The Milestone Program supports private sector companies to develop their technological roadmaps toward viable early-stage fusion power-plant designs. As of April 2026, there are eight companies in the Milestone Program[37] (listed alphabetically): Commonwealth Fusion Systems (CFS), Focused Energy, Realta Fusion, Thea Energy, Tokamak Energy, Type One Energy, Xcimer Energy, and Zap Energy. These companies were selected during the initial Milestone solicitation and there is a possibility of new companies being selected in calendar year 2026.[38]

In the near term (2-3 years), PPPs in FES have substantial opportunities to grow and better support the domestic fusion ecosystem. Toward this end, beginning in Fiscal Year 2026, DOE plans to implement the Fusion Bringing Regional Investments to Develop and Grow a U.S. Fusion Engine (Fusion BRIDGE) PPP.

The Fusion BRIDGE program, a modality of the Public-Private Consortium Framework (PPCF), will extend beyond collaborative research at private facilities by co-sponsoring the construction of new experimental capabilities with the private sector and other stakeholders. 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 will also seek to grow the American fusion supply chain, with an emphasis on manufacturing and digital engineering. ■

Figure 5.
Summary of PPP modalities.



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. The 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 high-temperature refractory metal-based components will require a combination of robust advanced manufacturing methods (e.g., laser bed 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 power 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 U.S. Government (USG) entities, for example, the National Science Foundation (NSF), and provide cost-sharing to enable fusion workforce pathways, such as training and education in fusion engineering. Recently, an 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 infrastructure development with training and education, and by 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 and Simulation, Fusion Materials, and Fusion Nuclear Science, among others) and 3) linking universities with private sector via INFUSE 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 PPPs 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 lithium fluoride-beryllium fluoride (FLiBe) coolant, supporting Commonwealth Fusion Systems' efforts to develop a FLiBe-based tritium breeding blanket. Fusion has also benefited from benchmarks of the DOE NE efforts to accelerate advanced nuclear R&D. This includes the DOE INFUSE program (modeled after GAIN), and efforts to develop a fusion code repository similar to NEAMS (Nuclear Energy Advanced Modeling and Simulation). PPPL is also investigating its FuRTH (Fusion Research and Technology Hub) facility as a potential site to 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 (Experimental Breeder Reactor-II) dome to test 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. Many factors impact fusion energy adoption, including innovation in measurement for tritium accountancy, increased lifetime of fusion components, regulatory frameworks[39,40] with proportional risk defined for fusion energy (see recent 2024 ADVANCE Act), and by-product material minimization. In a recent paper from the Atlantic Council, titled: "Building a path toward global deployment of fusion: Non-proliferation and export considerations",[41] the authors outlined a compelling argument for keeping fusion energy out of the context of nuclear fission frameworks for regulatory and non-proliferation policy.

In February, 2026, the U.S. Nuclear Regulatory Commission (NRC) published a proposed rule on regulatory requirements and consolidated licensing guidance for fusion machines. The proposed rule amends NRC regulations to augment the existing byproduct material framework to be inclusive of fusion machines, with. requirements that are technology-inclusive to accommodate the wide variety of anticipated fusion machine designs.

Key advantages for fusion energy adoption include 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 safety of traditional nuclear power, fusion energy provides a complementary pathway toward 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

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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 chemical fuels. The inverse relationship between regulatory burden and innovation speed means that thoughtfully adopting regulatory and non-proliferation regimes that accurately assess and appropriately mitigate fusion-specific risks carries outsized societal value.

The NRC Vision and Strategy: Regulating Fusion Machines Across the National Materials Program[42] sets forth principles for a clear, efficient, independent, reliable, and open regulatory framework that shapes the approach to regulating the emerging fusion industry. Implementing this vision will yield a focused approach suitable for commercial-scale fusion technologies. In response to the ADVANCE Act, the NRC, in coordination with the Agreement States, developed a Fusion Industry Indicator action matrix to outline milestones to assess industry readiness for regulations or guidance that will support licensing of mass-manufactured commercial fusion machines. These milestones, coupled with industry's critical path to demonstrate, deploy, and commercialize, will need to be achieved alongside the technical metrics and milestones in this Roadmap for the U.S. fusion energy industry to truly achieve its potential.

To support the development of right-sized fusion energy regulatory and non-proliferation regimes, DOE aims to 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 non-proliferation.

DOE will also make investments targeted at shortening the timeline to widespread fusion energy deployment through innovation addressing fusion waste streams. Large volumes of nuclear byproducts 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 nuclear byproducts and extend component lifetimes. ▪

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

10. Provide a Path to Commercialization

Following the initial release of this Roadmap in October 2025, DOE established the Office of Fusion (OF). In the near term, the OF will lead the coordinated efforts across DOE and develop the partnership strategies and ensure execution of the Roadmap. The key indicators that signal readiness for an applied fusion energy program are:

1. Demonstration of a reliable and scalable burning plasma platform in the private sector to pivot the 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).

2. The establishment of a platform of small-, medium-, and large-scale test stands and capabilities to support TRL 0-4 R&D, complementing 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 OF is developing a Fusion Energy Innovation (FEI) implementation plan that focuses on coordinating fusion equities across the department and delivering on the Roadmap. The FEI implementation plan will also have an interagency activity to ensure that 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 the 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 with the Roadmap strategy to Build-Innovate-Grow. The Roadmap will enable a transition to a future set of FEI programs at DOE when the 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 FES, and a PPCF for fusion energy development, positioning the U.S. for fusion energy deployment in the 2030s. ▪

Part II.

Gaps, Technical Milestones, and Infrastructure Pathway

Part II. Gaps and Technical Milestones

The Technical Roadmap Milestones (Appendix 3) provide a detailed timeline on the infrastructure capabilities that are needed and the scientific metrics and key milestones that will track progress toward closing gaps across the six core Challenge Areas.

The milestones and metrics help both the program and the fusion ecosystem assess progress in closing the gaps. This section describes the core Challenge Areas and outlines how they will be organized over the Roadmap timeline phases of the near-, mid-, 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.

Each Challenge Area, described in the next section, is broken down further into S&T 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 advancing technology readiness. The technical metrics and milestones for each Core Challenge Area are provided in Appendix 3.

The Roadmap is designed to be an adaptive tool. As 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 keeping a clear trajectory toward U.S.-led delivery of commercial fusion power plants.

Roadmap Methodology and Milestone Selection

The milestones and metrics presented in this Roadmap were developed through an extensive, community-driven process that spanned multiple years and engaged a broad cross-section of the public and private fusion ecosystem. DOE drew on inputs from the FES Community Planning Process and FESAC long-range planning reports, supplemented by more than a dozen Basic Research Needs workshops, principal investigator meetings, fusion roadmap forums, and three major FESAC activities completed between 2023 and 2025. In total, more than 800 scientists and engineers contributed to shaping the shared vision reflected here. These were drawn from more than 15 private companies, 10 national laboratories, 72 universities, and included allied international partners. This participatory approach ensures that the Roadmap aligns with community priorities and captures the scientific and technical requirements needed to advance fusion toward commercial deployment.

To structure the Roadmap, a broad collection of inputs was distilled into a set of the most prominent and representative milestones across the near-, mid-, and long-term. While each core Challenge Area and technology stream maintains its own detailed set of incremental milestones and associated metrics (Appendix 3), the Roadmap highlights those milestones that best measure progress at a national level. These selected milestones serve as clear indicators of advancement across the Challenge Areas, while still reflecting the depth and complexity of the underlying work.

A key principle guiding the development of milestones and metrics was recognizing the substantial system-level coupling that exists across fusion science and technology. Significant overlap exists among the challenge areas in topics such as fusion plasma core-edge integration, tritium burn efficiency and extraction, fueling and injection systems, materials maintenance, functional materials, heat exchange, and corrosion in structural and plasma-facing armor materials. These issues cannot be solved in isolation; they require integrated solutions and coordinated expertise across plasma physics, materials science, nuclear engineering, fuel systems engineering and chemistry, data science, and advanced manufacturing.

By presenting milestones that reflect the distinct needs of each challenge area and their interdependencies, the Roadmap emphasizes the collaborative, interdisciplinary effort required to close critical gaps. This approach ensures that the metrics not only measure technical progress within individual domains but also track the further growth of a cohesive fusion program capable of supporting commercial fusion development.

AI-Fusion DCP

The Genesis Mission is a unifying national capability that brings together advanced computing, high-quality data, and cutting-edge AI/ML tools to accelerate innovation across various domains of science and technology. The AI-Fusion DCP is the central contribution of FES to the **Genesis Mission**. The platform functions as an integrating layer, enabling coordination and shared capability across a broad set of activities, including predictive modeling and digital twins, plasma control, and materials discovery. To clearly indicate where this impact occurs, the accompanying icon will appear alongside all Roadmap milestones that rely on or are significantly advanced by the Genesis Mission. This visual marker (below) will help readers quickly recognize the cross-cutting importance of AI-fusion integration enabled by the Genesis Mission and understand how it threads through diverse program elements. By highlighting these connections, the Roadmap underscores the essential role of the convergence platform in driving progress toward commercially viable fusion energy.

Learn more about the Genesis Mission at:
→ www.energy.gov/genesis-mission

Genesis Mission

U.S. DEPARTMENT *of* ENERGY

Aligning S&T Milestones with the Fusion Industry

This Roadmap is structured to stay aligned with the pace, priorities, and evolving timelines of private fusion development, while preserving the public program's distinct responsibility to steward the shared foundations that accelerate the commercial deployment of fusion power plants. In practice, this means prioritizing the fundamental research, technology, frameworks, validation pathways, standards, and qualification requirements, interoperable data approaches, and test infrastructure that reduce risk across the national fusion enterprise. This is especially true where no single company can justify the full cost for the capability or scale required.

Accordingly, priorities and milestones will be shaped to remain deployment-relevant and will emphasize demonstrable validation evidence, clear performance metrics, and "fit-for-purpose" qualification expectations that reflect what designers, investors, and regulators will ultimately require. Central to this will be the integration of private-sector validation needs into milestone definitions by maintaining continual engagement with developers to ensure public efforts are additive rather than duplicative. This input will regularly revalidate whether a given milestone will genuinely unblock development, whether it is already being pursued internally, and what form of public support (shared infrastructure, methods, datasets, standards, or cross-cutting research) would have the greatest leverage.

To institutionalize this alignment, DOE will use targeted industry engagement mechanisms, such as industry roundtables, focused on near-term technical bottlenecks and validation priorities, and the Office of Science Advisory Committee to provide sustained input to guide the development and refresh of Roadmap metrics and milestones (including data needs, test conditions, and evidence expectations). These mechanisms will ensure that the Roadmap is continually recalibrated against industry timelines. These engagements will also inform priorities for data standardization and for the AI-Fusion DCP frameworks needed to ensure comparability, traceability, and efficient learning across facilities, experiments, and simulation. A central principle is that standards, qualification requirements, and validation expectations should be defined through industry–regulator leadership, supported by the public program's technical basis, shared data, and accessible test environments.

There are already extensive areas of collaboration between private companies and public programs. For each core Challenge Area, this document lists the relevant FIRE Collaboratives, which illustrate the intended R&D interface between industry and the public program. ■

Part II. Core Challenge Areas → A - F

S&T Gaps and Technical Milestones are organized across the six core Challenge Areas, which the U.S. fusion community identified as priorities.

Core Challenge		Description
A	**Structural Materials Science and 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.
B	**Plasma-Facing Components and Plasma-Material 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.
C	**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.
D	**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.
E	**Blanket Science and 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.
F	**Fusion Plant Engineering and 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 modeling.

Structural Materials Science and 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 Nondestructive 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 iron alloys (Fe-alloys), Vanadium alloys (V-alloys), silicon carbide (SiC), silicon carbide composites (SiC-SiC), 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.

S&T Gaps

A1. Require qualified materials for vacuum vessels and in-vessel supports.
Including fusion-relevant irradiation data for swelling, transmutation, embrittlement, joint toughness, creep-fatigue, tritium transport, and coolant compatibility. Emerging/alternative material options require exploration.

A2. Require qualified materials for blanket and first wall structural components.
Closure of dose-temperature design windows and qualified joining/repair methods for Fe-alloys. V-alloys require developed tritium permeation/embrittlement datasets. Emerging/alternative material options require exploration.

A3. Require predictive, multiscale modeling capabilities and open databases.
Need to link atomistic damage and evolving chemistries to long-term engineering performance. Includes gaps such as establishing validated inter-atomic potentials; hydrogen and helium transport models; irradiation defect and transmutation models; mesoscale chemistry and defect-evolution models; mechanical models, and developing open, code-ready datasets.

A4. Require a path to codes and standards.
Fusion-specific design rules and validated small-specimen methods are not yet in place, and there are no clear fusion-specific functional requirements for codes and consistent "rules of the road" for qualification.

A5. Industrial manufacturing, joining and quality assurance are required at scale.
Multi-ton "fusion-power-plant-grade" heats with controlled impurities and repeatable properties require demonstration, along with thick-section product forms, dissimilar joints and repair welds. NDE/QA criteria need to be developed and adopted.

A6. Integrated environment compatibility testing for blanket/first-wall structures is required.
Long-duration coolant and/or breeder compatibility, tritium transport/retention and magnetohydrodynamic (MHD)/electrical insulation effects are not adequately quantified under thermal, mechanical, magnetic, and irradiation loads.

A7. Fusion-spectrum neutron effects testing is required.
Validated data are lacking on fusion-prototypic neutron damage (and high-flux X-ray damage for some approaches), including He/H generation and its coupling to swelling, embrittlement, creep-fatigue, and weld/joint performance.

FIRE Collaboratives

- Integrated Materials Program to Accelerate Chamber Technologies (IMPACT)
- 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

Plasma-Facing Components and Plasma-Material 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 $GW \cdot m^{-2}$; even with mitigation, surfaces must endure 10-20 $MW \cdot m^{-2}$ steady loads and transient spikes far higher. Continuous bombardment by neutrons, ions, and neutral 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 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.

S&T Gaps

B1. Design-quality, predictive PMI basis must be developed.
Insufficient availability of physics-based, validated models that reliably connect near-surface evolution (erosion, morphology, microstructure, composition, retention) to component lifetime and core contamination for the relevant variety of PMI interface solutions.

B2. No divertor solution is validated for pilot plant power exhaust.
Need a scalable divertor concept that survives long pulse >10 $MW \cdot m^{-2}$ loading with transients. Divertor operation (e.g., detachment/impurity-seeding physics) and coupling to the plasma core-edge remain highly uncertain. The integration of reaching high enough divertor neutral pressures for sufficient particle and helium exhaust is critical and has not been fully integrated with seeded, detached divertor solutions.

B3. Solid PFCs and first-wall armor materials must be developed to operate in established operational windows over quantified lifetimes.
Need to prevent/mitigate the effects of simultaneous transmutation, lattice damage, thermal cycling, HHF, erosion/redeposition, tritium retention/permeation, and transients. Emerging/alternative materials in the solid-state class require exploration for power-plant viable solutions.

B4. Liquid metal PFC viability at the component-level and system scale is unproven.
Core uncertainties span plasma-liquid interface physics, MHD/flow/wetting control in strong magnetic fields, corrosion/compatibility with substrates and tritium/impurity extraction at rate and scale.

B5. Heat-sink and joint reliability under combined loads is unqualified.
Creep/fatigue and irradiation limits for Cu-alloy heat sinks, hydrogen/helium embrittlement thresholds, and robust joints lack quantified life rules and accepted QA/NDE standards. Reliability, Availability, Maintainability, and Inspectability (RAMI) aspects of heat sinks are largely unexplored.

B6. U.S. combined-effects test infrastructure and boundary diagnostics are insufficient.
Underdeveloped domestic capability for simultaneous HHF and representative particle flux and x-ray/neutron damage from the coupon to the subcomponent scale. Need to resolve key diagnostics gaps, including scrape-off layer (SOL) and divertor diagnostics, and in-situ diagnostics for QA/NDE evaluations.

B7. 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.

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 (APP-FPP)
- Target Injector Nexus for Development Research (TINEX)
- Fuel Cycle FIRE
- Mitigating risks from abrupt confinement loss
- Fusion Energy Data Ecosystem and Repository

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-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 being a central determinant of plant-scale gain. Together, these technologies are the levers that translate physics headroom into sustained, controllable performance.

S&T Gaps

C1. 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 (MFE); and compression/burn (IFE) and combine their general functionality into design-capable Model-Based Systems Engineering (MBSE) schemes.

C2. 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, high efficiency, reliable driver and target systems at low cost.

C3. Need to achieve high-efficiency fuel delivery/coupling.
Continuous core plasma fueling required (MFE). Overcome laser-plasma interaction limits and optics/debris constraints (in laser IFE) and current shunting in PMF.

C4. Require demonstration of a sustained burning plasma and core performance.
Need a coupled understanding of α-particle physics, confinement, transport, stability and plasma boundary compatibility in fusion-relevant regimes across concepts and show uninterrupted operation at high triple product and net gain (Q).

C5. 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 and helium “ash” without degrading confinement.

C6. Need to demonstrate stability and controllability for reliable plant operation.
Require avoidance and/or mitigation of transient events and certifiable AI/ML supervisory control (MFE). Demonstrate management of symmetry and hydrodynamic instability tolerances and predictive energy coupling (LPI or magnetically insulated transmission lines (MITL) current shunting) (IFE).

C7. Diagnostics require progress and facilities are required to validate relevant scenarios.
Require minimal sets of radiation-hard, control-grade diagnostics for α-particles, impurities, boundary state and fast transients, integrated into FPP-level control schemes. Need shared platforms to validate confinement with exhaust at scale (MFE) and IFE coupling/LPI.

FIRE Collaboratives

- Advanced Profile Prediction for Fusion Pilot Plant Design
- Mitigating risks from abrupt confinement loss
- Neutron-Irradiation-Tolerant REBCO (rare-earth barium copper oxide) Tapes for Compact Fusion (NIT-REBCO)
- 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

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 DT, 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 DT operation, meeting safety standards, and demonstrating the viability of fusion as a large-scale energy source.

S&T Gaps

D1. Tritium self-sufficiency and accountancy as first-order design drivers remain unresolved.
Fuel systems need to self-produce tritium within accountability requirements set by regulators, with validated measurement approaches; efficient tritium processing at relevant rates requires demonstration; effects of fusion neutron irradiation on tritium retention by transmutation are unknown.

D2. 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 a target to fuel-cycle co-design to constrain isotopic/chemical impurities.

D3. 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.

D4. Isotope supply, separation/rebalancing, and storage are not mature.
High-throughput isotope separation and rebalancing, compact safe storage and materials down-selection all require maturation. Planning must address fuel cycle supply risks and by-design minimization of inventory.

D5. 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 release modeling must be defined and validated for power-plant operations.

D6. 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.

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
- Blanket Collaborative on Test Facilities

Blanket Science and 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 plant 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, 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, CO_2, 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.

S&T Gaps

E1. Functional and structural material performance in relevant environments is uncertain.
Corrosion/compatibility for lithium salts, metal alloys, and steels/ceramics, long-term irradiation effects, and tritium thermophysics remain poorly quantified for lifetime predictions and maintainability.

E2. 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 relevant conditions.

E3. 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.

E4. Tritium management within blankets is not mature.
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.

E5. 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.

E6. No validated, integrated blanket design for fusion power plants.
No end-to-end blanket concept fabricated to meet tritium self-sufficiency and heat removal simultaneously, with clear down-selection/qualification rules.

E7. 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.

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
- Integrated Materials Program to Accelerate Chamber Technologies
- Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems

Fusion Plant Engineering and 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 transition toward integrated engineering, where RAMI aspects become primary design principles.

An important part of this is the BOP: the secondary loops of coolants, pumps, heat exchangers, turbines, and controls that convert high-grade heat into usable power. These systems cannot simply be "bolted on"; their physical requirements feed back directly into choices of blanket design, coolant chemistry, tritium control, and materials. This means co-optimizing the fusion engine and BOP so that efficiency, safety, and serviceability are considered from the outset.

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

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. 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 design 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.

S&T Gaps

F1. No validated end-to-end plant-level integrated modeling environment.
Need a modular whole-plant data-model integration environment with standards and UQ to support design, optimization and licensing-relevant analyses. Lack shared library of reference designs, benchmarks, and workflows to compare models, train users, and maintain provenance between experimental data, predictions, and safety-case methodology.

F2. RAMI 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 show a pathway toward target availability.

F3. 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, validated on representative mockups with time-to-repair KPIs and tooling qualification.

F4. 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, including shared engineering standards, design-for-manufacture, and design-for-replacement principles.

F5. 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 remains underdeveloped.

F6. 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. Interfaces (pressures, temperatures, allowable chemistry windows, transients) are poorly defined and not yet treated as design-controlling constraints.

F7. 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.

FIRE Collaboratives

- Blanket Collaborative on Test Facilities
- Fusion Energy Data Ecosystem and Repository
- Accelerating Fusion Blanket Development through Nuclear Testing

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Part II. Technical Milestones → Core Challenge Areas

Figure 6.

Summary of key milestones across all challenge areas over the near-, mid-, and long-term. These represent technical priorities; Congressional appropriations and private investment are required to realize these timelines.

Challenge area	Near term (2-3 years)	Mid term (3-5 years)	Long term (5-10 years)
Structural Materials Science and Technology A	• Develop accelerated qualification pathways for Fe-alloys 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 Fe-alloy and 500 kg V-alloy heats. • Deliver corrosion loops and HHF facility; leverage IMPACT and BCTF FIRE Collaboratives.	• Complete irradiation campaigns and ost-irradiation examinations (PIEs) defining fusion-specific functional requirements up to ~10 dpa for Fe-alloys 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 functional requirements 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, and expanded domestic test infrastructure.
Plasma-Facing Components and Plasma-Material Interactions B	• 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 edge-localized mode (ELM)-like loads. • Quantify erosion-redeposition, cracking and thermal-shock limits for PFC candidates. • Develop coupled physics to digital engineering 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 C	• Expand access to IFE platforms (Omega, NIF, Z) 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 α particle-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-aspect 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. • Launch high-field MHD test loops linking materials, flow and magnet design data via BCTF, Accelerating Fusion Blanket Development through Nuclear Testing (BNT), and Fusion Energy Data Ecosystem and Repository (FEDER) FIRE Collaboratives. • Realize plant-ready IFE target systems and establish validated projection tools integrating lessons from 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 D	• 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 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 IB-FCTF coupling tritium breeding, extraction, and fueling under fusion-relevant conditions.
Blanket Science and Technology E	• 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, Accelerating Fusion Blanket Development through Nuclear Testing (BNT), and Fusion Energy Data Ecosystem and Repository (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-principle 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 and System Integration F	• Launch a centralized, standards-based data repository implementing FAIR principles and tiered access for experiments and simulations. • Publish a common VV/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 and cutting methods for irradiated materials to enable modular in-vessel replacement. • Demonstrate remote handling and 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 and protection systems with radiation-hardened sensors. • Demonstrate automated controls and remote operations in steady state and 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.

43. Progress depends on future appropriations and private investment.

Part II. Infrastructure Pathway

Charting an FS&T Infrastructure Pathway for the Next Era of U.S. Fusion Energy Leadership

The preceding sections have established what the Roadmap aims to deliver and how progress will be measured. This section outlines assumptions on how the infrastructure itself will be developed; the mechanisms that will be employed, how they align with private industry timelines, and the pathway across eight infrastructure streams.

Supporting and Aligning with Private Industry Timelines

This infrastructure pathway reflects a new reality: multiple private developers are already moving toward FOAK demonstration facilities on rapid timelines, backed by substantial private investment to de-risk and demonstrate their approaches. The public program's infrastructure role is therefore twofold: to enable near-term pilot and demonstration needs while also building, or securing access to, the capabilities that allow rapid iteration from first-generation plants to second-generation designs and beyond.

Infrastructure is a primary risk-reduction lever that must harmonize with commercial timelines while preserving long-lived national capabilities. Across a range of emerging private plant concepts, first-generation facilities can also serve as critical integrated test environments for testing component lifetime, maintainability, materials resilience, and the combined effects that only appear under sustained operation with fusion-relevant conditions. The Roadmap emphasizes infrastructure that accelerates credible validation and qualification, supports S&T milestones and metrics, retires technical risk, and informs potential commercial design choices.

No single facility can replicate the full FPP environment; therefore, a portfolio of complementary experimental platforms is needed. Progress depends on coordinated physical testing in relevant conditions, from small-scale loop experiments and test stands to neutron-irradiation and fusion-relevant facilities to prototype power-plant demonstrators. These environments close the data validation loop that links predictive models, AI, manufacturing, and operations. Integration is a staged ecosystem of physical and virtual testbeds where progressively increasing realism feeds model maturity, uncertainty reduction, and ultimately licensing confidence and qualification.

Near-term infrastructure priorities focus on what must exist before first plants demand it: rapid post-irradiation examination capabilities, validated modeling workflows and digital twins to link tests to design margins, and provisional codes, data standards, and qualification pathways. As first-generation systems enter operation, infrastructure must then enable rapid learning and iteration via component and subsystem test facilities, maintenance and remote-handling testbeds, supplier qualification and manufacturing pathways, and DCP infrastructure, which leverages experimental results to inform code development and technology development (i.e., materials discovery). Over longer timescales, the emphasis shifts toward infrastructure that enables cost reduction and performance improvement at scale, such as plant optimization, higher-throughput qualification, improved component and materials options, and repeatable manufacturing and testing capabilities.

Infrastructure Development Mechanisms

Delivering all the critical capabilities across eight Infrastructure Streams will require the public and private sectors to work together with the unified strategy laid out by this Roadmap. DOE will work in concert with the private sector to pursue all options to secure needed capabilities, including:

1. Partnering with private industry and private/strategic capital structures through public-private collaborations to enable access to emerging testing capabilities while simultaneously accelerating private industry maturation.
2. Leveraging international access to unique platforms and capabilities operated by partners within the TBDP while ensuring reciprocal benefits.
3. Upgrading existing domestic infrastructure to develop deeper sovereign capability.
4. Developing new domestic infrastructure that is critical for the advancement of the commercial fusion industry in areas such as HHF testing, blanket and fuel-cycle technology integration, advanced manufacturing, and fusion-prototypic neutron sources integrated in the TBDP.

In addition, infrastructure must support the fusion value chain. This includes developing strategic supply chains in fusion fuels, fusion cycle and breeder blanket components, advanced materials, plasma heating technologies, HTS magnet manufacturing technology, high-power capacitor technology, high-power laser components, and pulser system components, among others.

Partnering with Private Industry and Private/strategic Capital Structures

A central mechanism for near-term infrastructure capacity is a structured partnership with private developers, whereby public objectives (validation evidence, qualification pathways, and shared learning) align with industry's drive to build and operate integrated systems. PPPs can provide access to emerging test stands and de-risking platforms and operational environments that are being created on commercial timelines, while ensuring that the resulting data, methods, and lessons learned can be translated into broader community benefit where appropriate. This includes "bridge" approaches that connect public testing needs to privately built capabilities, as well as the strategic use of private company user-facility models to expand access to specialized platforms. The Roadmap also recognizes the value of leveraging near-term private system opportunities (such as SPARC and ST-40) where collaboration can accelerate validation, mature testing practices, and strengthen the evidence base needed for progress. Another element of PPPs is aligning investments from private/strategic capital structures such as limited partnerships, sovereign wealth funds, and venture capital to critical fusion supply chain technologies that require large-scale infrastructure to address key technological bottlenecks. For example, the development of laser diode components that can be tested at PPP laser beamlet platforms on a path toward fusion commercialization.

> Infrastructure is not an abstract "future need" – it is a primary risk-reduction lever that must harmonize with commercial timelines while preserving long-lived national capabilities.

Leveraging International Access

International partnerships remain essential for timely access to unique capabilities that are already operating (or are closer to readiness) outside of the U.S. The strategy includes deepening existing relationships and establishing targeted and pragmatic partnerships with allies that provide U.S. researchers and developers access to specialized platforms, while also ensuring reciprocal benefit and sustained collaboration. This includes greater engagement with allied nations that have made substantial investments in relevant areas such as science-based long-pulse fusion plasma facilities, materials testing infrastructure, fusion fuel cycle and blanket technology, ion-beam capabilities, and HHF testing platforms. Scientific exchange and coordinated access arrangements can expand U.S. utilization of these assets while also enabling international partners to benefit from U.S. capabilities in complementary areas, strengthening overall coherence and accelerating shared progress. An example is the development of advanced diagnostics to validate multiphysics plasma models used in the design of fusion power plants by private sector developers. The Roadmap is underpinned by quantified metrics along a timeline with milestones to enable prioritization of which international partnerships and infrastructure could be leveraged to address key gaps not addressed by existing or future planned infrastructure. In addition, some redundancy is necessary from the perspective of validation and verification of data that is used to train advanced-algorithm AI models to accelerate the design of advanced fusion systems toward cost-competitive fusion power plants in the U.S.

Upgrading or Accessing Existing Domestic Infrastructure

A major near-term opportunity is to use the extensive U.S. infrastructure ecosystem to address critical gaps outlined by the Roadmap, with special focus on FM&T challenges outlined by the LRP. This includes leveraging expertise in advanced materials characterization from national laboratory light sources and user facilities, high-intensity laser and neutron-based platforms, tritium materials interaction facilities, hydrogen isotope processing and handling infrastructure, and advanced manufacturing capabilities.

In many cases, targeted enhancements or upgrades can unlock significant new capabilities more rapidly than greenfield builds at both user facilities and strategic infrastructure facilities. This strategy will also leverage coordinated planning across DOE offices and relevant agencies, connecting capabilities to ensure that existing assets are modernized and integrated into a coherent national infrastructure network for fusion energy development.

Developing New Domestic Infrastructure

Where gaps cannot be closed through partnerships, enhancements, or upgrades, the Roadmap outlines a plan to develop new domestic infrastructure (subject to annual appropriations) that is essential for commercial fusion progress and cannot be reliably sourced elsewhere. Priorities include facilities and platforms that enable fusion-relevant validation and qualification, particularly in HHF testing, non-radiological and radiation-relevant blanket and fuel-cycle technology development, and their integration, materials component irradiation, irradiated materials handling, fusion supply chain technology development, and development of fusion-prototypic neutron source capabilities. The collection of these small- to medium-scale test stands and capabilities make up the TBDP as described earlier. The TBDP, combined with large-scale facilities such as an FPNS and the IB-FCTF, complemented by the AI-Fusion DCP, comprises the U.S. fusion enterprise to enable fusion energy commercialization. In parallel, the Roadmap anticipates joint investments with DOE equities (subject to annual appropriations) to strengthen the computational and data backbone required to make infrastructure more effective – advancing fusion HPC capacity, AI/ML-enabled workflows, and validated multiphysics tools through the Genesis Mission that accelerate learning across experiments, testing, and operations. Together, these new capabilities reinforce domestic capacity while ensuring that the U.S. infrastructure portfolio remains aligned to deployment-relevant evidence needs over time. In addition, the Genesis Mission is leveraged to unify digital engineering, advanced manufacturing, and extreme robotics to enhance the capabilities necessary for advanced FM&T components development toward cost-competitive fusion power-plant commercialization. Furthermore, these investments are also combined with existing and growing supply chain sectors that benefit fusion energy commercialization and, together with spin-off technologies in broader sectors of nuclear medicine, energy generation, space technology, and industrial plasmas, deliver national and economic prosperity to the U.S. taxpayer for decades to come.

An FS&T Infrastructure Pathway

This Roadmap has identified eight distinct Infrastructure Streams that are critical for the development of an FPP on industry timelines and aligned with the Roadmap's core Challenge Areas. These streams are shown in Figure 7.

Executing this strategy requires tracking the national and international infrastructure landscape, including the broad suite of DOE assets and collaborations, and capturing what the U.S. private fusion industry (including Milestone Program companies) is delivering and what can be accelerated through PPPs. This vantage point enables the public program to focus on identifying and filling critical gaps that strengthen validation and qualification pathways, expand access to fusion-relevant testing, and convert operational learning into faster iteration toward next-generation plants. Appendix 4 provides detailed descriptions for each Infrastructure Stream, including the potential delivery options, and near-, mid-, and long-term timelines for capability development. As with the technical metrics and milestones, the near-, mid-, and long-term timelines that are mapped out to close gaps across the different streams will be tracked, evaluated, and updated over time.

Building, and in many cases integrating, capabilities across the eight Infrastructure Streams is foundational to our ability to address the core Challenge Areas. Together, these streams deliver the scientific and technical basis for the fusion energy industry, as encompassed by the LRP's science drivers to Sustain a Burning Plasma, Engineer for Extreme Conditions, and Harness Fusion Energy. At the highest level, DOE must employ infrastructure strategies and development mechanisms to meet these critical infrastructure needs. The FS&T Infrastructure Pathway (Figure 8) illustrates what foundational infrastructure looks like for a rapidly scaling, successful, world-leading U.S. fusion energy industry of the 2030s and 2040s. It charts the path and sets direction for DOE to prioritize and employ various strategies to deliver on this Roadmap. ▪

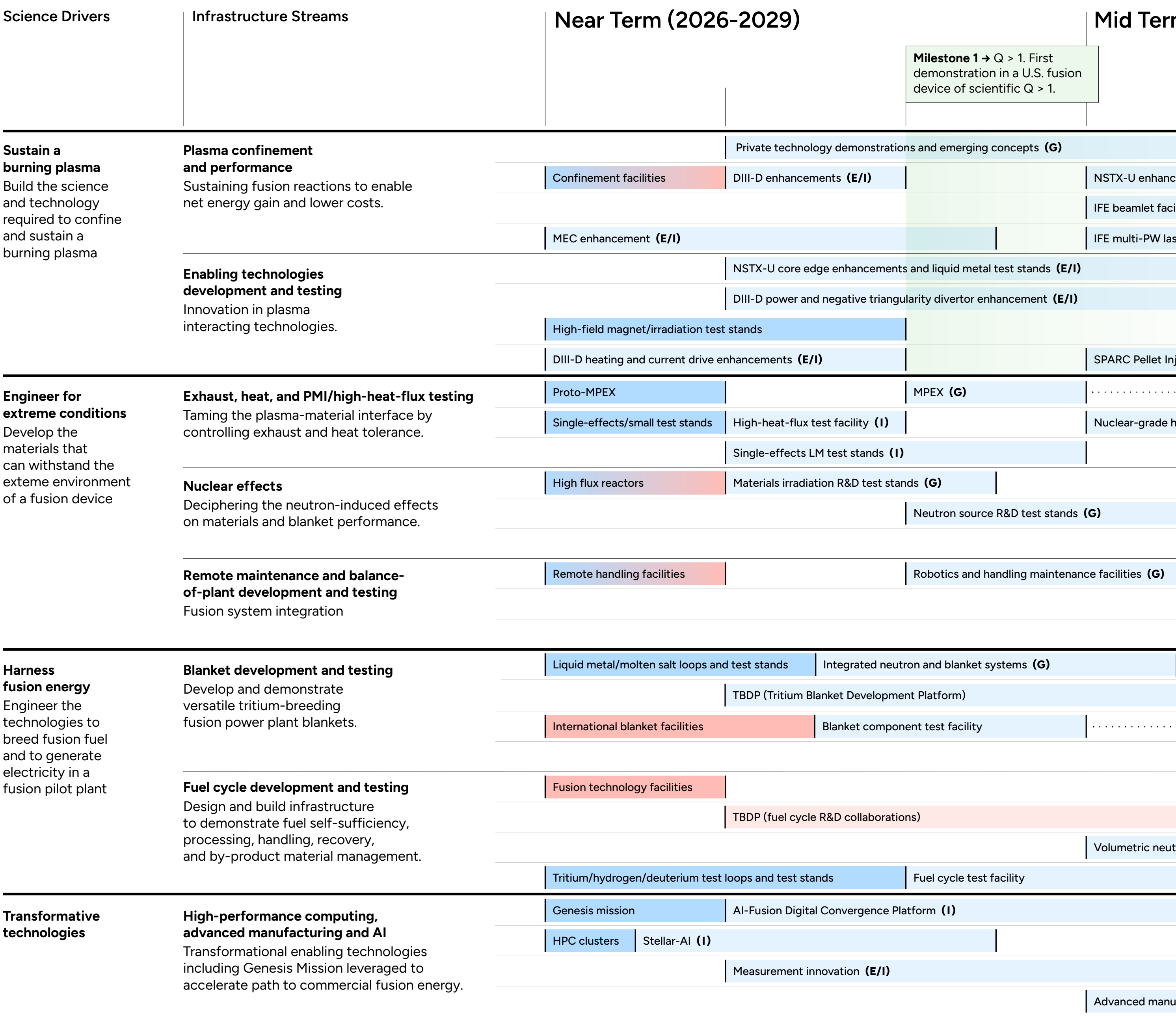
Figure 7.
Infrastructure is arranged across eight distinct Infrastructure Streams critical for developing a fusion power plant on industry timelines, aligned with the three science drivers.

Science Drivers	Infrastructure Streams		
Sustain a burning plasma Build the science and technology required to confine and sustain a burning plasma	**Plasma confinement and performance**	→	Sustaining fusion reactions to enable net energy gain and lower costs.
	Enabling technologies development and testing	→	Innovation in plasma interacting technologies.
Engineer for extreme conditions Develop the materials that can withstand the exteme environment of a fusion device	**Exhaust and plasma/ high-heat-flux testing**	→	Taming the plasma-material interface by controlling exhaust and heat tolerance.
	Nuclear-effects testing (including fusion prototypic neutrons and hot cell capabilities)	→	Deciphering the neutron-induced effects on materials and blanket performance.
	Remote maintenance and balance-of-plant development and testing	→	Fusion system integration
Harness fusion energy Engineer the technologies to breed fusion fuel and to generate electricity in a fusion pilot plant	**Blanket development and testing**	→	Develop and demonstrate versatile tritium-breeding fusion power plant blankets.
	Fuel-cycle development and testing	→	Design and build infrastructure to demonstrate fuel self-sufficiency, processing, handling, recovery, and by-product material management.
Transformative technologies	**High-performance computing, advanced manufacturing and AI**	→	Transformational enabling technologies including Genesis Mission leveraged to accelerate path to commercial fusion energy.

Part II. Infrastructure Pathway

Figure 8.

This FS&T Infrastructure Pathway provides a potential future set of foundational infrastructure for a rapidly scaling, successful, world-leading U.S. fusion energy industry of the 2030s and 2040s. It helps set direction for the U.S. public and private sector to identify needs and align capabilities toward achieving Roadmap goals.



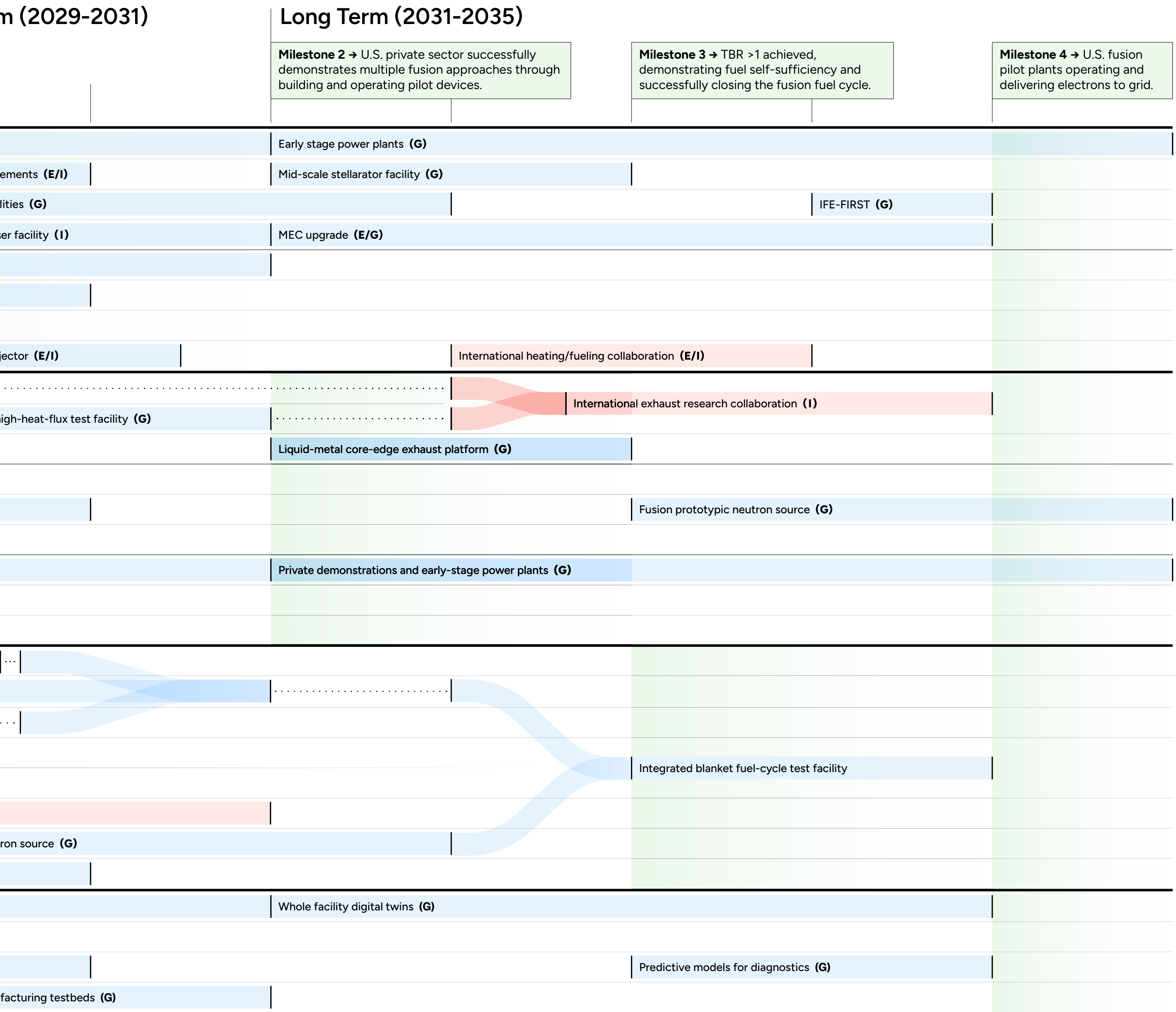
Development Type

- Domestic delivery window of infrastructure → **Existing**
- Domestic delivery window of infrastructure → **Future**
- International delivery window of infrastructure → **Existing**
- International delivery window of infrastructure → **Future**

Development Stage

- **(E)** Enhancement
- **(I)** In planning
- **(G)** Gap identified
- Key Milestone

The information in this graphic does not commit the Department of Energy to specific funding levels, collaborations, or activities, and future funding will be subject to Congressional appropriations. Facilities listed may be existing, under construction, in planning, notional, or needed and include any domestic (public or private) and/or international capabilities that the U.S. ecosystem may be able to leverage in the future.

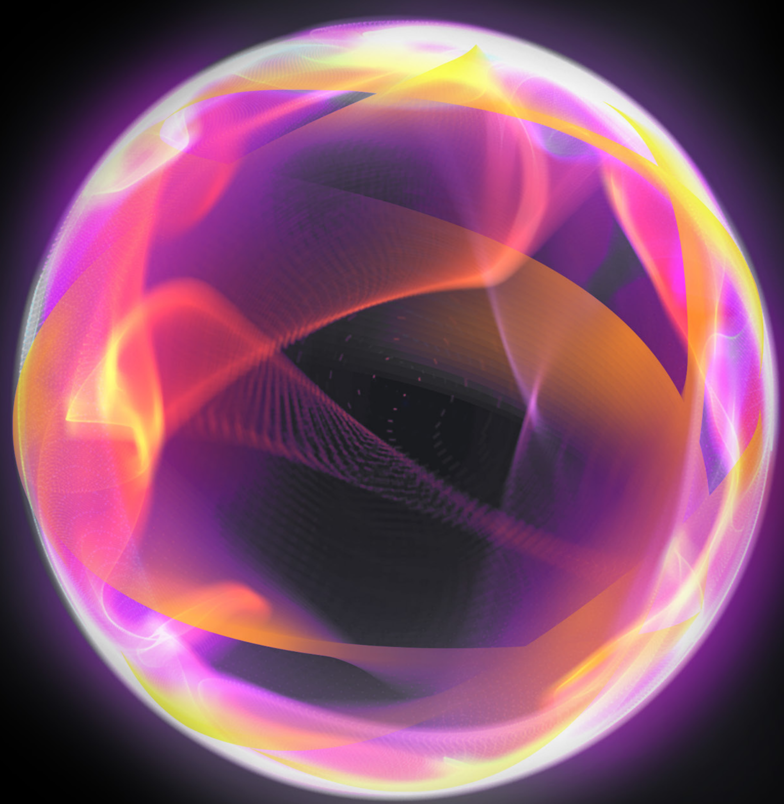


This FS&T Roadmap reflects DOE's vision to align the public and private sectors and sets the course to Build-Innovate-Grow the world-leading U.S. fusion energy industry. The goal of the Roadmap is to deliver the public infrastructure that supports the fusion private sector scale-up in the 2030s.

Roadmap Key Actions set the course for capability delivery, while Technical Metrics and Milestones track progress on closing the most critical scientific and technical challenges. The prioritization of infrastructure is the foundation of this Roadmap and is reflected in the FS&T Infrastructure Pathway. Closing critical gaps by achieving these metrics and milestones requires delivering on the FS&T Infrastructure Pathway and will ensure that the U.S. fusion industry has access to the capabilities required for its critical path to successful deployment and commercialization.

The Roadmap charts a path for the public and private sectors to work together with a unified strategy to ensure that the U.S. is progressing toward fusion commercialization on the most rapid, credible timeline in history. This approach enables the public program to remain nimble and prioritize resources with decisions that may require pivoting as fusion developers accelerate toward 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 communities. ■

"The Roadmap charts a path for the public and private sectors to work together with a unified strategy to ensure that the U.S. is progressing toward fusion commercialization on the most rapid, credible timeline in history."



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Appendix 1

A New Era of U.S. Fusion Energy Leadership

Appendix 1

A New Era of U.S. Fusion Energy Leadership

The U.S. has led innovation in nuclear fusion since the 1940s,[44,45] with significant fusion research carried out during the Manhattan Project, including measurements of the fusion DT cross section. In the 1950s, the U.S. launched Project Matterhorn under the Atomic Energy Commission (AEC) to pursue stellarator-based, magnetically-confined thermonuclear fusion research led by Lyman Spitzer, an effort that later became part of the DOE's 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 multiple fusion energy efforts. The Princeton Large Torus at PPPL demonstrated record electron temperatures using neutral beam heating in a magnetically-confined plasma. In parallel, experimental successes in inertial confinement at KMS Fusion and LLNL confirmed the viability of producing thermonuclear neutrons with lasers. The U.S. deployed advanced diagnostic systems internationally, including instruments on magnetically-confined tokamak devices such as TEXTOR in FZ Juelich (Germany) and 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 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 technology.[46]

Since the early 1990s, building on decades of fusion energy R&D, the U.S. has developed some of the world's most sophisticated multiphysics computational codes validated with world-leading diagnostic tools,[47,48] on world-class domestic facilities such as DIII-D (a joint U.S.-Japan collaboration), NIF,[49] 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 (deuterium-deuterium) plasma devices.

In the 2000s, fusion technology activity began to grow modestly in the U.S. under the Advanced Power Extraction (APEX) and Advanced Limiter-divertor Plasma-facing Systems (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 in earnest.

In the 2010s, the rise of 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 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, U.S. companies have received over $10 billion in private equity investment. According to the FIA's 2025 Global Fusion Industry report, the U.S. is home to the largest number of fusion companies (29) in the world, including the only three companies to have raised over $1 billion in 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 toward 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 PPPs 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 an FPP, 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 toward adoption by electricity markets. The report also referred to the innovation and technology necessary to meet these specifications, and the projects needed to close the science gaps of a burning fusion plasma at the scale of a power plant. Since 2021, significant progress has been made toward defining an FPP pathway to fusion energy. Collaboration in the U.S. among the USG, FIA, and other entities, such as the Special Competitive Studies Project (SCSP), is helping drive momentum toward 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 no longer reflect current realities:

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 has supported 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. In 2024, delays in ITER first plasma until mid-2030s and DT operations until end of 2030s were announced. In parallel, progress is being made toward an FPP in the 2030s, supported by both DOE investments (e.g., FIRE Collaboratives, the Milestone Program, INFUSE, and the base research program) and private sector investment. While ITER remains a part of the U.S. fusion energy development strategy, the fast-evolving private sector provides new opportunities for federal investment in commercially-relevant de-risking platforms and infrastructure. Emerging priorities include leveraging PPPs that enable a path toward an FPP in the U.S. at a timescale commensurate with the investments made from the private sector. Major technology de-risking paths are outlined in the Roadmap Challenge Areas and accompanied by 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, since the 2021 report, the concept of a national program where the public program would lead an effort to design and construct an FPP has been revised. While the public program continues to support the foundational science required for fusion energy, near-term deployment of an FPP is supported by the Milestone Program led by the private sector and enabled by the public investment. The accelerated path of the private sector requires federal research investment to address the most common and critical gaps that the private sector will not be able to de-risk. ▪

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Appendix 2

FIRE Collaborative Ecosystems

Appendix 2

FIRE Collaborative Ecosystems

The FIRE Collaborative Ecosystems bridge foundational science activities (TRL 1-2) and more mature development (TRL 3-4), connecting scientific discovery to the early-stage technology development needed by the growing fusion industry (e.g., the technology roadmaps of Milestone Program awardees). They link the incubation of ideas in the FES base program to industry-defined FM&T gaps through PPP activities.

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 FIRE Collaboratives to function as accelerated, result-driven research projects. They will use real-time results to inform research direction, allowing agile adjustments and, where outcomes or shifts in priorities warrant, discontinuation of projects. 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 below.[50]

→ **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. This project enables two U.S. materials (steel and V-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. This project accelerates U.S. leadership in rapid materials modeling, development, and assessment to support the commercial fusion industry.

→ **Accelerating Fusion Blanket Development through Nuclear Testing**
This project will provide relevant nuclear testing and data on blanket technologies using existing fission irradiation facilities and establish the nuclear infrastructure necessary to test blanket components.

→ **Fuel Cycle FIRE**
This project will integrate modeling, materials, and processing R&D to de-risk DT fuel cycles, reduce tritium inventory and releases, validate DIR, and align designs with industry for fusion power plants.

→ **Target Injector Nexus for Development Research**
This project 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**
This project produces high-fidelity whole-device predictions of density, temperature, and 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. This project will develop an integrated design loop for composite architectures of materials in reactor-relevant scenarios.

→ **Blanket Collaborative on Test Facilities**
This project is 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 that are 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 University of Wisconsin-Madison (UW-Madison) Wisconsin HTS Axisymmetric Mirror (WHAM) facilities. Additionally, this project will develop cooling components with additive manufacturing.

→ **Neutron-Irradiation-Tolerant REBCO Tapes for Compact Fusion**
Fusion concepts require HTS magnets using REBCO tapes 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 the technical readiness of liquid metal PFCs for their consideration in fusion reactor designs.

→ **Mitigating Risks from Abrupt Confinement Loss**
This project will 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 project will provide the critical infrastructure enabling accessibility, interoperability, and standardization of datasets, models, and workflows across the fusion community.

50. 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.

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Appendix 3

Technical Appendix: Detailed Metrics, Milestones, and Timelines for all Challenge Areas

This section outlines ideal metrics, milestones, and timelines to address the challenge areas. Execution will depend on Congressional appropriations for public funding and private investment.

Structural Materials Science and Technology

Backbone of a Fusion Power Plant

Structural materials represent the load-bearing framework of a fusion power plant, forming the vessel, internal supports, blanket structures, and shielding that must operate reliably in one of the harshest engineered environments. These materials must endure sustained high thermal loads, intense x-ray and neutron irradiation, corrosive coolants, and strong mechanical stresses while retaining strength and toughness and providing overall functional performance over long service lifetimes.

Structural materials underpin nearly every major subsystem. The vacuum vessel and in-vessel support must provide a robust structural boundary and preserve dimensional integrity while absorbing electromagnetic forces during disruptions and other transients (MFE) and X-ray and ion discharges (IFE). The first wall and blanket structures support components that directly face the plasma and contain working fluids, transferring heat for power conversion and enclosing tritium-breeding materials. Structural materials must also support magnets, cooling channels, and maintenance interfaces, all while being manufacturable at scale, compatible with joining and repair techniques, and meeting NDE/QA criteria required of a power plant.

Fusion operating conditions are extreme. High-energy neutrons displace atoms and transmute elements, causing swelling, embrittlement, and changes in chemistry and associated material properties; intense x-ray bursts can ablate first wall layers; cyclic thermal and mechanical loading drives creep-fatigue damage; and exposure to coolants or liquid-phase functional materials can accelerate corrosion and erosion, effects which may be intensified by simultaneous irradiation. Hydrogen isotopes, including tritium, can also permeate and become trapped within materials, posing additional safety and lifetime risks.

Developing and qualifying structural materials, such as iron alloys (Fe-alloys), Vanadium alloys (V-alloys), silicon carbide (SiC), silicon carbide composites (SiC-SiC), 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.

S&T Gaps

A1. Require qualified materials for vacuum vessels and in-vessel supports. Including fusion-relevant irradiation data for swelling, transmutation, embrittlement, joint toughness, creep-fatigue, tritium transport, and coolant compatibility. Emerging/alternative material options require exploration.

A2. Require qualified materials for blanket and first wall structural components. Closure of dose-temperature design windows and qualified joining/repair methods for Fe-alloys. V-alloys require developed tritium permeation/embrittlement datasets. Emerging/alternative material options require exploration.

A3. Require predictive, multiscale modeling capabilities and open databases. Need to link atomistic damage and evolving chemistries to long-term engineering performance. Includes gaps such as establishing validated inter-atomic potentials; hydrogen and helium transport models; irradiation defect and transmutation models; mesoscale chemistry and defect-evolution models; mechanical models, and developing open, code-ready datasets.

A4. Require a path to codes and standards. Fusion-specific design rules and validated small-specimen methods are not yet in place, and there are no clear fusion-specific functional requirements for codes and consistent "rules of the road" for qualification.

A5. Industrial manufacturing, joining and quality assurance are required at scale. Multi-ton "fusion-power-plant-grade" heats with controlled impurities and repeatable properties require demonstration, along with thick-section product forms, dissimilar joints and repair welds. NDE/QA criteria need to be developed and adopted.

A6. Integrated environment compatibility testing for blanket/first-wall structures is required. Long-duration coolant and/or breeder compatibility, tritium transport/retention and MHD/electrical insulation effects are not adequately quantified under thermal, mechanical, magnetic, and irradiation loads.

A7. Fusion-spectrum neutron effects testing is required. Validated data are lacking on fusion-prototypic neutron damage (and high-flux X-ray damage for some approaches), including He/H generation and its coupling to swelling, embrittlement, creep-fatigue, and weld/joint performance.

FIRE Collaboratives and FES program areas

- 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

The Fusion Materials and Internal Components sub-element of the FES program will also advance the milestones listed in this section.

Symbol indicates **Genesis Mission** impact

Near term → 2-3 years	**Validate accelerated qualification pathways for fusion materials** **Metric →** Qualification data for at least one fusion structural material produced within three years. **FIRE →** Integrated Materials Program to Accelerate Chamber Technologies → Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design **S&T Gaps → A4**	**Develop AI-enabled material database strategy** **Metric →** Complete first-generation fusion materials database with strategy for implementing AI. **FIRE →** Fusion Energy Data Ecosystem and Repository → Integrated Materials Program to Accelerate Chamber Technologies **S&T Gaps → A3**	**Establish American industrial bulk-scale production capability for priority materials** **Metric →** Multi-ton Fe-alloy heats; ≥1 metric ton melts of solution-strengthened V-alloy heat(s); three separate melts for industrial standard qualification. **FIRE →** Integrated Materials Program to Accelerate Chamber Technologies **S&T Gaps → A5**	**Close the tritium/coolant/breeder knowledge gaps for blankets/first wall structural materials** **Metric →** Defined corrosion limits for all materials; maintain strict redox control; validate dissolution limits. **FIRE →** Blanket Collaborative on Test Facilities → Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design **S&T Gaps → A6, E1**	
Mid term → 3-5 years	**Ion and neutron irradiation and qualification data and analysis for domestic V and Fe-based, industrial heat, structural alloys** **Metric →** For at least one advanced Fe-alloy: dual-beam ion irradiations to 1-50 dpa centralized around 350-400 °C. For at least one V-alloy dual ion irradiations performed at 400-750 °C at doses of 1-50 dpa. For both alloys, neutron irradiation campaign at 2-5 dpa, and elevated temperatures. **FIRE →** Integrated Materials Program to Accelerate Chamber Technologies **S&T Gaps → A1, A2**	**Establish baseline tritium retention, permeation, and transport property datasets** **Metric →** For at least one domestic Fe-alloy: measure H/D/T retention and permeation in unirradiated vs. irradiated samples. For V-alloys quantify hydrogen isotope diffusion/solubility up to ~700 °C in at least one domestic alloy. **FIRE →** Fusion Energy Data Ecosystem and Repository → Integrated Materials Program to Accelerate Chamber Technologies **S&T Gaps → A2, A6**	**Build property databases and define safe operating windows under fusion-relevant conditions for Fe-based and V-alloys** **Metric →** Transmutation and synergy (He/H and damage) studies: establish mechanisms for swelling/phase stability/dislocation evolution. Set up irradiation campaigns (with ion, fission/mixed spectrum; fusion-prototypic source later. Coolant compatibility screening for candidate grades. **FIRE →** Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems → Integrated Materials Program to Accelerate Chamber Technologies → Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design **S&T Gaps → A1, A2**	**Close environmental coatings knowledge and performance gaps** **Metric →** H isotope permeation (permeation reduction factor (PRF) at temperatures > 100 °C) **FIRE →** Blanket Collaborative on Test Facilities → Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design **S&T Gaps → A6**	**Identify emerging structural materials for progression to TRL 3/4 (including structural composites)** **Metric →** Fracture toughness: >30 $MPa\sqrt{m}$ at room temperature after irradiation up to 50 dpa. → Swelling: <1% at 50 dpa (RAFM steel). Thermal conductivity: >33 $W \cdot m^{-1} \cdot K^{-1}$ at 20 °C (RAFM steel). → High-temperature yield strength: >280 MPa at 650 °C. Demonstrated pathway to scalability. **FIRE →** Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design **S&T Gaps → A1, A2**
Long term → 5-10 years	**Demonstrate domestic manufacturing at scale with QA/acceptance standards** **Metric →** Impurity thresholds: For Fe-alloys, O, N, C levels kept below ~200–300 weight parts per million (wppm) in "clean steels". For AM-assisted builds <1% porosity (ideally <0.5%) and anisotropy in tensile/creep <10% across orientations. **FIRE →** Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design **S&T Gaps → A5**	**Complete post-irradiation examination milestones to anchor design requirements using data from fusion prototypic irradiation campaigns** **Metric →** For at least one alloy, PIE after neutron irradiation to ≥~5 dpa at ~400-700 °C; integrate with high-temperature test data for V-alloys. Validate "low swelling up to ~25–50 dpa" for Fe-alloys. Metrics may be adjusted through continual private sector input process. **FIRE →** Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems **S&T Gaps → A1, A2**	**Codify materials/joints for FPP component classes** **Metric →** Enable code qualification for an initial stage of ~3–5-year design lifetime, as required in collaboration with private industry and regulators. **FIRE →** Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems **S&T Gaps → A1, A2, A5**	**Release integrated design tools for fusion-relevant material evolution** **Metric →** Level of fidelity, level of accessibility by fusion companies, and level of VV. **S&T Gaps → A3**	

Structural Materials Science and Technology

Mapping the Near-term Milestones

In the near term, a high priority will be placed on developing and validating accelerated qualification pathways for fusion materials. This will be applied first to RAFM steels and V-alloys, with the ambition of developing qualification datasets within four years (SiC and SiC-SiC pathways will also be considered as a long-term solution). Complementing this will be the development of a centralized materials database strategy, initially focused on leveraging partner fission facilities, AI, high-performance computing for dataset population, and multi-scale computational materials modeling validation and verification, driving material discovery. These two initiatives will position the U.S. as a leader in fusion materials qualification and standards development.

Parallel progress will be made on domestic capabilities to produce industrial heats. A path will be developed toward the production of multi-ton RAFM steel heats, 500 kg V-alloy heats, and pilot-scale advanced tailored alloys, as well as the scaling of functional coatings and composites for optimization of the PMI and aiding tritium accountancy and permeation issues. These production pathways will mark a milestone in establishing a reliable domestic supply chain and manufacturing capability.

Addressing compatibility and tritium management gaps will also be critical. Dedicated test loops and hot-cell studies will quantify RAFM and V-alloy interactions with Li, PbLi, and FLiBe coolants (among others), including weld performance and tritium permeation, and solid solution, i.e., pebble-bed technology. These results will narrow operating windows and guide early blanket and first-wall concepts. Concurrently, researchers will continue to develop and progress emerging low-activation structural materials, benchmarking them against RAFM through ion irradiation and mechanical testing to identify candidates ready for TRL advancement. This includes graded composites and functional coatings being developed through the FIRE Collaboratives.

These milestones will be supported by new proposed infrastructure, including corrosion test loops, thermal creep, fracture, and fatigue testing rigs, high-heat-flux facilities, fission high-flux research reactors, ion-beam surrogate irradiation facilities with in-situ electron microscopy capabilities, and expanded hot-cell capacity. FIRE Collaboratives, such as the Integrated Materials Program to Accelerate Chamber Technologies and the Blanket Collaborative on Test Facilities, will also support these milestones and provide vital links into industry. The Fusion Materials and Internal Components sub-element of the FES program will also advance the milestones listed in this section.

Mapping the Mid-term Milestones

Over the next 3-5 years, the program aims to complete irradiation campaigns and post-irradiation examinations that anchor fusion-specific functional requirements for priority alloys for structural material. Work will focus on Fe-alloys and V-alloys, using fission/mixed-spectrum irradiations and controlled thermal exposure to deliver design-useful datasets on high-temperature creep-fatigue, end-of-life swelling, and ductile-to-brittle transition temperature (DBTT)/helium-assisted embrittlement characterization. A key outcome will be to quantify bulk property changes up to ~10 displacements per atom (dpa) in leading RAFM steels, establishing validated bounds for deformation, toughness, and swelling resistance in fusion-relevant windows. In parallel, teams will determine the temperature-stress-He conditions that trigger unacceptable high-temperature helium embrittlement in candidate materials.

In tandem, the community will establish baseline tritium retention, permeation, and transport datasets across Fe-alloys, V-alloys, and composites, including the use of functional coatings and composites to aid tritium permeation performance. Dose-dependent databases will integrate irradiation response, coolant compatibility/corrosion results, high-heat-flux and mechanical testing, and H/He effects, so that safe operating windows can be defined coherently for each material class. Data frameworks and AI-enabled selection and advancement, e.g., via FEDER, will standardize formats and uncertainty quantification to progress these datasets. This will also enable connecting to system-based engineering approaches to translate the gap closure research to industrial R&D and project mapping. The program will also examine environmental coatings, emphasizing electrical resistivity targets and tritium permeation-reduction performance under gradients, cyclic thermal stresses, and controlled impurities.

These milestones will be enabled by domestic spallation sources, high-flux fission facilities and hot cells, targeted ion and proton capabilities at multiple facilities, including the Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center (PSFC), the UW-Madison Ion Beam Lab, the University of Tennessee, Knoxville (UTK) Ion Beam Materials Laboratory (IBML), and the University of California San Diego (UCSD) POSEIDON, PISCES-RF, and limited-access DT sources for select exposures. The strategy leverages cross-office infrastructure (BES, Nuclear Physics (NP), NE) to provide surrogate environments where fusion-only options are not yet available. FIRE Collaboratives, including FIRE IMPACT and the Rapid High-Fidelity Bulk Irradiated Materials Data effort, will coordinate bulk irradiated datasets and accelerate ingestion into the shared repositories that drive qualification.

Mapping the Long-term Milestones

In the long term, structural materials research will shift from exploratory and surrogate campaigns to full demonstration of sub-component-relevant performance under fusion-prototypic conditions, including access to a U.S.-based FPNS, and/or international facilities. Fe-alloys and V-alloys will need to be carried forward into the regime of tens of dpa and hundreds of atomic parts per million helium at high temperatures. Post-irradiation examinations of specimens and mock-ups will generate validated datasets on creep-fatigue, swelling, and helium-assisted embrittlement, providing confidence in time-to-failure projections.

With these datasets in hand, and as determined by the fusion industry to be helpful for obtaining regulatory approval, design rules and fusion-specific functional requirements will be codified into recognized standards such as American Society of Mechanical Engineers (ASME) code cases, anchored by validated small-specimen methods. This step will inform licensing approaches for pilot plant components and establish component-class acceptance criteria for Fe-alloys and V-alloys subassemblies. In parallel, integrated multiscale modeling tools will be released, allowing designers to simulate material evolution under complex loading, irradiation, and tritium exposure histories – moving predictive capability from research codes into industry practice. Equally critical will be the demonstration of domestic manufacturing at scale. Thick-section heats, dissimilar joints, and advanced tailored alloys (ATAs) will be produced under rigorous QA processes in alignment with regulatory requirements, with additive manufacturing qualified for complex geometries.

These milestones will be advanced through FEDER, IMPACT, and the Rapid High-Fidelity Bulk Irradiated Materials Data Collaborative, which will ensure standardized data capture, uncertainty quantification, and design integration. Infrastructure will focus on progress to build and commission a domestic FPNS and expanded domestic high-heat-flux and plasma flux facilities. These platforms will provide the critical testbeds needed to validate materials performance, manufacturing, and code qualification under prototypic fusion conditions that enable materials discovery to support a competitive U.S. fusion power industry. ■

Plasma-Facing Components and Plasma-Material Interactions

Materials at the Edge of Fusion

PFCs form the critical interface between the plasma and the engineered systems of a fusion power plant. Depending on the specific fusion approach, they may include the first wall and its possible coatings, which shield the vacuum vessel and blankets; the divertor, which exhausts most of the heat and particles; protection limiters, which shield the first wall from on- and off-normal events; and HHF cooling structures, which 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 $GW{\cdot}m^{-2}$; even with mitigation, surfaces must endure 10-20 $MW{\cdot}m^{-2}$ steady loads and transient spikes far higher. In pulsed/inertial confinement approaches, materials are subject to extremely intense bursts of x-rays and neutrons. Continuous bombardment by neutrons, x-rays, ions, and neutral 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 power, remove helium ash and impurities, and maintain high plasma densities without degrading plasma confinement. Divertor geometry and magnetic configuration will define operating limits of the FPP, and advanced divertor designs, such as super-X, snowflake, and liquid-metal divertors, aim to expand this space in the divertor (and hence the FPP) operational regime. For inertial fusion approaches, the chamber will face high-heat fluxes and dynamic environmental conditions. The materials to withstand repetitive IFE burn conditions at 1-20 Hz need to be addressed. In many magnetic fusion systems, 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 operations.

S&T Gaps

B1. Design-quality, predictive PMI basis must be developed. Insufficient availability of physics-based, validated models that reliably connect near-surface evolution (erosion, morphology, microstructure, composition, retention) to component lifetime and core contamination for the relevant variety of PMI interface solutions.

B2. No divertor solution is validated for pilot plant power exhaust. Need a scalable divertor concept that survives long pulse >10 $MW{\cdot}m^{-2}$ loading with transients. Divertor operation (e.g., detachment/impurity-seeding physics) and coupling to the plasma core-edge remain highly uncertain. The integration of reaching high enough divertor neutral pressures for sufficient particle and helium exhaust is critical and has not been fully integrated with seeded, detached divertor solutions.

B3. Solid PFCs and first-wall armor materials must be developed to operate in established operational windows over quantified lifetimes. Need to prevent/mitigate the effects of simultaneous transmutation, lattice damage, thermal cycling, HHF, erosion/redeposition, tritium retention/permeation, and transients. Emerging/alternative materials in the solid-state class require exploration for power-plant viable solutions.

B4. Liquid metal PFC viability at the component-level and system scale is unproven. Core uncertainties span plasma-liquid interface physics, MHD/flow/wetting control in strong magnetic fields, corrosion/compatibility with substrates and tritium/impurity extraction at rate and scale.

B5. Heat-sink and joint reliability under combined loads is unqualified. Creep/fatigue and irradiation limits for Cu-alloy heat sinks, hydrogen/helium embrittlement thresholds, and robust joints lack quantified life rules and accepted QA/NDE standards. RAMI aspects of heat sinks are largely unexplored.

B6. U.S. combined-effects test infrastructure and boundary diagnostics are insufficient. Underdeveloped domestic capability for simultaneous HHF and representative particle flux and x-ray/neutron damage from the coupon to the subcomponent scale. Need to resolve key diagnostics gaps, including SOL and divertor diagnostics, and in-situ diagnostics for QA/NDE evaluations.

B7. 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.

FIRE Collaboratives and FES program areas

- 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

In addition to FIRE Collaboratives, the Materials and Internal Components and Sustain a Burning Plasma sub-elements of the FES program also address key gaps and Milestons outlined in this section.

Symbol indicates **Genesis Mission** impact

Near term → 2-3 years	**Establish American leadership in throughput for HHF/PMI steady-state testing** **Metric →** Complete testing of candidate PFMs (tungsten, liquid metal) at steady-state heat flux between 1 and at least 10 MW·m^{-2}, with PMI-relevant plasma phenomena, component-scale exposure area (1 m^2), and He cooling. **S&T Gaps → B6**	**Compile FPP-relevant data and component behavior for solid PFCs and heat sinks (W/Cu classes)** **Metric →** H/He/impurity surface evolution at high-fluence (>10^{28} m^{-2}) ELM-like thermal shocks: ~0.3-0.6 GW·m^{-2} as cracking threshold (especially surface temperatures < 500 °C). **FIRE →** Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems → Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components → Fusion Energy Data Ecosystem and Repository **S&T Gaps → B3**	**Develop tools and workflows for divertor design and optimization for MFE concepts** **Metric →** Calculate heat-flux and predict particle pumping for a divertor in the order of 1-5 CPU hours inside an optimization loop. **FIRE →** Advanced Profile Prediction for Fusion Pilot Plant Design → Mitigating risks from abrupt confinement loss **S&T Gaps → B2**	**Progress liquid first walls for IFE chamber applications** **Metric →** Remove evaporated and recondensed material from the chamber to a sufficient degree to allow successful propagation of the driver beam into the chamber to ignite the target and to allow successful injection of the target into the chamber. **FIRE →** Advancing Maturity of Liquid Metal Plasma-Facing Materials and First Wall Concepts → Target Injector Nexus for Development Research **S&T Gaps → B4**	**Develop insulators and purification techniques of liquid Li streams, and small-scale component inserts** **Metric →** Compare efficiency of hydrogenic species extraction from liquid Li, and demonstrate sufficient recovery efficiency of hydrogen from liquid Li. Evaluate multiple impurity removal techniques from liquid Li stream. Liquid-Li compatible insulators demonstrated for >100 hours of continuous operation. Down-select and test candidate liquid Li system inserts in plasma confinement device(s), to prepare for larger scale deployment. **FIRE →** Advancing Maturity of Liquid Metal Plasma-Facing Materials and First Wall Concepts **S&T Gaps → B4**
Mid term → 3-5 years	**Demonstrate liquid PFC systems in controlled, flowing configurations** **Metric →** A liquid metal system demonstrated in a confinement device(s) that dissipates peak heat flux of 5-10 MW·m^{-2} and maintains H-mode level energy confinement. A liquid Li system that demonstrates handling of transients between 10-100 MW·m^{-2}. **FIRE →** Advancing Maturity of Liquid Metal Plasma-Facing Materials and First Wall Concepts **S&T Gaps → B4**	**Demonstrate divertor designs that are capable of detached operation with high particle exhaust and core performance** **Metric →** Radiated power fraction above 90% at high unmitigated parallel heat flux > 5 GW·m^{-2} No more than 10% drop of stored energy when plasma detaches. Divertor neutral pressure sufficient to exhaust He ash and control density and simultaneous particle flux mitigation, heat flux no more than 10 MW·m^{-2}, surface temperature < recrystallization temperature. **FIRE →** Mitigating risks from abrupt confinement loss **S&T Gaps → B2**	**Demonstrate survivability of joints and heat affected zone evolution, impact on joining technique and integrated PFC survivability under fusion-relevant conditions** **Metric →** Demonstrate component-level joints/graded interfaces that survive ≥10 MW·m^{-2} steady loads. Joint/Transition Integrity under low- and high-cycle fatigue testing at these thermal loads without macro-cracking/debonding. **FIRE →** Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components **S&T Gaps → B5**	**Identify emerging PFC materials for progression to TRL 3/4** **Metric →** Thermal conductivity: >170 W·m^{-1}·K^{-1} at 20 °C (Pure tungsten) Plasma erosion: <3.4 μm/h at 650 °C and 10^{22} ions·m^{-2}·s^{-1} of plasma ion flux (Erosion of 30 mm thickness in 1 year) Tritium solubility: <5 × 10^{20} tritium/√Pa·m^3 at 650 °C (Pure tungsten) Tritium diffusivity: >1.6 × 10^{-8} m^2/s at 650 °C (pure tungsten). Demonstrated pathway to scalability. **FIRE →** Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components → Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems **S&T GAPS → B3, B4**	
Long term → 5-10 years	**Validate solid PFC (W-based alloys) components and integrated behaviors in relevant environments** **Metric →** Plan thermal loads around 0.3-0.6 GW·m^{-2} crack thresholds for pure W (stricter at T < 500 °C). Component manufacturing with radiation-tolerant properties. **FIRE →** Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components → Advanced Profile Prediction for Fusion Pilot Plant **S&T GAPS → B1, B3**	**Conduct prototypic-fusion spectrum irradiation campaigns on W-based PFCs and key joints** **Metric →** Neutron-produced defects and transmutation products data gaps at >10 dpa. Joint/Transition Integrity under low- and high-cycle fatigue testing at prototypic heat loading without macro-cracking/debonding (in both pre- and post-irradiation testing). Interfacial tensile strength ≥100-130 MPa, with retention post-irradiation. **FIRE →**Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems **S&T GAPS → B3, B5**	**Release integrated design tools for fusion-relevant material evolution** **Metric →** Produce datasets at high particle fluence (>10^{28} m^{-2}) and relevant T for W and W-based PFMs Steady heat flux of at least 10 MW·m^{-2}, with PMI-relevant plasma phenomena. **FIRE →** Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components → Mitigating risks from abrupt confinement loss → Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems **S&T GAPS → B7**	**Deliver focused W-PMI data campaign to progress candidate solid PFCs in fusion relevant conditions** **Metric →** Current erosion rate of W first-wall armor is ~3 μm/h under a high-energy (~keV) ion flux ~10^{22} ions/(m^2·s). Requires a significant (factor of ~50) reduction in this metric. **FIRE →** Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components → Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems **S&T Gaps → B1, B2, B3**	**Validate liquid PFCs in fusion-relevant flux conditions** **Metric →** 10-100 MW·m^{-2} steady removal in tokamak-relevant geometry with flowing Li including dissipation by plasma-liquid metal interactions. **FIRE →** Advancing Maturity of Liquid Metal Plasma-Facing Materials and First Wall Concepts → Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components **S&T Gaps → B4**

Plasma-Facing Components and Plasma-Material Interactions

Mapping the Near-term Milestones

In the near term, the priority is to establish U.S. leadership in PFC and PMI science under fusion-relevant conditions. "Fusion relevant" in this case means representative heat and particle fluxes as well as high-energy neutral particles. The impact of neutrons on material performance metrics is a multiphysics problem and needs to be separated due to limited testing under representative scenarios. Central to this effort will be the commissioning of the MPEX facility, which will deliver plasma exposure of solid materials with heat fluxes approaching 10 $MW{\cdot}m^{-2}$ over component-relevant areas. Complementary domestic high-heat-flux facilities will enable helium-cooled component testing, while international access, e.g., to CHIMERA at the UKAEA, provides exposure to the highest transient loads. Together, these platforms will begin to close the critical data gaps that limit predictive divertor and first-wall design.

Building a comprehensive database of solid PFC and heat sink properties is equally urgent. Tungsten and Cu-based materials remain leading candidates, but long-term viability depends on quantifying materials degradation mechanisms, such as recrystallization, loss of fracture toughness, and ductile-to-brittle transition shifts under cyclic and transient loads. Near-term campaigns will define erosion-redeposition balances for refractory and liquid metal material candidates, ELM-like thermal-shock thresholds (~0.3–0.6 $GW{\cdot}m^{-2}$), and high-fluence H/He/impurity surface evolution. Tensile and thermophysical data from irradiated samples will be integrated into design windows, yielding the first validated performance envelopes for FPP PFCs.

At the design level, new computational workflows will streamline divertor concept development. By coupling physics codes with CAD (computer-aided design) and optimization frameworks, researchers will be able to project heat flux, pumping, and impurity control within sub-hour design cycles, shortening the path from physics insight to engineered concept.

For liquid components, the critical issues of purifying the liquid metal stream of impurities and hydrogen, as well as the development of insulators, will need to be handled in existing and new domestic test stands. This work also extends to liquid walls for IFE where near-term milestones will focus on demonstrating debris removal and chamber recovery sufficient for target injection and driver propagation, supported by activation and reset analyses.

Near-term progress will be accelerated by multiple FIRE Collaboratives, including Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components (SWIFT-PFC), the Integrated Materials Program, and FEDER. It will also be supported by MPEX, domestic HHF facilities (e.g., the PPP FORGED PFCs with ORNL and Type One Energy in Tennessee), MIT's 30 MeV cyclotron, liquid-metal loops, the DIII-D divertor enhancement, and access to selected international test stands. Furthermore, the Materials and Internal Components sub-element of the FES program also addresses key gaps and milestones outlined below in this section.

Mapping the Mid-term Milestones

In the medium term, PFC and PMI research will move from establishing baseline capabilities toward demonstrating integrated solutions that combine materials science, component design, and plasma performance. A central thrust will be further advancing liquid metal systems in strong magnetic fields to assess stability, compatibility with structural alloys, and tests of heat removal capabilities in dedicated test stands and initial tests with plasma exposure in a confinement device(s). These campaigns will push beyond static exposures toward sustained operation and active isotope management, to qualify liquid PFCs as a credible alternative pathway to tungsten, noting that tungsten will remain the leading substrate material.

At the same time, researchers will work to demonstrate divertor concepts capable of detached operation while maintaining high core performance. Integrated modeling and experiments will explore regimes that exhaust heat and helium ash efficiently, sustain pumping, and preserve energy confinement. These studies will begin to show whether divertors can provide the simultaneous solution of robust exhaust and stable confinement, long viewed as one of the most challenging integration problems in fusion energy.

For solid PFCs, the focus will shift to sustained joint survivability and durability under fusion plant-like conditions. Testing will progress from coupons to mock-ups of tungsten armor and advanced copper-based heat sinks, addressing fatigue, creep, and thermomechanical stability. In parallel, the community will identify emerging PFMs with improved thermal stability, reduced erosion, and lower tritium retention, using high-throughput screening, irradiation studies, and AI-guided design tools to advance the most promising candidates.

These efforts will be supported by SWIFT-PFCs, the Advancing Maturity of Liquid Metal Plasma-Facing Materials and First Wall Concepts, and FEDER FIRE Collaboratives, and access to spallation sources, liquid-metal/core–edge facilities, and international divertor testbeds that enable validation under increasingly integrated conditions.

Mapping the Long-term Milestones

In the long term, plasma-facing component (PFC) research is expected to mature into full validation of both solid tungsten-based alloys and liquid metal systems in fusion-prototypic environments. For solid PFCs, the emphasis will be on demonstrating component-relevant durability: recrystallization resistance under cyclic thermal loading, crack-onset behavior under disruption-like shocks, and the combined effects of neutron damage and high-heat-flux on strength and swelling. Advanced tungsten alloys with engineered precipitates or dopants will be carried forward to raise recrystallization thresholds and extend lifetimes, while prototypic irradiation campaigns will aim to close long-standing gaps in understanding transmutation effects and tritium retention. This data will underpin the first generation of qualified solid PFC prototypes.

In parallel, a sustained program will validate fusion-spectrum irradiation of PFCs and critical joints, linking microstructural evolution to mechanical stability and PMI response. These campaigns will provide the integrated datasets needed to codify performance standards and to refine design tools that capture material evolution under coupled nuclear, thermal, and plasma conditions. A specific focus will be put on understanding changes in tritium permeation and retention from virgin to irradiated materials with transmutation. Extrapolation through modeling will take center stage for this long-term projection.

Liquid PFCs will also be tested at scale in high-power confinement facilities, moving from bench-top loops to continuous-flow systems operating under fusion-relevant heat and particle fluxes. Demonstrations will focus on maintaining flow stability in magnetic fields, mitigating MHD effects, and verifying tritium recovery and impurity control. Success will show whether liquid walls can simultaneously reduce erosion, suppress impurity influx, and improve plasma performance, transforming them from a speculative option into a deployable solution.

These advances will be supported by SWIFT-PFCs, the Advancing Maturity of Liquid Metal Plasma-Facing Materials and First Wall Concepts collaborative, and FEDER, supported by a domestic fusion prototypic neutron source, international facilities, and integrated facilities that combine high-heat-flux, plasma, and neutron environments. Together, these efforts will validate PFC technologies for pilot plant deployment. ■

Advancing Confinement Approaches

Linking Plasma Physics to Sustained Fusion Performance

Advancing confinement spans both magnetic and inertial concepts, with a common performance objective of achieving fusion-relevant gain and sustaining it reliably. Net electricity will require temperatures and pressures that deliver high fusion power density, with energy confinement sufficient to maintain these conditions for a sufficient duration. Three practical target metrics: fusion triple product/gain (Q), pressure power density, and limiting recirculating power (e.g., bootstrap current fraction, or inertial fusion driver efficiency) are key metrics for progress.

Confinement is a multi-faceted 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 challenge symmetry and gain in both laser-driven and pulsed power-driven systems. Similarly, physics such as LPI and partial current shunting in MITLs affect the coupling of energy from the driver to the target in inertial approaches. Across concepts, credible design requires validated, predictive modeling spanning micro-to-macro physics and coordinated experiments that resolve uncertainties (e.g., boundary heat loads, transient suppression, and impurity control in compact, high-power-density regimes). Radiation-hard, control-grade diagnostics are also required to control and optimize performance.

Delivering fusion-relevant confinement also depends on the tools that shape and control the plasma. High-efficiency actuators, including gyrotrons, neutral beams, fueling and feedback systems, establish profiles, sustain current, and suppress instabilities. Their electrical efficiency and reliability directly impact Q_{eng} and plant availability in magnetic concepts and repetition-rate inertial systems. HTS magnets enable higher fields for all magnetic concepts and improve power density, 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 high efficiency and reliable plant-scale gain. Together, these technologies are the levers that translate physics headroom into sustained, controllable performance.

S&T Gaps

C1. 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 (MFE); and compression/burn (IFE) and combine their general functionality into design-capable MBSE schemes.

C2. 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, high efficiency, reliable driver and target systems at low cost.

C3. Need to achieve high-efficiency fuel delivery/coupling. Continuous core plasma fueling required (MFE). Overcome laser-plasma interaction limits and optics/debris constraints (in laser IFE) and current shunting in PMF.

C4. Require demonstration of a sustained burning plasma and core performance. Need a coupled understanding of α-particle physics, confinement, transport, stability and plasma boundary compatibility in fusion-relevant regimes across concepts and show uninterrupted operation at high triple product and net gain (Q).

C5. 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 and helium "ash" without degrading confinement.

C6. Need to demonstrate stability and controllability for reliable plant operation. Require avoidance and/or mitigation of transient events and certifiable AI/ML supervisory control (MFE). Demonstrate management of symmetry and hydrodynamic instability tolerances and predictive energy coupling (LPI or MITL current shunting) (IFE).

C7. Diagnostics require progress and facilities are required to validate relevant scenarios. Require minimal sets of radiation-hard, control-grade diagnostics for α-particles, impurities, boundary state and fast transients, integrated into FPP-level control schemes. Need shared platforms to validate confinement with exhaust at scale (MFE) and IFE coupling/LPI.

FIRE Collaboratives and FES program areas:

- 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

In addition to FIRE Collaboratives, the Sustain a Burning Plasma sub-element of the FES program also addresses key gaps and Milestones outlined in this section.

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Symbol indicates **Genesis Mission** impact

Near term → 2-3 years	**Validate divertor and exhaust concepts at FPP heat/particle flux** **Metric →** Establishing equilibrated core-edge conditions on a 'plasma resistive' timescale. Define minimum divertor leg length/volume and geometry for efficient dissipation without confinement loss. Validate island divertor detachment with high pumping and core compatibility. **FIRE →** Advanced Profile Prediction for Fusion Pilot Plant Design → Advancing Maturity of Liquid Metal Plasma-Facing Materials and First Wall Concepts **S&T Gaps → C1, C5**	**Conduct cryogenic irradiation characterization of REBCO tapes** **Metric →** Cooled to 4-20 K Fast fluence of approximately 0.5 x 10^{22} m^{-2}. **FIRE →** Neutron-Irradiation-Tolerant REBCO Tapes for Compact Fusion → Accelerating Fusion Blanket Development through Nuclear Testing **S&T Gaps → C6**	**Define minimum viable plasma diagnostic architecture (radiation-hard, control-grade) for burning plasmas and machine protection** **Metric →** Define the metric (in $n{\cdot}cm^{-2}{\cdot}MeV^{-1}$) and its threshold. **S&T Gaps → C7**		
Mid term → 3-5 years	**Develop drivers with IFE-relevant efficiencies and repetition rates** **Metric →** For laser fusion approaches, Demonstrate a 0.25-10-Hz, 5–10-kJ per pulse, 10–20-ns shaped pulses, with a >7% electrical wall-plug efficient beamline. **Metric →** For PMF approaches, demonstrate reproducible pulses at 1-Hz, 2 terawatt per pulse, 100-ns rise with high reliability. **FIRE →** Target Injector Nexus for Development Research **S&T Gaps → C2**	**Realize sustained fusion gain and burning plasmas** Achieve sustained fusion reactions where the energy generated by the reactions exceeds the energy input into the plasma and extend performance to a burning plasma state where the dominant source of plasma heating is from fusion α particles. **Metric →** Achieve a plasma with a Q > 1 for a duration exceeding the relevant timescale. Extend the same result to Q > 5. **FIRE →** Advanced Profile Prediction for Fusion Pilot Plant Design **S&T Gaps → C4**	**Deliver tools for real-time 3-D magnetic-topology reconstruction and control in stellarators** **Metric →** Strike line accuracy within 1 cm of state-of-the art slow reconstruction tools Real-time strike line control with latency of ¼ of confinement time and accuracy to within 2 cm. **FIRE →** Advanced Profile Prediction for Fusion Pilot Plant Design **S&T Gaps → C1, C6, C4**	**Fully elucidate confinement scaling with aspect ratio** **Metric →** Generate a spherical tokamak (A < 2) plasma with electron collisionality $\nu_e^*(q=2) \leq 0.01$ in FPP relevant regime. **S&T Gaps → C1**	**Demonstrate stability and transient control in toroidal systems** **Metric →** Statistically reproducible plasmas in FPP regime with mitigated ELMs and either disruption-free or with disruptions controlled below damage thresholds. **FIRE →** Advanced Profile Prediction for Fusion Pilot Plant Design → Mitigating risks from abrupt confinement loss **S&T Gaps → C6**
Long term → 5-10 years	**Deploy design-grade predictive transport and confinement models with UQ** **Metric →** Reproduce density and temperature profiles within 20% Control of objective profile within 20%. **FIRE →** Advanced Profile Prediction for Fusion Pilot Plant Design → Mitigating risks from abrupt confinement loss **S&T Gaps → C1**	**Demonstrate pilot-grade core-exhaust operating scenarios across configurations and close ITEP gap** **Metric →** Minimize core radiation to preserve confinement; maximize edge radiation to protect PFCs. Achieve neutral particle pressure to exhaust He and impurities. Simultaneous achievement of benign divertor conditions (e.g., T_{target} <5 eV) and high-performance core in terms of triple product, $\langle p \rangle \tau / (I{\cdot}\, a{\cdot}B)a{\cdot}B)$. **FIRE →** Advanced Profile Predictin for Fusion Pilot Plant Design → Mitigating risks from abrupt confinement loss **S&T Gaps → C4, C5**	**Develop and demonstrate steady-state heating and current drive (H&CD) actuators at FPP duty/efficiency: ECRH and ICRH** **Metric →** Wall plug efficiency >70% at >250 GHz, and 90% at 1 MW at >100 s pulse width. Operation for 10 x 1 h with no fault. Steady-state ECRH ~3-6 MW at 170 GHz. Steady-state ICRH ~5-10 MW at 50-200 MHz. **S&T Gaps → C2**	**Develop and demonstrate steady-state H&CD actuators at FPP duty/efficiency: NBI** **Metric →** Wall plug efficiency >70%, ≥1 MeV beam energy, ≥250 A/m^2, ≥1 A total current, ≥1 h pulse length. Steady-state NBI ~10-40 MW at 100-500 keV beam energy. Pulse width: >100 s for 2 h at 50% duty cycle (to ensure RAMI). **S&T Gaps → C2**	**Validated wave/beam coupling through the edge** **Metric →** Theoretical models predict observed wave/beam coupling to core plasma to within 20% in relevant plasma conditions. **FIRE →** Advanced Profile Prediction for Fusion Pilot Plant Design **S&T Gaps → C2**

Symbol indicates **Genesis Mission** impact

Near term → 2-3 years					
Mid term → 3-5 years	**Define and validate HTS cables and coil electro-mechanical characteristics and critical current limits** **Metric →** High background – 12-20 T in a high current cable test facility. **S&T Gaps → C6**	**Demonstrate minimum viable plasma diagnostic architecture (radiation-hard, control-grade) for burning plasmas and machine protection** **Metric →** Aim at fluences >10^{15} n·cm^{-2}·MeV^{-1}. **S&T Gaps → C7**	**Mature Emergent Confinement Concepts to high performance conditions** **Metric →** Separately achieve n, T, τ consistent with fusion reactor conditions. Ultimately, realize a plasma with simultaneous nTτ of 10^{21} m^{-3}·keV·s. **S&T Gaps → C4**	**Resolve transport mechanisms governing near-SOL and far-SOL heat and particle transport, and identify operating regimes/ boundaries that set SOL width/ wall heat fluxes** **Metric →** Experimentally validated identification of dominant transport regimes with quantified transition boundaries expressed in dimensionless parameters. Predictive agreement of λ_q trends within ±20% across operating regimes. **S&T Gaps → C1, C5**	**Demonstrate energy coupling and validate hydrodynamics at scale for IFE systems** **Metric →** Demonstrate driver-to-capsule coupling efficiency ≥10% for laser- and PMF-IFE, and >90% for direct drive. Hydroefficiency ≥5%. **S&T Gaps → C3**
Long term → 5-10 years	**Develop validated projection capability for pulsed- and steady-state compact tokamak operational scenarios** **Metric →** Understand plasma and first wall material evolution over the equivalent duration of a full power month of FPP operation. **FIRE →** Advanced Profile Prediction for Fusion Pilot Plant Design → Mitigating risks from abrupt confinement loss **S&T Gaps → C1, C2, C3, C4, C5, C6**	**Demonstrate IFE target technologies at plant cadence** **Metric →** Projectile velocity ≥ Chamber radius x rep rate (beam-driven), 0.25–16 Hz shot rate; tracking accuracy < hot-spot radius. Demonstrate pathway to mass production: 50,000 targets/day. **FIRE →** Target Injector Nexus for Development Research **S&T Gaps → C3**	**Extend burning plasmas toward high-gain FPP performance** Demonstrate a robust, high-gain burning plasma that exhausts helium ash and would be capable of net electrical energy delivery, if all necessary energy conversion technology was in place. **Metric →** Sustain a plasma with Q_{sc} > 10 for a timescale longer than characteristic timescale of the plasma. **S&T Gaps → C4**	**Sustain an ignited plasma** Demonstrate a core-edge integrated ignited plasma that could serve as the basis for a fusion energy source, if all necessary energy conversion technology was in place. **Metric →** Sustain fusion reactions for a timescale longer than the evolutionary timescale of the PFMs without the use of auxiliary heating and current drive. **S&T Gaps → C4, C5**	

Advancing Confinement Approaches

Mapping the Near-term Milestones

In the near term, advancing magnetic confinement approaches will center on resolving the integration of high-performance plasma with the core boundary and the magnet-property data needed for qualification. For IFE, focus will be applied to increasing access to experimental platforms, such as Omega, to support systematic studies of beamlines, chambers, target injection, and diagnostics under conditions approaching those of an FPP. These experiments will provide an opportunity to extend the validation of driver-target coupling physics across different driver and target architectures and to test methods for enhancing driver-target energy coupling, both of which are critical for scaling toward reliable gain.

On the magnetic fusion side, the focus will be on validating divertor and exhaust concepts at power and particle fluxes relevant to a pilot plant. Tokamak programs will define the optimal divertor leg length, geometry, and neutral pressure needed to sustain dissipative regimes without degrading confinement, while stellarator research will aim to establish the viability of island and non-resonant divertors, including their detachment behavior and effect on core performance. These efforts will be focused on addressing the long-standing integration challenge of simultaneously protecting plasma-facing components while maintaining high confinement and reaching high enough neutral pressure to exhaust helium and impurities.

In parallel, the community will take first steps toward qualifying next-generation high-field superconducting magnets and their constituent functional materials by conducting cryogenic irradiation campaigns on REBCO conductors. Developing shared standards and databases for critical current, alternating current (AC) loss, and joint performance will lay the foundation for reliable, radiation-tolerant magnets suitable for compact, high-field devices.

These near-term activities will be supported by the FIRE Collaboratives, including APP-FPP, TINEX, and the NIT-REBCO effort, which connects physics advances with engineering readiness. Infrastructure investments are expected to enhance existing capabilities at DIII-D, NSTX-U, and major stellarators such as W7-X, while building out new magnet testing and high-performance computing platforms for integrated modeling. Together, these steps will establish a credible physics basis for confinement and exhaust solutions, accelerate progress toward viable IFE and MFE pilot plant concepts, and ensure that magnet technology development keeps pace with plasma performance advances.

Mapping the Mid-term Milestones

In the medium term, confinement research will move decisively from proof-of-principle demonstrations toward sustained burning-plasma performance and integrated control capabilities. A central milestone for MFE will be the realization of sustained fusion gain and reaching plasmas where fusion α particles dominate the heating. Demonstrations of $Q_{sc} > 1$ sustained beyond resistive timescales, and progress toward $Q_{sc} > 5$, will provide the experimental foundation for validating confinement models toward pilot-plant scale.

On the inertial fusion path, emphasis will turn to high-efficiency, high-repetition-rate drivers to determine a path from scientific gain ($Q_{sc} > 1$) to engineering or facility gain ($Q_{eng} > 1$). High-average-power lasers and advanced pulsed-power systems will be advanced to the point where they close the energy balance at high cadences, transforming today's proof-of-concept platforms into plant-ready technologies. Parallel progress will expand access to a domestic single-beamline demonstrator and next-generation facilities supporting scaled studies of driver-target coupling under repetitive conditions.

For magnetic confinement, the focus will be on control and predictability. Stellarator programs will deliver real-time reconstruction and control of 3-D magnetic topology, enabling autonomous management of islands and strike points. Tokamak programs will extend the physics basis for confinement scaling to low aspect ratio, clarifying how spherical tokamak devices could achieve optimal FPP-relevant performance. In both, the challenges of stability and transient control will be addressed through transient resilience, avoidance, and mitigation.

These advances will be reinforced by progress in enabling technologies: qualification of HTS cables and coils under high fields and fast ramp rates, definition of critical current and mechanical limits, and the deployment of radiation-hard, control-grade diagnostics for α particles, impurities, and transients. In parallel, emergent confinement concepts will be matured toward high performance, with non-tokamak plasmas reaching $nT\tau$ benchmarks that position them as credible alternatives for lower-cost fusion cores.

Progress will be supported through APP-FPP, TINEX, and Mitigating Risks from Abrupt Confinement Loss FIRE Collaboratives, the CTC program research collaborations on SPARC, and will require new capabilities, including a public mid-scale stellarator facility, the full utilization of new NSTX-U capabilities, and a complete suite of digital twins for scenario modeling and design.

Mapping the Long-term Milestones

In the long term, confinement research is anticipated to deliver integrated solutions that demonstrate sustained performance and predictive capability. Central to this effort for MFE will be the deployment of design-grade transport and confinement models with rigorous uncertainty quantification. These models will close the experiment-theory gap on turbulence, pedestal dynamics, impurities, and fast ions, providing validated workflows that span core to edge. They should then be translated into component and system-level performance models that can be integrated into an MBSE approach for fusion.

For magnetic fusion, the goal will be sustained high-performance fusion plasmas operating compatibly with power and particle exhaust at pilot-plant conditions. Close coordination with fusion toroidal confinement developers will be key. Tokamak programs plan to demonstrate detached divertors that minimize strike-line motion and balance radiation between core and edge, while stellarators plan to validate high-pumping island divertors that preserve core confinement. These integrated demonstrations aim to represent a true solution to the long-standing challenge of coupling high-performance cores with survivable boundaries at the edge.

Progress will also depend on maturing the actuator suite for steady-state operation. High-frequency, fault-tolerant gyrotrons, efficient ICRH, and reliable negative-ion beams will be operated at full duty, while predictive control of wave and beam coupling through dense, high-field edges will be validated. Meeting efficiency goals for startup, preheat, and sustainment will be critical to closing the energy balance.

On the inertial fusion energy side, progress is needed to realize plant-ready target technologies. Targets will be injected and tracked at a relevant cadence, with repeatable placement, radiation-hardened diagnostics, and mass-production pathways proven at industrial scale.

Finally, the community plans to establish a validated projection capability for pulsed and steady-state concepts, integrating lessons from SPARC, DIII-D, NSTX-U, and next-generation facilities. This capability will give confidence that pilot plant designs can be executed with predictable outcomes, transforming confinement approaches from experimental frontiers into deployable power-plant solutions.

These advances will be supported through the APP-FPP, TINEX, and Mitigating Risks from Abrupt Confinement Loss collaboratives, with data integration via FEDER. Infrastructure will expand to include the MEC-U upgrade, enhanced DIII-D heating and current drive, access to a mid-scale stellarator, core-edge integration facilities, and emerging pilot plants. Whole-device digital twins and synthetic diagnostic suites will complete the predictive framework needed to design, operate, and optimize next-generation confinement systems with confidence. ■

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 DT, 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 extraction 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 DT fuel, and impurities. Concepts such as DIR aim to minimize system inventories by recirculating hydrogen isotopes directly back to the fueling systems. 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 blanket system, typically based on lithium-containing materials and fluids, 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 conditions, electromagnetic and mechanical stresses, high neutron energies, fluxes and fluences and oxidation; all while maximizing tritium recovery efficiency and minimizing 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 systems for recovering tritium from air, water, gloveboxes, and solid components. Advanced detritiation reduces both environmental releases and the volume of 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. Furthermore, accounting for radiation-driven effects in solid-based multi-phase systems and their impact on tritium transport is key, and the appropriate characterization tools are required to validate and verify advanced blanket design modeling tools.

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 DT operation, meeting safety standards, and demonstrating the viability of fusion as a large-scale and safe energy source.

S&T Gaps

D1. Tritium self-sufficiency and accountancy as first-order design drivers remain unresolved. Fuel systems need to self-produce tritium within accountability requirements set by regulators, with validated measurement approaches; efficient tritium processing at relevant rates requires demonstration; effects of fusion neutron irradiation on tritium retention by transmutation are unknown.

D2. 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 a target to fuel-cycle co-design to constrain isotopic/chemical impurities.

D3. 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.

D4. Isotope supply, separation/rebalancing, and storage are not mature. High-throughput isotope separation and rebalancing, compact safe storage and materials down-selection all require maturation. Planning must address fuel cycle supply risks and by-design minimization of inventory.

D5. 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 release modeling must be defined and validated for power-plant operations.

D6. 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.

FIRE Collaboratives and FES program areas

- 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
- Blanket Collaborative on Test Facilities

In addition to FIRE Collaboratives, the Closing the Fusion Cycle sub-element of the FES program also addresses the key gaps and Milestones outlined in this section.

Symbol indicates **Genesis Mission** impact

Near term → 2-3 years	**Establish fuel-cycle performance targets and design specifications across concepts** **Metric →** Capability to achieve TBR ≥1.1; Each subsystem can reasonably manage 100% of FPP duty cycle. **FIRE →** Fuel Cycle FIRE **S&T Gaps → D1**	**Advance pathways for detritiation technologies and techniques in solid materials** **Metric →** Meet tritium release limit (0.01 Ci/m^3). Reduction of energy intensity, achieving high detritiation factor, and in the case of getters decreasing vapor pressure at room temperature. **FIRE →** Fuel Cycle FIRE **S&T Gaps → D5**	**Develop and release byproduct material management strategy frameworks** **Metric →** Release of strategies. **FIRE →** Fuel Cycle FIRE **S&T Gaps → D5**			
Mid term → 3-5 years	**Develop pumping technologies for the fusion fuel cycle to TRL 5-7** **Metric →** Pumping system to demonstrate in the near term ≥2.3 Pa·m^3/s (throughput needs may range from 1–100 Pa·m^3/s) continuous exhaust flow with ultimate pressure <10^{-4} Pa. No significant degradation or leakage over 1 year exposure to tritium (target leak rate <10^{-6} Pa·m^3/s). **FIRE →** Fuel Cycle FIRE **S&T Gaps → D2**	**Release isotope separation models** **Metric →** Within ±10% for separation efficiency and ±10% for product purity over the full operating range At least two independent measurements of D/T ratio in the product stream (for redundancy) with accuracy <±1% in composition. Flow measurement accuracy <±2% of actual flow. **FIRE →** Fuel Cycle FIRE **S&T Gaps → D3, D4**	**Demonstrate isotope separation technologies to TRL 7** **Metric →** Metrics: ≥5 mol/h D/T throughput; ≥90% stage cut; tritium holdup <1% of daily throughput in the separation system; ≥99% T recovery per stage; product purity ≥90% T. **FIRE →** Fuel Cycle FIRE **S&T Gaps → D4**	**Demonstrate integrated vacuum pumping, exhaust processing, impurity removal and DIR in fuel cycle loop** **Metric →** Demonstrate DIR pumping capacity for a fraction of exhaust flow. Reduce the required outer loop processing by at least 20-30% via internal recycle. Impurity removal threshold: <10%, then <1%. maintain vacuum conditions (pump exhaust pressure ~1-10 Pa) while directly reinjecting fuel. **FIRE →** Fuel Cycle FIRE **S&T Gaps → D2**	**Release computational framework for efficient fueling** **Metric →** Fueling response times <1 second to modulate or cut off fuel during off-normal events. Maintain stable plasma operation while providing continuous fueling. **FIRE →** Fuel Cycle FIRE **S&T Gaps → D2, D3**	
Long term → 5-10 years	**Develop and qualify improved hydrogen isotope storage technologies and materials** **Metric →** Storage capacity ≥2 wt% tritium in the material. Achieve full loading or unloading within <1 hour. >1000 cycles with <10% loss of capacity. <1% of total T capacity remains unrecoverable after discharge. Vapor pressure at room temperature. **S&T Gaps → D4**	**Demonstrate tritium measurement/accountancy technologies to TRL 6** **Metric →** Measuring isotope ratios, composition, and tritium inventory with a resolution of +/-1% and response time of less than a minute. Detection limits on the order of 10^{-3} to 10^{-2} Ci/m^3 for gaseous streams. Readings on a sub-minute timescale for dynamic systems. Needs to include irradiated materials effects over time. **FIRE →** Fuel Cycle FIRE **S&T Gaps → D1**	**Demonstrate pellet/target injector technology in integrated testing environments** **Metric →** For IFE, 1-10 Hz target injection with ≤~0.5 mrad accuracy and 50-200 m/s velocities. For MFE pellet fueling throughput up to ~27.5 Pa·m^3/s during transient peaks. D:T ratio of 1:1, 2:3, 3:2 with 1% accuracy in pellet. Continuous operation for periods of ~1000 s **FIRE →** Target Injector Nexus for Development Research **S&T Gaps → D2**	**Demonstrate a fuel-cycle control system** **Metric →** Response time <0.1 s from disruption signal to fueling cutoff. Reliability demonstrated over >1000 plasma pulses without failure. **S&T Gaps → D2**	**Demonstrate stable plasma operation while providing continuous fuel-cycle operation** **Metric →** Tritium self-sufficiency. Demonstrate duty cycle (3 h continuous operation). **FIRE →** Fuel Cycle FIRE → Advancing Maturity of Liquid Metal Plasma-Facing Materials and First Wall Concepts **S&T Gaps → D2**	**Release AI-enabled open-source fuel cycle computational process models** **Metric →** Model accuracy such that predictions of tritium retained inventory are within ±20% of experimental values over a range of conditions. **FIRE →** Fuel Cycle FIRE **S&T Gaps → D2, D3, D4**

Fuel Cycle and Tritium Processing

Mapping the Near-term Milestones

In the near term, the program will support clear performance targets and design specifications across MFE and IFE concepts. This includes target to fuel-cycle co-design to limit isotopic/chemical impurities from IFE targets and reduce in-plant tritium inventories; defining FPP-scale fueling requirements; adopting TBR > 1.1 as a design goal in conceptual studies; and demonstrating that each fuel-cycle subsystem (fueling, tritium-compatible vacuum pumping, impurity removal, exhaust processing, isotope management, byproduct management/cleanup systems, and storage) can maintain continuous operation at pilot duty.

In parallel, the program will support advancing detritiation pathways in both solid materials and water. Priorities include improved getter materials and selective chemistries/adsorbents that remove tritium at low concentrations and enable recycling, alongside flowsheets that minimize byproduct materials and enable practical regeneration. These developments will be integrated with impurity-control strategies and compatible pumping trains (from ultra-high vacuum to above atmospheric pressure) so that detritiation is treated as part of the end-to-end fuel-cycle solution.

Concurrently, the program will support lifecycle and byproduct-material management frameworks, updated classification guidance, and plant-level tritium accountability and analytics standards, so designers can build to clear operational and regulatory expectations.

The Fuel Cycle FIRE Collaborative will support early co-design studies, detritiation technology development, and accountancy frameworks that support regulatory requirements. The Liquid Metal Plasma Facing Component (LM PFC) FIRE Collaborative will address a liquid lithium PFC fuel cycle challenge, specifically the efficient separation and concentration of hydrogenic species from exhausted fuel in a low-recycling approach. Near-term investments will emphasize building the infrastructure needed to enable medium- and long-term milestones by establishing access to tritium-capable facilities (e.g., UNITY-2, H3AT) for integrated subsystem validation; expanding domestic D/H loops and non-nuclear testbeds to support component and process development.

Mapping the Mid-term Milestones

In the medium term, the program will target pilot-relevant subsystems research and development milestones. A priority will be maturing tritium-compatible vacuum pumping, from turbomolecular and mechanical trains to cryogenic or metal-foil concepts, so that systems sustain high D/T and impurity throughput in harsh environments (radiation, particulates, magnetic fields) and hand off directly to tritium-safe containment and processing. Reliability, maintainability, and minimized hold-up will be treated as design objectives.

A separate effort will focus on the release of validated isotope-separation and rebalancing models, tied to metrology and accountancy. Pilot-scale isotope separation technology demonstrations will also be pursued, emphasizing modular scaling, low inventory hold-up, and efficient protium removal, advancing NASEM priorities on efficient tritium processing and clear accountability.

In parallel, the program will pursue integrated demonstrations of impurity removal and DIR. These efforts will show that a tritium-enriched stream can be cleanly returned to fueling while depleted exhaust is routed to outer-loop processing, reducing overall system burden. Success will be measured by stable operation under pilot-relevant loads, efficient impurity removal, and high recycle fractions, providing evidence that core elements of the fuel cycle can work together to lighten processing demands at the plant scale.

To strengthen operational readiness, the program will also release a computational fueling framework, linking experimental data to models that guide fueling strategies. This will enable responsive control during off-normal events, high assimilation efficiency in the burning plasma, and integration with plant-level tritium accountancy.

The Fuel Cycle FIRE Collaborative will support development across these parallel tracks (vacuum pumping, isotope separation, impurity removal, and DIR). Progress will be supported by access to tritium-capable facilities (UNITY-2, H3AT), domestic D/H loops and non-nuclear platforms (INL / Savannah River National Laboratory (SRNL)), and a nuclear fuel-cycle test facility to validate performance, components, and functional materials under representative conditions.

Mapping the Long-term Milestones

In the long term, the program will focus on pilot-ready capability that demonstrates an integrated fuel cycle, which demonstrates tritium self-sufficiency and performance over the full duty cycle. It will support the demonstration of measurement and accountancy technologies to meet operational requirements: radiation-tolerant, near-real-time sensing on process streams; in-situ methods for effluents; and, critically, qualified techniques for inventory within solid matrices. In parallel, the program will develop and qualify advanced hydrogen-isotope storage technologies and functional material for continuous duty (high capacity, fast charge/discharge, and multi-cycle durability) with regeneration strategies and integrated monitoring.

It will support the demonstration of fuel delivery in integrated testing environments. For IFE, target injectors will demonstrate accurate placement and tracking at driver cadence while limiting non-useful carrier gas and coordinating with target fabrication and recovery. For MFE, pellet injectors will be validated for assimilation, geometry-aware deposition, and reliable DT blending, supported by models that tie fueling to burning-plasma conditions and machine protection.

Validation of fuel-cycle control systems is also critical to demonstrate coupling diagnostics, storage buffers, and delivery hardware to plasma control, adjusting or halting fueling on off-normal signals, and protecting the plant while maintaining steady power during routine operation.

To make this projectable, the community will need to develop and release AI-enabled, open-source fuel-cycle process models, a digital-twin suite that predicts inventories, permeation, compositions, and power consumption, validated against dedicated test-facility data, and link these tools to plant-level designs. Together with qualified measurement, storage, delivery, and control, this will support stable plasma operation with continuous fuel-system service and credible paths to tritium self-sufficiency.

Fuel Cycle FIRE will support the development of accountancy standards, storage qualification, and control/data architectures; TINEX will lead injector integration for IFE; and the LM PFC effort will inform wall-interaction and permeation management. Long-term delivery will build on existing testbeds and add an IB-FCTF to exercise tritium production, extraction, measurement, and closed-loop fueling under pilot-relevant conditions. ■

Blanket Science and Technology

Tritium Breeding and Power Extraction

In a DT fusion power plant, the blanket is the central 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 cycle loop, and shielding magnets, structures, and other sensitive components from radiation damage. Advancing blanket technology readiness is essential to selecting and optimizing a concept for 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, like lead-lithium (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 in order 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 for MFE, 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, carbon dioxide (CO_2), 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.

S&T Gaps

E1. Functional and structural material performance in relevant environments is uncertain. Corrosion/compatibility for lithium salts, metal alloys, and steels/ceramics, long-term irradiation effects, and tritium thermophysics remain poorly quantified for lifetime predictions and maintainability.

E2. 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 relevant conditions.

E3. 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.

E4. Tritium management within blankets is not mature. 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.

E5. 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.

E6. No validated, integrated blanket design for fusion power plants. No end-to-end blanket concept fabricated to meet tritium self-sufficiency and heat removal simultaneously, with clear down-selection/qualification rules.

E7. 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.

FIRE Collaboratives and FES program areas

- 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
- Integrated Materials Program to Accelerate Chamber Technologies
- Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems

In addition to FIRE Collaboratives, the Closing the Fusion Cycle sub-element of the FES program also addresses the key gaps and Milestones outlined in this section.

Symbol indicates **Genesis Mission** impact

Near term → 2-3 years	**Create an open physical property database for blanket and fuel-cycle materials** **Metric →** Establishment of a database team, who creates a database framework, establishing a format to compile data into. **FIRE →** Fusion Energy Data Ecosystem and Repository **S&T Gaps → E1, E7**	**Define and demonstrate minimum viable diagnostic architecture** **Metric →** Monitoring temperature, pressure, neutron flux, and tritium levels in real-time is crucial for predicting and preventing failures. In-situ tritium sensing to ~10^{-3} appm in breeder; real-time telemetry demonstrated. **S&T Gaps → E5**	**Operate corrosion/compatibility rigs for RAFM, V-alloys, and SiC** **Metric →** PbLi/Li: Limit uniform corrosion to 10-50 μm·yr^{-1}; apply chemistry/MHD controls and coatings as needed. → FLiBe: Maintain strict redox and impurity control; qualify steel/SiC/V-alloy compatibility and dissolution limits. Water: Limit RAFM corrosion to ≤50 μm·yr^{-1} with tight chemistry/oxygen control. → Tritium Permeation: Implement permeation barriers to reduce through-wall T flux to a few percent of blanket production. **FIRE →** Blanket Collaborative on Test Facilities → Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design → Accelerating Fusion Blanket Development through Nuclear Testing **S&T Gaps → E1**	**Develop high-field, multi-effect MHD test capability** **Metric →** Flexible liquid-breeder facility operating >500 °C with ≥2 T initially and path to ≥5 T. **FIRE →** Blanket Collaborative on Test Facilities **S&T Gaps → E3**	**Down-select tritium permeation barriers at coupon/component scale** **Metric →** Permeation reduction factors of 10^2-10^3. Thermal stability: effective up to at least 500 °C. Capability to manufacture ~10 m^2. **FIRE →** Accelerating Fusion Blanket Development through Nuclear Testing **S&T Gaps → E2, E4**	**Demonstrate capability to produce blanket components** **Metric →** Component sizes adequate to provide necessary flow rates (>30 cm diameter); leak rates for high-temperature connections <1 × 10^{-6} mbar·L^{-1}·s^{-1}. **S&T Gaps → E6**	
Mid term → 3-5 years	**Demonstrate continuous tritium extraction at loop scale, with accountancy** **Metric →** Extraction efficiency 50-90% per pass. Ability to measure tritium down to 10^{-3} appm. ≥95% of tritium entering the extractor is recovered. **FIRE →** Blanket Collaborative on Test Facilities → Accelerating Fusion Blanket Development through Nuclear Testing **S&T Gaps → E4**	**Demonstrate a closed-loop cooling system operating under relevant pressures, flow rates, heat loads, and operational conditions** **Metric →** Demonstrate helium loop at prototypic blanket conditions (surface heat fluxes up to 0.5-1 MW·m^{-2}, helium temperature up to 550 °C and pressure 8-10 MPa) at flow rates over 1 kg·s^{-1}. **FIRE →** Blanket Collaborative on Test Facilities **S&T Gaps → E4, E6**	**Qualify MHD mitigation techniques and demonstrate insulation/flow channel inserts at field and temperature** **Metric →** Demonstrate reliable flow channel inserts/insulators and manifold/channel designs up to 8 T and >450-500 °C. Demonstration of MHD pressure drop reduction. **FIRE →** Blanket Collaborative on Test Facilities → Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design **S&T Gaps → E3**	**Identify and fill critical neutronics data gaps for fusion blankets to support transport modeling** **Metric →** Predictive capabilities for tritium breeding performance in a fusion environment with a spectral neutron flux distribution, with errors in computational-to-experimental (C/E) ratios less than 3%. **FIRE →** Accelerating Fusion Blanket Development through Nuclear Testing **S&T Gaps → E7**	**Develop and release properties database for functional materials** **Metric →** Release of the database. **FIRE →** Blanket Collaborative on Test Facilities → Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design → Accelerating Fusion Blanket Development through Nuclear Testing **S&T Gaps → E1**	**Advance multiple blanket concepts and their associated technologies through TRL 4-5** **Metric →** Progression of concepts to TRL 5. **FIRE →** Blanket Collaborative on Test Facilities → Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design → Accelerating Fusion Blanket Development through Nuclear Testing **S&T Gaps → E6**	**Develop capability to construct test blanket modules (TBMs)** **Metric →** Production capability of 5 TBM-sized modules/year scaling to 30 modules/year. **S&T Gaps → E6**
Long term → 5-10 years	**Release validated first-principles informed code to accurately predict tritium retention, trapping, and permeation in blankets** **Metric →** Retention per dpa through temperature ranges. Permeation rate reduction. Validated tools for thermo-fluids, structural modeling, and neutronics, with a focus on radiochemical modeling tools. **S&T Gaps → E2, E7**	**Conduct fusion-spectrum irradiation testbed and qualification campaigns for functional materials** **Metric →** Irradiate material components to fusion-relevant damage levels (e.g. 1-5 dpa). **FIRE →** Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design → Accelerating Fusion Blanket Development through Nuclear Testing **S&T Gaps → E1, E7**	**Demonstrate integrated blanket concept at TRL 7 meeting self-sufficiency requirements** **Metric →** TBR > 1.1. Tritium losses <1% of tritium consumption averaged over an environmental cycle. Bound limit on mean time to failure of blanket structural materials. **FIRE →** Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design → Accelerating Fusion Blanket Development through Nuclear Testing → Blanket Collaborative on Test Facilities → Advancing Maturity of Liquid Metal Plasma-Facing Materials and First Wall Concepts **S&T Gaps → E6**				

Blanket Science and Technology

Mapping the Near-term Milestones

In the near term, the program will support a measure-model-design loop for blanket systems that turns experiments into actionable design inputs. First, it will support the creation of an open physical-property database with common data standards, so thermophysical, corrosion, tritium transport, and mechanical properties flow directly into blanket and fuel-cycle models. This shared backbone will let designers compare materials and coolants on equal footing and accelerate down-selection. In parallel, the program will support the definition of a minimum-viable diagnostic architecture for blankets. Priority is on radiation-hardened temperature, heat-flux, flow, strain, and tritium sensing, proven in non-nuclear loops with high-rate streaming and real-time telemetry. Establishing in-situ tritium monitoring alongside thermal-hydraulic measurements will enable predictive maintenance and tighter inventory control.

The program plans to operate corrosion/compatibility rigs for PbLi and FLiBe, exercising Fe-alloys, V-alloys, and SiC under controlled chemistries with in-situ monitoring and (where feasible) radiation-coupled exposures. The resulting data will clarify operating windows, precipitate stability, and long-duration behavior at relevant temperatures, feeding back to the shared database and model benchmarks. Concurrently, the program will support down-selection of tritium permeation barriers at coupon/component scale, screening coating and joint processes for adhesion, microstructure, durability, thermal stability, and radiation tolerance, so permeation budgets and inventories can be designed rather than estimated.

Finally, to link materials, flows, and magnet design, the program will stand up high-field, multi-effect MHD test capability for liquid breeders (PbLi, Li). Small-scale channels in variable geometries and fields will be integrated with modeling to quantify drag, turbulence, heat transfer, and corrosion under fusion-relevant conditions, de-risking manifolds and piping. To deliver these outcomes, the program will leverage the Blanket Collaborative on Test Facilities, Fusion Neutrons for Integrated Blanket Technology, BNT, and FEDER FIRE Collaborative. Progress will be enabled by using capabilities such as UKAEA's LIBRTI, UNITY-1, ORNL's Helium and Salt Technology Experiment, and CHIMERA.

Mapping the Mid-term Milestones

In the medium term, the program will support the transition from foundational measurements to validated blanket sub-systems that perform predictably under fusion-relevant conditions. It will support the advancement of multiple blanket concepts and their associated technologies through TRL 4-5, emphasizing “high-fidelity” laboratory integration of components with reasonably realistic supporting elements and testing in simulated environments.

A first thrust will qualify MHD-mitigation approaches, flow-channel inserts/insulators and manifold/channel designs, so pressure-drop and heat-transfer behavior match model predictions and reduce pump power. This work will be tied to high-field liquid-metal testing and coating/insulation development begun in the near term, closing the loop between experiment and design. In parallel, the program will identify and close neutronics data gaps that govern activation, shielding margins, and tritium breeding performance. Updated datasets will feed integrated, multiscale workflows so designers can co-optimize structures, breeders, and coolants with quantified uncertainty.

The program also aims to also demonstrate loop-scale tritium extraction with accountancy, down-selecting candidate architectures and showing continuous removal with clear mass and energy balances. Real-time tritium monitoring in breeder loops will be matured alongside extraction, so residence-time and inventory targets are engineered rather than assumed. Nuclear-assisted tests will anchor models and accelerate qualification of extraction hardware. To ensure thermal viability, the program plans to operate closed-loop cooling systems at prototypic pressures, temperatures, and heat loads, validating manifolds, flow distribution, and channel enhancements that keep structures within limits while minimizing pumping requirements.

Alongside these engineering demonstrations, the program will curate comprehensive property datasets for functional materials (including breeder and multiplier materials) capturing thermophysical, chemical, irradiation-response, and MHD-relevant data.

The program will leverage the Blanket Collaborative on Test Facilities to conduct component-scale MHD and thermal tests, Fusion Neutrons for Integrated Blanket Technology and BNT to provide nuclear environments and inform a nuclear blanket component test facility (n-BCTF), and leverage near-term platforms (e.g., UNITY-1, LIBRTI) to validate extraction, cooling, and MHD mitigation under representative conditions.

Mapping the Long-term Milestones

In the long term, the program will support moving blanket concepts into pilot-plant-ready systems that reliably extract heat and breed tritium with quantified margins. A central thrust will be releasing validated, first-principles-informed models that predict tritium retention, trapping, permeation, and recovery in both PFCs and blankets. These tools will incorporate microstructural evolution (irradiation damage, interfaces, and joints) and will be anchored by targeted campaigns that expose materials and components to fusion-relevant neutron damage and subsequent tritium loading, so safety cases, permeation budgets, and end-of-life inventories are engineered rather than inferred.

In parallel, the program will support comprehensive modeling for blanket design, performance, and maintenance, coupling plasma, blanket, and fuel-cycle physics in both low-fidelity rapid-iteration tools and high-fidelity optimizers. The software will handle 3-D configurations (including stellarators), integrate diagnostics and maintainability, and provide uncertainty-aware “design gates” that align with licensing and operations.

To underpin qualification, the program plans to establish and operate fusion-spectrum irradiation testbeds and campaigns, providing fusion-prototypic neutron exposures for structural and functional materials, tritium-system components, and diagnostics. These efforts will produce design-quality, QA/QC-ready datasets that close lingering gaps and enable acceptance of materials and sub-assemblies in integrated systems.

The program expects to support an integrated blanket demonstration at TRL-7 that meets self-sufficiency requirements: end-to-end tritium breeding (TBR > 1.1) with credible heat removal, tight bounds on losses, and maintainability confirmed through embedded diagnostics. This facility-scale proof would give developers and regulators confidence that blanket performance, reliability, and tritium management are ready for a pilot plant.

The program will leverage work from the Blanket Collaborative on Test Facilities on integrated test plans and system demonstrations; Fusion Neutrons for Integrated Blanket Technology and BNT on fusion-spectrum exposures and qualification datasets; and the LM PFC effort on wall/permeation inputs to blanket design. Infrastructure will build on near- and mid-term platforms and add an integrated blanket-and-fuel-cycle test facility to exercise tritium production, extraction, measurement, and closed-loop operation under pilot-relevant conditions. ■

Fusion Plant Engineering and 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 RAMI aspects become primary design principles rather than afterthoughts.

An important consideration of this integration is the BOP: the secondary loops of coolants, pumps, heat exchangers, turbines, generators and controls that convert high-grade heat into usable power. These systems cannot simply be "bolted on" after the fusion engine is designed; their thermal and chemical requirements feed directly back 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 that interventions are predictable.

All of these decisions are guided by whole-system modeling and integration frameworks. Multiphysics 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. 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 and manufacturable 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.

S&T Gaps

F1. No validated end-to-end plant-level integrated modeling environment. Subsystem tools remain siloed. Lack a modular whole-plant model integration environment with data standards and UQ to connect test facility data to projectable, validated models; and support design choices, plant optimization and licensing-relevant analysis. There is no shared library of reference designs, benchmarks, and workflows to compare models, train users, and maintain a traceable digital thread between experimental data, predictions, and safety-case methodology.

F2. RAMI 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 show a pathway toward target availability.

F3. 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, validated on representative mockups with time-to-repair KPIs and tooling qualification.

F4. 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, including shared engineering standards, design-for-manufacture, and design-for-replacement principles.

F5. 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 remains underdeveloped.

F6. 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. Interfaces (pressures, temperatures, allowable chemistry windows, transients) are poorly defined and not yet treated as design-controlling constraints.

F7. 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.

FIRE Collaboratives and FES program areas

- Blanket Collaborative on Test Facilities
- Fusion Energy Data Ecosystem and Repository
- Accelerating Fusion Blanket Development through Nuclear Testing

In addition to FIRE Collaboratives, the Theory and Simulation and Sustain a Burning Plasma sub-elements of the FES program also address the key gaps and Milestones outlined this section.

Symbol indicates **Genesis Mission** impact

Near term → 2-3 years	**Stand up a centralized, standards-based fusion S&T data repository** **Metric →** Deliver FAIR (findable, accessible, interoperable, and reusable)-based schemas across all experiments and simulations, as relevant and informed by industry. **FIRE →** Fusion Energy Data Ecosystem and Repository **S&T Gaps → F1**	**Demonstrate end-to-end integrated workflow relevant for whole-plant modeling against experimental data with quantified uncertainty** **Metric →** Workflow executed with automated provenance, common data schema, and independent reproducibility. Uncertainty quantification identifies contributors, and domains of model validity are defined and enforced. Modules validated against at least one test stand measurement and trend with holdout validation (different operating point/case/facility) showing maintained uncertainty bounds. **FIRE →** Fusion Energy Data Ecosystem and Repository **S&T Gaps → F1**	**Publish pre-licensing modeling and validation evidence template** **Metric →** Produce a structured "evidence package" suitable for pre-licensing review of model description and VV history, assumptions and validity, uncertainty propagation, configuration control and provenance, mapping to a safety-relevant claim (e.g., max temperature margin, tritium inventory bounds, radiation dose constraints). **S&T Gaps → F1, F7**	**Publish reference availability budgets, remote maintenance sequences and feasibility envelopes, and RAMI design constraints** **Metric →** Evaluate plant availability target (e.g., >75%) decomposed into planned maintenance (in-vessel components, BOP systems, controls and diagnostics), unplanned failures, recovery time. Define reference replacement tooling/time under activation and tritium constraints and identify top RAMI risks. **S&T Gaps → F2, F3**	**Define standardized interfaces and design-for-replacement** **Metric →** Mechanical, thermal, hydraulic, electrical interfaces defined for candidate components to enable virtual swap-in comparisons and scoring rubric studies such as number of interfaces, alignment tolerances, tooling complexity, and replacement time sensitivity. **S&T Gaps → F4**	**Define minimum diagnostic and protection set tied to availability and safety** **Metric →** Sensors mapped to failure modes, protection actions, maintenance triggers. Required accuracy, survivability, and replacement cadence defined as part of the RAMI budget. **S&T Gaps → F5**
Mid term → 3-5 years	**Demonstrate remote re-connection of irradiated interfaces with quantified tritium containment and mechanical integrity** **Metric →** Tritium leak rate from a joint. Mechanical properties of the joint region (acceptable values of mechanical property degradation need to be specified). Inventory/volume of irradiated component storage/packaging/disposal (to minimize). **S&T Gaps → F3**	**Demonstrate repeatable remote inspection, alignment, and handling for blankets and PFCs, including sensing, metrology, and automated protection interlocks** **Metric →** Handling capability (size, position accuracy, connector success rate); Mean time to repair (to meet availability goals). Quantitative requirements are design-dependent and need to be articulated. **S&T Gaps → F4, F5**	**Publish a RAMI-driven availability budget and top failure mode list** **Metric →** Availability target allocated by subsystem; Define initial set of top failure modes across concepts which represent top X% of availability loss; Reliability input to track confidence levels. **S&T Gaps → F2**	**RAMI demonstrated in non-nuclear demonstrations** **Metric →** Number of prototypes built. Achieve time-to-replace and remote-connector cycle life targets for top 10 maintenance tasks. Demonstrate logistical throughput consistent with blanket/first-wall replacement reference scenarios. **S&T Gaps → F2, F3, F4**		
Long term → 5-10 years	**Plant-wide diagnostics and protection (baseline) capable of operating in fusion environments** **Metric →** Diagnostic coverage mapped to known RAMI and safety-relevant failure modes, radiation/thermal/EMI (electromagnetic interference) tolerance demonstrated for relevant envelopes. Failure threshold defined by total fluences (n/cm² at 14 MeV) and, more importantly, by radiation hardness tolerance under prompt loss (rad(Si)/s). **S&T Gaps → F5**	**Demonstrate integrated fusion-plant-relevant heat extraction and power conversion cycles within chemistry, tritium, and reliability constraints** **Metric →** Conversion efficiency measured over sustained operation; Tritium permeation and inventory accounted for, coolant chemistry stability maintained within limits; Reliability, demonstrated coupling between blanket heat extraction, BOP performance, and diagnostic/protection actions. **FIRE →** Blanket Collaborative on Test Facilities **S&T Gaps → F6**	**Release modular digital twin fusing live test-stand facility data and interconnected simulations** **Metric →** Capable of fusing live facility data and interconnected simulations for forecasting/optimization/control; Capable of supporting automated protection and condition-based maintenance. **FIRE →** Fusion Energy Data Ecosystem and Repository **S&T Gaps → F1, F7**	**Validate whole-plant integrated models against coupled prototype operation** **Metric →** Model predictions match measured behavior within uncertainty bounds. Includes transient and fault scenarios. **S&T Gaps → F1**	**Qualify controls and data operations for repetition-rate operations** **Metric →** Steady state/repetition for full duty cycle. Six months of operations. **S&T Gaps → F7**	

Fusion Plant Engineering and System Integration

Mapping the Near-term Milestones

In the near term, the program will establish the structural foundations that make integrated fusion plant design possible, defining common standards, validation practices, and reliability constraints that allow disparate models, data sources, and designs to be evaluated and ultimately integrated on consistent, transparent grounds. As an enabling element, the program will launch a centralized, standards-based fusion data repository, guided by an industry advisory board to prioritize content and ensure relevance. This repository will implement FAIR-based schemas, establish clear intellectual property boundaries, and enable tiered access across experiments and simulations, providing a common backbone for information sharing to inform plant design and analysis. The repository will be deployed within the DCP to accelerate the delivery of fusion energy.

Building on this foundation, the program will publish a common verification, validation, and uncertainty quantification (VV/UQ) framework with standardized metadata and schema for whole-plant models. By ensuring interoperability between different codes and outputs, this framework will allow systems engineers to integrate physics, technology, and operations models within a traceable, auditable design process. This framework will explicitly support end-to-end integration demonstrations in later phases by defining how experimental data, model predictions, and uncertainty bounds are carried forward into design and licensing-relevant analyses.

The program will also expand pathways that link AI and HPC directly to fusion facilities, enabling near-real-time model calibration and rapid turnaround of integrated simulations. Early efforts will connect key facilities such as DIII-D, NSTX-U, and MPEX into HPC and AI workflows, advancing digital-twin capabilities that can operate on operator-relevant timescales through surrogate modeling.

Finally, to embed reliability into plant design from the outset, the program will define RAMI metrics and test methods and publish an initial FPP RAMI handbook. This guidance will establish availability factor targets, failure modes and effects analysis (FMEA)-style methods, and remote-maintenance design standards, making RAMI a first-class design basis for future pilot plants. These metrics will be used to establish reference availability budgets and identify early "design killers," ensuring that candidate plant architectures are screened against maintainability and availability constraints before advancing to detailed design.

The FEDER will support standards and repository development, while centralized HPC assets, DOE user-facility integration via the American Science Cloud, and the Stellar-AI upgrade will provide the computational infrastructure to connect facilities, models, and data streams.

Mapping the Mid-term Milestones

In the medium term, the program plans to translate foundational frameworks into design-driving integration demonstrations, using representative environments and mock-ups to determine whether candidate plant components and architectures can meet availability, maintainability, and safety requirements at plant scale. A key step will be qualifying joining and cutting methods in nuclear-relevant environments, ensuring that irradiated materials can be re-connected or separated with minimal tritium release. This capability is essential for enabling modular replacement and repair of in-vessel components under realistic activation and environmental conditions. Results from these demonstrations will inform standardized interface classes and qualification requirements for coolant, electrical, and instrumentation connections in replaceable in-vessel components.

At the same time, the program will advance prototype remote sensing and handling systems for high-value, high-downtime components such as blankets and PFCs. These prototypes will be exercised in facilities that simulate the challenges of activated structures, corrosive coolants like PbLi, hazardous byproducts, and beryllium or dust management. These demonstrations will integrate sensing, metrology, handling, and automated protection into complete maintenance sequences, enabling quantitative assessment of time-to-repair, alignment tolerance, error rates, and recovery actions. Emphasis will be placed on throughput and maintainability studies, showing how complex operations can be performed safely and within acceptable downtime windows.

To guide these demonstrations, the program will expand RAMI analysis into targeted studies of top failure modes, providing quantitative insight into which components drive availability, safety, and lifecycle cost. These studies will establish clear reliability and maintainability targets that inform plant architecture and investment decisions, enabling down-selection from candidate design features or architectures, providing a clear feedback loop between RAMI analysis and design. Finally, the program will support RAMI demonstrations in non-nuclear settings, using remote-maintenance mock-ups to validate workflows for sector isolation, blanket or divertor change-out, and precision metrology. These efforts will also begin collecting structured reliability data, providing the foundation for predictive maintenance and inspection budgets in pilot plant design.

The FEDER will provide data standards and curation for RAMI studies and reliability data. Delivery will leverage the foundation of HPC-enabled digital twins and modeling established in the near term, while adding a dedicated robotics and handling maintenance facility to prototype and qualify remote operations before deployment.

Mapping the Long-term Milestones

In the long term, the program plans to support plant-scale demonstrations of diagnostics, controls, and integrated operation that establish regulatory confidence and operational readiness for fusion power plants, providing the evidence base required for licensing, sustained operation, and fleet deployment. A central focus will be the development of plant-wide diagnostics and protection systems, with hardened sensors for operations and machine protection, coupled to advanced leak and contamination detection for tritium. These capabilities will establish the baseline for safe, accountable operation in fusion plant environments.

In parallel, the program will advance controls, automation, and remote operations to the required standards. Plant-wide architectures for data handling, automated protection, and remote operation will be demonstrated in conjunction with operating facilities, proving that critical functions can remain robust under radiation, heat, and high-availability duty cycles. As repetition-rate facilities mature, controls and data pipelines will be validated for uniform architecture, automated ML analysis, and real-time response, ensuring readiness for both steady-state and high-rep-rate pilot plants. Demonstrations will include fault scenarios and recovery actions, showing that autonomous and remote operations can maintain safe operation and availability without continuous human intervention.

The program also aims to support end-to-end demonstrations of power generation cycles from blanket heat extraction. Closed Brayton and Rankine cycles will be qualified under prototypic conditions, including helium loop tests of manifold distribution, pressure drop, and heat-transfer coefficients at pilot-plant-relevant pressures, temperatures, and flow rates. These efforts will confirm that blanket heat can be delivered as stable, high-efficiency power. These demonstrations will be used to validate co-optimization of blanket design, coolant choice, and power-conversion architecture, ensuring that thermal and chemical constraints are treated as plant-level design drivers.

Digital infrastructure will be equally critical. The digital twin infrastructure envisioned here will function as a shared, regulator-credible integration environment rather than a plant-specific proprietary tool. A modular digital twin will be released that fuses live facility data with interconnected simulations at multiple fidelities, supporting forecasting, optimization, automated protection, and condition-based maintenance. This will culminate in validated whole-of-system models, benchmarked against coupled experiments such as blanket and fuel-cycle loops or IFE high-rep-rate diagnostics, with quantified error bars to support licensing and design decisions.

Infrastructure is expected to extend medium-term platforms with whole-facility digital twins, predictive diagnostic models, and synthetic diagnostic suites, enabling fully validated, digital-driven fusion power-plant design and operation. ■

Figure 10.
Summary of key milestones across all challenge areas over the near, mid, and long-term. These represent technical priorities; Congressional appropriations and private investment are required to realize these timelines.[51]

Challenge area	Near term (2-3 years)	Mid term (3-5 years)	Long term (5-10 years)
Structural Materials Science and Technology A	• Develop accelerated qualification pathways for Fe-alloys 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 Fe-alloy and 500 kg V-alloy heats. • Deliver corrosion loops and HHF facility; leverage IMPACT and BCTF FIRE Collaboratives.	• Complete irradiation campaigns and PIEs defining fusion-specific functional requirements up to ~10 dpa for Fe-alloys 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 functional requirements 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, and expanded domestic test infrastructure.
Plasma-Facing Components and Plasma-Material Interactions B	• 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 digital engineering 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 C	• Expand access to IFE platforms (Omega, NIF, Z) 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 α particle-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-aspect 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 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 D	• 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 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 IB-FCTF coupling tritium breeding, extraction, and fueling under fusion-relevant conditions.
Blanket Science and Technology E	• 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-principle 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 and System Integration F	• Launch a centralized, standards-based data repository implementing FAIR principles and tiered access for experiments and simulations. • Publish a common VV/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 and cutting methods for irradiated materials to enable modular in-vessel replacement. • Demonstrate remote handling and 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 and protection systems with radiation-hardened sensors. • Demonstrate automated controls and remote operations in steady state and 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.

51. Progress depends on future appropriations and private investment.

Appendix 4

Technical Descriptions and Mapping of the Infrastructure Streams

This section details the landscape and delivery options to implement the FS&T Infrastructure Pathway and deliver capabilities across each of the eight Infrastructure Streams. Execution will depend on Congressional appropriations for public funding and private investment.

1. Plasma Confinement and Performace
2. Enabling Technologies Development and Testing
3. Exhaust and Plasma/High-Heat-Flux Testing
4. Nuclear-Effects Testing
5. Remote Maintenance and BOP Development and Testing
6. Blanket Development and Testing
7. Fuel Cycle Development and Testing
8. HPC, Advanced Manufacturing, and AI

Technical Descriptions

Plasma Confinement and Performance

Name (acronym)	Description	Category	Stage	Timeframe
National Ignition Facility (NIF)	Laser-based inertial confinement fusion research facility. NIF's mission is to achieve fusion ignition with high energy gain.	National laboratory (LLNL)	Existing/under construction	Near term
Omega	User facility dedicated to inertial confinement fusion research and high-energy-density physics experiments	University (University of Rochester)	Existing/under construction	Near term
Private facility research on emergent confinement concepts	Use of private demonstration and pilot plants to conduct core performance and confinement research.	Private (various)	Planned	Near term
National Spherical Torus Experiment - Upgrade (NSTX-U)	Low aspect ratio core physics test facility investigating core confinement improvements, heat-flux mitigation, and non-inductive operation in a core-edge optimized plasma with majority self-driven current.	National laboratory (PPPL)	Existing/under construction	Near term
DIII-D Negative Triangularity Enhancement	Enhancements to enable operation of the DIII-D tokamak in strongly negative plasma triangularity configurations to investigate high-performance, disruption-resilient plasma regimes.	DOE user facility	Existing/under construction	Near term
Wendelstein 7-X (W7-X)	Advanced superconducting stellarator, designed to demonstrate steady-state plasma confinement using optimized 3-D magnetic geometry.	International (Germany)	Existing/under construction	Near/mid/long term
Axially Symmetric Divertor Experiment Upgrade (ASDEX-UG)	A medium-sized tokamak designed to investigate plasma performance and divertor physics under fusion-relevant conditions, particularly with tungsten plasma-facing components.	International (Germany)	Existing/under construction	Near term
Mega Ampere Spherical Tokamak Upgrade (MAST-U)	Upgraded spherical tokamak investigating advanced plasma exhaust solutions, including the Super-X divertor, and to explore high-performance plasma scenarios relevant to compact fusion power plants.	International (UK)	Existing/under construction	Near term
SPARC Diagnostics and Hardware Toward Q > 1 Physics	Diagnostic instruments and fuel injection hardware and design to support the delivery and physics studies of the first magnetically confined Q > 1 plasmas on the SPARC high field tokamak.	PPP (CFS, various DOE national laboratories and universities)	Existing/under construction	Near term
Spherical Tokamak 40 (ST40)	A high-field spherical tokamak developed to demonstrate compact, high-temperature plasma performance as a pathway to commercial fusion power.	PPP (Tokamak Energy)	Existing/under construction	Near term
Japan Torus-60 Super Advanced (JT-60SA)	Large superconducting tokamak designed to support ITER and advance steady-state, high-performance plasma scenarios relevant to future fusion power plants. It enables long-pulse operation with strong plasma shaping and advanced control capabilities to study stability, confinement, and integrated plasma performance.	International (Japan)	Existing/under construction	Near term
Korea Superconducting Tokamak Advanced Research (KSTAR)	Superconducting tokamak designed to investigate long-pulse, high-performance plasma operation and advanced control scenarios relevant to ITER and future fusion power plants. It has achieved world-record steady high-temperature plasma durations and is a leading platform for steady-state operation research.	International (Republic of Korea)	Existing/under construction	Near/mid/long term
Tokamak à Configuration Variable (TCV)	Highly flexible tokamak designed to explore a wide range of plasma shapes and configurations, including extreme elongation, triangularity, and alternative divertor geometries. It is particularly known for pioneering work in advanced plasma shaping, negative triangularity regimes, and novel divertor concepts.	International (Switzerland)	Existing/under construction	Near term
Private facility research on emergent confinement concepts	Use of private research platforms to progress emergent concepts	Private (various)	Needed/gap identified	Mid/long term
Private company demonstrations and pilot plants	Use of private demonstration and pilot plants to conduct core performance and confinement research.	Private (various)	Needed/gap identified	Mid/long term

Mapping

Plasma Confinement and Performance

Mapping the Near-term Infrastructure

In the near term, infrastructure priorities focus on broad, coor-dinated access to existing domestic and international plasma facilities to rapidly reduce confinement, stability, and scenario uncertainty across multiple approaches. Rather than constructing new confinement platforms, the emphasis is on maximizing the value of mature facilities through integrated experimental campaigns, shared diagnostics development, and coordinated data use.

Domestic infrastructure anchors include DIII-D (including its negative triangularity mission) and NSTX-U, which together provide complementary access to high-performance core plasmas, low-aspect-ratio physics, and core-edge integration challenges. These facilities also serve as critical testbeds for fusion-relevant diagnostics, materials, and enabling technologies, while supporting convergence between advanced plasma control and AI-enabled analysis. Smaller-scale experiments across national laboratories and universities provide additional infrastructure for targeted studies and workforce training.

International access remains central in the near term, particularly for long-pulse and stellarator operation, through facilities such as W7-X, MAST-U, JT-60SA, KSTAR, WEST, ASDEX-UG, and ST40. These platforms collectively support closure of key S&T gaps related to confinement scaling, stability control, and integrated core-edge behavior under extended pulse conditions.

In parallel, structured engagement with privately operated facilities through public-private access mechanisms expands the experimental portfolio and enables early exploration of emergent confinement concepts. For IFE, continued access to NIF and expanded, dedicated access to OMEGA, support sub-scale implosion physics and IFE-relevant confinement studies. The near-term objective is to establish validated operating scenarios and confinement scalings, supported by sufficient diagnostic capability to enable meaningful extrapolation to pilot plant designs.

Mapping the Mid-term Infrastructure

In the mid term, confinement infrastructure shifts from scenario validation toward predictive control and integrated core-edge performance, supported by higher-field and higher-gain operating regimes. A central feature of this phase is the maturation of SPARC as a core confinement and burning-plasma-relevant platform, providing access to regimes that close long-standing gaps between experimental plasmas and fusion-relevant conditions.

Mid-term infrastructure use emphasizes integration rather than expansion: confinement, heating and current drive, boundary conditions, and diagnostics are treated as a coupled system. A minimum viable diagnostic set becomes a defining infrastructure requirement, ensuring that measurements are sufficient to validate models, enable real-time control, and support extrapolation, without imposing unsustainable complexity or cost. This diagnostic philosophy is critical for SPARC and subsequent devices to qualify as relevant platforms for magnetically confined fusion.

At the same time, infrastructure access expands through private facilities, including the emergence of a private stellarator platform in partnership with the public program that provides flexibility for configuration optimization, control development, and sustained operation studies. Public-private/international partnerships and dedicated access programs enable public research on devices such as W7-X, and potentially to privately owned infrastructure, ensuring that advances in confinement performance and control are broadly accessible and integrated into national modeling and design frameworks.

The mid-term outcome is a confinement infrastructure ecosystem capable of supporting burning plasma studies, validating first-principles and AI-augmented models, and producing predictive tools that can be credibly applied to pilot plant and early commercial designs.

Mapping the Long-term Infrastructure

In the long term, plasma confinement infrastructure increasingly relies on access to pilot-scale and near-pilot facilities, many of which are expected to be privately developed, as platforms for sustained, integrated operation under power-plant-relevant conditions. These facilities demonstrate that high-performance plasmas can be maintained with the reliability, control and robustness required of power systems.

Long-term infrastructure priorities center on true core-edge integration: coupling high-performance confinement with survivable exhaust, maintainable diagnostics and actuators, and realistic duty cycles. Access to private, pilot-scale platforms will enable confinement performance to be evaluated as a plant-relevant capability, rather than as an isolated physics metric.

International infrastructure, including ITER as it transitions into nuclear operation, will contribute critical data on long-pulse, high-performance plasmas and inform the validation of predictive models. In parallel, emerging confinement concepts continue to be supported through public-private partnerships and dedicated access mechanisms, ensuring that alternative configurations remain viable contributors to future power plant options.

The long-term objective is to establish a validated projection capability for both pulsed and steady-state confinement concepts, integrating lessons from DIII-D, NSTX-U, SPARC, and next-generation facilities, to support confident execution of pilot plant designs and scalable fusion power deployment. ■

Techncial Descriptions

Enabling Technologies Development and Testing

Name (acronym)	Description	Category	Stage	Timeframe
High-Field Vertical Magnet Test Facility (HFVMTF)	Provides high-current, cryogenic testing of superconducting cables and conductors (including Nb_3Sn and high-temperature superconductors) under fusion-relevant magnetic field and mechanical stress conditions.	National laboratory (Fermilab)	Existing/ under construction	Near term
Fusion specific high-field irradiated superconductor technology development capabilities	FIRE Collaborative on superconducting materials irradiation.	University (University of Houston)	Existing/ under construction	Near term
Demo4	High-field platform to generate and study fusion-relevant forces across a system coil set (14 toroidal field magnets and two poloidal field magnets), providing engineering insight and data to inform power-plant designs of the future.	Private (Tokamak Energy)	Existing/ under construction	Near term
National Spherical Torus Experiment - Upgrade High Harmonic Fast Waves (NSTX-U HHFW (4 MW))	Enhances the High Harmonic Fast Wave radiofrequency heating system on NSTX-U to improve plasma heating, current drive capability, and operational reliability in spherical tokamak configurations.	National laboratory (PPPL)	Existing/ under construction	Near term
DIII-D Electron Cyclotron Resonance Heating (ECRH) Enhancement	Enhancement expands the facility's Electron Cyclotron Resonance Heating system to a total of ten gyrotrons, increasing power for plasma heating.	DOE user facility	Existing/ under construction	Near term
Matter in Extreme Conditions (MEC)	An open-access user facility, MEC enables a wide range of research, providing new insight into the atomic and structural properties of dynamic plasma and high-pressure material states.	DOE user facility	Existing/ under construction	Near term
LaserNetUS	A scientific ecosystem to advance and promote intense ultrafast laser science and applications by coordinating, and improving access to, key high-power laser facilities across North America.	Various	Existing/ under construction	Near term
ZNetUS	Provides researchers access to advanced experimental platforms, from compact, student-accessible systems to megampere-class generators.	Various	Existing/ under construction	Near term
Amphion HTS magnet	Eos-spec planar shaping coil. Partially insulated, large-bore HTS coil operated at 20 K. De-risks the magnetic field-shaping coil system of the Eos stellarator, and future power plants. De-risks the phenomena of manufacturability, controllability, and quench-resilience.	Private (Thea Energy)	Planned	Near term
Advanced Technology Lasers for Applications and Science (ATLAS)	A laser-driven fusion research center that will host two cutting-edge petawatt-class diode pumped laser systems built by Marvel Fusion and its collaborators to demonstrate their unique high repetition rate fusion driver technology. These lasers will produce 200 J pulses of 100 fs duration at 10 Hz repetition rate with integrated second harmonic generation for high-contrast laser-target coupling.	PPP (CSU/Marvel)	Existing/ under construction	Near term
Thea Energy gyrotron test stand	A MW-class, 100+GHz gyrotron tube in test stand prototypical of Eos or power plant. Includes power supplies, magnet, matching optics, transmission optics, and dummy load.	Private (Thea Energy)	Planned	Near term
CFS large magnet test stand	Magnet test infrastructure includes two large magnet test stands capable of testing all SPARC TF and PF magnets to their rated current and field at 20 K; two intermediate temperature test stands that operate at 77 K and test magnet subcomponents; and a dedicated superconductor test facility for HTS tape qualification.	Private (CFS)	Existing/ under construction	Near term

Name (acronym)	Description	Category	Stage	Timeframe
OpenStar magnet laboratory	HTS cable-in-conduit conductor development, flux pump development, quench detection systems.	Private (OpenStar)	Planned	Near term
Argos	A >100 kJ single excimer amplifier.	Private (Xcimer Energy)	Planned	Near term
Thunderwall-Test	IFE laser amplifier, optics, and diode test stands facilities.	Private (Inertia Enterprises)	Planned	Near term
Domestic IFE Beamlet testbeds	Testbeds in collaboration with private sector.	PPP	Needed/ gap identified	Mid term
GigaPulse Foundry	Details not publicly available.	Private (Pacific Fusion)	Planned	Mid term
TeraPulse Foundry	Details not publicly available.	Private (Pacific Fusion)	Planned	Mid term
Anvil	A 2-beamline, 200 kJ total, laser-target experimental facility (two-sided).	Private (Xcimer Energy)	Planned	Mid term
Thunderwall	Full-scale IFE laser beamline demonstrator; unit cell of the power plant.	Private (Inertia Enterprises)	Planned	Mid term
Magnet fabrication, testing, and refurbishment facility (OpenStar)	Production-cadence manufacturing. The annual core magnet replacement cycle makes this an ongoing production facility.	Private (OpenStar)	Planned	Mid term
Matter in Extreme Conditions - Upgrade (MEC-U)	A multi-kilojoule laser facility coupled to LCLS.	DOE user facility	Needed/ gap identified	Long term
Inertial Fusion Energy - Fusion Integration Research and Science Test Facility (IFE-FIRST)	Integrated multi-kilojoule implosion laser facility at repetition rate relevant to IFE.	Needed/ gap identified	Needed/ gap identified	Long term

Mapping

Enabling Technologies Development and Testing

Mapping the Near-term Infrastructure

In the near term, infrastructure priorities focus on strengthening and coordinating the national hardware testing ecosystem required to advance fusion drivers, actuators, and magnets across both magnetic and inertial fusion approaches. The emphasis is on leveraging existing high-value platforms, expanding access through public-private mechanisms, and filling critical gaps in component-level testing before integrated demonstrations.

For magnet and actuator development, near-term infrastructure includes high-field magnet and conductor testing facilities, such as those at FNAL, alongside superconducting cable and coil test facilities capable of validating HTS cable performance under high background fields. These facilities will be used to define and validate electro-mechanical characteristics, critical current limits, and degradation mechanisms of HTS cables and joints under conditions relevant to compact, high-field fusion systems. Complementing these facilities will be the development of private magnet test facilities (e.g., Thea Energy, CFS, OpenStar).

Near-term actuator capability will be strengthened through RF and heating system enhancements on existing plasma devices, including NSTX-U HHFW and DIII-D ECRH enhancement, which provide essential platforms for testing coupling, efficiency, reliability, and control of heating and current-drive systems. Together with private test stands (i.e., Thea Energy), these platforms support the early integration of actuator performance with plasma scenarios, diagnostics, and control architectures.

On the inertial fusion and pulsed-power side, near-term infrastructure leverages national user networks such as LaserNetUS and ZNetUS, providing community access to mid-scale laser and pulsed-power facilities for driver physics, materials response, and platform prototyping. MEC (SLAC) serves as a unique national capability for studying matter under extreme conditions relevant to IFE drivers and targets, while enabling tight coupling between optical drivers and advanced x-ray diagnostics. Together, these facilities support early exploration of high-power laser drivers, pulsed-power components, and diagnostics while training the next generation of fusion engineers.

The near-term objective is to convert key uncertainties such as efficiency, repetition rate, thermal management, radiation tolerance, and manufacturability into measurable, testable performance envelopes, establishing public-domain benchmarks where possible to accelerate convergence across the U.S. fusion ecosystem.

Mapping the Mid-term Infrastructure

In the mid term, driver, actuator, and magnet infrastructure will progress from component validation toward pilot-relevant demonstrations, emphasizing integrated performance, reliability, and maintainability.

For magnetic fusion, enhancements to DIII-D heating and current-drive systems (including expanded ECRH and NBI capability) provide a bridge between scenario development and power-plant-relevant actuator operation. Coordinating with private industry, these platforms support studies of steady-state and long-pulse heating, including ICRH operation tightly coupled to SPARC-relevant physics, enabling validation of actuator performance across confinement regimes. For inertial fusion and pulsed approaches, mid-term infrastructure includes dedicated driver demonstrators and beamline-scale testbeds, such as the ATLAS laser facility (CSU/Marvel Fusion), which will enable validation of repetition-rate, efficiency, and reliability pathways for advanced laser drivers. Additional demonstrators, including Inertia Enterprises' IFE beamline demonstrator, will explore alternative driver technologies, such as diode-pumped solid-state lasers and excimer-based approaches, through close collaboration with private sector partners. These platforms will support driver performance to be evaluated alongside control systems, thermal management, optics lifetime, and maintainable packaging.

Mid-term infrastructure also begins to address PMF needs by establishing community-accessible testbeds for giga-scale pulsed-power electronics and terawatt-class, repetition-rated PMF test platforms integrated with vacuum chambers and advanced diagnostics. These facilities will enable early validation of pulsed drivers, switching technologies, and system integration under conditions relevant to pulsed fusion concepts.

The mid-term outcome is an infrastructure ecosystem capable of supporting integrated actuator and driver demonstrations that meaningfully inform pilot plant design, rather than isolated component tests.

Mapping the Long-term Infrastructure

In the long term, infrastructure priorities shift to national-scale integration platforms that validate driver, actuator, and magnet systems under fusion-relevant environments and duty cycles.

For inertial fusion, long-term infrastructure plans include upgrades such as MEC-U and a high-repetition-rate fusion integration test facility (e.g., IFE-FIRST). These platforms enable integrated testing of driver-target-chamber systems at repetition rate, addressing coupled nuclear, thermal, debris, and electromagnetic effects. They also support studies of material degradation, tritium breeding interfaces, heat extraction, and the response of diagnostics and electronics to neutron and x-ray environments characteristic of IFE systems.

For magnetic fusion, long-term infrastructure supports the validation of projection capability for both pulsed and steady-state compact tokamak operation, integrating lessons from SPARC, DIII-D, NSTX-U, international facilities, and next-generation platforms. Pulsed operating scenarios are expected to mature earlier, while steady-state operation remains a longer-horizon challenge that may require dedicated facilities beyond existing devices.

Across both approaches, emerging confinement and driver concepts continue to be supported through public-private partnerships and shared access mechanisms, ensuring that innovation remains coupled to national testing infrastructure. The long-term objective is to establish a validated, integrated understanding of how fusion drivers, actuators, and magnets perform as systems, providing the confidence required to deploy pilot plants and scale to commercial fusion power. ■

Techncial Descriptions

Exhaust and Plasma/ High-Heat-Flux Testing

Name (acronym)	Description	Category	Stage	Timeframe
ST40 Lithium Evaporations to Advance Plasma-facing components (ST40 LEAPS)	Facility exploring lithium PFC impacts on core confinement, and wettability on high-Z substrates.	PPP (Tokamak Energy)	Existing/ under construction	Near term
DIII-D Advanced Divertor Enhancement	Major hardware enhancement to the DIII-D tokamak designed to test advanced divertors. configurations and power-exhaust solutions relevant to future fusion power plants.	DOE user facility	Existing/ under construction	Near term
Prototype Material Plasma Exposure eXperiment (Proto MPEX)	High-intensity linear plasma device designed to expose materials to fusion-relevant plasma conditions to study PMI, heat flux handling, and surface damage relevant to divertor environments in future fusion power plants.	National laboratory (ORNL)	Existing/ under construction	Near term
Material Plasma Exposure eXperiment (MPEX)	High-power linear plasma device designed to produce fusion-relevant plasma fluxes and heat loads for testing PFMs under conditions comparable to those expected in the divertor region of future fusion power plants.	National laboratory (ORNL)	Existing/ under construction	Near term
Tritium Integrated Loop test facility (TREX)	Tritium Integrated Loop system for training and testing.	PPP (Type One Energy, SRNL)	Planned	Mid term
International linear plasma facilities	Use of international R&D platforms for exhaust, heat, and PMI research (i.e., Magnum-PSI (Netherlands), JUDITH-II (Germany), HHFTF (India), JEBIS (Japan), GLADIS (Germany)).	International (various)	Existing/ under construction	Near term
Private company demonstrations and pilot plants	Use of private demonstration and pilot plants to conduct exhaust, heat-flux, and PMI research.	PPP (various)	Needed/ gap identified	Long term
Millennium	Details not publicly available.	Private (Zap Energy)	Planned	Near term
Tungsten (W) Environment in Steady-state Tokamak (WEST)	Long-pulse, steady-state plasma facility to test tungsten plasma-facing components and long-pulse, steady-state divertor operation under ITER-relevant conditions. It serves as a key platform for validating tungsten divertor technologies, heat flux handling, and plasma-wall interaction physics in preparation for ITER and future fusion power plants.	International (France)	Existing/under construction	Near term
Dynamics of ION Implantation and Sputtering Of Surfaces (DIONISOS)	A linear plasma exposure and surface analysis experiment that couples a plasma source with a high-energy ion beam and in-situ diagnostics to study PMI under well-controlled fusion-relevant plasma conditions.	University (MIT)	Existing/under construction	Near term

Name (acronym)	Description	Category	Stage	Timeframe
Plasma On Simultaneous Energetic Incident Damage by iONs (POSEIDON)	Facility for exploring the synergistic response of PFMs undergoing simultaneous high-flux plasma exposure and displacement damage in the near surface of PFMs.	University (UCSD)	Existing/ under construction	Near term
Plasma Interaction with Surface Component Experiment (PISCES-B)	Linear plasma test stand to examine PMI for ITER and future DEMO devices.	University (UCSD)	Existing/ under construction	Near term
Tritium Plasma Experiment (TPE)	A high-flux linear plasma device that can handle beryllium, tritium, and neutron-irradiated PFMs.	National laboratory (INL)	Existing/ under construction	Near term
Hybrid Illinois Device for Research and Applications (HIDRA)	A medium-sized toroidal magnetic fusion device dedicated to the study of the PMI and PFC issues.	University (University of Illinois Urbana-Champaign)	Existing/ under construction	Near term
IGNIS 1 and 2	In-situ experimental surface science facilities capable of surface characterization of materials under extreme conditions such as those found in nuclear fusion environments or irradiation-driven conditions.	University (University of Illinois Urbana-Champaign / Pennsylvania State University)	Existing/ under construction	Near term
Liquid metal core-edge (LMCE) test stands	Small-scale test stands, delivered as part of LM FIRE Collaborative and possible separate awards, to develop LM PFCs at module scale.	Not yet determined	Existing/ under construction	Mid term
Private company demonstrations and pilot plants	Use of private demonstration and pilotplants to conduct exhaust, heat-flux, and PMI research.	PPP (various)	Needed/ gap identified	Long term
Private company demonstrations and pilot plants	Use of private demonstration and pilot plants to conduct exhaust, heat-flux, and PMI research.	PPP (various)	Needed/ gap identified	Long term
LLiquid metal core-edge (LMCE) platform	Integrated plasma confinement platform with LM PFCs that demonstrates the simultaneous management of prototypic heat fluxes, particle (including He) exhaust, and the retention of high plasma confinement.	Needed/gap identified	Needed/gap identified	Long term
Divertor Tokamak Test (DTT)	Planned research facility to test the physics and technology of various alternative divertor concepts under plasma conditions that can be confidently extrapolated to an FPP.	International (Italy)	Planned	Long term

Mapping

Exhaust and Plasma/ High-Heat-Flux Testing

Mapping the Near-term Infrastructure

In the near term, a coordinated portfolio of planned, existing, and enhanced domestic plasma facilities, high-heat-flux test stands, and university-based platforms will ensure U.S. leadership in HHF and PMI. This strategy focuses on complementary infrastructure that collectively spans the relevant space of heat flux, particle flux, plasma exposure, and displacement damage.

DOE is activly working to deliver the MPEX at ORNL, which will provide steady-state, high-flux plasma exposure over extended durations and enables systematic studies of erosion, redeposition, co-deposition, surface morphology evolution, and hydrogen isotope retention at the sub-component scale. MPEX is complemented by domestic high-heat-flux test facilities, DIONISOS (MIT), and established PMI platforms, including POSEIDON and PISCES-B, which together support repeatable testing of materials, diagnostics, and cooling concepts.

In parallel, NSTX-U will play a unique and critical role in near-term infrastructure by providing a domestic platform capable of accessing extreme unmitigated heat fluxes (approaching 0.1 $GW{\cdot}m^{-2}$) in a tokamak boundary plasma environment. This capability is essential for studying divertor concepts under conditions of intense particle flux and shallow detachment, where radiation-dominated heat exhaust becomes a central challenge. NSTX-U, therefore, anchors early development of advanced divertor and first-wall concepts, including liquid-metal plasma-facing components, which are expected to play an increasingly important role in future power-plant exhaust solutions.

The near-term objective is to establish an infrastructure ecosystem that enables rapid, comparative testing of solid and liquid PFC concepts, produces repeatable datasets, and closes key gaps between single-effects testing and integrated boundary-plasma conditions.

Mapping the Mid-term Infrastructure

In the mid term, exhaust infrastructure will need to evolve from high-throughput testing toward combined-effects and integrated boundary plasma testing, with particular emphasis on liquid-metal divertor and first-wall concepts. This includes the development of a domestic LMCE test capability and a liquid-metal exhaust testing testbed, designed to operate under sustained heat and particle flux while enabling active control of surface conditions, impurity behavior, and plasma detachment.

Mid-term infrastructure must address synergistic loading conditions, including heat flux, particle flux, and displacement damage, recognizing that exhaust component viability depends on the interaction of these effects rather than any single parameter. Facilities will need to accommodate actively cooled PFCs, radiation-tolerant diagnostics, and modular component replacement to support iterative testing and maintainability studies.

International access expands capability, with facilities such as WEST, international linear plasma devices, and planned tokamak divertor test facilities providing long-pulse and steady-state operation that complements domestic assets. Expanded access to long-pulse fusion devices allows validation of detachment control, impurity management, and operational stability over timescales relevant to pilot plants. Mid-term infrastructure must support converging on exhaust solutions that are not only survivable under extreme loads, but operable and maintainable within realistic control and availability constraints, supported by infrastructure that produces transferable, design-relevant evidence.

Mapping the Long-term Infrastructure

Within 5-10 years, exhaust and high-heat-flux infrastructure will need to deliver validation in fusion devices that most closely resemble pilot-plant boundary conditions, integrating core performance, boundary plasma control, and plasma-facing components within a single operating environment. At this timescale, access to planned private company infrastructure (e.g., SPARC) for integrated core-edge scenarios, and international platforms that are specifically designed for advanced divertor development can provide critical aspects of these capabilities.

Infrastructure use shifts from concept exploration to lifetime validation and reliability assessment, with testing focused on confirming component survivability, replacement strategies, and control robustness under representative operating envelopes. The exhaust test ecosystem increasingly supports coupled experimental-modeling workflows, enabling predictive tools to be validated against integrated facility data. ■

Technical Descriptions

Nuclear-Effects Testing

Name (acronym)	Description	Category	Stage	Timeframe
Intermediate-energy Proton Irradiation Platform (IEPI)	Compact, superconducting cyclotron to produce a 12 MeV proton beam for the rapid, high-fidelity testing of structural materials (e.g., tungsten, nickel alloys) for fusion energy systems, including helium generation studies.	University (MIT)	Existing/ under construction	Near term
High Flux Isotope Reactor (HFIR)	A high-flux research reactor for fundamental and applied research on the structure and dynamics of matter.	National laboratory (ORNL)	Existing/ under construction	Near term
MIT Nuclear Research Reactor (MITR)	A 6-MW light-water cooled and moderated research reactor providing high neutron flux for research in materials testing, neutron activation analysis.	University (MIT)	Existing/ under construction	Near term
Advanced Test Reactor (ATR)	A light-water-cooled, beryllium-reflected reactor designed for producing high neutron fluxes.	National laboratory (INL)	Existing/ under construction	Near term
Materials irradiation R&D test stands	Facilities to generate high dpa from high-energy neutrons.	Needed/ gap identified	Needed/ gap identified	Mid term
Magnetic-mirror-based volumetric neutron source	A magnetic mirror-based VNS operating in steady state with DT fusion for integrated fusion materials (displacement damage), blanket, and fuel cycle testing. One or more TBMs will be available. At least one TBM will use lead-lithium, but others may be available for testing other blanket concepts.	Private (Realta Fusion)	Planned	Mid term
Magnetic dipole volumetric neutron source	VNS available to broader fusion community for nuclear effects testing. Hot-cell co-located with Māui for activated materials handling, post-irradiation examination, and core magnet refurbishment. Designed for shared use. OpenStar requires large hot cell capacity for annual magnet refurbishment, and this capacity can serve the broader community.	Private (OpenStar)	Planned	Mid term
U.S. High-Flux Fusion Innovation Center	Details not publicly available.	Private (Pacific Fusion)	Planned	Long term
Domestic volumetric neutron source (VNS)	High-flux fusion component irradiation facility suitable for high-throughput testing of tritium breeding blanket and fusion power plant components.	Needed/ gap identified	Needed/ gap identified	Long term
Domestic fusion prototypic neutron source (FPNS)	High dpa fusion prototypic irradiation facility for fusion materials testing.	Needed/ gap identified	Needed/ gap identified	Long term

Mapping

Nuclear-Effects Testing

Mapping the Near-term Infrastructure

In the near term, infrastructure priorities focus on maximizing actionable learning from existing irradiation and characterization environments, while deliberately laying the foundations for both volumetric and fusion-prototypic neutron sources. The strategy emphasizes neutron exposure capability first, coupled to advanced characterization and modeling, rather than waiting for a single future facility to resolve all gaps.

Core near-term infrastructure includes domestic assets such as HFIR (ORNL), ATR (INL), the MIT Nuclear Research Reactor (MITR), and selected international materials test reactors, which enable irradiation of fusion-relevant materials. These reactors are complemented by spallation and ion-beam platforms, including proton irradiation capabilities at MIT, to probe transmutation, defect evolution, and dose-rate effects not accessible through fission spectra alone.

Near-term infrastructure use is tightly coupled to advanced characterization platforms, including beamlines, neutron scattering, microscopy, and spectroscopy; and to hot-cell and tritium laboratory access, enabling full experimental workflows from irradiation through post-irradiation examination. A key outcome of this phase is the establishment of validation benchmarks for small-specimen test methods (tensile, fracture toughness, creep-fatigue, and joint performance), anchored in fission and mixed-spectrum data that can be systematically translated to fusion-relevant conditions.

In parallel, near-term development aims to advance R&D-scale neutron source infrastructure, including cyclotron-based deuteron acceleration and early fusion-neutron access where available. These efforts support method development, specimen strategies, and early exposure campaigns, while a strong modeling emphasis links surrogate irradiation results to expected behavior under fusion neutron spectra with quantified uncertainty. The near-term objective is to establish a credible translation framework, connecting fission, spallation, ion-beam, and limited fusion-neutron data, rather than to defer learning until an FPNS is available.

Mapping the VNS Track

In the mid term, nuclear-effects infrastructure advances through the delivery of a domestic VNS that provides higher-flux, higher-throughput neutron exposure, preferably with a fusion-relevant energy and momentum spectrum, than fission reactors or charged-particle techniques for a broad class of fusion-relevant questions. The VNS track has two primary goals. One is to provide a workhorse capability, supporting materials, components, diagnostics, magnets, and tritium-system subsystems under neutron environments that more closely approximate fusion conditions while remaining deployable on pilot-relevant timelines. The second is to deliver a source of prototypical volumetric fusion neutrons to a versatile blanket test stand with tritium fuel cycle capability.

In addition to a VNS capability integrated into the TBDP, there is scope to leverage private demonstrators to provide access for materials and component testing (e.g., ATLAS/Marvel, Realta Fusion, OpenStar).

Mapping the Long-term infrastructure: FPNS Track

In the 5-10 year time scale, nuclear-effects infrastructure culminates in establishing an FPNS capability as a central pillar of fusion deployment readiness. This track addresses the fundamental limitation of existing neutron sources: the inability to fully replicate fusion neutron spectra, damage rates, and transmutation effects that drive swelling, embrittlement, and lifetime limits in plasma-facing and structural materials.

FPNS infrastructure is designed explicitly for component- and system-relevant testing, exposing blanket-relevant materials, plasma-facing components, joints, diagnostics, magnets, and tritium-system hardware to fusion-relevant neutron conditions. The facility is expected to be integrated with nuclear-grade hot cells, advanced characterization, and QA/QC-ready data systems, enabling the production of design-quality datasets suitable for codes, standards, and licensing.

Recognizing the urgency of fusion-specific neutron data, the FPNS track is developed as a priority endpoint. Where appropriate, time-bound access to fusion devices or pulsed fusion environments that provide relevant neutron spectra complements FPNS development, supporting early validation of models and materials behavior.

The long-term objective of the FPNS track is to enable a step change in confidence: moving from extrapolation based on surrogate data to direct validation of fusion neutron effects, with verified lifetimes and performance limits that de-risk pilot plant construction and early commercial replication. ■

Technical Descriptions

Remote Maintenance and Balance-Of-Plant Development and Testing

Name (acronym)	Description	Category	Stage	Timeframe
ORNL Reliability, Availability, Maintainability and Inspectability (RAMI) Test Stand	Experimental facility providing in-situ measurements of material properties during irradiation for dynamic observation of damage evolution.	National laboratory (ORNL)	Existing/ under construction	Near term
Helium Loop Karlsruhe (HELOKA)	Experimental facility testing high-pressure (4-10 MPa) and high-temperature (up to 700° C) conditions for blanket components. 800 kW of electron beam heating, tests blanket and first wall mockups, Helium cooling.	International (Germany)	Existing/ under construction	Near term
Integrated European Lead Lithium Loop (IELLO)	A large-scale experimental liquid PbLi loop designed to investigate thermal-hydraulics, MHD, corrosion, and material compatibility under fusion-relevant conditions. It supports development of the European Helium-Cooled Lead-Lithium (HCLL) and related breeding blanket concepts for DEMO.	International (France)	Existing/ under construction	Near term
Remote Applications in Challenging Environments (RACE)	Dedicated facility for the development, testing, and validation of robotics and remote handling systems for use in extreme environments, including future fusion power plants. It supports the design and qualification of remote maintenance technologies required for devices such as ITER, DEMO, and spherical tokamak pilot plants.	International (UK)	Existing/ under construction	Near term
Robotics and handling maintenance facility	Facility targeted at developing robotics needed for remote maintenance and handling of activated equipment.	Needed/ gap identified	Needed/ gap identified	Mid term
Private blanket and divertor remote handling mock-up	Details not publicly available.	Private (Kyoto Fusioneering)	Planned	Mid term
Private company demonstrations and pilot plants	Use of private demonstration and pilot plants to conduct research and development on RAMI and BOP gaps.	Private (various)	Planned	Long term

Mapping

Remote Maintenance and Balance-Of-Plant Development and Testing

Mapping the Near-term Infrastructure

In the near term, infrastructure priorities will focus on establishing the shared foundations for plant-relevant operability, with an emphasis on reliability, maintainability, and integration challenges that are common across fusion concepts. The public program are expected to play a central stewardship role in this phase by supporting the development of common RAMI frameworks, data standards, and test methods that enable credible comparison and reuse of results across the fusion enterprise.

Early infrastructure anchors will include the ORNL RAMI test stand, complemented by international platforms such as HELOKA, IELLO, and RACE, which together support task-level remote-maintenance prototyping using representative mock-ups. These facilities are used to develop and validate repeatable maintenance tasks, tooling concepts, and workflows, while generating early reliability and maintainability data that can directly inform RAMI-driven design constraints.

In parallel, near-term investments will be aimed at strengthening the digital and procedural backbone of maintainability. Shared RAMI methodologies, data structures, and analysis workflows will be established and connected to facility operations and digital models, ensuring that maintainability, availability, and recoverability are treated as design inputs rather than late-stage validation checks. The near-term objective is to ensure that all major fusion development efforts can draw on a common, credible operability framework, reducing duplication and systemic risk.

Mapping the Mid-term Infrastructure

In the mid term, remote maintenance and BOP infrastructure are expected to expand from task-level prototyping to pilot-relevant integration testing, enabled by a robotics and handling maintenance capability. This infrastructure aims to support the qualification of joining and cutting techniques, remote connectors, sensing and metrology approaches, and representative component handling in activated and contaminated environments.

Facilities in this phase are expected to be configured to test not only whether maintenance actions are possible, but whether they can be executed within time, safety, and repeatability constraints consistent with power-plant availability targets. They will be complemented by private industry infrastructure, including a blanket and divertor remote handling mock-up (Kyoto Fusioneering).

Mapping the Long-term Infrastructure

In the long term, remote maintenance and balance-of-plant infrastructure can be advanced through structured PPPs with early pilot and demonstration plants, using these facilities as integration platforms to close remaining gaps in operability, licensing, and system reliability. Rather than duplicating pilot-scale infrastructure within the public program, the strategy is to leverage first-generation pilot plants as shared learning environments, supported by targeted public investment, access agreements, and data-sharing frameworks.

Facilities such as ARC (CFS), Hammir (Realta Fusion), FAST (Kyoto Fusioneering), Argo-1 (Inertia Enterprises), Eos (Thea Energy), Vulcan (Xcimer Energy) and other demonstration platforms (e.g., Pacific Fusion, Zap Energy) provide opportunities to exercise remote maintenance, tritium management, diagnostics, controls, and balance-of-plant systems under increasingly realistic operating conditions. Through public-private collaboration, these plants may be accessed to validate maintenance concepts, RAMI-driven design assumptions, and operational workflows that cannot be credibly demonstrated in standalone test stands.

There is an opportunity for long-term infrastructure to focus on plant-scale demonstrations of integrated operations, including remote handling in activated environments, recovery from off-normal events, tritium inventory control and accountancy, and sustained balance-of-plant performance. These demonstrations can be structured to generate licensing-relevant evidence, including validated maintenance timelines, availability projections, safety functions, and protection system behavior, supported by traceable data and standardized analysis methods. ■

Technical Descriptions

Blanket Development and Testing

Name (acronym)	Description	Category	Stage	Timeframe
Liquid Immersion Blanket: Robust Accountancy (LIBRA)	Tritium-breeding/tritium-accountancy experiment for the "liquid immersion blanket" concept, using molten FLiBe ($LiF-BeF_2$). It focuses on measuring tritium breeding, containment, extraction, and related chemistry control with tritium production of up to ~2000 Bq per breeding run.	University/ national laboratory (MIT/INL)	Existing/ under construction	Near term
Helium Loop Karlsruhe (HELOKA)	Experimental facility testing high-pressure (4-10 MPa) and high-temperature (up to 700° C) conditions for blanket components.	International (Germany)	Existing/ under construction	Near term
Magneto-Hydro-Dynamic Effects in Karlsruhe (MEKKA)	Experimental facility focusing on liquid metal MHD flow, pressure drops, and flow distribution in breeding units.	International (Germany)	Existing/ under construction	Near term
Lithium Breeding Tritium Innovation Facility (LIBRTI)	Non-nuclear experimental facility focused on testing and developing lithium-based breeder materials and tritium extraction technologies for future fusion power plants. It supports validation of tritium breeding and recovery processes under prototypical thermal and chemical conditions relevant to fusion blanket systems.	International (UK)	Existing/ under construction	Near term
Unique Integrated Testing Facility 1 (UNITY-1)	Large-scale experimental test plant integrating molten liquid metal (e.g., lithium-lead) loops, heat transfer and power conversion components, and hydrogen isotope handling technologies to validate heat extraction, energy conversion, and fuel cycle technologies critical for commercial fusion energy.	Private (Kyoto Fusioneering)	Existing/ under construction	Near term
Unique Integrated Testing Facility 2 (UNITY-2)	Integrated tritium fuel cycle test facility capable of full-loop operations, designed to demonstrate key aspects of a DT fusion fuel cycle, from fueling and exhaust to isotope separation, storage, and recycling.	International PPP (Kyoto Fusioneering and Canadian Nuclear Laboratories)	Existing/ under construction	Near term
FLiBe Research Yuryo Advanced Loop (FREYA)	Laboratory-scale forced convection loop built to enable research and development on molten FLiBe as a candidate tritium breeding and coolant medium for fusion breeder blankets.	Private (Kyoto Fusioneering)	Existing/ under construction	Near term
Kyoto Liquid Lithium Loop (KL3)	Experimental forced-convection loop for liquid lithium, developed to support fusion breeder blanket technology research by characterizing flow, thermal behavior, materials compatibility, and tritium-related properties in liquid lithium under controlled conditions.	Private (Kyoto Fusioneering)	Existing/ under construction	Near term

Name (acronym)	Description	Category	Stage	Timeframe
Private molten salt test facilities (CFS)	Molten salt facility circulating ~100 tons of FLiBe molten salt, transmitting >50 MW of heating power through an intermediate nitrate salt to heat exchangers.	Private (CFS)	Existing/ under construction	Near term
Target Integration Facility (OpenStar)	Facility and team designing and integrating target modules, including blanket modules, for Māui in the levitated dipole geometry. Collaborators: UW-Madison, Kyoto Fusioneering, General Atomics.	Private (OpenStar)	Planned	Near term
Millennium (Zap Energy)	Details not publicly available.	Private (Zap Energy)	Existing/ under construction	Near term
Helium and Salt Technology Experiment (HASTE)	Proposed integrated experimental facility at ORNL designed to replicate the pressures, temperatures, flow rates, and magnetic fields inside a fusion blanket in order to test and evaluate prototype coolant and breeder systems using helium and molten salts.	National laboratory (ORNL)	Existing/ under construction	Near term
Combined Heating and Magnetic Research Apparatus (CHIMERA)	Research facility to test full-scale or prototype fusion engine component modules (such as blankets, divertors, and diagnostics) under simultaneous fusion-relevant loads, including high-heat-flux, static and pulsed magnetic fields, and high temperatures/pressures.	International (UK)	Existing/ under construction	Near term
Unique Integrated Testing Facility	Planned as a fusion breeding blanket test facility designed to validate performance of next-generation tritium breeding blanket concepts under prototypical nuclear conditions using real neutron flux and component geometries.	PPP (DOE, Kyoto Fusioneering, ORNL)	Needed/ gap identified	Mid term
Low-fluence volumetric neutron sources	Large format low-fluence source of fusion prototypic neutrons built to support irradiation testing of breeding blanket components and other fusion power plant components.	PPP	Needed/ gap identified	Mid term
Private tritium breeding test facility	Large tritium breeding mockup facility to test tritium measurement and extraction; and an industrial scale molten-salt facility.	Private (Xcimer Energy)	Planned	Mid term
Thunderdome	First wall and blanket thermal, chemical, and mechanical test facility.	Private (Inertia Enterprises)	Needed/ gap identified	Mid term
Integrated blanket and fuel cycle test facility (IB-FCTF)	Integrated testing for every aspect of blanket and fuel cycle component testing, including high-heat-flux, high magnetic fields, high flux, high-energy neutron fields, and tritium breeding and extraction.	Needed/ gap identified	Needed/ gap identified	Long term

Mapping

Blanket Development and Testing

Mapping the Near-term Infrastructure

In the near term, infrastructure priorities focus on ensuring that the U.S. fusion ecosystem has access to capabilities to make significant advancements (advancing from TRL 0 to 4) in blanket and fuel cycle R&D over the next 2-3 years. Rapid access to existing blanket-relevant test facilities will enable high-throughput, replicable experimentation on materials compatibility, chemistry control, and tritium behavior. A near-term priority will be to begin a phased approach to integrated facilities by building infrastructure that leads to a TBDP. The TBDP is a network of public and private test stands, loops, testbeds, and capabilities supporting overall FM&T priority infrastructure for the Roadmap. Over the next 2-3 years, the focus will be on delivering small-to-medium scale capabilities such as a blanket component test facility and a low-neutron flux blanket test system, testing novel blanket designs and prototypes at component scale.

Key near-term infrastructure includes leveraging facilities through collaboration at KIT (Germany), LIBRTI/LIBRA (UK/MIT), UNITY-1 (Japan), UNITY-2 (Canada), and CHIMERA (UK), which collectively provide non-nuclear and surrogate testing environments for blanket components, joints, and materials systems. Domestically, the Helium and Salt Technology Experiment at ORNL provides a critical capability for operating helium and molten-salt loops at blanket-relevant temperature, pressure, and flow conditions, enabling controlled studies of corrosion, impurity management, hydrogen permeation, and tritium surrogate behavior.

Near-term infrastructure use is deliberately focused on replicable test methods, not on optimizing operating points. The near-term objective is to establish an accessible, infrastructure-rich testing ecosystem that prioritizes speed of learning, method development, and workforce training, while building clear bridges to nuclear-coupled testing. In addition, the near-term will identify PPPs that begin to build infrastructure in a staged approach, beginning with design and modeling of blanket system platforms to be delivered in the late near term. The collection of blanket-relevant capabilities, including non-radiological and radiological blanket component test facilities, will be coordinated with fuel cycle system infrastructure construction and neutron source R&D.

Mapping the Mid-term Infrastructure

In the mid term, blanket infrastructure will need to expand from non-nuclear testing to incorporate neutron exposure, addressing coupled effects that dominate uncertainty in blanket lifetime and tritium performance. This includes the integration of neutron sources with versatile blanket test systems, enabling irradiation-coupled experiments on materials, joints, and functional components in breeder and coolant environments. This infrastructure aims to advance and augment the TBDP, beginning the process of integrating the blanket aspects of TBDP with fuel-cycle infrastructure and supporting fusion power-plant scale-up with elements like a blanket advanced manufacturing testbed.

Infrastructure in this phase builds on earlier facilities at KIT, LIBRTI, UNITY-1, and UNITY-2, while adding domestically anchored blanket component test stands designed for modularity and reuse across concepts. These facilities are explicitly connected to irradiation environments, hot-cell capabilities, and tritium laboratories, enabling full experimental workflows from fabrication through post-test examination. It will be necessary to leverage lower-flux neutron sources to advance salt chemistry, radiochemistry, and tritium extraction understanding, recognizing that many critical blanket science questions can be addressed without high-dpa exposure.

Mapping the Long-term Infrastructure

In the long term, integrated system-level testing is expected to be enabled by a TBDP that couples blanket operation with tritium fuel-cycle functionality and a volumetric neutron source demonstration facility, to make significant advances in integrating the blanket and fuel cycle technologies of the TBDP to a versatile blanket system and support breakthroughs in materials innovation.

An integrated TBDP enables lifecycle testing of blanket components, irradiation, operation, inspection, and repair under controlled chemistry and flow conditions, and allows companies to test and qualify components within shared infrastructure. Demonstrating high tritium breeding ratios through experimentation becomes a high-value outcome at this stage.

An IB-FCTF will be critical to validating system-level tritium transport, inventory control, and operational interfaces under fusion-relevant conditions. The long-term objective is to deliver the experimental results required for pilot plant deployment: repeatable operations, defensible datasets, validated models, and maintainable architectures that reduce licensing and investment risk while preserving flexibility across commercial fusion approaches. ■

Technical Descriptions

Fuel Cycle Development and Testing

Name (acronym)	Description	Category	Stage	Timeframe
Unique Integrated Testing Facility 1 (UNITY-1)	Large-scale experimental test plant integrating molten liquid metal (e.g., lithium-lead) loops, heat transfer and power conversion components, and hydrogen isotope handling technologies to validate heat extraction, energy conversion, and fuel cycle technologies critical for commercial fusion energy.	Private (Kyoto Fusioneering)	Existing/ under construction	Near term
Unique Integrated Testing Facility 2 (UNITY-2)	Integrated tritium fuel cycle test facility capable of full-loop operations, designed to demonstrate key aspects of a DT fusion fuel cycle, from fueling and exhaust to isotope separation, storage, and recycling.	International (Kyoto Fusioneering and Canadian Nuclear Laboratories)	Existing/ under construction	Near term
FLiBe Research Yuryo Advanced Loop (FREYA)	Laboratory-scale forced convection loop built to enable research and development on molten FLiBe as a candidate tritium breeding and coolant medium for fusion breeder blankets.	Private (Kyoto Fusioneering)	Existing/ under construction	Near term
Kyoto Liquid Lithium Loop (KL3)	Experimental forced-convection loop for liquid lithium, developed to support fusion breeder blanket technology research by characterizing flow, thermal behavior, materials compatibility, and tritium-related properties in liquid lithium under controlled conditions.	Private (Kyoto Fusioneering)	Existing/ under construction	Near term
Thunderstruck	IFE fuel target injection, tracking, and engagement test facility.	Private (Inertia Enterprises)	Planned	Near term
TRITON	Tritium testing facility for developing and testing fuel cycle technologies with tritium on individual test stands, at 1/5 scale, up to full scale in some cases.	PPP (Type One Energy, SRNL)	Planned	Near term
Tritium Integrated Loop test facility (TREX)	Tritium Integrated Loop system for training and testing.	PPP (Type One Energy, SRNL)	Planned	Near term
Hydrogen-3 Advanced Technology Tritium Loop Facility (H3AT)	Pilot-scale, closed-loop tritium fuel cycle test facility under development to study processing, storage, purification, and recycling of tritium.	International (UK)	Existing/ under construction	Near term
Hydrogen/Deuterium Loop-Related R&D Capabilities (PROTEUS)	Research facilities focusing on hydrogen isotope processing (protium, deuterium, and tritium) as part of developing efficient fusion fuel cycles, including experiments on isotope separation, gas processing, real-time monitoring, and tritium inventory reduction technologies.	National laboratory (SRNL)	Existing/ under construction	Near term
Safety and Tritium Applied Research Facility (STAR)	Fuel cycle safety and research laboratory with the ability to handle tritium and other hydrogen isotopes (including deuterium/tritium mixtures) for fusion-relevant experiments, such as Tritium Plasma Experiment (TPE) and Tritium Gas Absorption/Permeation (TGAP) studies that investigate isotope permeation and material interactions.	National laboratory (INL)	Existing/ under construction	Near term
Unique Integrated Testing Facility	Planned as a fusion breeding blanket test facility designed to validate performance of next-generation tritium breeding blanket concepts under prototypical nuclear conditions using real neutron flux and component geometries.	Proposed PPP (DOE, Kyoto Fusioneering, ORNL)	Planned	Mid term
Thunderbolt	IFE fuel target mass manufacture production line prototype facility.	Private (Inertia Enterprises)	Planned	Mid term
Integrated blanket and fuel cycle test facility (IB-FCTF)	Integrated testing for every aspect of blanket and fuel cycle component testing, including high-heat-flux, high magnetic fields, high flux, high-energy neutron fields, and tritium breeding and extraction.	Needed/ gap identified	Needed/ gap identified	Long term

Mapping

Fuel Cycle Development and Testing

Mapping the Near-term Infrastructure

In the near term, the priority for fuel cycle development and testing infrastructure is focused on establishing an accessible, subsystem-scale fuel-cycle testing capability that supports early validation of pumping, extraction, separation, storage, and control technologies under controlled conditions. The emphasis is on deploying and connecting existing domestic infrastructure, while enabling structured access to international tritium-capable facilities to accelerate learning.

Key near-term domestic infrastructure includes fuel-cycle laboratories and non-nuclear test loops (i.e., INL and SRNL), which support hydrogen and deuterium operation, tritium-ready facility design, and tritium handling workflows. The priority will be to deliver critical fuel cycle components of the TBDP: small-to-medium scale capabilities, including a medium-scale (60 g tritium) fusion fuel cycle test stand and loop facility complex. These facilities are expected to provide glovebox and enclosure-based environments for pump testing, tritium recirculation loops, and gas storage volumes, building on ongoing metal foil pump development at INL. In parallel, initial tritium handling and extraction capabilities aim to be be established for H/D operation, tritium-ready layouts, and interfaces to thermal-mechanical test loops for liquid metal and molten salts under high-temperature and thermal-cycling conditions.

Near-term infrastructure needs also include diagnostic and sensor test laboratories for the development and early qualification of radiation-hardened instrumentation, alongside permeation barrier testing infrastructure such as furnaces for heating components and vacuum systems for permeability measurements with isotope recovery. International access, particularly to H3AT (UK) and UNITY-2 (Canada), provides additional capability for tritium-relevant operations, accountancy methods, isotope storage materials, and fuel-cycle control system demonstrations.

The near-term objective is to convert fuel-cycle risks from conceptual uncertainties into testable, observable behaviors across multiple subsystem platforms, creating a coherent foundation for nuclear-coupled testing.

Mapping the Mid-term Infrastructure

In the mid term, fuel-cycle infrastructure will need to scale to mid-scale nuclear fuel-cycle testing capabilities, to support sustained tritium processing and integrated subsystem operation. At this stage, the TBDP must expand to a large-scale tritium processing and handling facility at the 1-kg capacity level to support fusion power-plant scale-up technologies. This will be necessary to close the gap between early tritium-capable experiments and the operational realities of pilot-scale fuel-cycle systems, including maintenance, fault recovery, and system availability.

A defining feature of fuel-cycle infrastructure required at this mid-term stage is the integration of innovative metrology and radiation-hardened diagnostics, allowing fuel-cycle control, tritium accountancy, and sensor technologies to be developed and qualified within operating systems. Planned private sector facilities (e.g., UNITY-2, CFS, Xcimer Energy) are expected to support the demonstration of tritium measurement technologies, improved isotope storage materials, injector technologies, and closed-loop fuel-cycle control strategies at higher readiness levels.

The mid-term outcome is a fuel-cycle testing platform that credibly supports coupled blanket-fuel-cycle experiments and informs system-level design and licensing pathways.

Mapping the Long-term Infrastructure

In the long term, fuel-cycle and blanket infrastructure converge into a coordinated platform of small-to-medium scale nuclear fuel-cycle and blanket system test stands, culminating in an IB-FCTF.

These long-term facilities will be required to enable closed-loop demonstration of tritium breeding, extraction, processing, storage, and fueling under fusion-relevant conditions, with infrastructure explicitly designed to support lifecycle testing, component replacement, and system reconfiguration. Fuel-cycle subsystems will be exercised at scales sufficient to validate inventory control, accountancy, and operational stability, while preserving flexibility across fuel-cycle architectures.

The long-term objective is to deliver a national asset underpinning fusion deployment: the evidence package required for pilot plant readiness: stable and auditable tritium inventories, maintainable and scalable processing systems, validated control and diagnostic architectures, and integrated datasets suitable for licensing and commercial decision-making. ■

Technical Descriptions

High-Performance Computing, Advance Manufacturing, and AI

Name (acronym)	Description	Category	Stage	Timeframe
Centralized HPC assets for integrated modeling	Establishing the groundwork for the AI-Fusion DCP.	Various	Existing/ under construction	Near term
Pulser Fusion Simulation Testbed	No publicly available details	Private (Pacific Fusion)	Existing/ under construction	Near term
Integration of DOE user facilities with HPC capabilities (Genesis Mission)	Linking existing DOE fusion user facilities to HPC.	DOE user facility	Planned	Near term
FRONTIER	ORNL's Leadership Class Computing Facility for exascale computing.	National laboratory (ORNL)	Existing/ under construction	Near term
Aurora	Argonne's Leadership Class Computing Facility for AI model training.	National laboratory (Argonne)	Existing/ under construction	Near term
National Energy Research Scientific Computing Center (NERSC)	User facility for traditional and exascale compute.	National laboratory (LBNL)	Existing/ under construction	Near term
PPPL compute cluster	High-performance computing clusters (Stellar and Traverse) operated to support large-scale plasma physics simulations, theory, data analysis, and integrated modeling for fusion research.	National laboratory (PPPL)	Existing/ under construction	Near term
Stellar-AI Upgrade	Major Stellar GPU upgrade (Stellar-AI).	National laboratory (PPPL)	Planned	Near term
Stormcaster	AI-enabled, Integrated Process Model for IFE power-plant system design and evaluation, connecting subsystem physics to FPP-level viability.	Private (Inertia Enterprises)	Existing/ under construction	Near term
AI-Fusion DCP (Genesis Mission)	A modular platform that integrates advanced simulation codes, AI foundation models, and data workflows to deliver predictions for facility operations.	Various	Planned	Mid term
Blanket advanced manufacturing testbed	No publicly available details.	Needed/ gap identified	Needed/ gap identified	Mid term
Complete set of foundation models and digital twins	Early AI applications trained on facility and high-fidelity simulation data to provide accelerated predictions.	Needed/ gap identified	Needed/ gap identified	Mid term
Starlight	AI-enabled model for target physics design coupled to existing experimental data and radiation-hydrodynamics simulations in the high-energy-density physics regime to optimize robust fusion designs.	Private (Inertia Enterprises)	Planned	Mid term
Predictive models for diagnostic minimization	A suite of synthetic diagnostics using facility-focused foundation models and surrogate models.	Needed/ gap identified	Needed/ gap identified	Long term
Whole-of-facility digital twin	Advanced surrogate models trained on facility data that extends beyond the first wall and accounts for real-time control and operations.	Needed/ gap identified	Needed/ gap identified	Long term
Completed set of synthetic diagnostics	Accurate, real-time data for control of actuators, utilizing a minimal set of diagnostics.	Needed/ gap identified	Needed/ gap identified	Long term

Mapping

High-Performance Computing, Advance Manufacturing, and AI

Mapping the Near-term Infrastructure

Under the Department of Energy's Genesis Mission, the FES program has been directed to establish U.S. leadership in AI applications through the development of a comprehensive platform. As stated in the Genesis Mission Executive Order: "The Genesis Mission will build an integrated AI platform to harness Federal scientific datasets — the world's largest collection of such datasets, developed over decades of Federal investments — to train scientific foundation models and create AI agents to test new hypotheses, automate research workflows, and accelerate scientific breakthroughs."

In the near term, infrastructure priorities focus on making computational and AI capabilities operationally integral to fusion facilities and test programs, rather than treating them as standalone analysis resources. The emphasis is on establishing a common digital backbone that connects experiments, test stands, and design activities through shared data infrastructure, model interfaces, and workflows as directed under the Genesis Mission.

Near-term infrastructure includes coordinated access to leadership-class computing platforms, including FRONTIER, Aurora, and NERSC, coupled to facility operations through cloud-enabled environments such as the AmSC. These platforms support rapid data ingestion from experiments and test stands, enabling tighter feedback between measurement and modeling across the fusion ecosystem.

The fusion-focused Stellar-AI supercomputing cluster at PPPL brings a new model of scientific computing infrastructure with buy-in from the technology industry, allowing for the sharing of cross-domain expertise at the forefront of both hardware and software.

A critical near-term focus is the establishment of standards-based data schemas, metadata practices, and model interfaces that allow data from diverse facilities (i.e., plasma devices, high-heat-flux stands, materials irradiation platforms, blanket and fuel-cycle loops) to be ingested into a common integration environment — the AI-Fusion DCP.

Throughout this period, the focus will be applied to:

- Centralizing material characterization datasets and training AI models to support the engineering, design, development, and qualification of materials that can withstand the high neutron flux, thermal loads, and environmental stresses of a fusion power plant.
- Deploying digital twins of heat and plasma exposure facilities to support the characterization of physical and mechanical properties, manufacturing, and qualification of materials that directly interact with the plasma and face the most extreme temperatures, neutron fluxes, and stresses.

- Applying AI and ML within real-time plasma control systems and between successive experimental pulses to create, sustain, and optimize fusion-relevant plasma scenarios with the goal achieve fusion-relevant confinement regimes and sustained energy output.
- Curating test loop data and developing AI models that track, forecast, and optimize tritium separation, storage, inventory, and accountancy across components and systems to enable fuel self-sufficiency and mature supporting technologies such as permeation barriers and detritiation systems.
- Building a standardized database for thermophysical corrosion, tritium-related effects, and mechanical properties; and deploying multiphysics AI models to advance blanket concepts (e.g., solid, liquid, molten salt).

Near-term investments also support cloud-based simulation testbeds, providing shared access to design-grade multiphysics studies and AI training environments, including those relevant to PMF and other emerging concepts such as quantum algorithms for fusion energy applications.

The Genesis Mission also directs these candidate projects to certify concrete AI Advantage within respective workflows and use cases with the end goal of improved scientific productivity. Additionally, the fusion theory, simulation, and AI/ML community should develop agile coding standards akin to the software industry, with improved modularity in workflow components that are focused on addressing the Challenge Areas under the FES Roadmap.

Mapping the Mid-term Infrastructure

In the mid term, HPC and AI infrastructure will need to evolve into a modular, plant-level integration environment that links facility data to validated digital twins and predictive models. This environment is not characterized as a single “plant code,” but a framework of shared libraries, interfaces, and uncertainty-quantification practices that allow models to be coupled, compared, and updated as new data becomes available.

Mid-term infrastructure enables the development of foundation models and facility-specific digital twins, trained and validated against coordinated datasets from multiple test stands and plasma devices. These twins support predictive capability across operating regimes, reduce diagnostic burden through validated synthetic diagnostics, and enable faster-than-experiment inference for planning and control.

A defining feature of this phase is the explicit creation of a data-to-decision pipeline: data from facilities feed digital twins; twins inform reduced-order and surrogate models; these models, in turn, support system-level studies, optimization, and design decisions for pilot plants. This infrastructure will support both magnetic and inertial fusion pathways, including PMF concepts, by providing common computational environments for multiphysics coupling and AI-driven optimization.

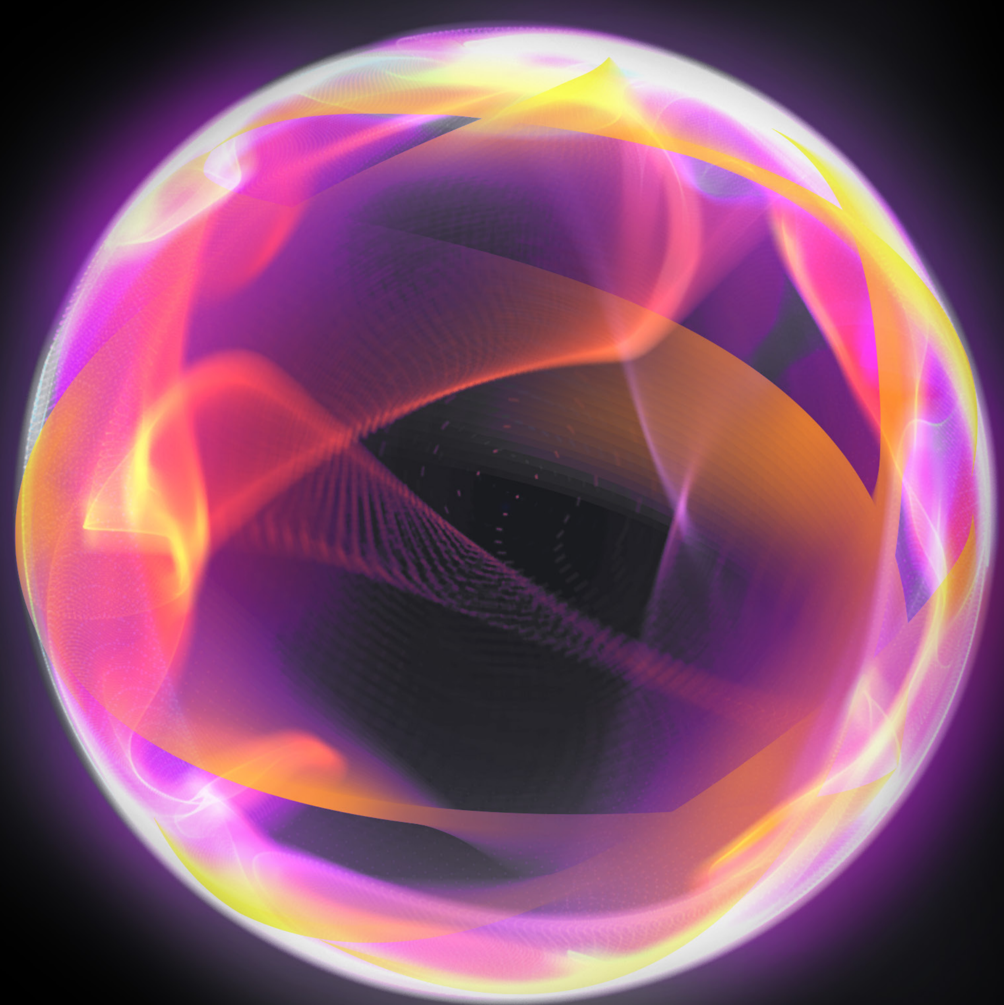
The mid-term outcome is an HPC/AI infrastructure ecosystem where models are embedded in experimental and operational decision loops, with quantified uncertainty and traceable validation histories that make them credible beyond the research context.

Mapping the Long-term Infrastructure

In the long term, high-performance computing and AI infrastructure will enable validated whole-plant digital twins that integrate plasma behavior, materials response, tritium systems, power conversion, controls, and hardened diagnostics into a coherent, plant-level representation. These digital twins will be calibrated and stress-tested against coupled prototype operation, with model predictions demonstrated to match measured behavior within quantified uncertainty bounds across steady-state operation, transients, and fault scenarios.

A defining feature of long-term infrastructure is the completion of a synthetic diagnostics and diagnostics-minimization framework. Physical and virtual diagnostics can be co-designed so that a minimal, robust set of plant-deployable diagnostics (hardened for radiation, heat, and electromagnetic environments) can be shown to provide sufficient information for control, protection, and performance validation. Synthetic diagnostics embedded in the digital twin will allow facility data to be interpreted consistently across platforms, reduce dependence on non-deployable instruments, and support validation of models under operating conditions that cannot be directly measured.

Long-term HPC/AI infrastructure will be aimed at supporting support licensing-grade verification, validation, and uncertainty quantification, linking diagnostics, models, and operational data into a traceable evidence chain. This infrastructure will enable forecasting, automated protection, condition-based maintenance, and availability optimization, and provide regulators and stakeholders with confidence that plant behavior can be predicted and bounded using a combination of measured and synthetic observables. ■



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