

From Plasma to (future) Power Plants

Fusion Technology Overview, Current Industry Landscape,
and EPRI Activities to Accelerate Commercialization



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EPRI Fusion Energy Strategic Program

UNC Charlotte Electromechanical Engineering Program Seminar
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Agenda



Introduction to Fusion Energy & Industry Overview



R&D Opportunities and Challenges for Commercialization



EPRI Research to Accelerate Fusion Energy



Introduction to Fusion Energy & Industry Overview

Fusion Role and Benefits



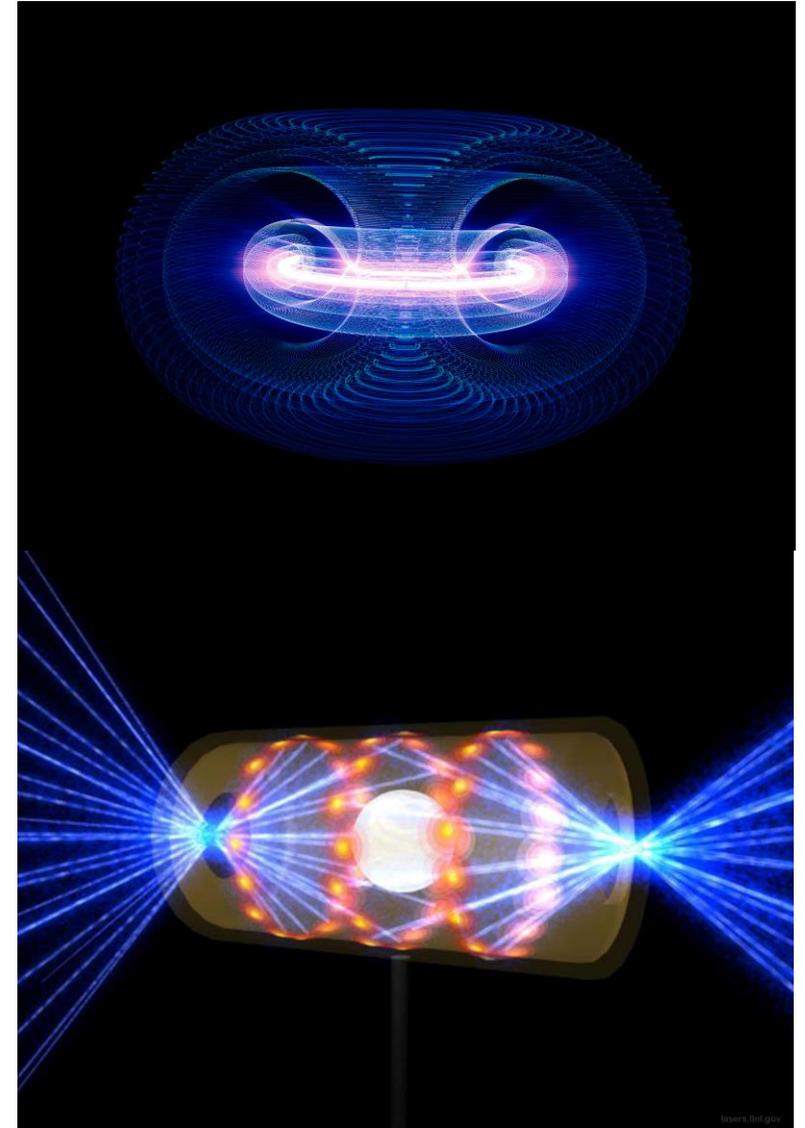
Fusion has a role in a resilient, net-zero energy system as a firm, non-emitting energy generation option



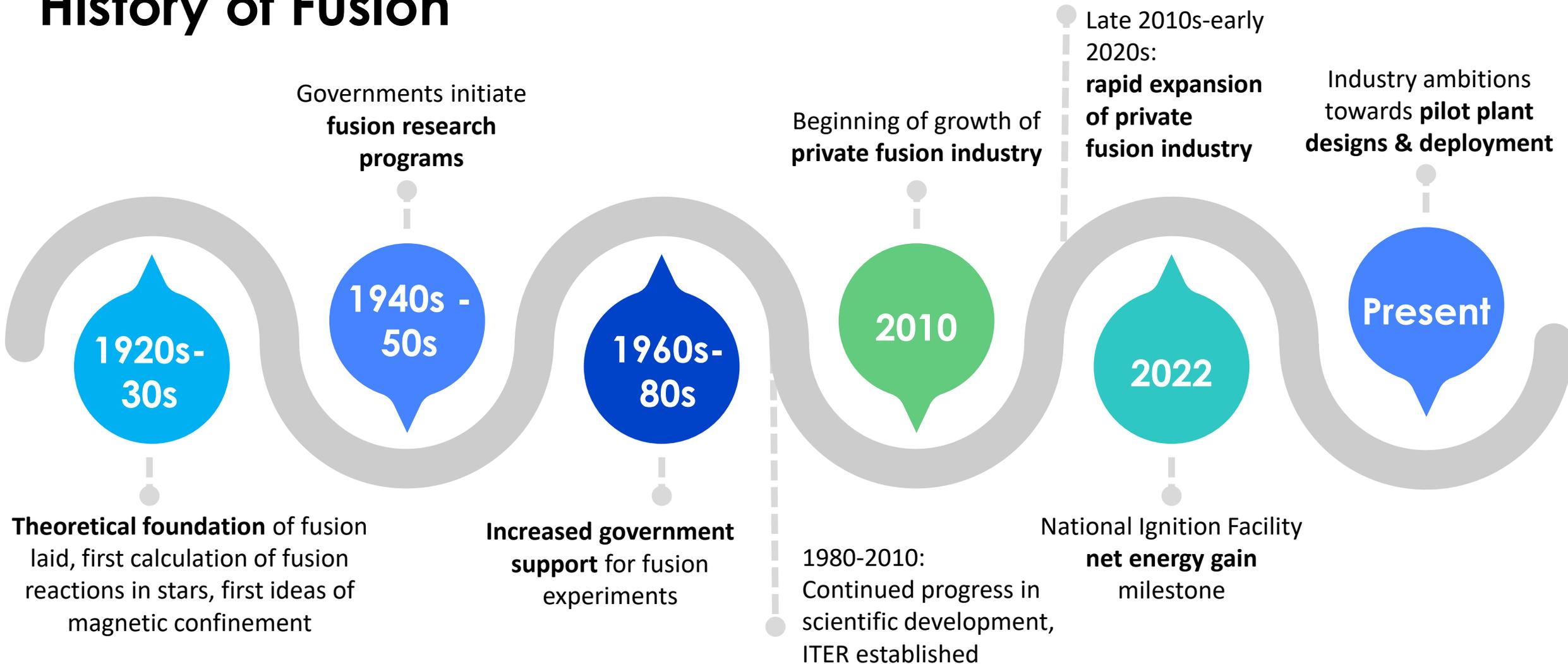
Most concepts are thermal sources and are compatible with existing balance-of-plant technologies



Compelling safety benefits. Driven reactions require external energy + replenished fuel source. Fusion is hard to initiate and likes to shut down.



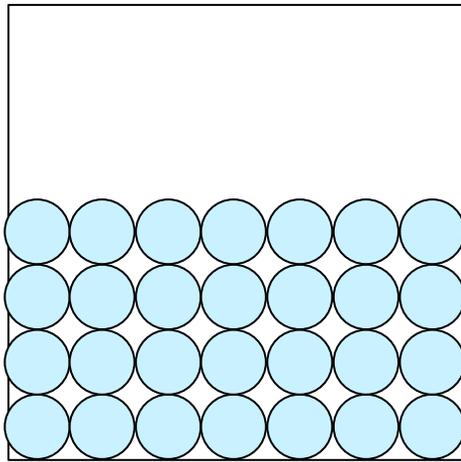
History of Fusion



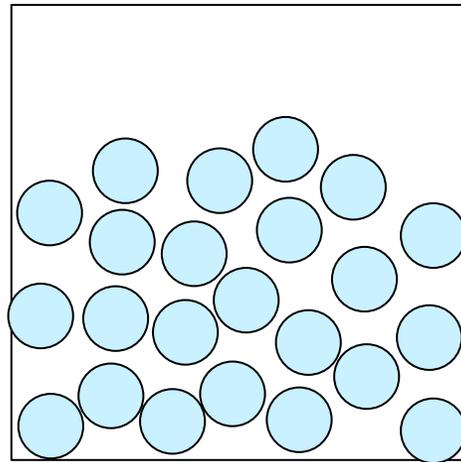
Decades of public sector activity set stage for private sector to drive towards commercial fusion

Fusion starts with plasma. What is plasma?

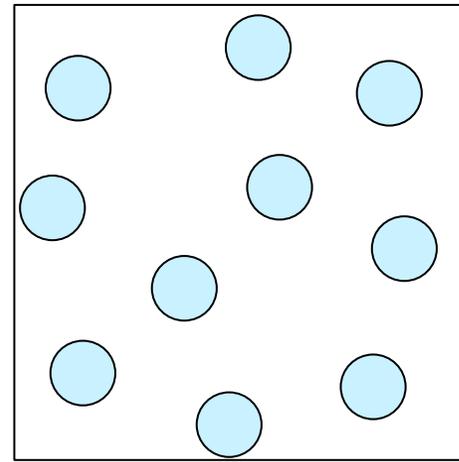
Add Energy (Heat) to System...



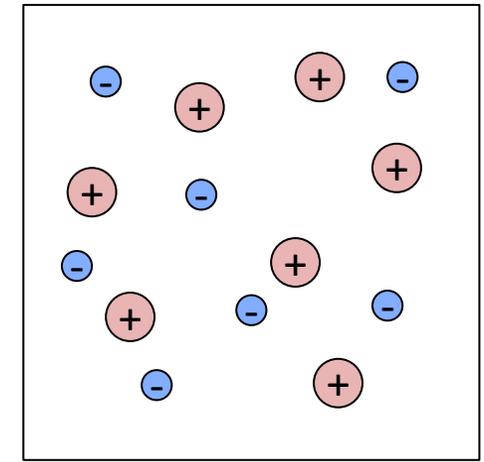
Solid



Liquid



Gas



Plasma

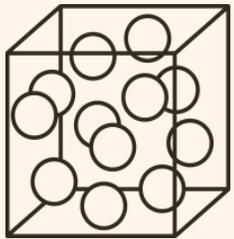
Plasma is the state of matter where electrons are stripped from atoms, exposing their nuclei – a prerequisite for fusion.

The Fusion Reaction

Fusion requires keeping a fuel bearing plasma:



Hot enough
(plasma temperature)

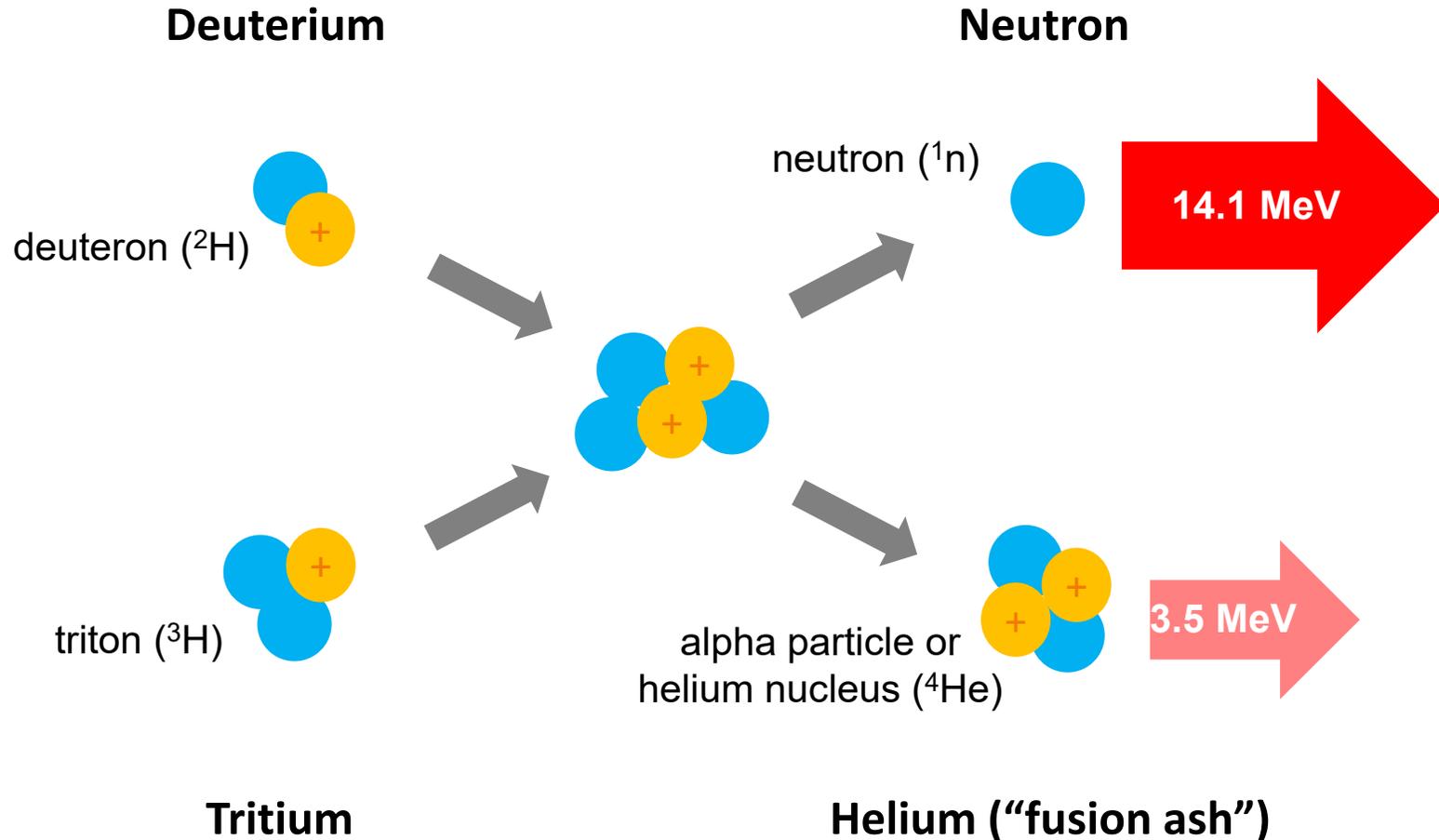


Dense enough
(plasma density)



For long enough
(plasma confinement time)

Light nuclei combine to form heavier nuclei



[Technology Insights Brief: A Review of Fusion Confinement Types, EPRI, Palo Alto, CA: 2023. 3002026585.](#)

Difference in mass before and after is released as energy ($E = \Delta mc^2$)

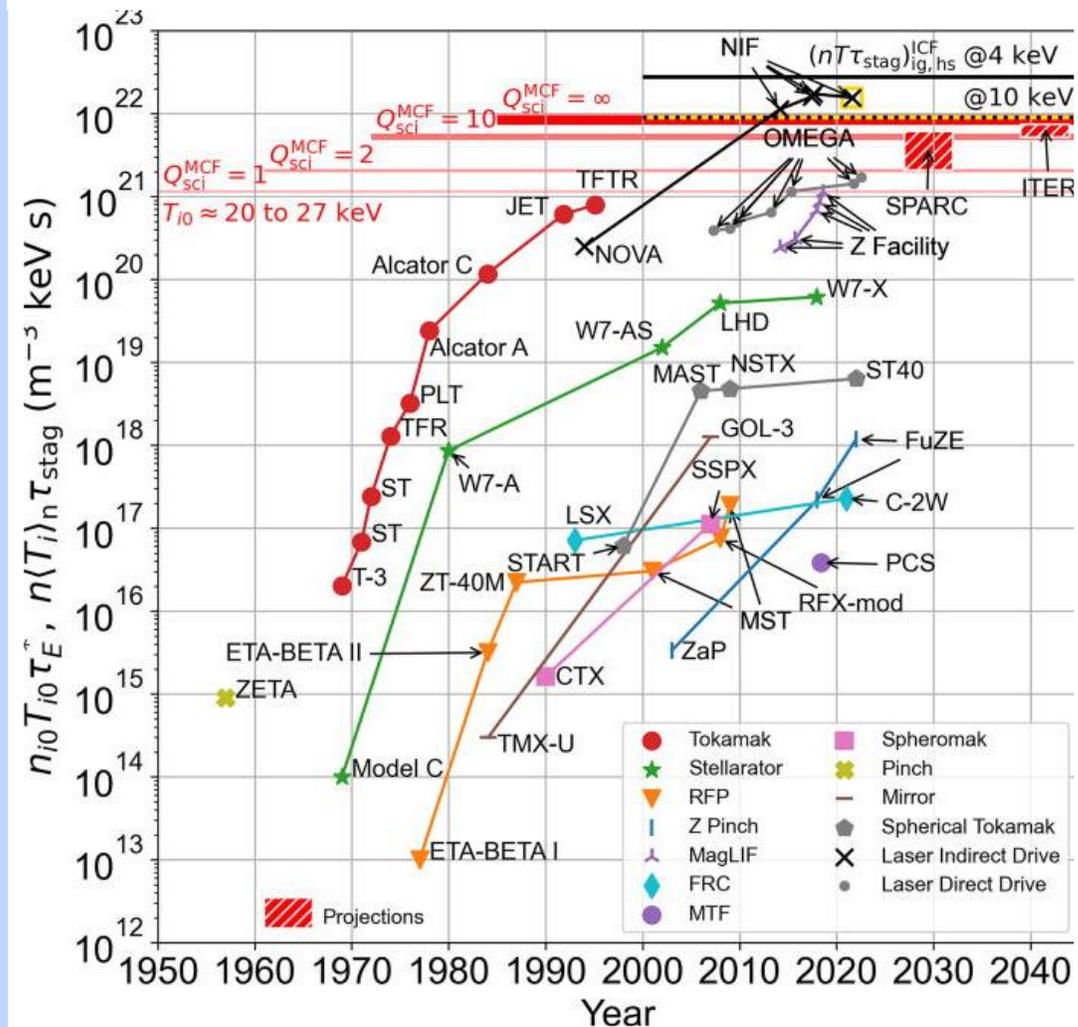
The Lawson Criterion

Three key parameters to achieve fusion

- Measures “hot enough, dense enough, for long enough”
- Net energy gain (Q) a function of:
 - temperature (T)
 - the product of fuel density (n)
 - confinement time (τ_e)
- Together these are known as the fusion triple product: $nT\tau_e$

While scientific net energy has been achieved at NIF, viable energy generation requires net “engineering” energy gain (more energy out than in)

Recorded and projected triple products vs year achieved or anticipated



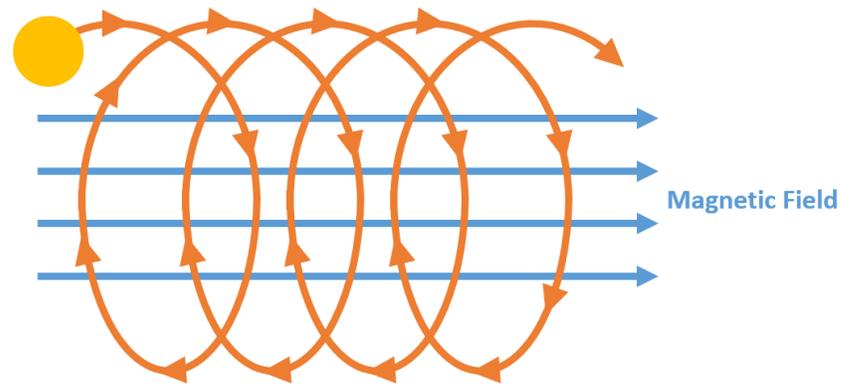
Samuel E. Wurzel, Scott C. Hsu; Continuing progress toward fusion energy breakeven and gain as measured against the Lawson criteria. Phys. Plasmas 1 November 2025; 32 (11): 112106. <https://doi.org/10.1063/5.0297357>

Plasma Confinement Approaches: Magnetic vs Inertial

Magnetic Confinement

Strong magnetic and electric fields contain the plasma fuel until fusion occurs.

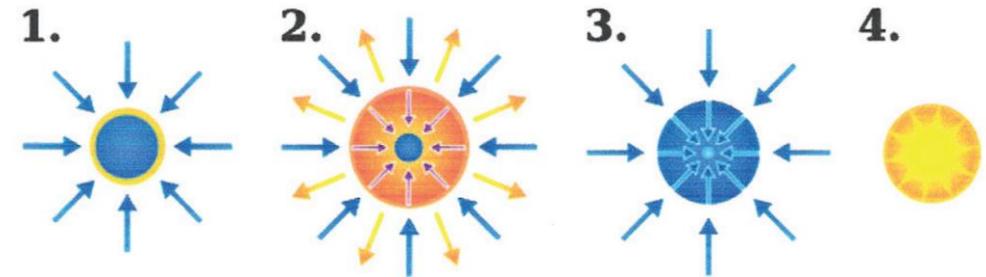
Motion of Charged Particle (e.g., positive ion or electron)



- Examples Devices: tokamak, stellarator, magnetic mirror
- Example Organizations: ITER, UKAEA, Commonwealth Fusion Systems, Tokamak Energy, Type One Energy Group

Inertial Confinement

Compression forces targeted at fuel create favorable temperature and pressure conditions for fusion.



- Example Devices: Laser-Driven Confinement, Shock-Driven Confinement
- Example Organizations: National Ignition Facility, Xcimer Energy, Marvel Fusion

Image credit: National Research Council. 2013. *An Assessment of the Prospects for Inertial Fusion Energy*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/18289>.

Plasma Confinement Approaches: Magnetic vs Inertial

Magnetic Confinement

Tokamak

ITER

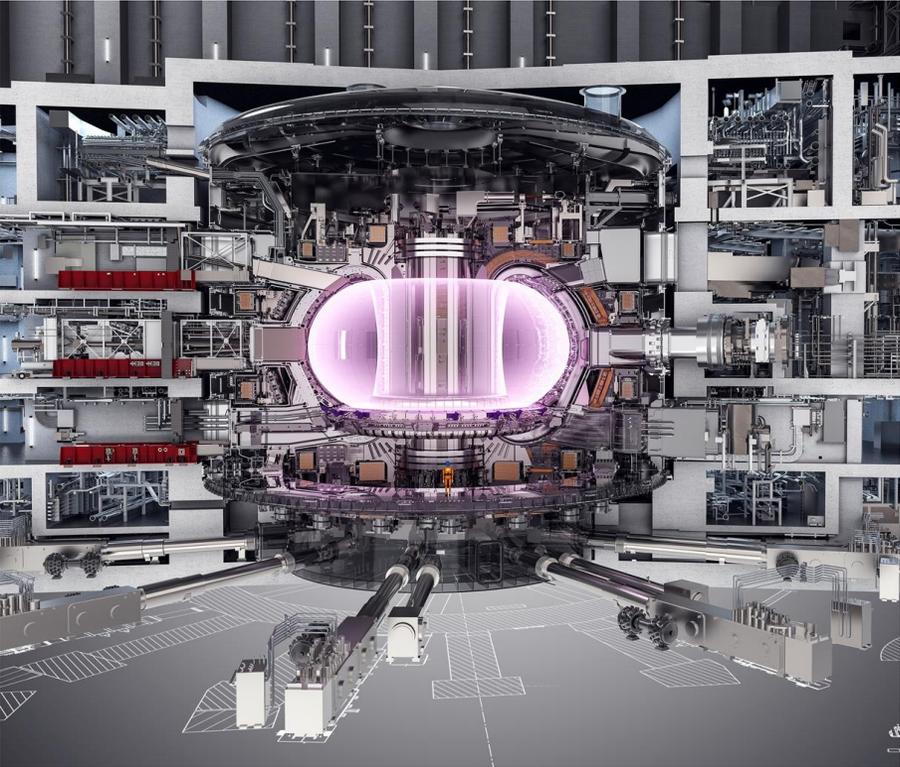


Image credit: Credit © ITER Organization, <http://www.iter.org/>

Inertial Confinement

Indirect Drive Laser Fusion

National Ignition Facility

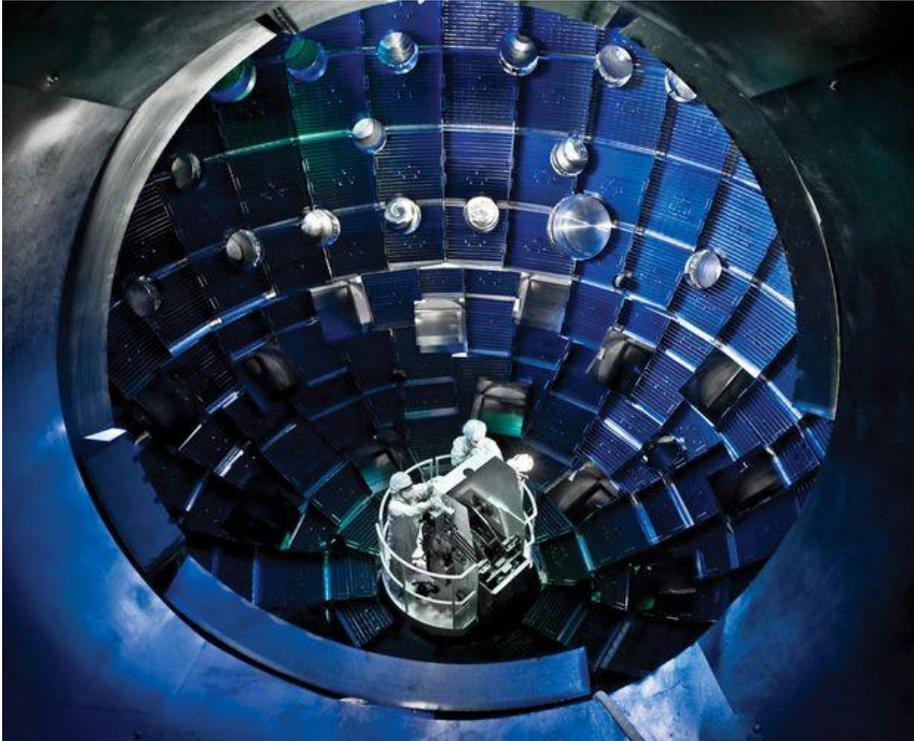


Image credit: Lawrence Livermore National Laboratory

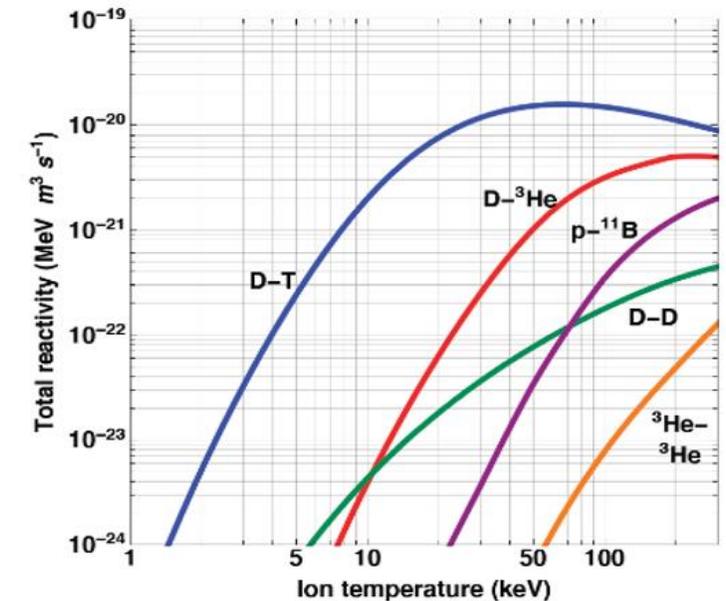
Fuel Options for Fusion Energy

	Fuel Option	End products
Neutronic	Deuterium-Tritium (D-T) Note: tritium is radioactive isotope of hydrogen with 12.3-year half life	Helium and 14 MeV neutron.
	Deuterium – Deuterium (D-D)	Helium-3 nucleus and neutron or tritium and proton
Aneutronic	Deuterium – Helium-3 (D-³He)	Helium nucleus and proton (low n yield from D-D rxns)
	Proton – Boron-11 (p-¹¹B)	¹¹ B fuses with a proton, briefly forming carbon 12 before splitting into three alpha particles

Fusion developer choice of fuel source



Source: The Global Fusion Industry in 2025. Fusion Industry Association. Washington, D.C. July 2025.



Source: National Academies of Sciences, Engineering, and Medicine. 2021. *Bringing Fusion to the U.S. Grid*. Washington, DC: The National Academies

D-T is most common fuel choice due to relatively low plasma temperature requirements.

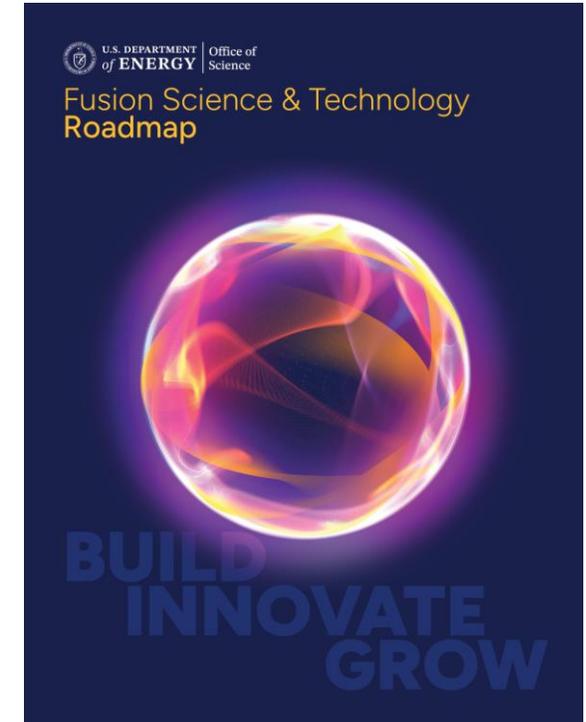
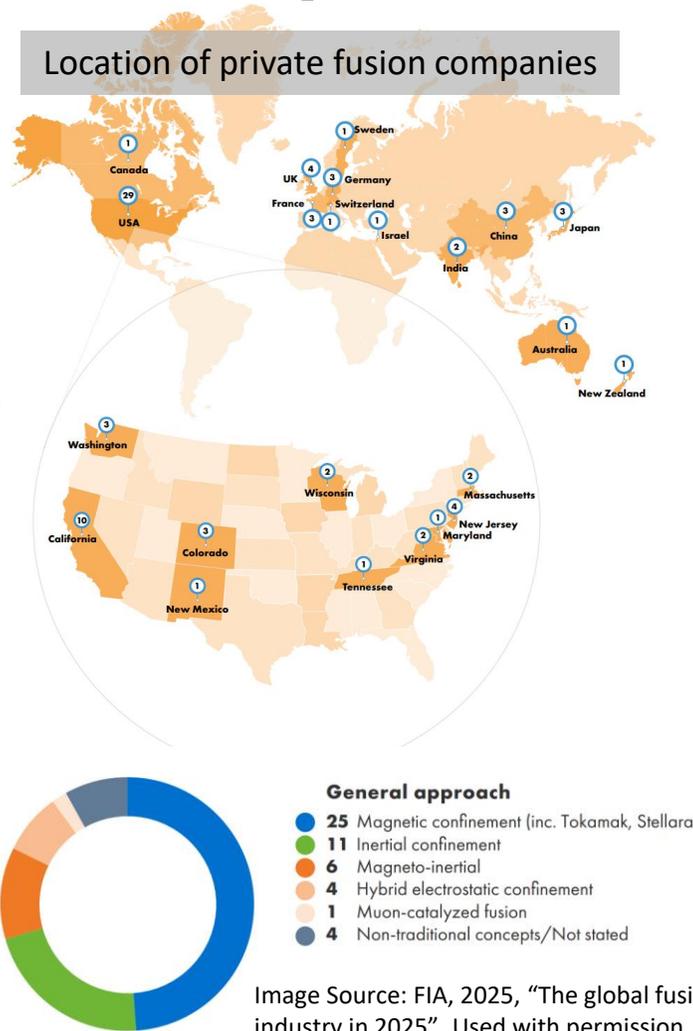
State of the Fusion Energy Industry

Private sector:

- 53+ companies, diversity of technology approaches
- >\$8.9 billion in private investment
- multiple private fusion developers with \$1 billion+
- Many companies planning pilot plants in the 2030s
- Acceleration and accumulation of technical milestones
 - magnets, confinement temperatures, new experiments, major construction projects, AI enabling technology

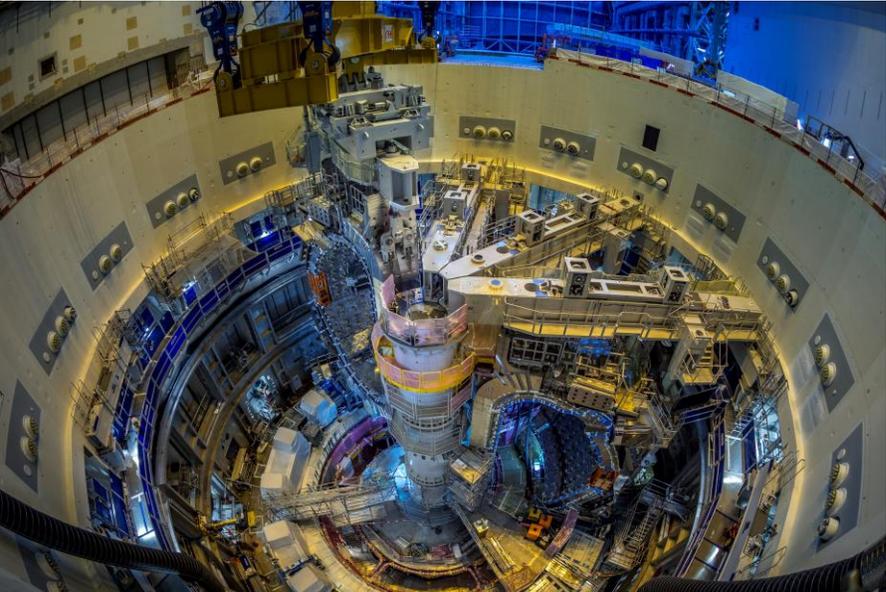
Public sector:

- U.S.
 - Aligning on R&D priorities and roadmap
 - Launched Fusion Innovation Research Engines
 - Desire to align public program with private industry needs
- International
 - Aligning on regulatory schemes
 - Acceleration of research funding opportunities

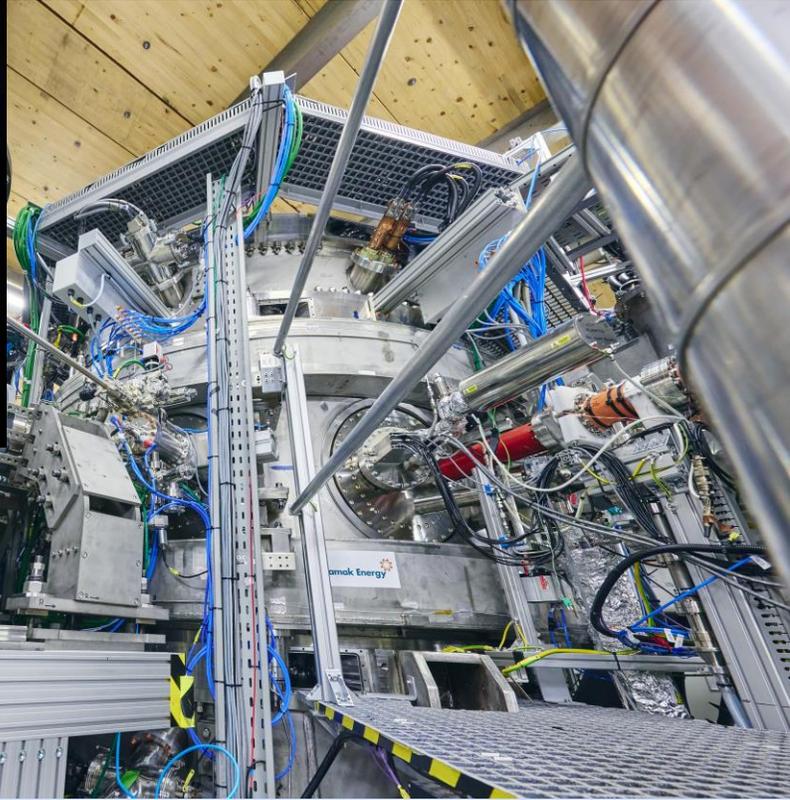
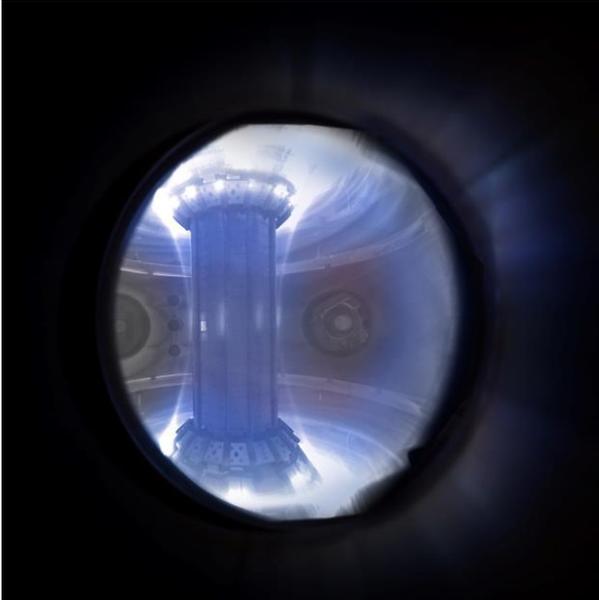


Transition occurring to accelerate development of materials, blanket, fuel cycle, and power plant concepts (R&D beyond plasma physics)

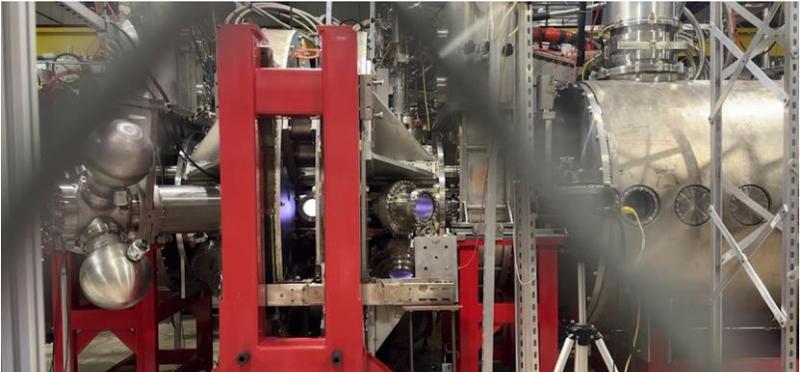
Fusion experiments and demonstration are happening...



ITER tokamak pit, with four sector modules installed. Credit © ITER Organization, <http://www.iter.org/>



Tokamak Energy ST-40 Spherical Tokamak with plasma (inset). Used with permission.



Realta Fusion, plasma pulse on WHAM magnetic mirror device. Photo taken & used with permission

Recent Agreements Towards Initial Deployments

Commonwealth Fusion Systems

- Agreement with Dominion Energy to site first power plant in Virginia
- Google signed power purchase agreement to buy 200 MW of fusion power (in early 2030s)

Type One Energy

- Agreement with TVA to site stellarator fusion prototype machine at former Bull Run Fossil Plant

Helion Energy

- Power purchase agreement with Microsoft to deliver 50 MW of fusion power by 2028. Constellation to serve as power marketer
- Agreement with Nucor to develop 500 MWe fusion plant to power steel manufacturing

Note: While agreements send signals of technology development, proposed timelines may not always match real technology maturity timelines



R&D Opportunities and Challenges for Commercialization

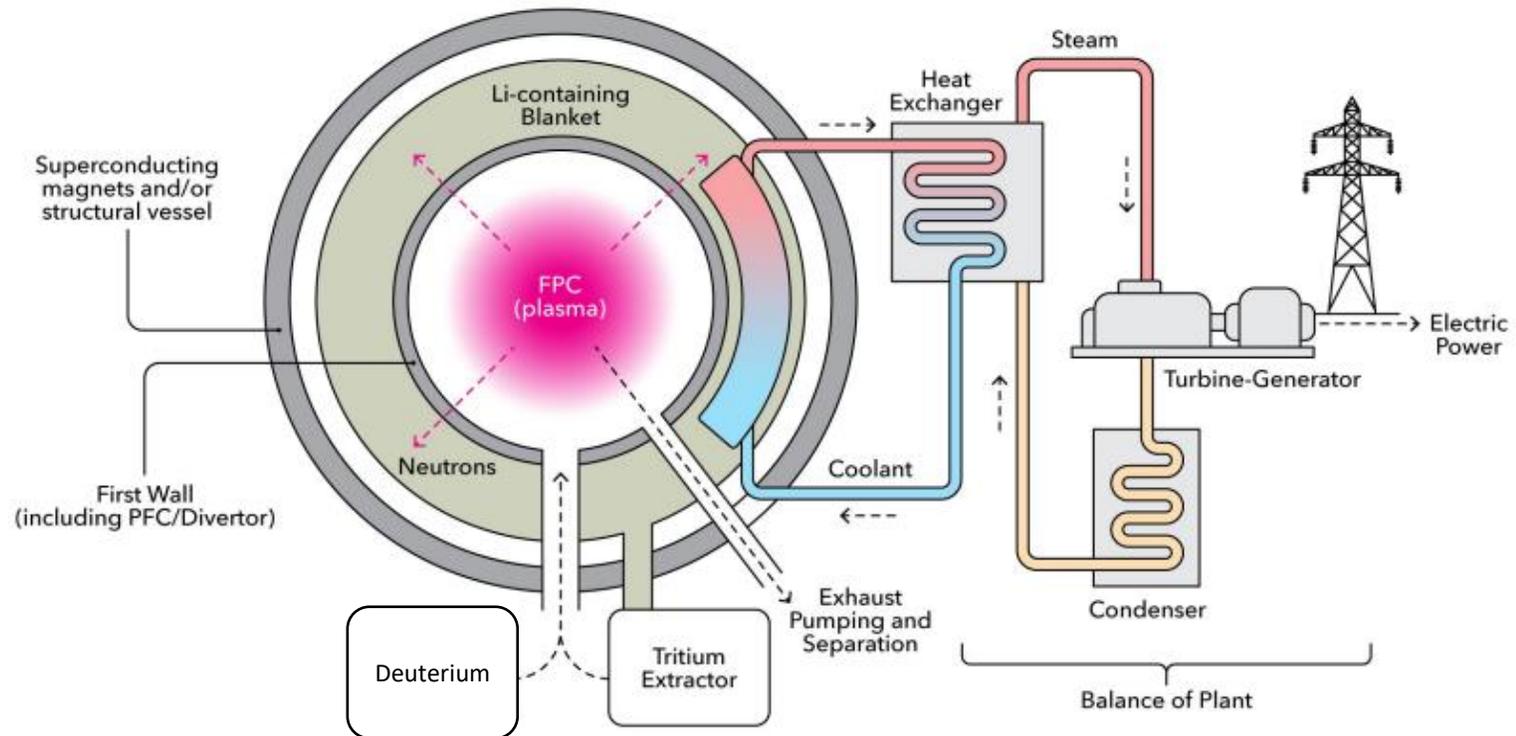
Net energy gain was achieved at NIF. So is fusion here?

Scientific net energy gain (Q_s) is a necessary but not sufficient milestone.

Significant science, technology, and engineering gaps remain on path to a fusion pilot plant:

- Fuel Cycle (tritium extraction and processing)
- Fusion Blanket Development (tritium breeding, shielding, heat transfer)
- Novel Materials

... in addition to plasma physics challenges



D-T Fusion Fuel Cycle

Sophisticated fuel cycle is needed to fuel, extract, and process tritium

- Tritium is rare and radioactive
- Impurities generated in tritium breeding must be removed before refueling
- Water/gas must be detritiated

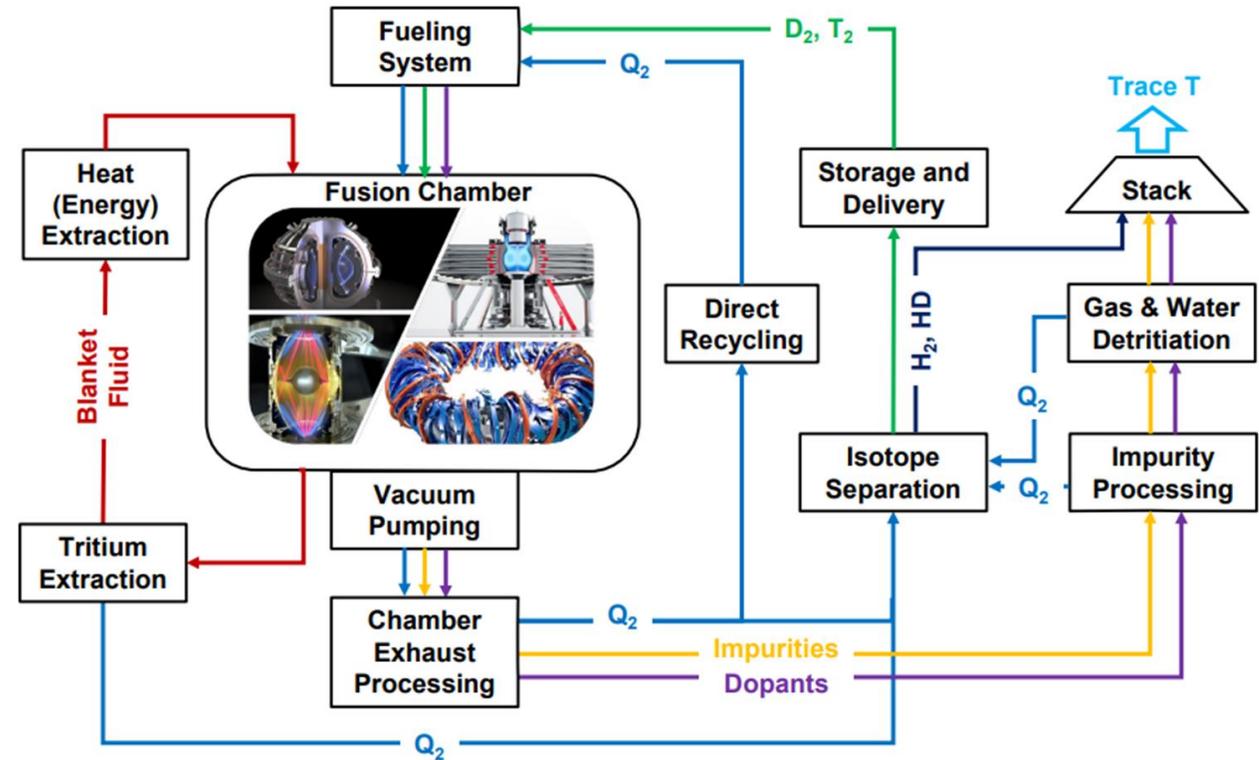
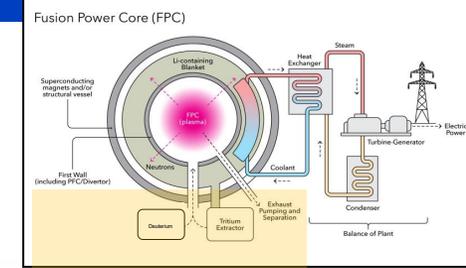
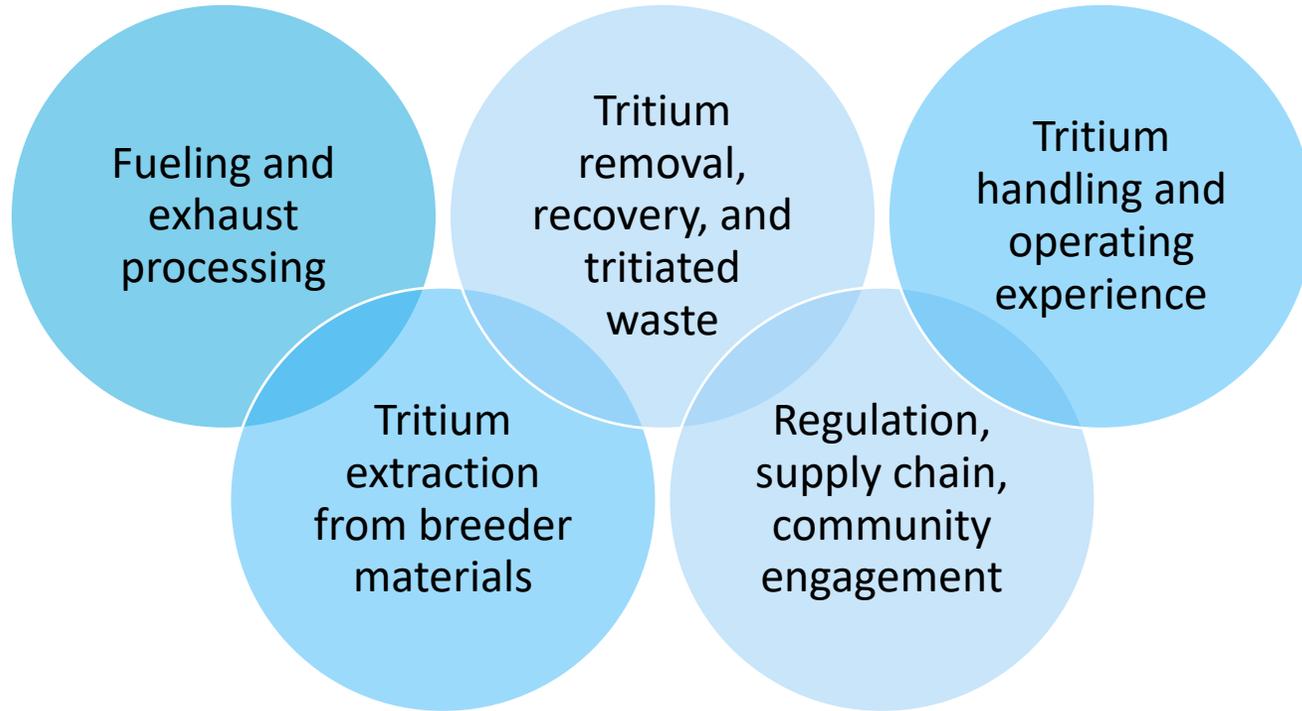


Image credit: Savannah River National Laboratory. Used with permission.

Many fuel cycle technologies are early TRL, and tritium operations not yet fully tested

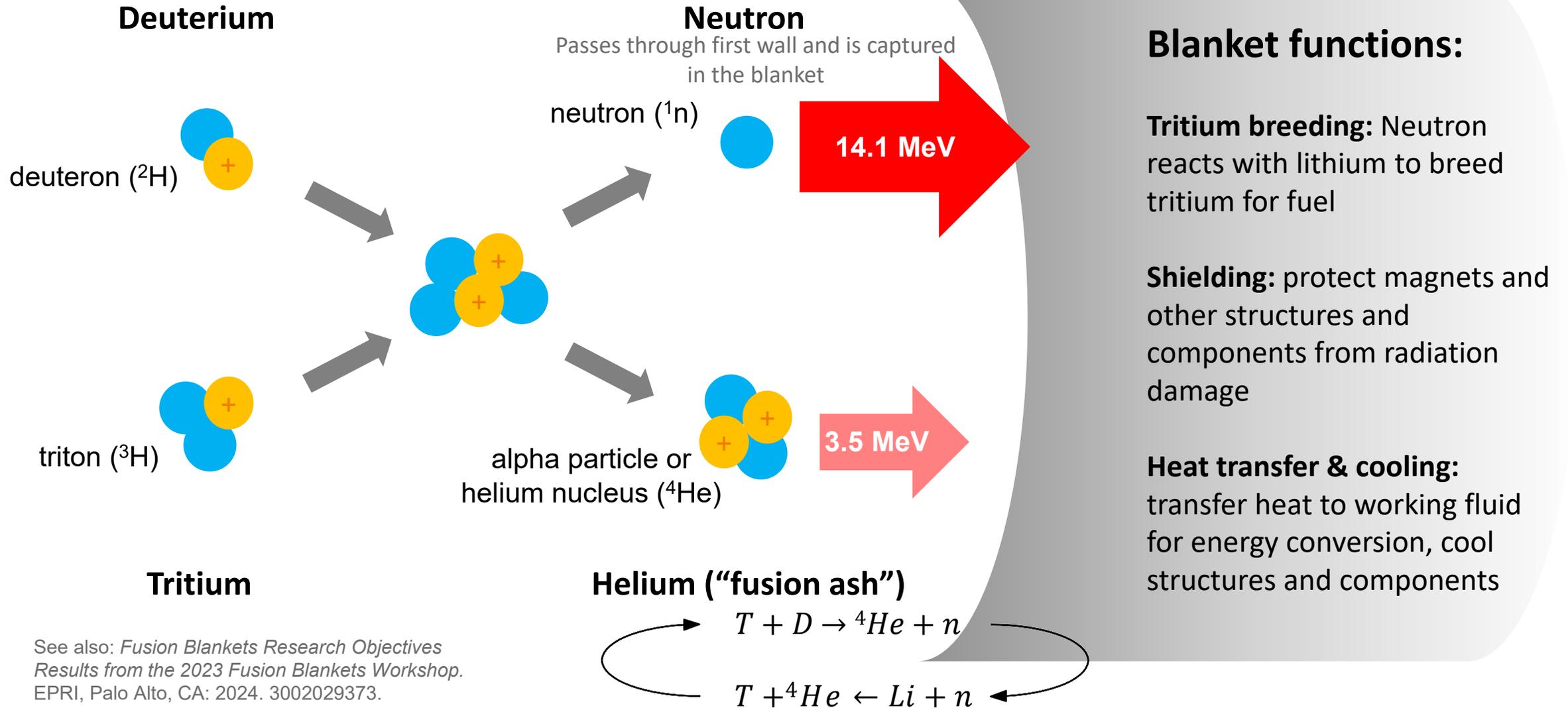
Challenges for D-T Fuel Cycle



See also: *Fusion Fuel Cycles Research Objectives Results from the 2023 Fusion Fuel Cycles Workshop*. EPRI, Palo Alto, CA: 2024. 3002029371.

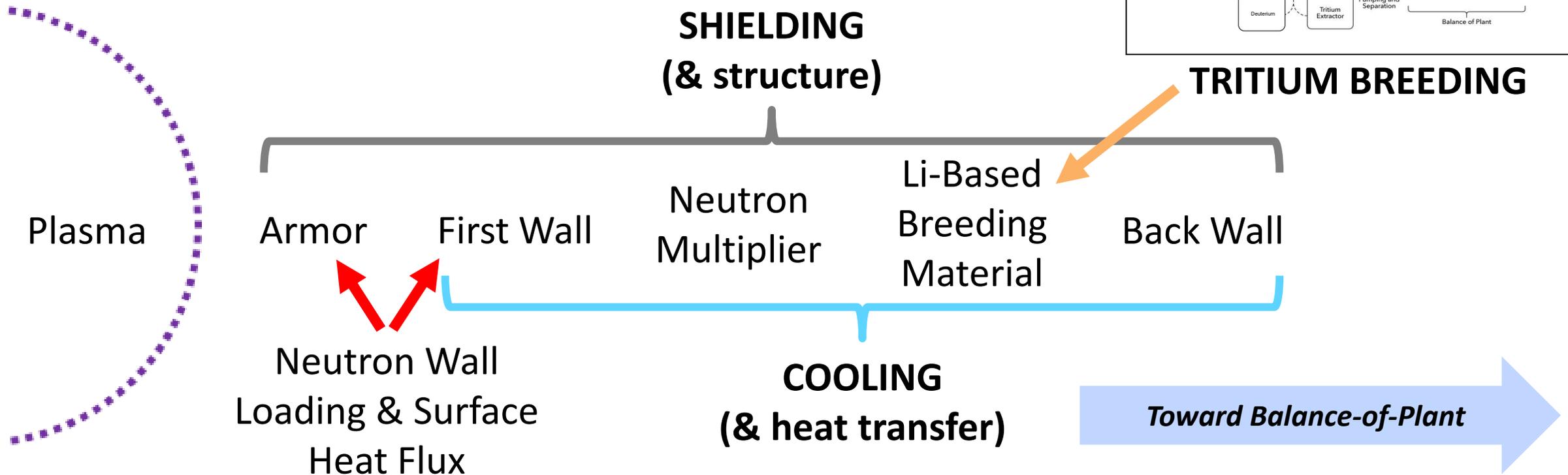
Fuel cycle technologies/processes represent a gap for fusion development

Fusion blankets: In D-T fusion, most energy is transferred by high-energy neutrons



See also: *Fusion Blankets Research Objectives Results from the 2023 Fusion Blankets Workshop*. EPRI, Palo Alto, CA: 2024. 3002029373.

Radial Blanket Design by Function



To serve multiple functions, the blanket requires a unique combination of (possibly novel) materials with specific functional and structural properties. Significant R&D remains for developing suitable blanket technology.

Candidate Blanket Materials

Breeders

- Liquid Metals: Li, PbLi
- Solid Ceramics: Li₂TiO₃, Li₄SiO₄, and many others possible
- Molten Salts: FLiBe (2LiF + BeF₂), FLiNaBe (LiF + NaF + BeF₂)

Multipliers

- Be (solid metal)
- Beryllide (solid intermetallic, e.g., Be₁₂Ti, Be₁₂V, others)

Structural

- Reduced-Activation Ferritic/Martensitic Steel – most mature fusion material
- Vanadium Alloys – need development
- Silicon Carbide – needs development

Coolant

- Self-cooled (liquid metal blanket)
- Water
- Helium

Selection of breeder material must be done while also considering coolant, multiplier, and structural material choice. Integrated decision making must be maintained.

Fusion Materials

Several materials will have to support multiple purposes while withstanding harsh environmental conditions (temperature, high energy neutrons, corrosion)

Plasma-facing materials

- **Materials that make up components lining the inside of the vacuum vessel and face the plasma**
- Subject to plasma exposure, neutron irradiation, and high thermal loads
- Example Candidates: tungsten (most common), SiC-based materials, ultra-high temperature composites

Structural materials

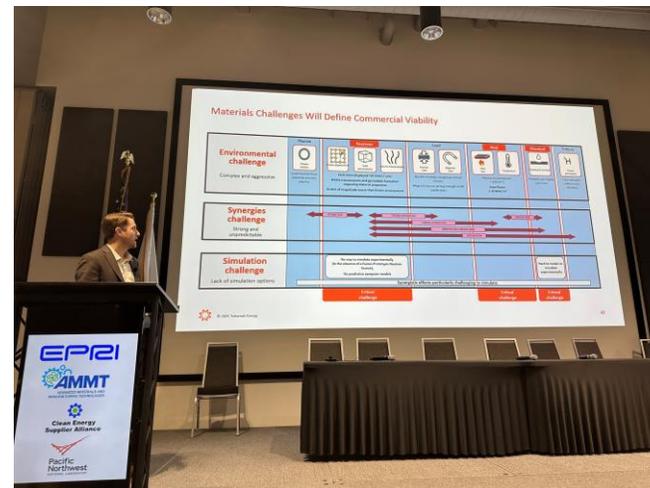
- **Materials used for their mechanical properties (e.g., blanket support structure)**
- Operating environment impacts: neutron irradiation, impurity uptake, corrosive fluids
- Example Candidates: RAFM steels, vanadium alloys, SiC/SiC composites

Functional materials

- **Non-structural materials with a determined function**
- Include materials needed for:
 - Tritium breeding (e.g., Li, PbLi, FLiBe)
 - Neutron multiplication (e.g., beryllium)
- Choice of functional material should consider integration with structural material

Challenges for developing fusion materials & robust supply chain

- In many cases, novel materials/alloys will be needed
- Lack of **fusion prototypic neutron source** to determine material performance under irradiation
 - EPRI is pursuing opportunities to establish irradiation testing capabilities
- Codes and standards are nascent: ASME BPVC Section III Div 4 “Fusion Energy Devices” under development



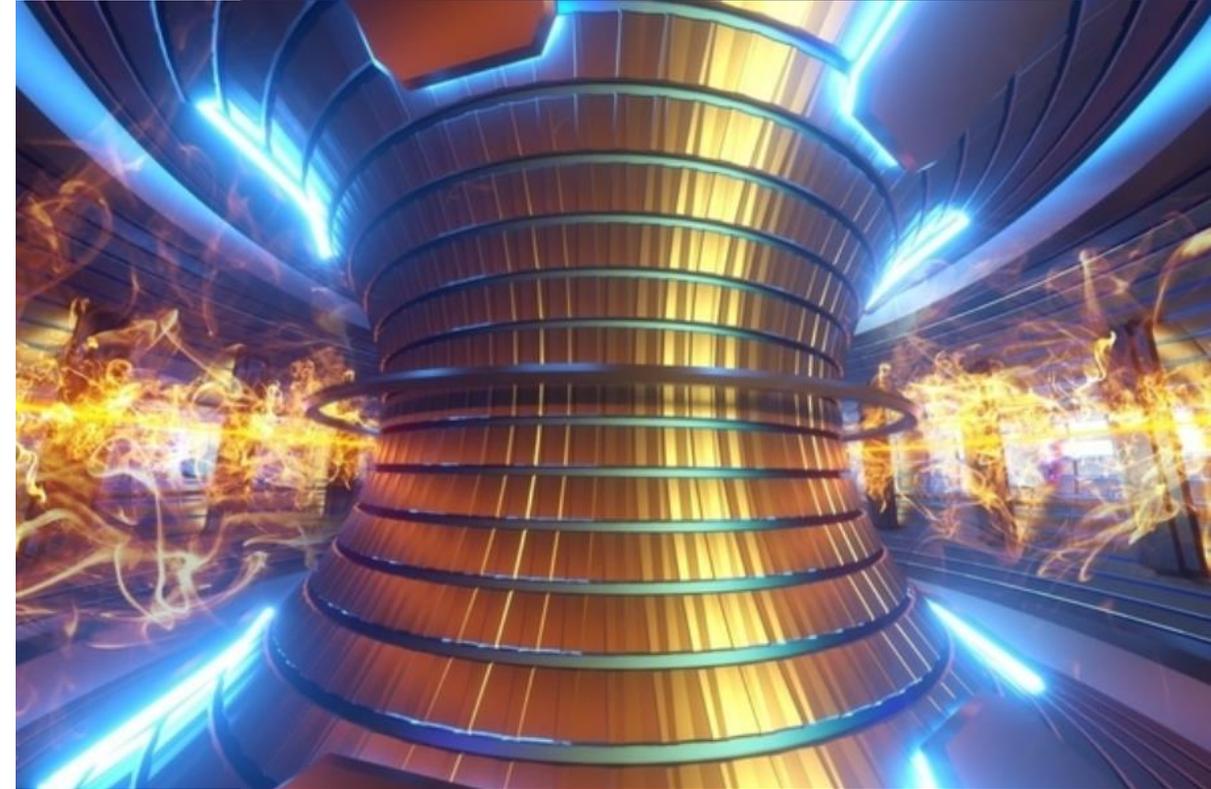
EPRI is leveraging experience in traditional and advanced energy system supply chains to support emerging fusion needs



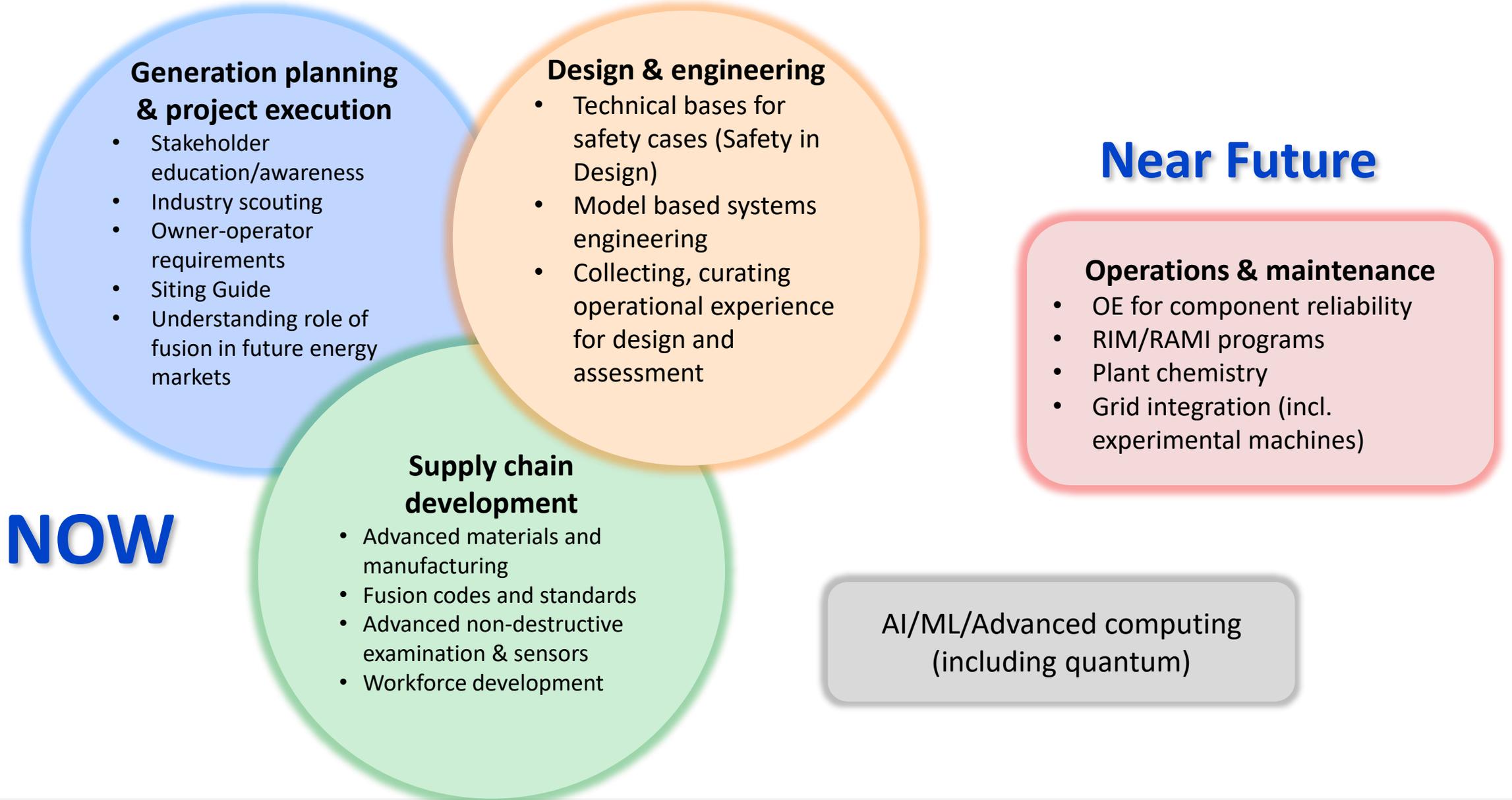
EPRI Research to Accelerate Fusion Energy

EPRI Fusion Energy Strategic Program: Objectives

- Inform EPRI and its members on technology, challenges, opportunities
- Provide value to fusion stakeholders through R&D products and resources
- Target broadest benefit for the public interest: safe, reliable, affordable, and sustainable energy generation and delivery



EPRI Strategic Themes



NOW

EPRI Fusion Forum

- Since 2021, EPRI has hosted representatives from fusion and EPRI communities to share updates on technology milestones and perspectives on commercialization.
- **Join us! The Fusion Forum is open to all who are interested!**



Fusion Forum Goals:

- 1 Introduce EPRI and its members to the fusion community**
Private fusion technology development companies, national laboratories, and fusion trade organizations.
- 2 Introduce fusion community (and technology) to EPRI and its members**
EPRI members exploring emerging technologies and EPRI staff researching common needs for driving innovations towards commercialization.

Fusion Forum materials can be found at <https://www.epri.com/fusion>

To join, contact Diana Grandas (dgrandas@epri.com) or Andrew Sowder (asowder@epri.com)

Fusion Fuel Cycle and Blankets Research Objectives Reports

- Contain results from discussions at the 2023 Fusion Fuel Cycles and Blankets Workshop (hosted at EPRI Charlotte)
- Contain overarching research gaps and 85+ topical research objectives in each report

- *Fusion Fuel Cycles Research Objectives: Results from the 2023 Fusion Fuel Cycles Workshop.* EPRI, Palo Alto, CA: 2024. 3002029371.
<https://www.epri.com/research/sectors/technology/results/3002029371>
- *Fusion Blankets Research Objectives: Results from the 2023 Fusion Blankets Workshop.* EPRI, Palo Alto, CA: 2024. 3002029373. <https://www.epri.com/research/sectors/technology/results/3002029373>



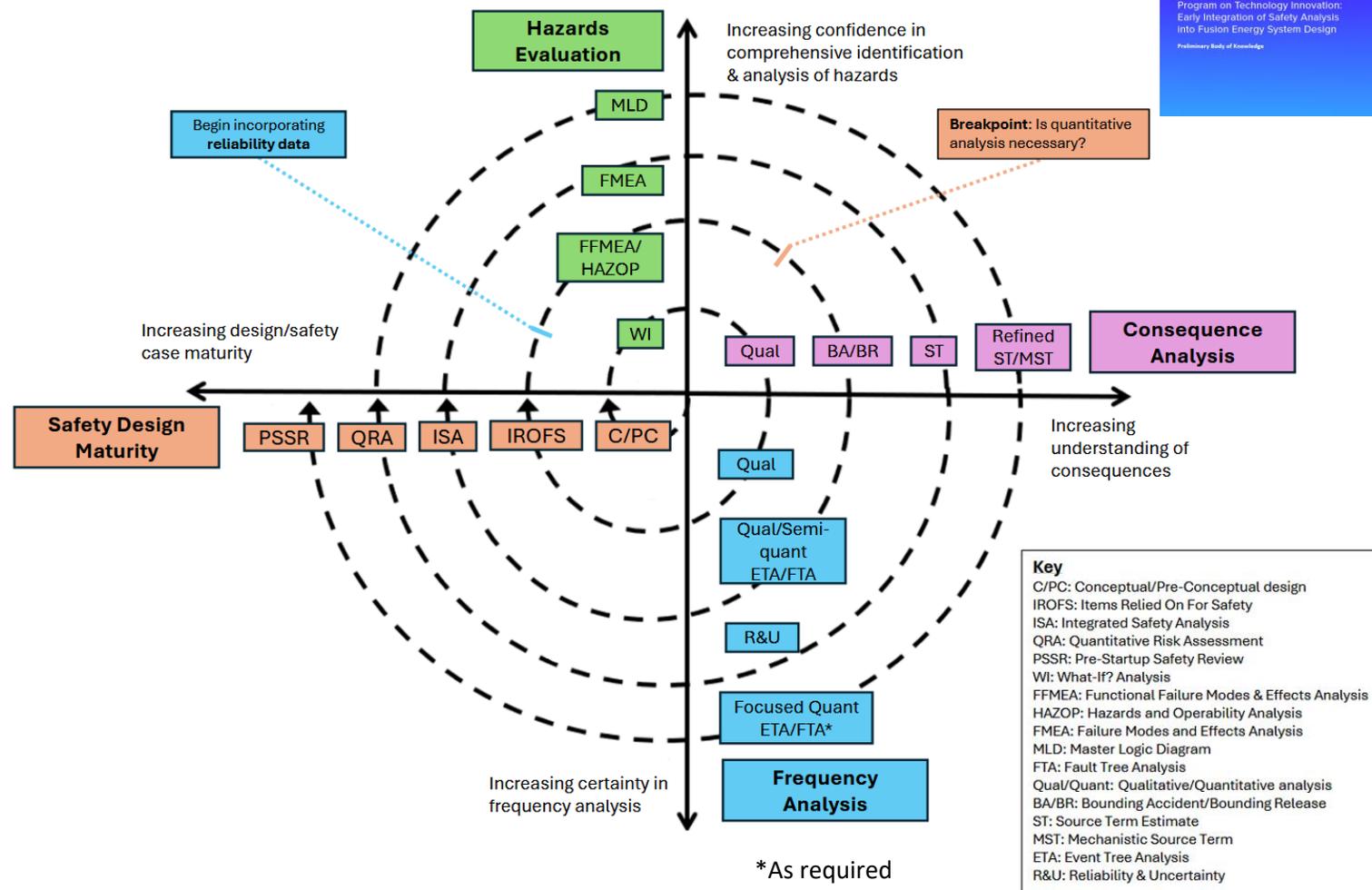
Full workshop summary reports also available:

- [2023 Fusion Fuel Cycles Workshop Summary: A Summary of the 2023 Fusion Fuel Cycles Workshop held in Charlotte, NC on May 22-23, 2023.](#) EPRI, Palo Alto, CA: 2024. 3002029370.
- [2023 Fusion Blankets Workshop Summary: A Summary of the 2023 Fusion Blankets Workshop held in Charlotte, NC on May 24-25, 2023.](#) EPRI, Palo Alto, CA: 2024. 3002029372.

Safety-in-Design for Fusion Energy Systems

Recent EPRI Report:

- Early Integration of Safety Assessment into Fusion Energy System Design: Preliminary Body of Knowledge ([3002031117](#))
- Highlights how a clean-slate, fit for purpose, and iterative application of standard safety analysis tools early and throughout design maturation can support efficient development of fusion system designs.
- Body of knowledge presents state of the art of fusion safety analysis experience to inform SiD application to fusion



Application of qualitative hazard assessment tools (HAZOP, FMEA) in early design stages can facilitate design iteration while cost impacts are minimal.

FIRE Collaborative With University of Wisconsin-Madison: Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design

- **Collaborative Goal:** development and validation of integrated blanket technology in prototypical environments, particularly under the irradiation of 14 MeV D-T neutrons and with high-magnetic fields
- **Task Groups:**
 - Tritium Breeding
 - Lead-Lithium cooling and performance under magnetic fields
 - Advanced manufacturing and testing of blanket materials
 - Volumetric Neutron Source (VNS) development and deployment considerations
- **EPRI Role:**
 - Define functional requirements for VNS, investigate siting and deployment considerations for VNS, and launch initial efforts to establish VNS deployment consortium
- Collaborative participants: UW-Madison, MIT, SHINE, Realta Fusion, EPRI, Rockwell Automation, UIUC, LLNL, UNM, ANL, PPPL



Image: WHAM facility at UW-Madison/Realta Fusion. Used with permission

2024 DOE FES INFUSE Award (with Savannah River National Lab)

Documenting Tritium Operating Experience

Tritium management is an established practice across many industries with many decades of collective operating experience (OE) and lessons learned.

Project Objective: Curate existing information on tritium handling experience to develop a resource for private-sector fusion energy technology developers and regulators. Understand the extent to which tritium may be a hazard and how to appropriately manage risk.

Strategy: Leverage information from existing industrial-scale tritium use-cases to inform practices for fusion facilities.

- Nuclear fission applications/byproducts
- Exit sign/lighting manufacturers
- Defense applications



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Current scope comprises:

- Engagement with tritium facilities in the US and Canada (initially) as a starting point for a Tritium OE Body of Knowledge
- Development of a common template for document OE
- Atmospheric modeling to assess impacts and site boundaries of potential fusion-relevant tritium releases
- Communication with fusion industry and other key stakeholders

This work is supported in part by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under INFUSE 2024 Award “Building a Tritium Facility Operating Experience Body of Knowledge to Support Commercial Fusion Power Plant Safety Case Development and Licensing” (CR-24-005)

Documenting Tritium Operating Experience: Current Status

Tritium OE Database

- Project team sourcing information on historical tritium release events from:
 - Public databases:
 - NRC ADAMS
 - CNSC databases, including CNL reports
 - DOE Occurrence Reports
 - Tritium exit sign manufacturers
 - Discussions with individuals at relevant operating facilities
- Fusion relevant events being analyzed for event description, release quantity, dose received, event impact, and corrective actions

Atmospheric modeling

- Illustrating bounding cases for tritium release scenarios subject to various environmental and atmospheric conditions.
- Investigating downwind doses and distances to various dose limits
 - Parameterizing scenarios based on total tritium quantity released and oxidation ratios at various locations
- Lower quantity release scenarios to correspond with more “typical” release in plant operation scenarios.

1982 EPRI Utility Requirements for Fusion

Purpose: Describe, define, and assess the relative importance of utility requirements associated with selection of fusion options.

Process:

- List of requirements compiled
- Requirements defined (with factors and metrics)
- Requirements refined via questionnaire mail survey sent to 100 utilities, manufacturers, architect engineering firms. 43 respondents.
 - Respondents weighed requirements based on importance
- Workshop held in August 1979 to discuss results of survey



Final set 23 of requirements ranked from “vital” to “slightly important”. Requirements determined to be “unimportant” were eliminated.

Vital	Very Important	Important	Moderately Important	Slightly/Not Important
<ul style="list-style-type: none"> • Plant Capital Costs • Financial liability • Plant safety • Licensability 	<ul style="list-style-type: none"> • Outage Rates • Plant Construction Time • Flexibility of Siting • Waste Handling and Disposal • Plant Operating Requirements • Plant Maintenance Requirements • Electrical Performance • Hardware Materials Availability • Industrial Base (supply chain readiness) • Fuel and Fertile Material Availability 	<ul style="list-style-type: none"> • Plant Operating, Maintenance, and Fuel Costs • Plant Life • Decommissioning • Weapons Proliferation • Startup Power Requirements 	<ul style="list-style-type: none"> • Unit Rating • Capability for Load Change • Part Load Efficiency • Minimum Load 	<ul style="list-style-type: none"> • None rated Slightly Important (indicates conservatism and importance of non-cost-of-energy issues) • Unimportant & dropped (all captured in other requirements): <ul style="list-style-type: none"> • Plant Efficiency • Dependence on Other Systems • Natural Resource Requirements

Utility Requirements for Fusion (EPRI AP-2254, 1982). EPRI, Palo Alto, CA: 1982. 3002023912.

Progress towards updating EPRI Fusion Owner-Operator Requirements

- **Motivation:** Significant growth of fusion industry coupled with energy system transformation prompts need to refresh alignment between fusion developers and potential future owner-operators
- **Methodology**
 - To inform preliminary results: EPRI first engaged energy generation owner-operator organizations and large energy end-users (e.g., hyperscalers) in a series of interviews over Summer and Fall 2025
 - Results from interviews reviewed with EPRI Technical Stakeholders Meeting in October 2025
 - Activities held to Chatham House Rules

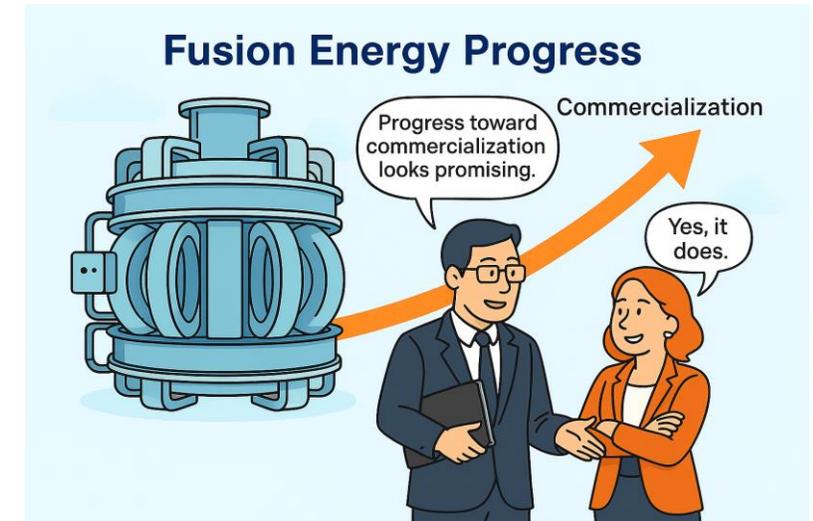


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Example evaluation criteria/requirements identified (thus far)

- Performance Metrics:
 - Net power output
 - Baseload capacity
 - Performance of blanket
 - Performance of balance of plant
 - Auxiliary/input power required
 - Reliability ratings
 - Outage rates (planned vs unplanned)
- Deployment, Operational Characteristics:
 - Maintenance schemes
 - Site needs
 - Fueling strategy
 - Staffing needs
 - Integration with existing infrastructure and interconnection availability
 - Byproduct materials management
- Commercialization readiness (Economics, Regulation, Supply Chain):
 - **Costs**
 - Regulatory pathways
 - Commercialization timelines
 - Supply chain readiness
 - Inclusive of material & manufacturing supply chains and tritium supply chains
 - Community benefits and workforce development



TOGETHER...SHAPING THE FUTURE OF ENERGY®