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FUSION ENERGY TECHNOLOGY DEVELOPMENT AND COMMERCIALIZATION EFFORTS

HEARING

BEFORE THE

COMMITTEE ON ENERGY AND NATURAL RESOURCES UNITED STATES SENATE

ONE HUNDRED EIGHTEENTH CONGRESS

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FUSION ENERGY TECHNOLOGY DEVELOPMENT AND COMMERCIALIZATION EFFORTS

THURSDAY, SEPTEMBER, 19, 2024

U.S. SENATE,
COMMITTEE ON ENERGY AND NATURAL RESOURCES,
Washington, DC.

The Committee met, pursuant to notice, at 10:00 a.m. in Room SD–366, Dirksen Senate Office Building, Hon. Joe Manchin III, Chairman of the Committee, presiding.

OPENING STATEMENT OF HON. JOE MANCHIN III, U.S. SENATOR FROM WEST VIRGINIA

The CHAIRMAN. This morning we are going to discuss the commercialization of fusion energy, one of the critical and emerging technologies that we are in a global race to develop. Fusion energy would be a total game-changer. It is dispatchable power that is zero-emitting, and unlike conventional nuclear fission, we have abundant and accessible fuel for fusion with minimal waste. We know energy has played a major role in spurring the wars of the past century, from Japan's dependence on imported oil in World War II to Europe's dependence on Russian natural gas and conflicts in the Middle East, but widely available fusion power would help end conflicts over energy. It would change the world.

In 2022, I visited the ITER experimental site in Provence, France, where the U.S. and 32 other countries are working together to get the first fusion reactor online, commercial—including not just our allies, but also countries of concern, such as China and Russia. While we are in conflict on other geopolitical issues, we are cooperating on ITER because all of these countries see the merit and promise of fusion energy. ITER gave me hope, and I saw a real opportunity for this technology to bring us together here in the United States. I saw, in a sense, world peace. What I saw there changed my outlook on energy forever. And I really encourage all of you to make the trip there. If you have not been able to do so, please do so.

Senator BARRASSO. And if you can't go to France, come to Wyoming.

The CHAIRMAN. And West Virginia.

[Laughter.]

The CHAIRMAN. I thought I was going to have a protest for my good friend here and my partner.

What I saw there changed my outlook on energy forever, and I will encourage all of you to make that trip. What we are doing with fusion is essentially trying to harness the power of the stars here on Earth. Lightweight elements fuse together and, in the process, release massive amounts of energy. But it is much more challenging to artificially produce fusion here on Earth because of the difference in gravity, which means that we need to create temperatures ten times hotter than the sun here in our labs. And believe it or not, we are actually able to do that today. But despite our scientific progress today, challenges remain that are preventing us from having operational fusion power plants today.

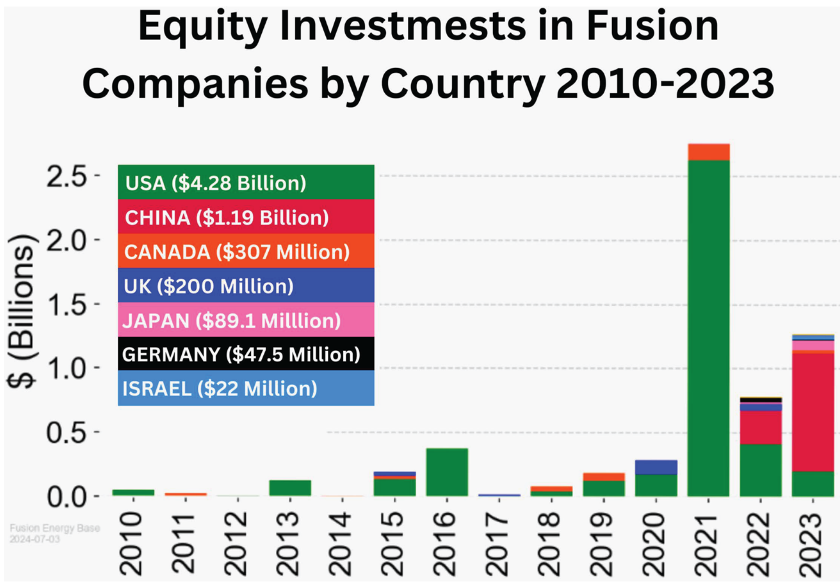
Currently, there are over 40 fusion companies globally that have raised a collective $7.1 billion of investment over the past five years, and over 85 percent of that is private capital. And there have been significant advances in fusion energy technology in recent years, such as the National Ignition Facility at the Lawrence Livermore National Lab achieving fusion ignition, for the first time producing more energy from fusion than was used to drive the reaction. This is the only facility in the world to reach that milestone. And we are also seeing many of these new designs making fusion reactors smaller, similar to how the nuclear fission industry is innovating from the large conventional reactors to the SMRs—small modular reactors—and micro-reactors. But despite decades of research and a rapid increase in global investment in fusion energy technologies, no one has been able to produce fusion energy at the grid level, commercial scale.

I look forward to hearing from our witnesses about the roadblocks that they are seeing. I understand that there are still outstanding scientific questions that need to be answered, which the Energy Act of 2020 and the CHIPS and Science Act aim to help address. And I know DOE's fusion energy program is busy implementing these laws and working with the private sector to coordinate efforts. But I have recently learned that ITER continues to face delays and its new startup date is now 2039, four years later than we had hoped. So we need to get a better understanding of why that is and how we can get things back on track.

Meanwhile, the private sector seems to be charging ahead. Helion Energy, one of our witnesses today, recently visited a Nucor steel facility in my home State of West Virginia, where the two companies are considering co-locating steel production with a fusion plant. It's really exciting, and everyone is kind of all hyped up about this. Helion is looking for an online date for their first grid-scale commercial fusion power plant in 2028. That would be more than a decade before ITER, and that almost seems too good to be true. Now, I understand that ITER and Helion's plants are designed for different purposes, but it is clear from these examples that there is a lot of uncertainty surrounding the potential deployment date for the first fusion power plant.

I would be remiss not to mention that the race against China, which we have discussed time and time again in this Committee, applies here as well. China has recently mimicked our own U.S. Strategic Plan for developing fusion energy, and is rapidly building out their research program and labs, modeled after our own DOE national labs. As you can see in the chart behind me, fusion investments have ramped up in the past few years.

[The chart referred to follows:]


Equity Investmests in Fusion Companies by Country 2010-2023
USA ($4.28 Billion)
CHINA ($1.19 Billion)
CANADA ($307 Million)
UK ($200 Million)
JAPAN ($89.1 Milllion)
GERMANY ($47.5 Million)
ISRAEL ($22 Million)
$ (Billions)
2.5
2.0
1.5
1.0
0.5
0.0
2010
2011
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The CHAIRMAN. The U.S. is still in the lead, but you can see China entering the field in a big way. China's investments in 2023 are more than all of the other countries combined, including ours. And China is not only trying to beat us in science, they are also working to corner the fusion energy supply chain by securing the market for critical materials needed to build fusion power plants, like they have for solar power and electric vehicle batteries. We cannot afford to lose our competitive edge in fusion energy technology.

I am looking forward to hearing from you all about the timeline we are facing for fusion power and about specific steps that we can take to ensure America is able to maintain our competitive edge.

With that, I am going to turn to my friend, Senator Barrasso, for his opening remarks.

OPENING STATEMENT OF HON. JOHN BARRASSO, U.S. SENATOR FROM WYOMING

Senator BARRASSO. Well——

The CHAIRMAN. And I won't interject——

Senator BARRASSO. Thank you, Mr. Chairman. Please feel free to interject. We have a great working relationship. So proud of what we were able to do with permitting. I continue to hear about the success of a bill that came out of this Committee that all of us sitting here today voted for, 15 to 4, and I would like to get that on the floor of the Senate as quickly as possible.

The CHAIRMAN. Amen.

Senator BARRASSO. And thank you for holding this hearing today, and I would like, also, as quickly as possible, to see this come to fruition, what we are talking about today. This is a critically important topic—nuclear fusion. It is a process of combining two elements such as hydrogen, to create a heavier element and generate energy. That's what it's about, generating energy. It is the atomic reaction that powers our sun, and if harnessed here on Earth, offers unlimited emission-free energy, often considered the holy grail of energy production.

This Committee last considered nuclear fusion—it doesn't seem that long ago, but it was actually two years ago that we had the hearing on this. And since then, there has been some noteworthy progress that has been made. In December 2022, the Department of Energy announced that scientists at the Lawrence Livermore National Lab achieved scientific break-even. This occurs when a fusion experiment produces more energy than it uses. And since then, the scientists at the Lawrence Livermore National Lab have been able to repeat this process on four additional occasions. Over the last two years, we have also witnessed growth of the fusion industry. In 2022, there were 33 companies working on this in the private sector, and now there are 45. According to the Fusion Industry Association, these companies have attracted over $7 billion of private investment, with over $900 million in new funding just in the last year. So it's clear that investors do see great potential in fusion.

While these developments are encouraging, we need to remain clear-eyed about the challenges ahead. There is no question that scientific break-even was significant. Yet scientists have not yet been able to reliably and consistently reproduce the reaction. Mastering scientific break-even is necessary before nuclear fusion can be commercially available. Another challenge that scientists face is converting fusion energy into electricity. To date, no fusion reactor has made it to this stage, yet several fusion companies expect to put electrons on the grid in the next decade. Helion, one of our witnesses today, has signed a power purchase agreement to provide Microsoft with electricity by 2028. Helion has signed an agreement to provide electricity to Nucor, a steel producer, by around 2030. I am interested to hear how the plans for Helion are to meet these ambitious commitments.

Advances in fusion energy come at a time when America's demand for electricity is expected to grow rapidly. I brought an article here previously from the New York Times saying by five years from now that the need for energy nationwide would be like adding a new California to the grid as a result of all the areas where new energy is needed. And much of this demand is going to be driven by data centers powering artificial intelligence, by Bitcoin mining, by cloud computing, and storage centers, and if we can't provide these facilities with affordable and reliable power, America is going to cede its leadership position on these critical technologies. China understands this. They understand that the race for artificial intelligence is also a race to secure the energy to power the computers. This is one reason why China is aggressively competing with us on fusion.

Mr. Chairman, I think you and I talked about this Wall Street Journal article headline. This was Tuesday, July 9th: "Beijing Leads U.S. in Fusion Race." You can see that.

[The article referred to follows:]

Wall Street Journal, July 8, 2024:

Appeared in the July 9, 2024, print edition as 'Beijing Leads U.S. in Fusion Race'

https://www.wsj.com/world/china/china-us-fusion-race-4452d3be

EXCLUSIVE CHINA

China Outspends the U.S. on Fusion in the Race for Energy's Holy Grail

China wants to dominate commercial fusion, a long-dreamed-of clean energy source that is attracting new investment

By Jennifer Hiller Follow *and Sha Hua* Follow

Updated July 8, 2024 12:11 am ET

Some scientists say China could surpass the U.S.'s and Europe's magnetic fusion capabilities in three or four years. PHOTO: CFOTO/ZUMA PRESS

A high-tech race is under way between the U.S. and China as both countries chase an elusive energy source: fusion.

China is outspending the U.S., completing a massive fusion technology campus and launching a national fusion consortium that includes some of its largest industrial companies.

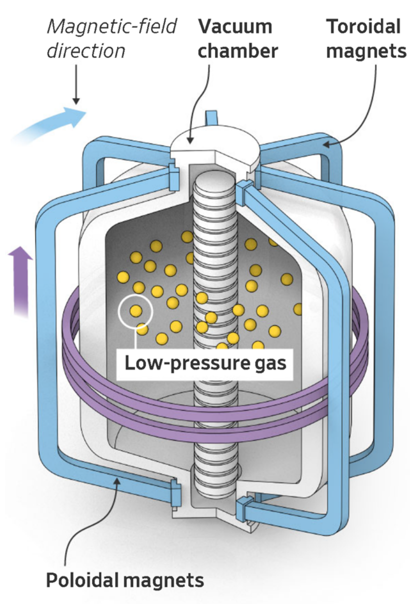
Crews in China work in three shifts, essentially around the clock, to complete fusion projects. And the Asian superpower has 10 times as many Ph.D.s in fusion science and engineering as the U.S.

The result is an increasing worry among American officials and scientists that an early U.S. lead is slipping away.

JP Allain, who heads the Energy Department's Office of Fusion Energy Sciences, said China is spending around $1.5 billion a year on fusion, nearly twice the U.S. government's fusion budget. What's more, China appears to be following a program similar to the road map that hundreds of U.S. fusion scientists and engineers first published in 2020 in hopes of making commercial fusion energy.

How magnetic-confinement fusion works

Fusion is the process by which two atomic particles combine to form a single, heavier one, releasing a huge amount of energy. In stars, gravity and heat do the job of getting atomic particles to collide. On earth, a common experimental fusion design uses a magnetic field to trap and squeeze atoms.



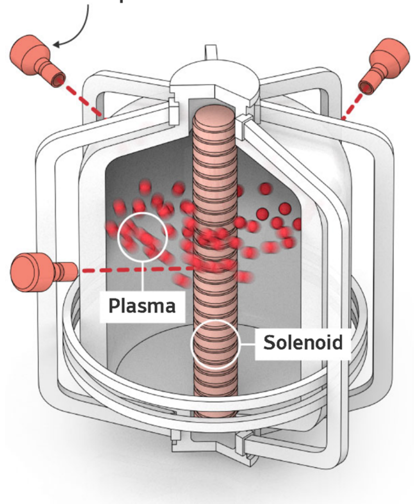
"They're building our long-range plan," Allain said. "That's very frustrating, as you can imagine."

Scientists familiar with China's fusion facilities said that if the country continues its current pace of spending and development, it will surpass the U.S. and Europe's magnetic fusion capabilities in three or four years.

Fusion has long been a clean-energy dream. The process of combining atoms is the same process that powers the sun, and scientists hope to harness it to deliver almost-limitless energy. The technology faces daunting scientific and engineering hurdles, and some experts consider it a mirage that will remain out of reach.

Though a scientific breakthrough on fusion could benefit all of humanity, 1 Magnetic-confinement fusion starts with a **vacuum chamber**. Air and impurities are evacuated.

2 **Toroidal** magnets and **poloidal** magnetic fields that will help trap and control the plasma are charged up. Gaseous fuel is introduced in the chamber.



3 The **solenoid** is an electric current-carrying magnet at the center of the chamber. As a powerful current is run through the vessel, the gas breaks down electrically. It becomes ionized, with electrons stripped from the nuclei. Plasma forms. The magnets keep the plasma away from the chamber walls.

4 **Neutral particle beams** heat the plasma. Fusion requires temperatures over 100 million degrees Celsius. As high-intensity current circulates within the chamber, plasma particles can become energized enough to collide and fuse.

Note: Design is a general representation of a magnetic-confinement device. Sources: PHD Comics and Princeton Plasma Physics Laboratory (chamber and magnet design); ITER and EUROfusion (magnetic-confinement process and fusion energy)
Jemal R. Brinson

some in the U.S. fear it would give China a leg up in a growing competition over energy resources as the U.S. and others try to shift more production and supply chains within domestic borders.

China already has a fast-growing nuclear-technology industry and is building more conventional nuclear power plants than any other country. The country's nuclear-plant development will give it an advantage when commercial fusion is reached, according to a report released last month by the Information Technology and Innovation Foundation, a Washington, D.C.-based think tank with backers that include big tech companies.

Nuclear fusion occurs when two light atomic nuclei merge to form a single heavier one. That process releases huge amounts of energy, no carbon emissions and limited radioactivity—if someone can get it to work.

Scientists around the world are trying to figure out how to sustain fusion reactions and engineer a way to turn that energy into net power. The U.S. leads on a technology that uses lasers to create fusion reactions, though magnetic fusion—using magnetic fields to confine plasma—is where many experts expect commercialization first.

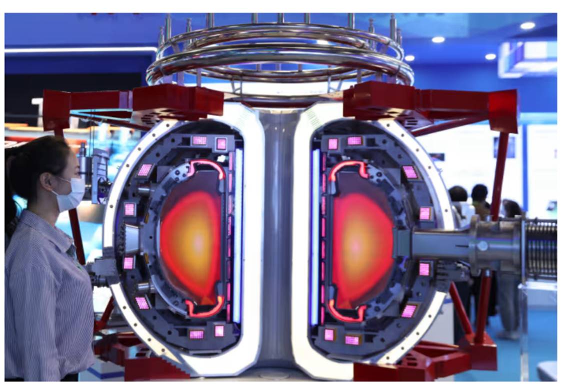
China's fusion push

China is putting vast resources into chasing the abundant-energy dream. Crews in China break only around Lunar New Year, according to scientists familiar with the efforts.

“They’re going to put a lot of human capital and a lot of money and a lot of organization around it. And the question will be, can they figure out the technology?” said Bob Mumgaard, chief executive of Commonwealth Fusion Systems, the largest private fusion company in the U.S., with investors that include Bill Gates.

The Chinese Academy of Sciences’ Institute of Plasma Physics in the eastern Chinese city of Hefei in 2018 broke ground on a nearly 100-acre magnetic fusion research and technology campus. The facility is expected to be completed next year but is already largely operational and focused on industrializing the technology.

Late last year, China said it would form a new national fusion company, and said the state-owned Chinese National Nuclear Corp. would lead a consortium of state-owned industrial firms and universities pursuing fusion energy. Among the largest efforts by a private Chinese company are those of ENN, an energy conglomerate, which created a fusion division from scratch in 2018.



A display model of a tokamak, a machine where fusion can happen using powerful magnets to hold plasma.
PHOTO: JIANG QIMING/CHINA NEWS SERVICE VIA GETTY IMAGES

Since then, ENN has built two tokamaks, the machines where fusion can happen, using powerful magnets to hold plasma. ENN's fusion work isn't well-understood outside of China and its pace of development would be difficult to replicate in the U.S. or Europe.

Fusion has seen a burst of interest from governments and private investors since August 2021. Investments in fusion technology surged in 2022 after scientists at Lawrence Livermore National Laboratory in California achieved "ignition"—a fusion reaction that produced more energy than it consumed. The federal research lab has achieved the key milestone four times since.

The Biden administration in 2022 set a goal of achieving commercial fusion energy within a decade and requested $1 billion for fusion in its recent budget proposal. Organizing a U.S. public-private fusion consortium, similar to a 1980s and '90s semiconductor program, was a suggestion discussed at a recent White House event. Some recent DOE awards were structured similarly to the way NASA has boosted the commercial space industry.

China, Russia and the U.S. are among the 35 countries involved in the International Thermonuclear Experimental Reactor, or ITER, in France. PHOTO: OLGA MALTSEVA/AGENCE FRANCE-PRESSE/GETTY IMAGES

Tammy Ma, lead for the Inertial Fusion Energy Initiative at Lawrence Livermore's National Ignition Facility, said the U.S. fusion budget of $790 million for the 2024 fiscal year, a 4% increase from the year prior, hasn't been enough to keep pace with inflation. The sluggish growth has meant fewer research grants and grant-funded positions available in U.S. graduate schools, Ma said.

Not clear who will win

The fusion world is full of frenemies who believe their technology and approach is the best to meet the world's energy needs. Most are collegial competitors with partnerships that spiderweb the globe. But cooperation has been complicated by the increasingly adversarial relationship between China and the West, especially the U.S.

China for decades has invested in raw materials and technologies that are key to the low-carbon transition. Many of those are also used by fusion firms and researchers, including powerful magnets to hold plasmas in place and lithium, which can be used as a blanket layer around a fusion reactor to absorb neutrons produced in plasmas, among other technologies.

Fusion scientists have swapped and shared information since the late 1950s, when countries began declassifying fusion energy research. China, Russia and the U.S. are among the 35 countries involved in the International Thermonuclear Experimental Reactor, or ITER, in France.

Chinese scientists participate in international fusion conferences and seem most comfortable sharing information through direct conversations, other scientists say, though language is an obstacle.

U.S. Rep. Don Beyer, a Virginia Democrat and co-chair of Congress's Fusion Energy Caucus, said that much U.S. fusion spending goes to legacy programs, "not the cutting-edge stuff."

"In China, from what we can tell, most of their billion and a half is actually going to build stuff that would compete with Helion or Commonwealth Fusion," Beyer said, referring to two of the largest private fusion firms in the U.S.

For decades, China had "almost nothing" of a fusion program, said Dennis Whyte, a professor of engineering at MIT, who for several years sat on Chinese fusion advisory committees. It took China about 10 years to build a world-class fusion science program and national labs.

"It was almost like a flash that they were able to get there," Whyte said. "Don't underestimate their capabilities about coming up to speed."

The U.S. has advantages with an entrepreneurial approach but needs better coordination between private companies, universities and the government, similar to what was used in the 1950s to develop the nuclear submarine program, Whyte said.

"It's not clear to me who will win," he said.

Write to Jennifer Hiller at jennifer.hiller@wsj.com and Sha Hua at sha.hua@wsj.com

Appeared in the July 9, 2024, print edition as 'Beijing Leads U.S. in Fusion Race'.

The CHAIRMAN. Is that this year?

Senator BARRASSO. Yes, that is this year.

The CHAIRMAN. That is this year, but it's not quite accurate compared to what we have been able to do in the past.

Senator BARRASSO. Apparently, it's fake news, but I am not convinced.

[Laughter.]

Senator BARRASSO. And I am concerned. It's a concern.

The CHAIRMAN. We are not out of the race yet, don't give up on the U.S.

Senator BARRASSO. It quotes Dr. Allain, who leads the Department of Energy's Fusion Office and is one of our witnesses here today. So we are going to get to that because according to your quote in this article, China appears to be following our roadmap of how to commercialize fusion energy. So, they tend to have this ability to copycat what we do and then try to advance it in ways to get ahead of us, to leapfrog us. His quote is, "They are building our long-range plan," and you say, "That's very frustrating, as you can imagine," because that is the way China does it on so many things.

So, I am interested to learn what we need to do to protect American interests and regain our competitive advantage. I would also like to learn how the Department can become a better steward of taxpayer dollars when it comes to fusion research. I want to thank you, thank the witnesses for being here. Thank you, Mr. Chairman, and I look forward to the testimony. I know everyone here does.

The CHAIRMAN. Thank you, Senator.

I am going to introduce our panelists for today.

We have Dr. Jean Paul Allain, who goes by JP, Associate Director for Fusion Energy Sciences at the Department of Energy.

We have Ms. Jackie Siebens, Director of Public Affairs at Helion Energy.

And we have Dr. Patrick White, Research Director at the Nuclear Innovation Alliance.

Thank you all for coming. Now we are going to start with you all, and Dr. JP, we will start with you.

STATEMENT OF DR. JEAN PAUL ALLAIN, ASSOCIATE DIRECTOR OF THE OFFICE OF FUSION ENERGY SERVICES, UNITED STATES DEPARTMENT OF ENERGY

Dr. ALLAIN. Thank you, Mr. Chairman.

Chairman Manchin, Ranking Member Barrasso, and distinguished members of the Committee, thank you for your longstanding support of fusion energy sciences research and development. As Associate Director of Fusion Energy Sciences, or FES, in the Department of Energy's Office of Science, it is an honor to testify about our work to realize the promise of fusion energy in alignment with Administration's Bold Decadal Vision for Commercial Fusion Energy. Simultaneously, we are also working to align with the recommendations of the Fusion Energy Sciences Advisory Committee Long-Range Plan. I want to thank this Committee for the strong support for the entire Office of Science—and fusion, specifically—reflected in the historic CHIPS and Science Act of 2022.

This past year, we have made tremendous strides. We began to realign the FES program to meet the rapidly changing fusion landscape, introduced new innovative funding mechanisms, and deepened international partnerships with like-minded nations. All the while, we have maintained our focus on the important foundational and enabling science that we steward for the nation, which has the potential to harness fusion energy and also deliver new plasma technologies that can improve human health, revolutionize microelectronics manufacturing, and more. The promise of fusion energy cannot be understated. Harnessing energy from fusion reactions has the potential to unlock a resilient baseload and a carbon-free source of energy essential to combating climate change. Further, with such broad and transformative potential, it is essential that we treat fusion energy as a national security imperative. The United States cannot afford to have other nations surpass its technological leadership and competitive edge.

To realize fusion energy in a decadal time frame, we must take bold action to address the critical scientific and technological gaps that remain, and enable fusion energy to scale. At FES, our approach to realizing this Bold Decadal Vision is built on three key actions. First, we must drive innovation by closing critical science and technology gaps. Investing in fusion energy sciences to align with the Bold Decadal Vision, as well as recommendations of the FESAC Long-Range Plan, will help us accelerate at the necessary speed and scale. Second, we must establish and leverage public-private partnerships. The proposed public-private consortium frameworks enable participants from across the economy to support the development of fusion science and technology to realize commercial fusion energy. Participants might include academia, government labs, private equity, loan programs, state and regional governments, philanthropic investors, and large-scale industries and corporations. Third, we must build a robust fusion technology manufacturing network, alongside partners. This investment will produce innovations and scale essential fusion technologies, including internal components, advanced materials, and tritium management systems needed to make fusion economically competitive at scale. This coming fiscal year, we will release the first-ever U.S. Fusion Science and Technology Roadmap, laying out the steps needed to advance each of these actions and clear metrics with input from industry to measure progress every year.

To close, we are in one of the most consequential moments of development for fusion energy. Translating decades of scientific and technological progress to a globally competitive energy resource will require significant investment and effort. History has taught us that the magnitude of effort needed to deploy and scale-up novel technologies, like for the first moonshot, the nation will need the foresight and will need to bring together our collective expertise and willingness to innovate across technology and policy if we are to win the race to commercial fusion energy. As we face challenges to our national, economic, and energy security, fusion energy is a mandate that we must realize to ensure global leadership this century and beyond.

Thank you.

[The prepared statement of Dr. Allain follows:]

Testimony of Dr. Jean Paul Allain

Associate Director for Fusion Energy Sciences

Office of Science

U.S. Department of Energy

Before the

Committee on Energy and Natural Resources

U.S. Senate

September 19, 2024

Introduction

Chairman Manchin, Ranking Member Barrasso, and distinguished Members of the Committee, thank you for your longstanding support of fusion energy sciences research and development (R&D). As Associate Director for Fusion Energy Sciences (FES) in the Office of Science (SC), at the Department of Energy (DOE), it is an honor to provide testimony regarding DOE's recent efforts to accelerate progress on realizing the promise of fusion energy, in alignment with the Administration's *Bold Decadal Vision for Commercial Fusion Energy* (BDV)[1]. Simultaneously, we are also working to align with the recommendations of the Fusion Energy Sciences Advisory Committee (FESAC) Long Range Plan (LRP).[2] This past year, we have made tremendous progress. We have taken decisive action to realign the FES program to meet the rapidly changing fusion landscape, redesign and introduce innovative funding mechanisms in support of the expanded mission of the program, and deepen international partnerships with like-minded countries. All the while, we have maintained our focus on the important foundational science we steward for the nation.

I have had the privilege of working closely with the Department's Lead Fusion Coordinator and our talented staff to set clear goals for DOE's work on fusion energy sciences through the publication of two documents: the *Building Bridges* vision for FES, and the *U.S. Fusion Energy Strategy 2024*, which was recently released[3] at the White House event marking two years of the BDV.[4] My remarks today will focus on the specific role of the FES program within SC, but all of our work is in the context of the broader actions of the DOE as guided by the *U.S. Fusion Energy Strategy 2024*.

[1] https://www.whitehouse.gov/ostp/news-updates/2022/04/19/readout-of-the-white-house-summit-on-developing-a-bold-decadal-vision-for-commercial-fusion-energy.
[2] Carter, T., Baalrud, S., Betti, R., Ellis, T., Foster, J., Geddes, C., ... & Rej, R. (2020). Powering the future: Fusion & plasmas. US Department of Energy (USDOE), Washington, DC (United States). Office of Science, https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf
[3] https://www.energy.gov/articles/doe-announces-new-decadal-fusion-energy-strategy.
[4] https://www.whitehouse.gov/ostp/news-updates/2024/06/06/fact-sheet-biden-harris-administration-announces-more-than-180-million-to-advance-implementation-of-its-bold-decadal-vision-for-commercial-fusion-energy.

The promise of fusion energy cannot be understated. Harnessing energy from fusion reactions has the potential to address climate change by providing a sustainable and resilient *firm and carbon-free* source of energy, and also to provide the economic engine for the world's future energy sector supply chain. The combination of scientific support for fusion energy as well as basic plasma science research will also create spin-off plasma technologies that will benefit society, such as microelectronics production, material and chemical production, surface processing, and decomposition of wastes.

Further, because of the transformative potential of this technology, it is essential that we treat fusion energy also as a national security imperative. The United States cannot afford to have other nations surpass our technological leadership if we hope to own this technology into the future. ***To realize fusion in a decadal timeframe, we will need to take bold action to address the critical scientific and technological gaps that remain and establish the supply chains that will enable fusion energy at scale.***

At DOE, we are taking a multifaceted approach to realizing this vision, recognizing that no single government program will be able to translate fusion and make it competitive in future energy markets. This can be accomplished through three key steps:

1. ***Drive innovation and close key science and technology (S&T) gaps.*** Investing in SC FES to align with recommendations of the FESAC LRP would accelerate advances at the necessary speed and scale.
2. ***Leverage Public-Private Partnerships (PPPs)***. Public-Private Consortium Frameworks enable participants from across the economy to support the development of fusion science and technology realizing commercial fusion energy. Participants might include academia, government laboratories, private equity, loan programs, state and regional governments, philanthropic investors, and large-scale industries and corporations.
3. ***Build a Robust Fusion Technology Manufacturing Network alongside partners***. This investment will produce innovations and scale essential fusion technologies—including internal components, advanced materials, and tritium management approaches—needed to make fusion economically competitive at scale.

Background

Over the past decade, the fusion energy R&D landscape has evolved significantly, especially in the U.S., building on decades of public investments in fusion S&T, major advances have been achieved both domestically and globally by public and private sector entities, such as the achievement of fusion ignition at the National Ignition Facility (NIF) at Lawerence Livermore National Laboratory (LLNL). These advancements are indications of fusion's increasing technological readiness. Major advances in related scientific fields, including high-temperature superconductors, advanced materials, exascale computing, and artificial intelligence/machine learning, have the potential to further accelerate and transform fusion R&D.

Currently, there is approximately $6.7 billion of cumulative equity investments in private fusion companies not including public investments.[5] While the shift toward greater private-sector

[5] *The Global Fusion Industry in 2024,* Fusion Companies Survey by the Fusion Industry Association, p. 5; available for download at https://www.fusionindustryassociation.org/fusion-industry-reports.

involvement in fusion R&D is seen most dramatically in the U.S., the trend can be observed globally, with equity investments into companies based in Canada, United Kingdom (UK), Japan, European Union (EU), China, and others. This trend is a strong indication of fusion's potential as a future commercial energy technology.

Within DOE, R&D in fusion energy is primarily funded through the SC's FES program. The mission of the FES program is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundations needed to develop a fusion energy source. This is accomplished by studying the plasma state and its interactions with its surroundings.

Section 2008 of the Energy Act of 2020 amended the Department of Energy Research and Innovation Act (42 U.S.C. § 18645) to expand the scientific mission of FES by adding the goal of *"supporting the development of a competitive fusion power industry in the U.S."* Since then, a number of strategic documents have been produced to align the goals of the program, SC, and the Department with this expanded mission. In 2020, the FESAC released the LRP,[6] which provided SC with key recommendations and articulated that achieving a thriving and sustainable fusion energy industry of the future will require addressing key S&T gaps with a diverse set of tools and strategic approaches. The FESAC LRP became the blueprint from which a new SC FES program has been designed, complemented by the National Academies of Sciences, Engineering, and Medicine (NASEM) report on Bringing Fusion to the U.S. Grid[7] and the BDV. In combination, these documents help guide programmatic priorities and timelines to ultimately converge the interests of the public and private sectors in the U.S. to establish a robust fusion energy industry.

Following those reports, a new FES vision entitled *Building Bridges* was published in December 2023. This new vision focuses on aggressively closing the S&T gaps needed to realize commercial fusion energy in the three key scientific areas identified in the FESAC LRP and shifts the balance of research toward fusion materials and technology. The structure of the FES program was realigned this past year to better facilitate the new vision.

Lastly, the DOE *Fusion Energy Strategy 2024* was published in June 2024, in recognition of the crosscutting nature of the challenges we face to realize commercial fusion energy. The strategy consists of three primary pillars: 1) closing S&T gaps to commercially relevant fusion pilot plants; 2) preparing the path to sustainable, equitable commercial fusion deployment; and 3) building and leveraging external partnerships. While FES has a central role to play across these pillars, it will require the concerted effort of our partners across the Department and the interagency especially to prepare the path for sustainable and equitable deployment, which has supply chain, regulatory, and other key components that extend beyond SC's mission.

[6] Carter, T., Baalrud, S., Betti, R., Ellis, T., Foster, J., Geddes, C., ... & Rej, R. (2020). Powering the future: Fusion & plasmas. US Department of Energy (USDOE), Washington, DC (United States). Office of Science, https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf
[7] https://nap.nationalacademies.org/catalog/25991/bringing-fusion-to-the-us-grid

International Partnerships

Fusion has become a global race[8] and our ability to build partnerships in the public sector will be critical to the success of our fusion power industry. The United States has been a world leader in fusion R&D for the past four decades driven by the development of computational tools, large-scale experimental devices, and a scientific workforce with deep expertise and know-how. However, with the rise of globalization and scale of the challenges, it has become increasingly important to build partnerships with public and private entities in like-minded countries.

For DOE, this includes strategic international partnerships as part of a U.S. strategy for *International Partnerships in a New Era of Fusion Energy Development*,[9] which was announced at the 28th session of the Conference of the Parties (COP28) in 2023. This strategy will support the timely development, demonstration, and deployment of commercial fusion energy in strategic areas like research and development and harmonization of regulatory frameworks. For example, this past year, we have announced two strategic international partnerships with the UK[10] and Japanese[11] governments supported by coordinated teams representing our public and private sectors in fusion energy. We continue dialogue with additional like-minded nations, including Canada, Germany, France, and Korea, and continue to nurture our strategic relationship with the EU on fusion energy.

Another key example is our role in ITER, which is a multi-national collaboration to construct a complex scientific facility that will help usher an industrial-scale burning plasma experimental platform. ITER will be equipped with diagnostic capabilities that will not be built into a commercial fusion power plant. ITER will also be an experimental facility that will support fusion developers when fusion pilot plants are stood up in the future, as well as a multi-national supply chain supporting fusion energy development today. U.S. investments in ITER have yielded more than $1 billion in support for over 100 U.S.-based supply chain companies that are now becoming key contributors to the growing fusion industry while engaging with our public program. We continue to find ways to build bridges to ITER for both our private and public sector performers. The tremendous learnings to-date from the ITER project should be translated to the growing U.S. fusion industry.

DOE has also worked to build bridges between public and private sectors globally. One example is the work by Princeton Plasma Physics Laboratory (PPPL) and Oak Ridge National Laboratory (ORNL) with the UK-based Tokamak Energy company. This collaboration enabled their compact spherical tokamak device (ST-40) to demonstrate temperatures greater than 100-million degrees, providing the heat required to scale towards commercial fusion energy production.

***Building Bridges* Report and the Vision for the FES Program**

The future of the FES program will be guided by the vision outlined in the *Building Bridges* report. The three key elements of the FES vision are:

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[8] G. Conroy, *Inside China's race to lead the world in nuclear fusion,* News Feature, Nature, 28 August 2024.

[9] https://www.whitehouse.gov/ostp/news-updates/2023/12/02/international-partnerships-in-a-new-era-of-fusion-energy-development.

[10] https://www.energy.gov/articles/joint-statement-between-doe-and-uk-department-energy-security-and-net-zero-concerning.

[11] https://www.energy.gov/articles/joint-statement-between-doe-and-japan-ministry-education-sports-science-and-technology.

- ***Workforce Development and Sustainment:*** Ensuring establishment of sustainable and resilient pathways for diverse and exceptional talent.
- ***Bridging Gaps:*** Creating innovation engines with national laboratories, universities, and industry to support science excellence and technology readiness for fusion energy.
- ***Transformational Science:*** Nurturing plasma science and technology discovery translating to innovation impact.

To achieve this vision, FES is taking action to build a U.S. fusion S&T roadmap aligned with the fusion industry, create new innovative funding mechanisms that can build and deepen public-private partnerships, and realign the structure of the program to better support its goals.

Developing a national fusion S&T roadmap aligned with industry: FES is developing a metrics-driven national fusion S&T roadmap that informs decision-making on the "how" and "when" (including facility needs) of closing the critical S&T gaps. The roadmap is being developed in part based on output from a series of community workshops held from 2022–2024 that were focused on several critical areas, including public-private partnerships in fusion energy R&D; inertial fusion energy; updating the requirements for a fusion prototypic neutron source (FPNS) and other large-scale fusion materials and technology facilities; fusion neutronics; magnet technology; fuel cycle and blankets; fusion materials; measurement innovation; and fusion workforce development. The roadmap will be unique because it will align government research with the fusion industry and ensure that FES is guided by innovation principles that bridge foundational research with user-inspired and user-defined goals.

Bridging gaps through the FIRE Collaboratives: To resolve S&T gaps to a commercially relevant, private sector-led fusion pilot plant and to support the creation of a fusion innovation ecosystem, the new FES FIRE Collaboratives program will consist of virtual, centrally managed teams (led by national laboratories and/or universities) called "Collaboratives." This program bridges FES's foundational and enabling S&T research programs to the work and needs of the growing fusion industry. Moreover, this initiative aims to create new economic opportunities, bolster U.S.-based manufacturing and supply chains, and enable the development of technologies that are also crucial for national security, defense, and other commercial industries.

Leveraging public-private partnerships: Public-private partnerships (PPP) will be employed as a key enabler of the DOE fusion strategy to accelerate the R&D needed to close S&T gaps to a fusion pilot plant and to achieve the pace required to meet the timeline of the BDV. Examples of recent and ongoing fusion PPP programs include the ARPA-E fusion capability teams, the FES Innovation Network for Fusion Energy (INFUSE), and the FES Milestone-Based Fusion Development Program ("Milestone Program").[12,13,14]

DOE has made significant progress in implementing the new Milestone Program over the past year. Through this program, we have signed highly flexible Technology Investment Agreements (TIAs) with eight companies, which are already beginning to deliver on their milestones. The

[12] https://www.energy.gov/science/articles/department-energy-announces-50-million-milestone-based-fusion-development-program.
[13] Funding opportunity announcement (FOA): https://science.osti.gov/grants/FOAs/FOAs/2022/DE-FOA-0002809.
[14] The Milestone Program supports a variety of fusion approaches at different technological readiness levels, which is a feature adopted from the DOE Nuclear Energy Advanced Reactor Demonstration Program.

awardees have collectively closed additional private funding rounds totaling more than $200 million since the announcement of their selections in the Milestone Program, validating one of the policy objectives of the program to significantly amplify federal funding in support of fusion energy commercialization. While DOE intends to continue streamlining our processes for partnering with the private sector, we are also in a good position to build on the precedent of these TIA terms and conditions for other innovative fusion public-private-partnership programs in support of the DOE fusion strategy and the U.S. Bold Decadal Vision.

To take these program innovations yet further, FES issued a Request for Information (RFI) to inform the establishment of a Public Private Consortium Framework (PPCF) that will bring the broad community together to advance the research, development, demonstration, and deployment (RDD&D) of commercial fusion energy. Complementary to the Milestone Program and Fusion Innovation Research Engine (FIRE) Collaboratives (discussed further below), a PPCF could amplify federal funding by catalyzing and bringing together state/local government, private, and philanthropic funding to resolve significant, remaining S&T gaps (with an emphasis on pre-competitive R&D and aligned with technology roadmaps of private-sector fusion developers and critical supply-chain providers) and to deliver essential small-to-medium scale R&D test capabilities. If built around regional hubs, such an effort could also stimulate distributed development of fusion supply chains and workforce and support regional economic development and community engagements. The DOE Foundation for Energy Security and Innovation[15] (FESI) could be a potential vehicle for convening non-Federal partners and launching a fusion PPCF.

Conclusion

We are in one the most consequential moments for the development of fusion energy. Translating this technology to a global competitive resource will require significant investment and effort. History has taught us the magnitude and scale of translating hard technologies, e.g., from the 12-second, 120-foot first flight in North Carolina to realizing that first step on the moon's surface resulting in commercial flight and the space age, respectively. Realizing fusion energy may be at least as challenging, we at DOE are up to this challenge. As one of the universe's most efficient and powerful energy resources, fusion energy is a mandate we must realize for our clean energy and economic goals and to ensure U.S. technological leadership this century and beyond.

[15] https://www.energy.gov/articles/doe-launches-foundation-energy-security-and-innovation.

The CHAIRMAN. Thank you.

Now we will turn to Ms. Siebens.

STATEMENT OF JACKIE SIEBENS, DIRECTOR OF PUBLIC AFFAIRS AT HELION ENERGY; NON-RESIDENT SENIOR FELLOW AT THE ATLANTIC COUNCIL GLOBAL ENERGY CENTER

Ms. SIEBENS. Thank you.

Chairman Manchin, Ranking Member Barrasso, and distinguished members of the Committee, thank you for the opportunity to testify today on the steps necessary to position the United States as the leader in a global fusion marketplace. It is an honor to speak before you, especially at such an inflection point for fusion technology with China trying to capitalize on our success.

Helion is based in Everett, Washington, and is a company of over 350 people with a mission to provide the world with clean, reliable, and abundant energy through commercial fusion technology. Over the past decade, we have developed six fusion prototypes, each reaching our goals of proving critical aspects of our approach and bringing us closer to commercial deployment. Today, we are building Polaris, our seventh prototype, which we expect to be the first machine to demonstrate electricity production. Following Polaris, we will construct the world's first commercial fusion power plant, backed by a power purchase agreement with Microsoft. We also have a customer agreement with Nucor to develop a 500-megawatt plant to power one of their steel mills. This shows that fusion energy is no longer a distant vision, it is becoming a reality today. But as exciting as this moment may be, deployment at scale is where the real race is. To meet projected energy demand growth and to secure U.S. leadership, we must prepare to deploy not just one, but many fusion power plants across America and the globe.

And this requires a strategic two-pronged approach. First, building resilient supply chains, and second, establishing bold new regulatory pathways. There are several things we must do to bolster our supply chains, including adapting existing government programs to fusion, such as the Department of Energy's Loan Programs Office, the 45X manufacturing production tax credit, and the CHIPS and Science Act. But eventually, we also need to develop a new bold program for fusion, akin to the CHIPS Act. It should include strategic manufacturing support to provide significant funding to build out the manufacturing capacity necessary for large-scale fusion deployment and move the U.S. toward applied materials R&D. And when it comes to regulation, the Nuclear Regulatory Commission and Congress have already made incredible strides. However, significant opportunities remain as we move toward commercialization.

Fusion generators are capable of being mass-produced, but they are currently licensed for each individual site. We have a proposal called Design-Specific Licensing, where fusion generators are treated like airplanes, where you license the design with the ability to site and operate the generator at any location nationwide. For environmental reviews, we must develop a tailored environmental regulatory approach—much like licensing—for the generator design, and not bucket fusion into the years-long processes that apply to fission. It is also important to look at grid interconnection and siting regulation, as the current system is not designed for scale. Federal and state regulators must work together to streamline interconnection processes to integrate fusion generators into the grid as soon as they are ready. Also, we must look at co-located generation, where power can be directly supplied to large energy consumers, like data centers, without the need for extensive grid infrastructure.

We recognize these ambitious asks in support of ambitious goals, but when a fusion company hits electricity production, these efforts need to be ready to go on day one to make sure fusion can scale in a competition where China will put everything on the table to win. China has made fusion a cornerstone of its national innovation strategy, aggressively investing in research, development, and manufacturing capabilities, both for civilian and military applications. It is estimated that China spends $1.5 billion a year on fusion and has ten times as many Ph.D.s as America in this space. And China has a history of replicating U.S. companies' designs to develop their own systems. This is happening right now in fusion with multiple Chinese companies. One company launched a direct copycat program, pursuing Helion's design, and another publicly stated its intent to replicate key aspects of Helion's approach. We have seen it before, in solar and batteries, where the U.S. pioneered breakthrough technologies, only to lose out to China in the race to mass deployment. Without a comprehensive U.S. response, we risk being outpaced by China again. This is why it is imperative for the U.S. to act now. By establishing resilient supply chains and the right regulatory frameworks, we can ensure that fusion transforms our energy system and secures America's leadership in the clean energy transition.

Thank you again for the opportunity to testify, and I look forward to your questions.

[The prepared statement of Ms. Siebens follows:]

Written Testimony of Jackie Siebens

Director of Public Affairs, Helion Energy

U.S. Senate Committee on Energy and Natural Resources

Full Committee Hearing to Examine Fusion Energy Technology Development

Thursday, September 19, 2024, 10:00 a.m.

Chairman Manchin, Ranking Member Barrasso, and distinguished members of the committee, thank you for the opportunity to testify today. I am here to identify key steps that the U.S. government can take to position the United States as the leader in a global fusion marketplace that is rapidly approaching.[1] It is an honor to speak before you, especially at such an inflection point for fusion technology.

At Helion, our mission is to provide the world with clean, reliable, and abundant energy through commercial fusion technology.[2] Over the past decade, we have developed six fusion prototypes, each advancing critical aspects of our approach and bringing us closer to commercial deployment. Today, we are building Polaris, our seventh prototype, which we expect to be the first machine to demonstrate electricity production from fusion.[3] This will mark a pivotal step towards the future of fusion energy.

Following Polaris, we will construct the world's first commercial fusion power plant, backed by a power purchase agreement with Microsoft.[4] We also have a customer agreement with Nucor to develop a 500-Megawatt plant to power one of their steel mills.[5] These developments signal that fusion energy is no longer a distant vision—it is becoming a reality.

But as exciting as this moment may be, it is important to understand that proving the technology and building the first fusion power plant is just the beginning. Deployment at scale is where the real race is. To meet projected energy demand growth and to secure U.S. leadership, we must prepare to deploy, not just one, but many fusion power plants across the U.S. and the globe.[6]

We need a clear policy framework now, so when we demonstrate electricity from fusion, we can move forward without delay. As energy demand skyrockets, the market is hungry for a clean, firm power source that can be mass-produced and deployed quickly—fusion can deliver. The nation that builds fastest will lead the global market and gain the geopolitical power that comes with it.

To that end, we cannot let competitors, especially China, seize the advantage from our success. As discussed more below, the Chinese government is outpacing us on fusion investment 2 to 1, with a larger focus on commercialization.[7] It has already created state-owned companies to lead fusion deployment

[1] White House Office of Science and Technology Policy, *Fact Sheet: Biden-Harris Administration Announces More Than $180 Million to Advance Implementation of its Bold Decadal Vision for Commercial Fusion Energy* (June 6, 2024).
[2] Helion Energy, Inc., *Team* (as of Sept. 16, 2024).
[3] Helion Energy, Inc., *Polaris* (as of Sept. 16, 2024).
[4] Helion Energy, Inc., *Announcing Helion's Fusion Power Purchase Agreement with Microsoft* (May 10, 2023).
[5] Nucor Corporation, *Nucor and Helion to Develop Historic 500 MW Fusion Power Plant* (Sept. 27, 2023).
[6] International Energy Agency, *World Energy Outlook 2024 - Executive Summary* (Oct. 24, 2023).
[7] *The Wall Street Journal, China Outspends the U.S. on Fusion in the Race for Energy's Holy Grail* (July 8, 2024).

and dominates key aspects of the supply chain.[8] However, the US can build faster and deploy faster than China—if the right policies are in place when we need them.

Mass Manufacturing Fusion to Meet Global Demand

As global electricity demand rapidly rises, fusion energy presents an unprecedented opportunity to meet this growth with clean, reliable power. In the U.S. alone, electricity demand is projected to increase by nearly 30% by 2050, driven by electrification in transportation, industrial sectors, and the digital economy.[9] And yet this is likely an underestimate given recent advances in AI and our push to onshore critical industries.[10] Globally, electricity consumption is expected to more than double during the same period, especially as developing nations industrialize and urbanize at a rapid pace. This surge in demand underscores the urgency of scaling up energy production, and fusion is poised to play a transformative role.

We are already on the cusp of fusion deployment, and now is the time to think beyond just a single fusion power plant. The U.S. can establish a leadership position with a bold but achievable goal: deploying hundreds of American-manufactured fusion power plants to the grid each year by the 2030s.

Fusion concepts, like Helion's, are built for mass production. Each device we create lays the groundwork for manufacturing tens or even hundreds more. With modular designs and mostly electronic components—such as power semiconductors, capacitors, and segmented magnets—fusion systems can be factory-built, shipped in parts, and quickly assembled on-site with minimal groundwork.[11] Unlike traditional nuclear power plants, fusion requires no massive pressure vessels, large and complex active safety systems, or upfront radioactive materials and licensing, making deployment faster and more scalable.

For example, our manufacturing space in Everett, WA is nearly 10 times the size of our Polaris prototype facility, which is under 30,000 sq. ft. and smaller than a football field. As we look toward our first commercial deployment in 2028 and beyond, we envision a future where fusion power plants roll off assembly lines daily, much like airplanes are produced today. With complexity akin to a 150-seat aircraft, a 50 MW fusion power plant can be built at scale.

Helion facility in Everett, WA housing our 7th prototype, Polaris

After delivering electricity to our first customers, we anticipate that over the following decade, Helion could meet rising demand and develop the capacity to manufacture one or more 500 MW fusion power plants per day. Achieving this vision could transform the U.S. power grid by the 2030s, enabling an era of energy abundance that fuels everything from steel production to AI deployment.

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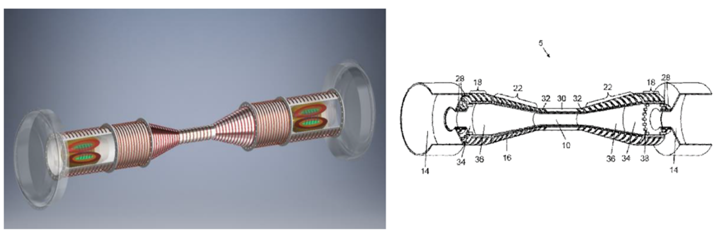
[8] American Nuclear Society, *China Launches Fusion Consortium to Build "Artificial Sun"* (Jan. 3, 2024) (describing the creation of China Fusion Energy Inc., to be led by the state-owned entity China National Nuclear Corporation).
[9] Statista, Projected Electricity Use in the U.S. 2022-2050 (June 28, 2024)
[10] Washington Post, *Amid Explosive Demand, America is Running out of Power* (Mar. 7, 2024)
[11] House Science, Space, and Technology Subcommittee on Energy, "From Theory to Reality: The Limitless Potential of Fusion Energy," *Helion CEO David Kirtley Testimony* (June 13, 2023).

However, this vision can only be realized if the right policies are in place to fast-track fusion deployment once the technology proves it can produce electricity. And the U.S. is not the only country with this ambition. China, in particular, is positioning itself as a formidable competitor, investing heavily in its own fusion research and manufacturing capabilities.[12] Their strategy is clear: dominate the fusion manufacturing supply chain and lead the global energy transition.[13] To win the fusion energy race of the 21st century, the U.S. must not only make fusion a reality but be ready with policies that allow us to outpace China in manufacturing and deployment.

The Strategic Challenge: U.S. Fusion Leadership vs. China's Ambitions

While the U.S. stands at the forefront of fusion innovation, we must recognize that global competition, particularly from China, is accelerating rapidly. China has made fusion a cornerstone of its national innovation strategy, aggressively investing in research, development, and manufacturing capabilities. This effort is not just aimed at civilian energy solutions but also has broader implications tied to its military-civilian fusion policy, where technological advancements in the civilian sector directly support military applications.

A notable example of China's ambition can be seen in ENN Energy Research Institute's HeLong Experiment (EHL Experiment). We understand that this program was initiated closely following our announcement of reaching 100-million-degree Celsius with Trenta, our 6th generation prototype.[14] The pictures below show a schematic published by ENN as compared to a publicly available diagram of Helion's technology. As you can see, the concepts are nearly identical.



Side by Side – ENN's HeLong concept (left) and Helion's fusion generator depicted in early patents (right)

Another example is China's HHMAX, a company based in Chengdu City, which recently acknowledged that Helion's approach to fusion is the fastest path to commercial power.[15] HHMAX has publicly stated its intent to replicate key aspects of Helion's design.[16] In fact, they appear to be utilizing technology from a Chinese university that has been attempting to copy key elements of Helion's fusion prototypes. This is a

[12] *Supra* n. 7.
[13] *See, e.g.,* Canary Media, *China Owns the Solar Supply Chain, Jeopardizing the Energy Transition* (July 25, 2022); NPR, *How China Dominates the Electric Vehicle Supply Chain* (Feb. 21, 2022).
[14] Helion Energy, Inc., *Helion Energy Achieves 100 Million Degrees Celsius Fusion Fuel Temperature and Confirms 16-Month Continuous Operation of Its Fusion Generator Prototype* (June 22, 2021).
[15] HHMAX, HHMAX – Exploring Clean Energy (as of Sept. 16, 2024).
[16] iNEWS, *Hanhai Juneng Completed an Angel Round of Financing of Tens of Millions of Yuan, led by Huaying Capital* (Sept. 17, 2024).

clear signal that China is positioning itself not only as a fast follower but as a potential leader in the fusion market.

This pattern is familiar. We've seen it before in industries like solar and batteries, where the U.S. pioneered breakthrough technologies, only to lose out to China in the race to mass deployment.[17] China leveraged its state-backed manufacturing capacity and low production costs to dominate those sectors, leaving the U.S. struggling to maintain a competitive foothold. If we allow history to repeat itself in the fusion industry, the U.S. risks falling behind once again—this time in a technology that is critical to our energy independence and national security.[18]

China's fusion efforts are backed by substantial government support, including the recruitment of top U.S. scientists and engineers to lead their programs. Meanwhile, the Chinese government is pouring resources into scaling up its manufacturing infrastructure, giving it a potential stranglehold on the global supply chain for fusion power plants. It is estimated China spends $1.5 billion per year on fusion and has 10 times as many PhDs in the field as America.[19] Without a bold and comprehensive U.S. response, we risk being outpaced by China's state-sponsored, rapid deployment strategy.

The stakes could not be higher. Fusion energy promises to be a game-changer—not just for decarbonizing the grid but for economic growth, national security, and maintaining technological leadership on the global stage. If China succeeds in building and deploying fusion power plants faster than the U.S., it could dictate global energy markets and secure long-term strategic advantages, much like it has in other key sectors.

This is why it is imperative for the U.S. to act now. We need a national fusion energy policy that not only supports applied research and development but also accelerates domestic manufacturing and deployment at scale. Such a policy must provide incentives for private-sector supply chain investment, update our regulatory pathways with bold new ideas, and create public-private partnerships to ensure that U.S. companies like Helion can lead production as well as innovation.

Fusion is the last great frontier in energy for this century—and likely the next thousand years. The U.S. must win this race, not just to stay competitive, but to secure our national interests and energy leadership for generations. Failing to act now means forfeiting a technology that will redefine the global energy landscape, potentially locking in China's dominance for centuries. After fusion, there are no more major energy breakthroughs on the horizon. We cannot afford to lose.

Policy Foundations for U.S. Leadership

Achieving our vision of large-scale deployment requires a strategic, two-pronged approach: (1) building resilient supply chains and (2) establishing bold new regulatory pathways. Both are critical to moving beyond the demonstration of a single fusion power plant to the mass deployment of hundreds across the U.S. and the world. These efforts must be pursued in tandem to secure the U.S.'s position as a global leader in fusion energy.

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[17] *Supra* n. 13.
[18] The Diplomat, *China and the Race for Nuclear Fusion* (June 11, 2024).
[19] *Supra* n. 7.

Helion understands that U.S. government investment requires industry progress, and we are ready to tie many of these proposals to key fusion milestones, particularly electricity production. But when that milestone is reached, we must be ready to hit the ground running on day one.

The stakes are high—our ability to scale fusion quickly and efficiently will determine whether we maintain energy leadership or risk being outpaced by China. To dominate this emerging industry, the U.S. must act decisively, leveraging our technological innovation to build and deploy fusion faster than our competitors.

1. Build Resilient Supply Chains

Fusion power plants, particularly those utilizing pulsed approaches like Helion's, rely on complex supply chains for critical components such as power semiconductors, high-voltage capacitors, and materials like high-quality metals for magnets and cabling. Helion, for example, has built some of the largest quartz tubes in the world for key sections of its fusion generator because no other facility in the world could produce them. These components not only represent a significant portion of fusion's production costs but also pose a substantial risk to U.S. energy security if these supply chains are not secured.

Much of the global supply of key components is concentrated in a few countries, particularly China, which already dominates industries like power semiconductors and is seeking to expand its influence in other critical areas of manufacturing. This represents an existential threat to U.S. fusion deployment. The risk is clear: even if the U.S. cracks the technical challenge of producing electricity from fusion, without a robust domestic supply chain, we will be unable to scale the technology quickly enough to compete globally.[20]

For fusion to drive key U.S. policy goals—like economic growth, job creation, and energy security—building a domestic fusion supply chain must be a top priority. As we've seen with solar and batteries, innovation alone isn't enough; without a strong manufacturing base, the U.S. risks losing its edge. We need immediate action to harness existing resources and launch bold new programs to compete with China on a global scale. Once we demonstrate electricity production, these programs must be ready to go.

Helion has built one of the largest high-voltage capacitor manufacturing facilities in the U.S. to meet our needs for Polaris and future generators

[20] Helion Energy, Inc., *Response to Request for Information: Implementation of the CHIPS Incentives Program (Regulations.Gov Docket DOC-2022-0001)* (Nov. 14, 2022) (discussing China's influence on power semiconductor supply).

A. Activate Existing Government Programs

The U.S. government already has several programs in place that can be leveraged to support the development of a fusion supply chain. For instance:

- **The Department of Energy's Loan Programs Office (LPO):** With $40 billion in available loan capacity,[21] the LPO can be a key source of funding to establish fusion manufacturing facilities. By making debt financing available to fusion earlier than traditional markets can provide, the LPO could not only accelerate deployment of first- and second-generation fusion power plants, but also enable the domestic production of critical fusion components such as magnets, capacitors, and specialized parts that will be essential for realizing scaled deployment.

- **45X Manufacturing Production Tax Credit:** This tax credit, designed to incentivize domestic manufacturing of renewable energy components, can be adapted to include fusion. By amending 45X,[22] Congress can provide a strong incentive and level playing field to companies manufacturing fusion-specific components like power semiconductors, high-voltage capacitors, and first-wall materials—which are currently not produced in the U.S.

- **The CHIPS and Science Act:** While the CHIPS Act is focused on revitalizing the U.S. semiconductor industry, its framework could be extended to fusion. Semiconductors are critical for the pulsed power systems used in many fusion generators, and creating a dedicated CHIPS sub-program to support the development and manufacturing of fusion-related semiconductors would be a natural extension of the program's goals.[23]

These existing programs provide a solid foundation, but they must be adapted and targeted specifically toward fusion to meet the scale of the challenge ahead. Congress should ensure that the demonstration of electricity production from fusion triggers the rapid mobilization of these resources.

B. Develop New Programs for Support

While existing programs provide a good starting point, they may not be enough to meet the full scope of the challenge. Fusion, as a transformative energy technology, requires targeted support beyond what current frameworks offer. To truly compete with China and secure U.S. leadership in the fusion marketplace, we need new, bold initiatives. To that end, the U.S. can take the best elements of a bipartisan program akin to the CHIPS Act but with a focus on fusion—a "Fusion Advantage Initiative." It should have the following programs:

- **Strategic Manufacturing Support:** This program would provide significant funding in a strategic manner to build out the manufacturing capacity necessary for large-scale fusion deployment. By establishing dedicated funding for fusion manufacturing, the U.S. can ensure that it is not left behind when the time comes to build at scale.

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[21] U.S. Department of Energy Loan Programs Office, *Loan Programs Office* (as of Sept. 16, 2024).
[22] Federal Register, *Section 45X Advanced Manufacturing Production Credit* (Dec. 15, 2023).
[23] Senator Cantwell, *Letter to Secretary of Commerce: Support for Fusion Consideration in CHIPS for America Fund* (June 30, 2023).

- **Applied Materials R&D:** Given the unique materials required for fusion generators, the whole industry could benefit from a major applied R&D program to discover new metals and ceramics that can withstand the high-energy environments inside fusion generators at a commercial operation. Unlike general R&D funding, which focuses on scientific breakthroughs, this initiative would focus specifically on solving the challenges getting us to producing fusion power reliably while enabling production of one fusion generator a day.
- **Strategic Materials Initiative for Fusion:** Given the unique materials required for fusion systems, the U.S. should create a strategic stockpile of key raw materials. This would include metals for high-performance magnets, ceramics or metals for first walls, and other specialized materials critical for fusion's core components. By ensuring that these materials are readily available domestically, the U.S. can reduce its reliance on foreign supply chains and protect against disruptions.
- **Fusion Manufacturing Hubs:** The government could establish designated "Fusion Manufacturing Hubs" in key regions,[24] offering enhanced tax incentives, streamlined permitting, and workforce development programs to attract fusion companies and suppliers. These hubs would serve as focal points for the rapid expansion of fusion-related manufacturing, fostering a concentrated ecosystem where the industry can thrive and scale efficiently.

These initiatives will not only advance our energy goals but also create thousands of high-paying jobs, fostering economic growth and reinforcing the U.S.'s position as a global leader in advanced manufacturing.

2. Establish Clear Regulatory Frameworks

Commercializing fusion energy hinges on building regulatory frameworks that enable safe and rapid deployment. Building a fusion generator a day is meaningless if we can't deploy them just as fast. While the NRC and Congress have made great strides, critical gaps remain as we push toward commercialization—especially in scalable licensing and environmental reviews, and faster energy grid integration.

These are complex, long-standing challenges, and we must tackle them now. Policy changes can take years, so we can't wait until the first fusion power plant is online. The demonstration of electricity production must trigger serious work to develop the regulatory groundwork needed to fully unleash fusion's potential in the U.S. energy landscape.

A. Licensing for Mass Production

In 2023, the NRC made a crucial decision to regulate fusion under its "byproduct materials" framework, the same used for handling radioactive materials in hospitals and universities.[25] This separates fusion from the stricter regulations applied to fission reactors, recognizing fusion's unique safety profile—it

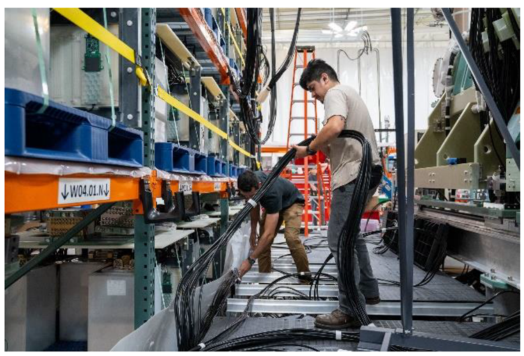
[24] Opportunity Zones may be an example. *See* Internal Revenue Service, *Opportunity Zones* (as of Sept. 16, 2024).
[25] U.S. Nuclear Regulatory Commission, *NRC to Regulate Fusion Energy Systems Based on Existing Nuclear Materials Licensing* (Apr. 14, 2023).

can't trigger a runaway chain reaction and doesn't produce long-lived high-level radioactive waste. This forward-thinking move lays the groundwork for licensing the first generation of fusion power plants.

However, while this was a critical first step, the current licensing process is still designed for one-off, bespoke power plants, where each facility is reviewed on a site-by-site basis. This process works for the first fusion power plants, but it is not conducive to mass deployment, which is important to both drive down costs and generate rapid adoption of this important source of clean, firm energy. To enable the widespread commercialization of fusion, we will need a more scalable licensing approach.

Helion to this end has proposed a design-specific license (DSL).[26] Under this model, second- and third-generation fusion generators could be registered with the NRC and Agreement States, much like smaller sources and medical technologies are under the existing byproduct materials framework. This registration would focus on the key systems that relate to fusion safety. Paired with a national generic environmental assessment, this would allow a single, one-time license to cover a standardized design and safety approach, enabling deployment anywhere within an approved environmental envelope. Regulators would be kept informed through notifications and rigorous oversight, avoiding repetitive, time-consuming reviews that don't enhance safety.

This DSL approach is particularly well-suited to fusion, given the potential for mass production of standardized fusion generators. By starting the conversation now on a regulatory pathway that supports the rapid and safe deployment of factory-built fusion plants, the U.S. can accelerate fusion's contribution to the energy grid and set a precedent for global regulatory harmonization.



Our team is hard at work completing construction on Polaris,
our 7th generation prototype that will demonstrate electricity production from fusion

B. Tailored Environmental Reviews

Fusion power plants, like those we're developing at Helion, have fundamentally different safety characteristics compared to traditional nuclear reactors, resulting in significantly smaller environmental impacts. Fusion systems generally proposed for deployment by the private sector don't require large-

[26] Helion Energy, Inc., Pre-Print Discussion Draft, *Preparing for At-Scale Deployment of Fusion Energy Via a Design-Specific License* (Jan. 19, 2024).

scale safety measures and pose no off-site risks in the event of a malfunction. Their modular design further reduces site impacts. For example, our power plant for Microsoft will use a standard utility water supply, avoiding the heavy water consumption typical of conventional plants.

Given these advantages, the regulatory approach to fusion's environmental reviews must account for its minimal risks. Congress should urge regulatory agencies to treat fusion energy projects with a fresh perspective, allowing for findings of "non-significant impact" rather than defaulting to large-scale environmental impact statements (EIS). Mitigation measures can be integrated into the permitting process to streamline deployment.

Looking ahead, and building on the DSL concept, we need an environmental framework by the 2030s that supports the mass deployment of fusion power plants across the U.S. A generic environmental assessment (EA) for registered generators—like what's already done in other energy sectors—would enable factory-built systems to be deployed efficiently while ensuring public participation early on. A tailored regulatory approach will accelerate fusion's ability to meet rising energy demand while maintaining strong environmental stewardship.

C. Energy Regulations: Grid Interconnection and Siting Challenges

Beyond the NRC's role in regulating the safety of fusion plants, energy regulations related to grid integration and siting must also evolve to accommodate fusion's unique characteristics. Fusion energy, as a clean, firm power source, has the potential to significantly impact the U.S. electrical grid, but here again the current regulatory process is not designed for scale.

- **Grid Interconnection:** One major challenge is the grid interconnection process. Fusion power plants will need quick and efficient connections to the electrical grid, but in many regions, interconnection timelines can stretch beyond six years,[27] potentially delaying fusion rollout. As we have experienced in the site selection process for our first commercial fusion plant, interconnection delays can take many locations off the table.

  To address this, federal and state regulators must all work to streamline interconnection permitting processes and ensure that fusion generators can be integrated into the grid as soon as they are ready for operation. As well, the same statutory opportunities for interconnection that have been made available to renewable energy providers should be made available to fusion generation, to allow for an even playing field for all zero-carbon energy sources.

- **Collocated Siting:** Fusion is ideally suited for collocated generation, where its firm, reliable power can be directly supplied to large energy consumers such as data centers or industrial facilities without the need for extensive grid infrastructure. However, the regulatory environment in many parts of the country is unclear and could limit the ability of fusion power plants to provide this type of generation. A lack of consistent rules can prevent fusion from realizing its full potential and inhibit the ability of industrial entities to manage their energy requirements in a way that meets their business and clean energy requirements.

[27] Electric Power Supply Association, *Scores for Interconnection Times Highlight the Need for Reform in PJM* (Apr. 1, 2024).

- **Coal Plant Repowering:** Fusion's small footprint and flexible siting options make it ideal for repurposing retiring coal plants and other fossil fuel infrastructure. By revitalizing these sites, fusion can create jobs, support energy communities, and reduce carbon emissions. To accelerate this, regulators should implement policies that streamline permitting and interconnection for fusion plants at retiring coal sites and encourage repowering fossil fuel plants with fusion technology.

We know these are bold asks for bold goals, but when fusion is ready to scale, the U.S. will have only one shot to win the deployment race. Conditioning this work—especially on the supply chain—on a core milestone like electricity production ensures we make the most of limited government resources. But we cannot afford to wait. The time to act is now, so that when Helion or any other fusion company hits that milestone, the U.S. is ready to lead and win.

Conclusion: Securing U.S. Leadership in Fusion Energy

Before us, is an opportunity to deploy virtually limitless safe, reliable, and clean power in the form of fusion energy. Helion is building the technology to make this a reality, already achieving 100-million-degree plasma temperatures and securing over $600 million in funding to back it.

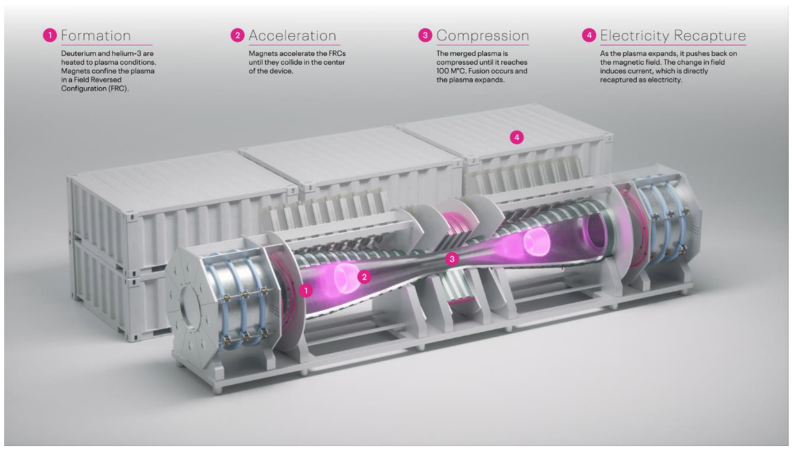
The U.S. stands at a crossroads. We're on the brink of unlocking fusion energy, but only if the public and private sectors work together. The next few years will decide if America leads the world in fusion—or gets left behind. With bold action on supply chains and smart regulatory frameworks, fusion can revolutionize our energy future and cement U.S. leadership in the global clean energy race

Thank you again for the opportunity to testify, and I look forward to your questions.

Appendix

Helion's Technology

Helion uses an approach to fusion called magneto-inertial fusion.[28] Our technology forms two ring shaped plasmoids, called field reversed configurations (FRCs), on each end of a symmetrical vessel. We then use electromagnets to accelerate the FRCs to the center of our machine until they collide. When the plasmoids collide, they combine into a single plasmoid, which is then compressed by very strong magnets to the point that particles become hot enough and dense enough to fuse in substantial quantities, releasing energy in the process.



Compared to other approaches in the field, our magneto-inertial fusion approach has three key differences:

1. **Our machine is pulsed** rather than steady state. This helps us overcome the hardest physics challenges in fusion, particularly around sustaining long-life plasmas. It also allows us to build more efficient devices, solve certain materials and impurity challenges, and adjust the power output based on need.

2. **We directly capture energy** from the expanding FRC during the fusion process instead of heating water to turn a steam turbine, while also recycling the energy used to create the initial pulse. The efficiency gains from directly capturing the fusion energy, while simultaneously saving the energy that goes into the fusion pulse, enables compact systems that can achieve commercial viability at much lower and easier to achieve levels of fusion gain (Q).

3. **We use deuterium and helium-3 as fuel** instead of deuterium and tritium. Deuterium and helium-3 are the ideal fuels for generating electricity because fusing these elements results in a proton and a normal helium nucleus—both charged particles whose energies can be directly

[28] Helion Energy, Inc., Technology (as of Sept. 16, 2024).

> converted to electricity. This fuel cycle also reduces neutron emissions, substantially reducing many of the engineering challenges faced by users of deuterium-tritium fuels.

Helion's technology benefited from early U.S. government support, which helped de-risk our core technology in its earliest stages, helping set the foundation for our continued progress.

Because our approach enables small, compact fusion systems, we were able to move from the drawing board to the shop floor quickly and start building prototypes. These prototypes and the progress they demonstrated in turn helped us raise the private sector funding needed to develop the final fusion technology we are using today. To date, our team has built six working fusion prototypes, which achieved record-breaking results and technological milestones. These prototypes have allowed us to learn from engineering and building working systems and ultimately bring theory to reality, giving us confidence in our ability to deploy.

The CHAIRMAN. Thank you.
And now we will turn to Dr. White.

STATEMENT OF DR. PATRICK WHITE, RESEARCH DIRECTOR, NUCLEAR INNOVATION ALLIANCE

Dr. WHITE. Great, thank you.

Chairman Manchin, Ranking Member Barrasso, and members of the Committee, thank you for the opportunity to testify today before this Committee and for holding this hearing. My name is Dr. Patrick White, and I am currently the Research Director for the Nuclear Innovation Alliance (NIA). Through an NIA partnership with the Clean Air Task Force (CATF), within their Global Programme for Fusion Energy, I lead the CATF International Working Group on Commercial Fusion Safety, Waste, and Non-Proliferation. Both NIA and CATF are 501(c)(3) organizations that provide independent technical research, analysis, and advocacy to help advance policies and technologies that enable deployment of clean energy solutions to meet our economic, societal, and climate needs. I hold a Ph.D. in nuclear science and engineering from MIT, where my doctoral thesis work focused on the safety, analysis, regulation, and licensing of commercial fusion technology. I am here today to provide insights on the development and deployment of fusion energy technology as an important future clean energy solution.

An affordable, reliable, secure, and clean energy future requires us to deploy a mix of variable clean energy generation, energy storage, and firm clean energy generation. Commercial fusion energy can play a significant role as a source of firm clean energy generation and would complement other existing firm clean energy sources, including hydroelectric, nuclear fission, geothermal, and natural gas with carbon capture. Successful development, commercialization, and deployment, and export of commercial fusion energy by the United States will have climate, societal, economic, and geopolitical benefits, including affordable clean energy, technology innovation spurred on by fusion energy research, on-shored supply chains and massive manufacturing, and increased energy security for us and our allies.

The past five years have seen incredible achievements by fusion experiments in the United States and around the world and record investment in private companies pursuing commercial fusion energy. And while we have passed several important milestones in the development and commercialization of fusion energy, I believe it is important to contextualize and discuss the pathway and future milestones that still lie ahead. A clear understanding of these milestones, their timing, and the pathways enables us to discuss how we can most effectively catalyze and accelerate the development, commercialization, and ultimate wide-scaled deployment of fusion energy.

The commercialization and deployment of fusion energy can be divided into four general phases. The first is the development and operation of scientific demonstration fusion machines that show we can control fusion energy and achieve net energy gain from fusion reactions. Second, the design and testing of engineering demonstration fusion machines that show we can harness fusion energy and consistently produce large amounts of power from fusion reactions.

Third, the construction and operation of commercial demonstration machines that show that we can produce commercially relevant energy products from fusion and integrate key commercial systems necessary for wide-scale deployment. And fourth and finally is the wide-scale commercial deployment of fusion energy, marking the availability of the technology as a viable clean energy source.

Fusion commercialization will require private companies to complete all four phases, but company-specific pathways may differ. Some concepts may be completed under a single demonstration phase, with one machine serving as a scientific and engineering and a commercial machine, while other companies may take a more iterative approach and use many smaller machines to show how their technology can develop and evolve toward a commercial product. But understanding these phases enables us to more clearly discuss and compare the progress that is currently being made by private fusion companies and assess how the Federal Government can most effectively support and accelerate the commercialization of fusion technology. Moving forward, the United States needs to consider what role we want to play in the global race for fusion energy.

Fusion technology innovation by U.S. companies is unmatched, but we need to ensure that they have the support and policy clarity to compete internationally against state-owned or state-supported fusion energy programs. The United Kingdom, European Union, China, Canada, Japan, and other nations have begun making investments in commercial fusion energy, and United States partnerships with the United Kingdom and Japan on fusion energy research highlight the opportunities for international collaboration with our allies. Supporting domestic development of a U.S. fusion industry is critical. As an example, China has a plan for domestic fusion energy in a domestic fusion industry, and they are executing on it. They have started construction on scientific and engineering demonstration fusion machines, and they have a detailed plan on a commercial demonstration fusion machine. They are also completing a facility that will lead cross-cutting fusion research and development for key materials, fuel-cycle technologies, and commercial systems. The Chinese plan shows both an understanding and a commitment to the scientific, engineering, and commercial steps necessary to get fusion energy onto the grid.

Accelerating fusion commercial development and deployment in the United States will require private-sector investment and continued Federal Government coordination and support. I believe two major factors should be prioritized as we work toward the commercialization of fusion energy. First, we need to ensure that clean energy policies are technology-inclusive to create a clear market pull for fusion energy as a firm clean energy source. Second, private companies, academic researchers, national labs, and the Federal Government must closely coordinate and collaborate to implement and support—with appropriate federal funding and policies—an integrated fusion energy program that effectively and efficiently prioritizes efforts to accelerate fusion energy commercialization through all four stages of development, demonstration, and deployment. Thank you.

[The prepared statement of Dr. White follows:]

Testimony before the U.S. Senate Committee on Energy and Natural Resources

Full Committee Hearing to Examine Fusion Energy Technology Development

Testimony of Dr. Patrick White

Research Director, Nuclear Innovation Alliance

September 19th, 2024

Chairman Manchin, Ranking Member Barrasso, and members of the Committee:

Thank you for the opportunity to testify today before this Committee and for holding this hearing. My name is Dr. Patrick White, and I am currently the Research Director for the Nuclear Innovation Alliance (NIA). NIA is a 501(c)(3) organization focused on creating the conditions for success for advanced nuclear energy as a climate solution. I hold a PhD in Nuclear Science and Engineering from the Massachusetts Institute of Technology, where my doctoral thesis work focused on the safety analysis, regulation, and licensing of commercial fusion technology.

NIA is partnering with the Clean Air Task Force (CATF) on independent research, analysis, and stakeholder engagement to support the commercialization and deployment of fusion energy around the world as a key clean energy source. CATF also is a 501(c)(3) organization working to rapidly reduce emissions while advancing bold, durable climate solutions to ensure a net-zero emissions, high energy planet at an affordable cost. Both NIA and CATF provide independent technical research, analysis, and advocacy to help advance policies and technologies that enable deployment of clean energy solutions to meet our economic, societal, and climate needs.

In early 2023, CATF created the Global Programme on Fusion Energy. Through the NIA-CATF partnership and within the Global Programme on Fusion Energy, I lead the CATF International Working Group on Commercial Fusion Energy Safety, Waste, and Non-Proliferation. The CATF Programme, led by Dr. Sehila M. Gonzalez de Vicente, is focused on paving the way towards commercial fusion energy and is organized around clarifying technology development pathways for fusion energy, de-risking the regulation and commercialization of fusion energy projects, supporting emerging commercialization pathways for fusion technology, and setting up the global case for fusion energy deployment.

I am here today to provide insights on the development and deployment of fusion energy technology as an important future clean energy source.

Introduction

The development, commercialization, and deployment of fusion energy technology has been a dream of scientists and engineers for decades. In 1951, the U.S. Atomic Energy Commission initiated Project Sherwood to coordinate national research efforts on controlled fusion in the United States. Generations of scientists and engineers have worked over the past seven decades to develop fusion machines that could control and harness one of the fundamental sources of energy in the universe.

We have made incredible advances since the earliest days of fusion energy research, and progress on fusion energy is accelerating. This year experimental fusion machines such as the Joint European Torus (JET) in the UK set records on total energy generation from a controlled plasma[1] and the WEST fusion machine in France set records for the continuous control and confinement of a high-temperature plasma.[2] And since December 2022, the National Ignition Facility (NIF) has been able to repeatedly demonstrate net energy gain, commonly described as scientific breakeven, from an inertially confined fusion reaction.[3] These experiments and others that are currently under way in the United States and around the world are providing scientific insights critical to controlling fusion energy.

Private companies are also now playing a significant role in the research and development of fusion energy. For decades, federally supported fusion energy programs at national labs and universities have played a leading role in fusion energy. Major fusion experiments such as the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Lab (PPPL), Alcator C-Mod at the MIT Plasma Science Fusion Center (PSFC), and DIII-D still operated today by General Atomics in San Diego provided scientific insights on the control of fusion energy. Building on decades of publicly funded fusion research and catalyzed by developments in enabling materials and components, novel fusion machine designs, and state-of-the-art computation analysis and control methods, private companies are leading in the United States on the development of fusion energy machines. These companies, funded by private investors and industrial partners, are working to create fusion machines capable of producing the energy that can help us meet our nation and our world's need for clean, reliable, and affordable energy. The Fusion Industry Association reported that total private investment for fusion energy companies exceeded $7 billion in 2024.[4]

Recent progress on both fusion energy research and private company developments are worth celebrating. And while we have passed several important milestones in the development and commercialization of fusion energy, it's important to contextualize and discuss the pathway and future milestones that still lie ahead for fusion energy. A clear understanding of the milestones, timing, and challenges on the pathway to global fusion energy enables us to discuss how we can most effectively catalyze and accelerate the development, commercialization, and widescale deployment of fusion energy.

Goals of fusion energy development and deployment

The goal of fusion energy development, commercialization, and deployment efforts is largely the same now as it was at the start of Project Sherwood in 1951: to control and harness fusion reactions. The impetus for fusion energy development efforts in the United States and

[1] JET's final tritium experiments yield new fusion energy record - GOV.UK (www.gov.uk)
[2] Fusion record set for tungsten tokamak WEST (phys.org)
[3] Momentary Fusion Breakthroughs Face Hard Reality (spectrum.ieee.org)
[4] 2024 Annual Global Fusion Industry Report (fusionindustryassociation.org)

around the world, however, has evolved with our changing views on how we produce and use energy to maximize the benefit to society. Today we recognize that access to clean, reliable, affordable, and secure energy is critical to improving the quality of life of people in the United States and around the world.

Studies by energy system researchers and grid operators show that an energy system that consists of only variable clean energy sources (such as solar and wind) and energy storage (such as battery storage) may be much less reliable and much more costly than energy systems that include firm clean energy sources.[5] Firm clean energy sources are generation technologies that can produce clean energy when it's needed and complement variable clean energy sources to meet system demand. Examples of firm clean energy sources currently used or under development include hydroelectric power, nuclear fission energy, geothermal energy, and natural gas with carbon capture and storage.[6]

Commercial fusion energy could play a significant role in future clean energy systems as a firm clean energy source and would complement other firm-clean energy sources. Fusion machines may not have the same geographic and geologic limitations as hydroelectric, geothermal, and natural gas with carbon capture and storage, enabling widescale deployment in the United States and worldwide. Fusion machines may not have the same geopolitical, safety, and export concerns as nuclear fission energy and could be deployed more easily in countries with and without prior commercial and regulatory experience with nuclear fission energy. Deployment of commercial fusion energy at scale could help enable the United States and other countries around the world to generate the vast amounts of reliable and affordable clean energy needed to meet our climate and economic goals.

Successful development, commercialization, deployment, and export of commercial fusion energy by the United States will have additional societal, economic, and geopolitical benefits. Research and development in enabling technologies for fusion energy will likely produce new discoveries in materials science, high-energy systems and controls, and healthcare. Developments such as lower cost and higher performance high-temperature superconducting magnets for different industrial applications[7], power management systems and storage for clean energy systems[8], and new radioisotope therapies for cancer and other medical diagnostics and treatments[9] are just a few of the innovations that may be unlocked as we develop the enabling technologies for fusion energy. The economic benefits from an on-shored supply chain for fusion technology and deployment of hundreds or

[5] The Role of Fusion Energy in a Decarbonized Electricity System (mit.edu)
[6] Review and Assessment of Literature on Deep Decarbonization (catf.us)
[7] HTS Magnets (cfs.energy)
[8] TAE Power Solutions (tae.com)
[9] Producing Medical Isotopes Lu-177 and Mo-99 (shinefusion.com)

thousands of fusion power plans would have economic benefits for workers across the country. And export of U.S. fusion technology abroad will help countries meet their clean energy goals, increase standards of living, and improve energy security.

The question that we need to address is how we can create a pathway from the fusion energy research and commercial developments underway today to a future where fusion plays a significant role in global clean energy production.

Development phases and milestones for commercial fusion energy

Clear performance milestones for commercial fusion energy development can help us assess the wide variety of different fusion energy concepts currently under development and prioritize federal support. Different approaches to fusion energy may have different scientific or engineering metrics that most accurately characterize technology development. Metrics such as plasma confinement time, plasma temperature, pulse time, pulse rate, peak magnetic field, fusion energy production, and net energy production are all examples of metrics that can be useful to scientists and engineers when researching, developing, and testing fusion machines. These metrics, however, are not always comparable across different fusion machines or technologies and can be challenging for policymakers and the public to accurately assess and compare. Even the relatively simple metric of the fusion energy gain factor from a fusion machine, typically termed “Q”, can be misinterpreted if a project does not specific how it is defining or using the metric.[10]

The specific operational characteristics, designed capabilities, and planned mission of a fusion machine will vary on a project-by-project basis, but four typical development phases can be defined for the commercialization of fusion energy. These four development phases define key transition points in the development and commercialization of fusion energy technology and enable more meaningful comparison between the fusion energy concepts at different phases of development. The four development phases are (1) scientific demonstration, (2) engineering demonstration, (3) commercial demonstration, and (4) commercial deployment.

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[10] The fusion energy gain factor, “Q”, is typically defined as the ratio of the energy released from fusion reactions to the energy input into a fusion reaction, experiment, or machine. If the Q value is equal to or greater than 1, the system is described as having achieved “breakeven” because the experiment has produced as much energy as it consumed. Some scientists and engineers, however, will discuss fusion energy gain factors differently depending on how they define the amount of energy used to power the fusion machine or experiment. Two common fusion energy gain factors, “scientific energy gain”/“scientific breakeven” and “engineering energy gain”/“engineering breakeven”, are described in more detail in footnotes 11 and 12 . Please see Progress toward fusion energy breakeven and gain as measured against the Lawson criterion (aip.org) for addition discussion.

Scientific demonstration of fusion energy is the operation of a fusion machine that demonstrates and tests the generation, control, and confinement of plasmas. These machines are focused on developing and mastering control of fusion energy and may only operate for short periods of time or with a focused scientific mission. This phase of operation may be defined by technical milestones such as achieving scientific breakeven (net energy gain from a fusion reaction)[11] for fusion energy, and demonstrating sustained plasma control and confinement for a specific technology or design.

Engineering demonstration of fusion energy is the operation of a fusion machine that demonstrates and tests integration of plasma systems with new systems required for continued or repeated operation of a fusion machine. This can include new fusion fuel cycle systems, systems that can capture energy from fusion reactions, or improved plasma generation, control, and confinement systems. These machines are focused on developing the engineered systems to harness fusion energy and may or may not demonstrate production of electricity or other energy products. This phase of operation may be defined by technical milestones such as achieving engineering breakeven (e.g., net system energy gain from a fusion machine)[12] and demonstrating a sustainable fusion fuel cycle for a specific technology or design. The engineering demonstration may be capable of producing net electricity for the grid but may not operate commercially or with high commercial availability. The 2020 Fusion Energy Sciences Advisory Committee (FESAC) definition of a "fusion pilot plant" generally aligns with this engineering demonstration phase.[13]

Commercial demonstration of fusion energy is the operation of a fusion machine that demonstrates and tests integration of all fusion energy systems required to produce energy commercially. This includes integration of electricity or energy product generation systems, fusion fuel cycle systems, and other auxiliary systems with the fusion power systems. These

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[11] "Scientific gain" is defined as the ratio of energy produced by fusion reactions to energy input required to produce a fusion reaction, typically by external heating of the fusion fuel. "Scientific breakeven" occurs when the "scientific gain" is equal to 1 – i.e., the amount of fusion energy produced by the reaction is equal to the amount of energy required to heat the fusion fuel to create the fusion reaction. "Scientific gain" and "scientific breakeven" do not account for any energy losses or inefficiencies in fusion machine systems.

[12] "Engineering gain" is defined as the ratio of energy produced by a fusion energy system to total energy input required to operate a fusion energy system. "Engineering breakeven" occurs when the "engineering gain" is equal to 1 – i.e., the amount of fusion energy produced by a fusion energy system is equal to the total amount of energy required to the operate the fusion energy system. "Engineering gain" and "engineering breakeven" account for the energy losses or inefficiencies in fusion machine systems and describe when a fusion energy system could begin to produce overall net energy. A fusion energy system that achieves "engineering breakeven" will have a "scientific gain" much higher than 1 because the calculation of "scientific gain" does not account for energy losses or other inefficiencies in fusion machine systems.

[13] Powering the Future: A Report of the Fusion Energy Sciences Advisory Committee (osti.gov)

machines would demonstrate that fusion energy is a commercially viable technology. This phase of operation may be defined by technical milestones such as achieving commercially relevant net energy production from fusion reactions (e.g., typically producing tens to hundreds of megawatts of net fusion power for most private concepts[14]) and demonstrating reliable integrated system operation. The EUROfusion program definition of a "demonstrate power plant" or "EU DEMO" generally aligns with this commercial demonstration phase.[15]

Commercial deployment of fusion energy is the deployment of fusion machines that can be operated to produce clean, reliable, and economically competitive energy. While fusion energy machines will continue to improve over time with increased operating experience and design optimization, commercially deployed fusion energy machines would signify the emergence of commercial availability of fusion energy as a viable firm, clean energy source. This phase of operation may be defined by socio-techno-economic conditions such as cost-competitive production of fusion energy (e.g., competitive with other firm, clean energy sources) and socially acceptable deployment of fusion energy globally (e.g., sustainable, geopolitically accepted deployment and operation).

Completion of all four development phases (and the associated technical milestones) is necessary for the realization of fusion energy as a future clean energy source. It is important to note, however, that there are multiple strategies to complete the four phases. Some private fusion energy companies may plan to build separate fusion machines for scientific, engineering, and commercial demonstrations, taking a more iterative approach to development (with completion of phases occurring in series or overlapping in parallel). Other programs may seek to combine one or more of their demonstrations into a single fusion machine and take a more accelerated approach development by demonstrating and testing multiple systems simultaneously. Different development strategies will have commercial benefits and risks that depend largely on the fusion energy technology, specific design, and company priorities. These different development strategies can also be accelerated by different types of government support.

Assessing development phases and milestones for commercial fusion energy

Each of these development phases has different challenges that we will need to identify, address, and overcome for us to achieve our goal for fusion energy to play a significant role in global clean energy production. Any fusion energy technology that will play a meaningful role in clean energy production will have to progress through each of these phases from research and development through commercialization. Some fusion energy technologies, however, may not be able to successfully commercialize for a variety of scientific, technical,

[14] 2024 Annual Global Fusion Industry Report (fusionindustryassociation.org)
[15] DEMO - EUROfusion (euro-fusion.org)

social, political, or economic reasons that are not yet known. But it's nearly impossible at this time to know with any certainty which technologies or companies will succeed. It is up to private fusion companies to demonstrate their specific designs and approaches.

Commercial deployment of any fusion energy technology will require multiple scientific and engineering breakthroughs to enable the control and harnessing of fusion energy. Prediction of these breakthroughs is challenging at best given our limited testing and operating experience with key emerging technologies, including enabling materials and systems, novel fusion machine designs, and state-of-the-art computation analysis and control methods. Supporting and promoting technology innovation by commercial fusion energy companies through public and private efforts will be key to the successful deployment of fusion energy as a clean energy solution.

Key activities to enabling commercial fusion energy development and deployment

It is important that we support and promote innovation in fusion energy development and commercialization and assess the progress of commercial fusion development on milestone-based pathways. This also, however, requires that we are pragmatic with federal support for commercial fusion energy and that we intentionally prioritize key activities needed to enable the widescale deployment of commercial fusion energy including:

- classifying and prioritizing gaps in fusion material science knowledge and enabling technology readiness to focus cross-cutting public and private technology research and development,
- identifying and planning for critical mineral supply, manufacturing supply chain, and workforce needs for the domestic production, manufacturing, construction, and deployment of commercial fusion energy systems,
- assessing and minimizing the potential safety hazards for future fusion machines that may look different from the scientific demonstrations currently under development today and ensuring effective, efficient and appropriate regulations,
- characterizing and managing the potential radioactive byproducts and wastes that could be produced by commercial fusion energy deployed at scale,
- understanding and mitigating any potential non-proliferation risks posed by fusion technology, and
- understanding and addressing potential siting, operational, or energy system integration challenges for fusion energy technology as a part of future electrical and industrial clean energy systems.

These key steps can be challenging to discuss because the importance of these steps for fusion energy technology will vary both over time and between private companies. First, some activities may not be relevant to all fusion energy technologies depending on the specific technology, design, or fuel cycle. Second, some activities may not be relevant to the near-term development of fusion energy as private companies construct and operate their scientific and engineering demonstrations. Third, fusion energy companies will play a major role in determining the significance of different steps through their technology, design, and operating choices and tradeoffs. Companies should assess these tradeoffs at the early stages of fusion technology development. Fourth, many activities are related to the societal acceptance of fusion energy technology and a broader understanding of different tradeoffs related to the benefits and costs of all energy production technologies.

Some activities may ultimately not require any actions depending on the results of technical and policy assessments or be relevant to the fusion energy technologies that are commercially deployed. Other activities may not be relevant in the near term for scientific and engineering demonstrations or even for limited domestic commercial deployment but should be considered for widescale domestic and global deployment of fusion energy. If we do not proactively address these key steps, especially those requiring significant time or resources to address, we may delay the successful commercial deployment of fusion energy. And until we accurately assess these potentially important activities, we will not know which activities could inhibit or delay the deployment of commercial fusion energy.

We also need to expect transparency and accountability from private companies when it comes to development of their fusion energy technologies. As Dr. Bob Mumgaard, CEO of Commonwealth Fusion Systems (CFS), recently wrote in an open letter entitled "Building Trust in Fusion Energy"[16]:

"The industry must not give into marketing hype. We must communicate clearly, openly, and accurately with investors, regulators, policymakers, and the general public."

I strongly agree with Dr. Mumgaard's statement. Discussions of the benefits and challenges of fusion energy commercialization should be clear. It is important to avoid overly broad or technically accurate but colloquially misleading statements. While this type of messaging may help in the near term with public relations or be used to clearly differentiate fusion energy from other technologies such as nuclear fission, public trust lost from promises made and promises broken will be much more challenging to regain.

Fusion energy's success depends on its merits as a safe, clean, firm energy source that will help the United States and countries around the world meet their energy needs. And with a common understanding of the pathways for fusion energy development and

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[16] Building Trust in Fusion Energy | Commonwealth Fusion Systems (cfs.energy)

commercialization (as well as the key steps to fusion energy deployment), we can now discuss how the United States should accelerate the pathways to commercial fusion energy.

Accelerating the pathways to commercial fusion energy

Private commercial fusion energy companies are leading the commercialization and deployment of fusion energy in the United States. New approaches to fusion energy, catalyzed by technological innovations, are creating faster pathways to fusion energy deployment. Private commercial fusion energy companies in the United States must take a leading role in the development and commercialization of fusion energy, but the federal government can play an important role in accelerating pathways to commercial fusion energy deployment.

The first step on the pathways towards commercial fusion energy is demonstrating controlled fusion energy and achieving scientific breakeven. Private companies are in the best position to lead, and many companies have already announced plans to demonstrate controlled fusion energy. Helion is constructing their *Polaris* fusion generator in Washington State[17], CFS is constructing their *SPARC* fusion machine in Massachusetts[18], and Type One Energy has announced plans to build their *Infinity One* fusion machine in Tennessee[19]. These activities have been made possible by private investment and the regulatory certainty provided by the U.S. Nuclear Regulatory Commission on the licensing of fusion technology under the byproduct materials licensing framework.[20] This work could be further accelerated by federal support that facilitates rapid public-private partnerships to access federal research and testing facilities, as well as enable access to important international scientific collaborations. For these companies, speed is key. We need to improve DOE solicitation, evaluation, and contracting so we can measure the time required to solicit and distribute federal program contracts for fusion in weeks and months and not in months and years.

The second step on the pathways towards commercial fusion energy is demonstrating fusion energy engineering and achieving engineering breakeven. Engineering a fusion machine requires the development, testing, and demonstration of new systems and components that can help control and harness fusion energy. Private companies are best positioned to lead and the diversity of fusion energy technologies currently under development by private companies makes federal support for any single technology risky. Continued use of a milestone-based support program can help the DOE prioritize private company support of multiple fusion energy concepts while ensuring effective use of federal funds.

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[17] Helion Polaris (helionenergy.com)
[18] CFS SPARC (cfs.energy)
[19] Type One Energy Infinity One (typeoneenergy.com)
[20] NRC to Regulate Fusion Energy Systems Based on Existing Nuclear Materials Licensing (nrc.gov)

The federal government can help significantly accelerate fusion energy development by supporting enabling technologies for fusion energy. Key engineering-relevant fusion energy technologies needed by many different private companies (such as fusion fuel cycle systems or tritium-related technology) require substantial research and development work. These industry cross-cutting activities require specialized knowledge and facilities to efficiently complete. Federal prioritization and support for industry-wide research and development activities by national labs or private companies on enabling technologies could help reduce the cost and accelerate the development of engineering demonstrations. Shortening schedules and maximizing the impact of federal funding is key. It is critical to have efficient award and contracting processes so that companies are not spending years finalizing relatively small amounts of federal support.

The third step on the pathways towards commercial fusion energy is demonstrating and harnessing fusion energy commercially. While we understand the general activities needed to complete this step of the pathway towards commercial fusion energy, the specific timing and needs of private industry are less clear. The success of private companies demonstrating scientific and engineering breakeven for fusion energy in the coming years will affect the technical and commercial priorities for the industry. Again, federal prioritization and support of cross-cutting research and development could help accelerate the commercialization of fusion energy. Specifically, funding or facilitating national testing capabilities for the development and testing of new materials for fusion energy and enabling technologies for commercial fusion energy systems will help benefit all U.S. private fusion energy companies. These research programs will take several years to get organized and begin producing meaningful data, so it is important that we start now to help create the future conditions for success for commercialization of fusion energy. It will also be important to collaborate with the commercial fusion industry to identify how the federal government can most effectively and efficiently help reduce the financial risk of commercial demonstrations and accelerate commercialization through public-private partnership or other milestone-based programs.

The fourth and final step on the pathway towards commercial fusion energy is deployment of fusion energy at scale as a clean energy source. We need to consider what it will take for fusion energy to deploy rapidly as a commercially viable source of clean energy. The most important step we can take for the widescale deployment of fusion energy is to ensure that the policy incentives available for other clean energy sources (including production tax credits, investment tax credits, and loan guarantees) are also made available for commercial fusion energy. A level playing field will enable commercial fusion energy to compete with other clean energy sources based on its economic and technical merits, and signal that fusion energy is a technology that can play a major role in our future clean energy system.

Fusion energy deployment will depend on the technology and business case for individual private companies, but several important activities should be addressed through partnerships between private companies and the federal government. Private industry will need to develop and optimize critical fusion energy systems and technologies for commercial fusion energy deployment (including fusion material development, sustainable fusion fuel cycles, and power generation systems) and can be accelerated by federally supported research facilities. Industry and government will need to ensure that the regulatory frameworks in place for the near-term deployment of fusion energy will be appropriate and can scale in the United States and around the world to ensure effective and efficient regulation of safe fusion energy. Industry should identify opportunities to lead on development of a robust supply chain and work force for fusion energy including raw materials (e.g., rare earth elements), manufactured components, and different segments of the future fusion energy workforce including construction and manufacturing, technicians, operators, scientists, engineers, and radiation protection professionals all with knowledge of fusion energy. The federal government can play a critical role in catalyzing private investments. Finally, we will need to enable the export of U.S. fusion technology around the world by creating effective codes, standards, and harmonized regulation and export controls that help ensure the safe, economically competitive, and fair deployment of fusion energy.

Comparison case study: Chinese commercial fusion energy development

It is important to note that the United States is not the only country working to develop and deploy commercial fusion energy technology. The United Kingdom, European Union (particularly Germany), and China all have substantial public and private programs to control and harness fusion energy. In Hefei, China, the Chinese Academy of Science's Institute of Plasma Physics is coordinating and directing billions of dollars of research and development each year on commercial fusion energy. China's scientists and engineers are already operating the Experimental Advanced Superconducting Tokamak (EAST), one of the leading experimental fusion machines in the world.[21] They are already constructing Burning Plasma Experimental Superconducting Tokamak (BEST) which is designed to serve as both a scientific and engineering demonstration machine – testing key fusion fuel cycle and tritium components for fusion energy – in China in three to five years.[22] The China Fusion Engineering Test Reactor (CFETR) is currently being designed and will be their first commercial demonstration machine in the 2030s as they envision widescale commercial deployment in the following decade.[23] They're also building enabling technology research facilities to help accelerate development. The Comprehensive Research Facility for Fusion

[21] Inside China's race to lead the world in nuclear fusion (nature.com)
[22] Controlled nuclear fusion emerges as new frontier for China's venture capitalist (news.cn)
[23] Building Bridges: A Bold Vision for the DOE Fusion Energy Sciences (osti.gov)

Technology (CRAFT) will be completed in 2025 and will enable and accelerate technology development to support their scientific, engineering, and commercial demonstrations.[24] Simply put, China has a plan for all phases of the fusion energy commercialization pathways and they are making investments to accelerate development and future deployment.

The United States needs to consider what role we want to play in the global race for fusion energy. Fusion technology innovation by private companies in the United States is unmatched, but we need to ensure they have the support and policy clarity to compete and win internationally against state-owned or state-supported fusion energy programs. Maintaining a clear plan across the entire federal government for the commercialization and deployment of fusion energy can help catalyze private investment in fusion energy companies. Federal support, coordination, and de-risking of commercial projects using cross-cutting fusion energy technology research and development programs can help accelerate fusion commercialization and free up important private investment for other development activities. Creating, maintaining, and implementing a roadmap for both private companies and federal support for the development and deployment of commercial fusion energy is critical to unlocking American competition and innovation, and enabling the United States to compete internationally to supply clean, safe, and affordable fusion energy.

Next steps on commercializing fusion energy

In closing, fusion energy can play a major role in our nation and our world's future clean energy system. Accelerating the commercial development and deployment of fusion energy will require investment by the private sector and continued coordination and support from the federal government. Two major factors should be prioritized as we work toward commercialization of fusion energy. First, we need to ensure that clean energy policies are technology-inclusive policies to create a market pull for fusion energy as a firm, clean energy source. Second, private companies, researchers, and the federal government should closely coordinate and collaborate to most effectively and efficiently prioritize efforts to accelerate fusion energy commercialization. Public and private partners should collaborate to:

- coordinate and intentionally prioritize federal support for fusion science research and fusion energy research and development with a focus on fusion commercialization
- evaluate and hold fusion development programs to milestones that are clear and realistic (in terms of both achievability and timing) to enable competition amongst a wide range of different fusion energy technologies and companies
- prioritize federal support for cross-cutting technology research and development programs that can help accelerate progress across private companies toward

[24] China Sets to Build Fusion Energy Research Facility (cas.cn)

commercial deployment at scale, with a focus on technically and economically viable pathways to fusion energy

- facilitate international collaborations so that we can most effectively engage with our allies on common research and development programs that help provide critical scientific and engineering data for private companies
- evaluate and address any safety and environmental impacts, byproduct and waste management, non-proliferation, and export controls concerns to enable the deployment and export of fusion energy at scale around the world.

These collaborations will help maximize the impact of federal investments in fusion energy research and development, multiply the impact of private investment on fusion energy technology commercialization, accelerate commercial development and deployment of fusion energy, and help us realize the climate, societal, economic, and geopolitical benefits of fusion energy as a key part of our clean energy future.

Operational Phase	China	U.S.
Scientific Demonstration	✓	✓
Engineering Demonstration	**Under Construction (BEST)***	
Commercial Demonstration	**Planned (CFETR)****	
Commercial Deployment		

Enabling Fusion Research	China	U.S.
Cross-Cutting Technology Facilities	**Near Completion (CRAFT)*****	

Source: Patrick White testimony & https://www.nature.com/articles/d41586-024-02759-x

* Integrated machine with tritium breeding capabilities, BEST, under construction

** Integrated fusion machine with fusion fuel cycle and commercial component testing capabilities, CFETR, planned

*** Cross cutting fusion energy technology development and testing center, CRAFT, is nearing completion

The CHAIRMAN. Let me thank all of you, and we are going to start our questioning now.

So this is really for all three, but what I want to know is, I am encouraged to hear what we are doing and things of that sort. I am concerned when I hear China now is doubling down and coming stronger and stronger at us, wanting to take the lead on that. So I am going to ask the hard question: when can we realistically expect the first fusion power plant to be online? And I know there is all difference, but with ITER being knocked back as far as it is, it has really alarmed us. How do you expect something to come on quicker than that, and why would you be able to do it on a smaller scale when they can't do it on a commercialized scale?

Dr. JP, we will start with you.

Dr. ALLAIN. Thank you, Mr. Chairman, for this question. There is no question that we are in a race, and I am glad that you point this out. The realization of fusion energy is one of the most significant challenges to mankind. So we need to recognize that. As we are putting together a lot of our expertise and leveraging a lot of our resources, we need to keep in mind that it is really important to have our eye on the ball and very much focus on closing the science and technology gaps that we have been talking about.

The good news is, after decades of investments in the public program and the public sector, these have actually enabled the private sector step up the investments toward fusion technology development, and this is good news. We have a signal, if you will, from the private sector.

The CHAIRMAN. You are thinking the private sector is going to come on before the public sector, right? I am just trying to—I only have so much time.

Dr. ALLAIN. Right.

The CHAIRMAN. I wanted to make sure, but I think I know where you are coming from on that. What you all have been able to—what we have been able to do with public investments and research through our labs is basically propelling the private sector to take it and run with it quicker.

Dr. ALLAIN. Well, that's true, but it's also about building bridges between the public and private sectors. This is key, right? It's not just the private sector, yes.

The CHAIRMAN. Thank you.

Ms. Siebens, do you have any comment real quick on that?

Ms. SIEBENS. Yes, thank you for that question, Senator. I will start by sort of taking a 50,000-foot view of the whole fusion ecosystem and where we are at today versus where we have been.

The CHAIRMAN. Well, you all believe you can come on before 2030?

Ms. SIEBENS. That is correct. Indeed.

The CHAIRMAN. Well, how? I want to hear that one.

Ms. SIEBENS. Right. So, first of all, right now, we have 21st century technology advancement that is enabling 20th century concepts. So for us at Helion, we are pursuing something called a pulsed approach to fusion, and when you look at things like ITER, which you have discussed, and many of the other companies, they are pursuing something called a tokamak design, which has been the predominant design that has been pursued over the past many decades. And in both of those instances, we have technologies available today that we have not had before that are accelerating this race toward commercialization and building that first working machine.

Combined with the fact that the regulatory framework for fusion allows companies like Helion to actually build and iterate and build again quickly, that is absolutely key for us moving quickly. For instance, for us at Helion, we have built six working fusion machines since we were founded approximately 11 years ago. You can't do that in almost any other field. In fission, it takes a very long time to get regulatory approval to build.

So the fact that we have technology advancements, particularly in power electronics for us at Helion, combined with a regulatory framework that allows us to build and iterate, has really led us to a place where we are moving quickly with our pulsed machine, particularly.

The CHAIRMAN. Dr. White, real quick.

We are going to go to seven minutes because with what we have here, I think it entails that.

Go ahead.

Dr. WHITE. Great. Thank you, Senator Manchin.

I think the real answer to why we think we can get fusion energy on the grid more quickly is technology innovation. If you take a look at almost all of the private fusion companies that are currently developing technologies, they are all leveraging innovation in things like high-temperature superconducting magnets, new power electronics, new laser technologies, and this is really what is enabling them to move faster and get better performance out of machines that have been developed at national labs for the last several decades.

The challenge is, with innovation, the timeline of that can be uncertain. And so, we have a lot of very promising concepts. It really is up to private industry to work through the innovation process and figure out if these enabling technologies can rapidly accelerate the deployment of fusion energy.

The CHAIRMAN. Let me throw this at you all—since we know that, and we know also the constraints we have on the grid system, do you believe you see an impediment there that might cause you a problem coming on, even if you have this technology? And I will give you the perfect example. In my state, we have retired coal plants, some of the older ones. They already have the switch gears. Everything is ready to go. And we have had SMRs—small modular, you know, looking at that. Do you all look at that type of a facility that's like a plug and play? If you can get this going, would that be attractive to you all? And are you concerned about the constraints you have hooking to the grid, the way we have it now, unless we are able to pass permitting which enables us to have—and how important is that to you all—the permitting?

Ms. SIEBENS. Thank you for that question. And yes, we are looking at co-location—that is, when we look at our customers and where the demand is, there is a lot of demand around co-location. For our first deployment, we are in good shape. But where we see the real race developing is beyond that first demonstration, that first deployment of a commercial facility——

The CHAIRMAN. Got you.

Ms. SIEBENS [continuing]. And building out and deploying at scale. That is where the real race with China is. And to your point, that is where we do see challenges in being able to deploy our machines at the rate that we can build them and to meet the demand that we see. I think the permitting bill goes a long way in helping ensure that we are able to connect to the grid and solve some of the transmission issues that we are facing. But when it comes to co-location—which you mentioned—in regulated markets, there is not currently a pathway that exists for a 500-megawatt facility like ours to serve electricity directly to a customer like Nucor. So I think there is a lot of work still to be done in the space of co-location.

The CHAIRMAN. Got you.

Anybody else want to comment on that?

Dr. ALLAIN. Yes, let me just expand on this, and we must remember that ITER—you referenced ITER—is not intended to be a commercial machine. However, it is an industrial-scale platform.

The CHAIRMAN. They were trying to prove on a commercial scale, that it can be——

Dr. ALLAIN. That's right. And we should remember that, in fact, the impact of ITER already at that industrial-scale level has impacted a lot of the supply chain aspects. For example, in manufacturing—let's say, magnets, and in terms of, you know, tritium-based systems, this is another aspect where we are, in fact, benefiting from that particular project, you know. And that is something that we don't have to wait until 2029 for.

The CHAIRMAN. The thing that impressed me more than anything was that 33 different countries have scientists at ITER.

Dr. ALLAIN. That's right.

The CHAIRMAN. I would encourage everyone in the Energy Committee, if they get a chance, to go there. It's worth it.

Dr. ALLAIN. That's right.

The CHAIRMAN. But you have to work in collaboration, and sharing this, and countries that we have concerns with——

Dr. ALLAIN. Yes.

The CHAIRMAN. China and Russia, still paying their share to be part of this.

Dr. ALLAIN. Yes, there is about $1.4 billion that has been invested in the U.S.—120 companies that have benefited from this. And we are trying to leverage that.

The CHAIRMAN. Dr. White, do you have something very quick, in closing?

Dr. WHITE. Yes, I will just really quickly reiterate, I believe the importance of having technology-neutral policies to really think about how we can get firm clean energy sources onto the grid.

The CHAIRMAN. Right.

Dr. WHITE. We hope to see many of these sources come online in the next decade, and so, having a clear pathway for them to either work behind the meter or integrate it onto the grid will be critical so that technologies like fusion can enter the grid when they are commercially ready.

The CHAIRMAN. Great.

Senator Barrasso.

Senator BARRASSO. Well, I just want to follow the direction of your questioning, Mr. Chairman.

Ms. Siebens, you know, your company is very confident that it's going to be able to generate electricity from fusion. More and more companies are getting into this area. In May 2023, your company entered into this power purchase agreement to provide electricity to Microsoft around 2028. To date, no one has been able to generate electricity from fusion, yet last year, you announced that it is expected to demonstrate the ability to produce electricity in 2024, which is this year. Are you still on track to show it can produce electricity by the end of this year? We are talking, you know, less than two and a half months to go.

Ms. SIEBENS. Thank you for that question, Senator.

Right now, we are constructing our seventh prototype, called Polaris. And this is the machine that we expect will demonstrate electricity production. We are on track to complete construction of this plant this year and begin testing likely this year and then continue that through next year. And yes, this is the machine that we believe will demonstrate electricity production, which is key to meeting the requirements of that PPA.

Senator BARRASSO. So since we sometimes ask one witness to comment on something or other, Dr. White, you know, companies like Helion generated significant excitement about their prospects for fusion energy. Are we really just a few years away from bringing fusion energy onto the grid?

Dr. WHITE. Great, thank you for the question, Senator.

I think this is where the topic of technology innovation really becomes the most important issue to discuss. Companies like Helion are using innovative approaches to generating fusion energy, but a lot of that is based on innovative technology approaches. And these are things that we are going to discover through the development, demonstration, and testing process. And so, I think it's really exciting to watch the progress that Helion is making in this space, and ultimately, we will be looking to them as they test their machines to see if they can perform and produce the electricity that they believe could be really impactful. And I think this is something across the space—how can we look to innovative technologies to really accelerate fusion, not just for Helion, but for many different private fusion companies in the space? But ultimately, the proof will be in electrons on the grid.

Senator BARRASSO. Great.

So Ms. Siebens, the power purchase agreement that you have with Microsoft, I think lots of people are interested to learn the specifics of these agreements. I am curious to know whether the agreement includes a firm deadline date by which Helion must provide electricity to Microsoft, and I am interested to know whether it includes meaningful penalties if you don't meet the deadline. What, if any, details can you share about the agreement?

Ms. SIEBENS. Sure. I can't share every detail of the agreement, but I can say that, yes, this indeed is a real PPA that comes with firm penalties. We do have penalties that evolve and change as we grow closer to the milestone of actually producing commercial power for Microsoft. And yes, we do have deadlines. So for 2028, we need to have the plant constructed and begin operations and then reach full commercial operations, providing electricity to Microsoft in 2029.

Senator BARRASSO. Dr. White, earlier this year, Representative Beyer from Virginia, you know, he is co-chair of the House Fusion Energy Caucus. He said that much of the U.S. fusion spending goes to legacy programs. His quote was, "Not the cutting-edge stuff." Is it time for Congress to reorder our priorities when it comes to fusion research?

Dr. WHITE. Thank you.

I think it's really important when we talk about a lot of these legacy programs, as was described by Representative Beyer, and thinking about the larger fusion energy portfolio, how can we try to refocus what their activities are toward fusion energy commercialization? A lot of the machines that we operate today and a lot of the international programs that we are in can provide really important scientific and engineering information to help accelerate the private industry. Insights and work done at ITER on the design, manufacture, and construction of the ITER device and a lot of the design work that was done to support that could be incredibly valuable for U.S. private fusion companies. The question is, how can we make sure that U.S. private companies in the U.S. fusion energy sector can get access to a lot of these lessons learned? And I think when we talk about U.S. fusion energy experiments, how can we make sure that they are really tailored and focused on either training scientists, producing research, or testing the system structures and components that are going to be needed for fusion energy?

And so, I think a lot of it is really having this focused plan on how to best use both the legacy experiments and the international collaborations that we have.

Senator BARRASSO. Dr. Allain, it's no surprise how China is approaching fusion. Just like they have done with other innovative technologies, they let us do all the hard work and then they try to copycat or steal it and do anything they can. They steal our ideas. They lock up the supply chains for raw materials, magnets, capacitors, semiconductors—you know all of this. The list goes on. What is the Department of Energy going to do to protect America's growing fusion energy industry?

Dr. ALLAIN. Yes, thank you, Senator, for that question.

I think it connects with a lot of the comments here as well. What we have to do is, we have to be very focused on making sure that we are not only closing the science and technology gaps, but that we have a roadmap—a direction—that provides us not just the timeline, but the way that we prioritize. The so-called legacy assets that we have, these are not just facilities. These are ecosystems. And what is really important to recognize, these ecosystems are working, not just on fusion science, they are working also on development of the very tools that are enabling many of the private-sector companies. Those ecosystems, as well, are what ties us to our international partners, and in fact, why the globe and why the world comes to the United States for many of their projects for us to be able to develop. The key piece here, basically, as was just shared here by my colleagues, is making sure that we are understanding the bridge to the private sector, identifying where those gaps have to be addressed, and making sure we take advantage of the resources and the assets that already exist.

Senator BARRASSO. Right. Well, thank you.

Mr. Chairman, thanks for going to seven minutes because I have two more questions.

The CHAIRMAN. Go for it.

Senator BARRASSO. Ms. Siebens, I understand fusion companies have raised over $7 billion across the board from the private sector. What types of metrics do investors use when they are trying to assess different companies' performance?

Ms. SIEBENS. Thank you for that great question. And it gives me a chance to talk about the diligence that we went through with both of our customers. We actually started talking to Nucor, as an example, back in 2021, and went through a very, very in-depth process with them, sharing what we could with them to have them in a place where they felt comfortable and excited about signing an energy development agreement with us for that 500-megawatt plant. Similarly, with Microsoft, the same thing. Both of these companies are very conservative and are very serious about announcing and pursuing an agreement of this type with us moving forward.

Senator BARRASSO. And Dr. White, my final question. You know, some people say nuclear fusion is inherently safe. Could you discuss a little bit the safety benefits as well as potential hazards associated with fusion technology?

Dr. WHITE. Thank you so much for that question, Senator Barrasso. I spent three years on my doctoral thesis working on it, so to help, I will give you the quick highlights version of it.

The CHAIRMAN. Here we go.

[Laughter.]

Dr. WHITE. I will go very quickly.

Really it's when you start looking at fusion reactions, they are producing, at least with some reactions, neutrons. And those neutrons that are produced can have the property of activating materials, causing them to become radioactive and then producing additional forms of radiation. The challenge there is we need to make sure that we have a way to control and confine that type of radiation that is produced and have pathways for its disposal in the long term. We need to make sure that we are protecting workers, the public, and the environment from any materials that might be produced as by-products during the fusion reactions and in fusion machines.

The other thing that we will need to consider is that the tritium that is used in some fusion fuel cycles is a radioactive form of hydrogen. While we have experience in the United States with handling tritium safely, we need to make sure that we continue those processes as we scale it up to industrial fusion energy. And so, I think we do have pathways on how to maintain safety, but it is something that's going to need to be a continued focus as we think about commercialization in fusion energy. But luckily, we have organizations like the Nuclear Regulatory Commission that are focused on this and are developing the regulations and guidance necessary, as well as the Agreement States that are going to take a leading role in the licensing of fusion energy technology in the near term.

Senator BARRASSO. Thank you.

Thank you, Mr. Chairman.

The CHAIRMAN. Senator Heinrich.

Senator HEINRICH. Thank you, Chairman. And I want to thank the Chairman for recently joining the Fusion Caucus, as well as Senator King, and we would very much welcome other members on this. Senator Todd Young has joined. We would love to have Senator Barrasso and Senator Padilla. I think this is an incredibly important opportunity for us and, as has been articulated, we have led on this for 70 years. And those efforts, however, have largely been physics-based, right? We spent a lot of time figuring out the process to make fusion successful. We are now in a place where we are shifting our focus to engineering and materials science and all the things that it takes, not just to prove that you can do this stuff in a lab, but to actually produce electrons on the grid.

And I do want to enter in another article. I would ask unanimous consent, Mr. Chair, it's "The U.S. led on nuclear fusion for decades. Now China is in a position to win the race." And this is what we need to make sure that we have the right focus to avoid.

The CHAIRMAN. Without objection.

[The article referred to follows:]

CNN Climate

The US led on nuclear fusion for decades. Now China is in position to win the race

By Angela Dewan and Ella Nilsen, CNN

Published 4:00 AM EDT, Thu September 19, 2024

(CNN) — The bustling city of Shanghai marks national celebrations with world-famous light shows, illuminating its skyscrapers with dazzling colors, like beacons of Chinese innovation.
It is here that scientists and engineers work around the clock to pursue the next big thing in global tech, from 6G internet and advanced AI to next-generation robotics. It's also here, on an unassuming downtown street, a small start-up called Energy Singularity is working on something extraordinary: nuclear fusion energy.

US companies and industry experts are worried America is losing its decades-long lead in the race to master this near-limitless form of clean energy, as new fusion companies sprout across China, and Beijing outspends DC.

Nuclear fusion, the process that powers the sun and other stars, is painstakingly finicky to replicate on Earth. Many countries have achieved fusion reactions, but sustaining them for long enough to use in the real world remains elusive.

Mastering fusion is an enticing prospect that promises wealth and global influence to whichever country tames it first.

The prize of this energy is its sheer efficiency. A controlled fusion reaction releases around four million times more energy than burning coal, oil or gas, and four times more than fission, the kind of nuclear energy used today. It won't be developed in time to fight climate change in this crucial decade, but it could be the solution to future warming.

The Chinese government is pouring money into the venture, putting an estimated $1 billion to $1.5 billion annually into fusion, according to Jean Paul Allain, who leads the US Energy Department's Office of Fusion Energy Sciences. In comparison, the Biden administration has spent around $800 million a year.

"To me, what's more important than the number, it's actually how fast they're doing this," Allain told CNN.

Private businesses in both countries are optimistic, saying they can get fusion power on the grid by the mid-2030s, despite the enormous technical challenges that remain.

The US was among the world's first to move on the futuristic gambit, working on fusion research in earnest since the early 1950s. China's foray into fusion came later that decade. More recently, its pace has ratcheted up: Since 2015, China's fusion patents have surged, and it now has more than any other country, according to industry data published by Nikkei.

Energy Singularity, the start-up in Shanghai, is just one example of China's warp speed.

It built its own tokamak in the three years since it was established, faster than any comparable reactor has ever been built. A tokamak is a highly complex cylindrical or donut-shaped machine that heats hydrogen to extreme temperatures, forming a soup-like plasma in which the nuclear fusion reaction occurs.

For a fledgling company working on one of the world's most difficult physics puzzles, Energy Singularity is incredibly optimistic. It has reason to be: It has received more than $112 million in private investment and it has also achieved

https://www.cnn.com/2024/09/19/climate/nuclear-fusion-clean-energy-china-us

a world first — its current tokamak is the only one to have used advanced magnets in a plasma experiment.

Known as high-temperature superconductors, the magnets are stronger than the copper ones used in older tokamaks. According to MIT scientists researching the same technology, they allow for smaller tokamaks that can generate as much fusion energy as larger ones, and they can better confine plasma.

The company is planning to build a second-generation tokamak to prove its methods are commercially viable by 2027, and it expects a third-gen device that can feed power to the grid before 2035, the company said.

In contrast, the tokamaks in the US are aging, said Andrew Holland, CEO of the Washington, DC-based Fusion Industry Association. As a result, the US relies on its allies' machines in Japan, Europe and the UK to further its research.

Holland pointed to a new $570 million fusion research park in eastern China under construction, called CRAFT, on track to be completed next year.

"We don't have anything like that," he told CNN. "The Princeton Plasma Physics Laboratory has been upgrading its tokamak for 10 years now. The other operating tokamak in the United States, the DIII-D, is a 30-year-old machine. There's no modern fusion facilities at American national labs."

There's a growing unease in the US industry that China is beating America at its own game. Some of the next-generation tokamaks China has built, or plans to, are essentially "copies" of US designs and use components that resemble those made in America, Holland said.

China's state-funded BEST tokamak, which is expected to be completed in 2027, is a copy of one designed by Commonwealth Fusion Systems, Holland said, a company in Massachusetts working with MIT. The two designs feature the same kind of advanced magnets Energy Singularity is using.

https://www.cnn.com/2024/09/19/climate/nuclear-fusion-clean-energy-china-us

Another machine being built by a private Chinese company looks very similar to one designed by the US company Helion, Holland said.

There is “a long history” of China copying American tech, he added.

“They’re fast followers and then take the lead by dominating the supply chain,” Holland said, using solar panel technology as an example. “We’re aware of this and want to make sure that’s not the way it goes forward.”

CNN did not receive a reply from China’s National Energy Administration when asked whether state-funded fusion research had copied or been inspired by US designs.

Lasers vs. tokamaks

Nuclear fusion is a highly complex process that involves forcing together two nuclei that would normally repel. One way to do that is to turn up temperatures in a tokamak to the tune of 150 million degrees Celsius, 10 times that of the sun’s core.

When they bind, the nuclei let off a large amount of energy as heat, which can then be used to turn turbines and generate power.

The US has been a fusion leader for decades; it was the first nation to apply fusion energy in the real world — in a hydrogen bomb.

In the early 1950s, the US military tested a series of nuclear weapons in the Pacific Ocean that were “boosted” by gases that created a fusion reaction, resulting in an explosion 700 times the power of Hiroshima blast.

Sustaining nuclear fusion for long periods is much more challenging, and while China races ahead with its tokamaks, the US is finding an edge in other technology: lasers.

In late 2022, scientists at the Lawrence Livermore National Laboratory in California shot nearly 200 lasers at a cylinder holding a fuel capsule the size of a peppercorn, in the world’s first successful experiment to generate a net gain of fusion energy. That means more power came out of the process than was used to heat the capsule (though they didn't count the energy needed to power the lasers).

There are yet more ways to achieve nuclear fusion, and the US is hedging its bets on a variety of technologies.

It's not impossible that approach could pay off.

"We don't know exactly which is going to be the best concept, and it may not be one," said Melanie Windridge, a UK-based plasma physicist and CEO of Fusion Energy Insights, an industry monitoring organization. There may ultimately be several viable approaches for fusion power, she told CNN. "And then it will come down to costs and other factors in the longer term."

But the tokamak is the best-researched concept, she said.

"Over time, it's had the most research put into it, so it's the most advanced in terms of the physics," said Windridge. "And a lot of the private companies are building on that."

With the money China is putting into research, the tokamak concept is rapidly evolving. China's EAST tokamak in Hefei held plasma stable at 70 million degrees Celsius — five times hotter than the core of the sun — for more than 17 minutes, a world record and an objectively astonishing breakthrough.

Mikhail Maslov of the UK Atomic Energy Authority described it as an "important milestone," adding that running long plasma pulses remains one of the biggest technical challenges to commercializing fusion energy.

While China's government pours money into fusion, the US has attracted far more private investment. Globally, the private sector has spent $7 billion on fusion in the last three to four years, about 80% of which has been by US companies, the DOE's Allain said.

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"In the US, what you have is that entrepreneurial spirit of being able to really think outside the box and innovate and really address some of these gaps, not just in science, but also in the technology," he said.

But if the Chinese government continues to invest more than $1 billion a year, that could soon eclipse US spending, even in the private sector.

And if those investments pay off, colorful celebrations in Shanghai will not only be powered by fusion, they will cast China in a whole new light.

CNN's Shawn Deng contributed to this report.

https://www.cnn.com/2024/09/19/climate/nuclear-fusion-clean-energy-china-us

Senator HEINRICH. So talk to me, from any of you, about the proper role of the DOE and government right now to shift our focus from our historic focus to one of supporting technology-agnostic support structures to develop those materials that can survive in this environment—all the engineering pieces that are going to be necessary for commercial development. How do we support the—not pick winners and losers—but support the industry across the board and just see who gets there the fastest?

JP, do you want to go first?

Dr. ALLAIN. If I may, yes, thank you, Senator.

One of the important aspects to realize is that in those 70 years that you speak about, a lot of the physics also were able to establish important technological questions. For example, in the early '70s, we recognized that stainless steel walls were not going to enable us to sustain these reactions, that we needed to move to carbon. Later on, of course, we realized, well, graphite-based systems are not going to make it and now we need to go to high temperature materials like tungsten. We are in a unique position today because there have been significant technological advancements outside of fusion. For example, AI/ML has been a tool that we have taken much advantage of, and the convergence with fusion, I would argue, is going to be one of the key elements for us to have that competitive edge.

How does government participate? How does government—what is our role in what is a burgeoning private-sector activity right now in fusion? Our role is there to target and focus steady on the common gaps of many of these approaches. For example, for those that are approaching tritium using that as a fuel—tritium fuel cycle, blanket technology. Advanced materials then need to survive those extreme conditions. Those are areas that the public program has not, in fact, prioritized in the past. And as was mentioned earlier, we really have to be decisive, focused, and swiftly then pivot and align to exactly address those gaps.

Senator HEINRICH. Do the two of you from the private sector agree with that kind of approach, a gaps-based approach?

Ms. SIEBENS. Thank you, Senator, for the question.

I will say, from Helion's perspective, we are very interested in seeing an increase in applied materials R&D. And at the end of the day, this is about making sure that we are focusing on commercially relevant work, and really weaving that more into what is happening within the DOE ecosystem as it relates to fusion. I will just give you a quick example so we can kind of dive into what we mean by applied here. For us, we would love to see a large multi-technology project where we tackle how to build commercialized new reliable materials for things like first walls so that we can get to scaled deployment. And a lot of times we have materials that work for that first machine to demonstrate, but we really still have some R&D gaps to——

Senator HEINRICH. That's different than surviving in that environment.

Ms. SIEBENS. Precisely.

Senator HEINRICH. Long-term.

Ms. SIEBENS. Correct.

Senator HEINRICH. Yes.

Dr. WHITE. And I think, just building on that, fusion materials is a perfect place for the Federal Government to take a lead on this. One of the challenges that I think that we have in kind of thinking about the long-term development, deployment of commercial fusion energy really is how do we design a fusion machine if we have never operated a fusion machine?

Senator HEINRICH. Right.

Dr. WHITE. It's a bit of a chicken and the egg problem. And to actually develop a lot of the scientific and engineering data that we need, creation of large national test facilities to do materials research, to do neutron irradiation of materials, and help develop and really optimize new alloys is critical to ultimately creating materials that can help facilitate the safe and economic production of fusion power. And that is something where it might be too large of a lift for any one private fusion company to take on, but a Federal Government-led program could allow for, essentially, the collective development of that really critical experience and really critical materials data.

Dr. ALLAIN. If I could add, Senator, also, it's not only the investments we are making in priorities, but in our community—I always share this when I do my visits to various performers—is a change in how we think about fusion, how we do fusion, is asking the right questions and making sure that we are building those bridges. So for example, we have talked a lot about the public-private consortium frameworks, which we did an RFI on. Really, the impetus of this was to identify ways that we could partner with the private sector. I have been at Helion. I have seen the tremendous effort and work that is done there. I think it is, in fact, the piece that we need to connect the public program to support those activities, also in terms of making sure we are supporting the workforce that will be needed in order to support this incredible fusion technology development time.

Senator HEINRICH. Dr. White.

Dr. WHITE. And just one last quick note for you, Senator. I think this is something where time is a really important factor to consider. While it might not be necessary to have some of these fusion materials, for example, to develop the very first or second generation of fusion machines, they could be incredibly valuable as we think about wide-scale deployment and commercialization.

Senator HEINRICH. Sure.

Dr. WHITE. But both the creation of these testing facilities and material testing will take time. So the sooner we start, the sooner we will have these materials available and we will be able to have really serious conversations about wide-scale deployment and commercialization.

Senator HEINRICH. Great. Well, I burned by seven minutes on one question, but I think that was very——

[Laughter.]

The CHAIRMAN. I think it was worth it.

Senator HEINRICH. Actually, it told us a lot about where we need to go.

The CHAIRMAN. It was worth it.

Senator HEINRICH. Yeah.

The CHAIRMAN. Senator King.

Senator KING. Can you tell he is the only engineer in the Senate?

[Laughter.]

Senator HEINRICH. Another one at the end down there.

Senator KING. Oh.

Senator PADILLA. Yes.

Senator KING. How about you? There you go. Only two engineers in the Senate.

[Laughter.]

Senator KING. I want to approach this from an entirely different perspective. We have talked a lot about competition with China. When this technology becomes available, large-scale, commercial, it is literally world-changing. This is one of the most important topics we will ever discuss around here. The single—probably the best thing we could do for the environment right now is to get China off of coal. What I am leading up to is, why does this have to be a competition with China? This isn't a military technology. This is a civilian technology that is going to affect all the rest of us. Why can't this be a breakthrough in the relationship between our two countries where we work together? They are going to get there and we are going to get there. Together, we might get there five years sooner. And clearly, we are already talking to our allies, but I don't see this as a military competition. Clearly, there are advantages to getting to this technology, but the advantages to the whole world, it seems to me, might make it worth entering into some kind of discussion about whether this is an area where we don't have to compete, we can collaborate, and therefore, drastically improve the prospects for saving the planet.

Thoughts, Mr. White.

Dr. WHITE. Great, thanks, Senator King.

So I think this is a case where availability of clean energy around the world is absolutely critical. If we look to the pathway of trying to have clean energy for all parts of the world, we are going to need more energy sources than we could possibly imagine.

Senator KING. Right.

Dr. WHITE. And having fusion energy alongside other firm clean energy sources, other variable clean energy sources, is going to be key. So my first answer is, the more competition the better, because that means we have more shots on goal to actually get this technology working. And so, I think there is a way to think about how competition breeds innovation and ultimately gets more smart people working on this topic because it is something, as you said, that could be world-changing.

Senator KING. But if you have a lot of smart people around the world working on it, it seems to me, it would be good if they were talking to one another.

Dr. WHITE. And I think you see that often in the scientific community. Where can you have collaboration on some of these key issues that really are cross-cutting questions? Going to the IAEA, going to international fusion conferences, you see conversations between scientists from around the world on the underlying science that they are doing. And I think that is where we can really try to identify international collaborations, international partnerships, that really raise our level of understanding of a lot of these enabling science and technology questions that get us to fusion energy.

Senator KING. Do either of you have thoughts about this? I noticed you were nodding when I was talking, but that doesn't——

Ms. SIEBENS. Aggressively nodding over here, yes.

Senator KING. That doesn't go into the record.

Ms. SIEBENS. Okay, thank you, Senator. Thank you for that great question. I would love to see a world where we are all working aggressively together toward deploying an energy technology that, as Senator Manchin said earlier, could potentially bring about world peace.

Senator KING. Right.

Ms. SIEBENS. The reality for us as a company right now is, we see the real race here beginning after we actually demonstrate and deploy that first machine where we are already watching China work aggressively to lock down that supply chain. And so, for us, when we think about all the demand we are forecasting and already seeing from customers to deploy not only at scale here in the U.S., but around the world, we think it's a national security issue to ensure that here in the U.S. and along with our allies, we can secure a supply chain that enables us to dominate this marketplace, because if we don't, China will, and all of the geopolitical influence that accompanies that——

Senator KING. Which is exactly what they have done with EV batteries.

Ms. SIEBENS. Precisely. That's right. We have seen this movie before. And I think we have a once-in-a-generation opportunity right now to avoid that same story.

Senator KING. Let me ask some specific questions about the technology. One is, I think one of you used the word affordable. One of the problems with current nuclear fission plants is cost—far more expensive than any other form of generation. Are there any—is it too early to have estimates? Will fusion be cheaper than fission?

Dr. WHITE. I guess I will take that very important question on first. I think the thing that we can really first think about is, how do we talk about the cost of different energy generating technologies? Sometimes we might say how much does one power plant cost versus another power plant, but we think as we move toward a clean energy future, we need to think about overall system costs, and what roles different energy generating assets are really playing. So it's not going——

Senator KING. The relevant question is cost per kilowatt-hour to the consumer.

Dr. WHITE. You are exactly right, and I think that is ultimately——

Senator KING. Nuclear is now pretty much at the top.

Dr. WHITE. Nuclear is at the top, but one of the things that we see is that as it's integrated into a clean energy system, it helps bring down system costs because it reduces the amount of buildout that you might need in some areas for renewables and storage. And so, I think as we talk about the commercialization of fusion energy, economics is going to be an absolutely key point. How can they make sure that it can play an economically competitive role in the marketplace? And that is something that we will see as these companies move through this technology development and demonstration.

Senator KING. I am assuming your contract with Microsoft is—you are not going to tell us the price—but it's at a price that Microsoft feels is competitive with what they are paying now.

Ms. SIEBENS. That is correct. So I can say that for the Microsoft agreement and the Nucor agreement, we are going to be at market rate or below. But what is really exciting about this, and I think we have heard the phrase "holy grail" mentioned a few different times here, is the ability to drive the cost down here. So I can say that for us at Helion, our machine is suited for mass manufacturing and it's built with factory components, which is very unlike traditional fission——

Senator KING. So is your short answer that this should be less expensive than the current fleet of——

Ms. SIEBENS. Significantly, to the tune of potentially——

Senator KING. Building a new fission plant?

Ms. SIEBENS. Yes, so if we are able to mass produce this on the scale we envision, which could ultimately be building one generator a day, we could reduce cost down to one cent per kilowatt-hour, which is truly world-changing.

Senator KING. I am delighted to hear that, but I still remember when the prediction in the '50s for nuclear power was that it would be too cheap to meter.

Ms. SIEBENS. Too cheap to meter? Yes.

Senator KING. So go for it.

[Laughter.]

Senator KING. And a follow-up question—is there an advantage of this technology over SMRs?

Ms. SIEBENS. There are a few. As I mentioned earlier, just the regulatory framework being fundamentally different.

Senator KING. I like your idea, by the way, about permitting a design.

Ms. SIEBENS. Yes.

Senator KING. You have to have localized impact assessment.

Ms. SIEBENS. That is correct.

Senator KING. But not go brand new on every plan.

Ms. SIEBENS. Right. I think that is correct. I think, when we really look at the details here, the fact that we can truly mass manufacture these machines and that they are built of primarily small factory components leads to a significant cost reduction when you compare it with traditional fission plants.

I just want to say for the record, too, I agree with Patrick. We need every low-carbon or no-carbon emissions technology we can get to solve this problem, but yes, there are significant differences in cost when we look at deploying these at scale.

Senator KING. Final question. I think it was Senator Barrasso who was asking about safety—is fusion inherently a safer technology than fission? My colleague said yes, but he's not——

Ms. SIEBENS. So I will just say, I have worked in the fission space for many, many years, and still am very excited about everything that is happening with small modular reactors and think we need this technology, but when we look at the material that we are using, the fuel that we are using for fusion versus what we see with fission, in fission it's something called special nuclear material. We are using uranium, which does have long-lived radioactive waste that accompanies it, and when you look at a fission reactor, you do have a higher risk, although it is very low, of having something like a runaway reaction, right, where we have seen incidents before.

With fusion, we are not using special nuclear material. We are using, in our machine, deuterium, or heavy water and helium-3, and these things, if you look at the periodic table, are at the opposite end of the periodic table from uranium. And it's the material that we used, that is where the real fundamental difference is when you look at what the safety case is.

Senator KING. Please.

Dr. WHITE. So I think this is really a case where it will depend on the different machines that are developed, the different fuel cycles that are used, and ultimately, the specific designs, that ultimately determine the safety case of different fusion technologies. While I agree with many of the things that my fellow witness said, I think there are certain hazards that we are going to have to address with fusion energy—the tritium fuels that are going to be present in some of these fusion machines will have to be managed. They can be managed safely, but we will need to manage them. And you can design facilities that are going to have different levels of risk depending on how they decide to design and optimize their systems.

Senator KING. Thank you.

Dr. WHITE. The same things with some of the radioactive materials that might be produced as by-products during operation from neutron irradiation. These are things that can be handled safely, but we need to make sure that we have both an emphasis in industry on design and optimization and then a regulatory framework that ensures safety of these technologies.

Senator KING. Thank you. Thank you, Mr. Chair.

The CHAIRMAN. Senator Padilla.

Senator PADILLA. Thank you, Mr. Chair.

First, to the chagrin of my staff, I am going to digress for a second from some prepared questions to touch on a conversation that took place a minute ago between Senator King and Dr. White because I think it's important to consider the context of this conversation, and I am referring to the question of a specific energy technology's per-unit cost versus the system cost. So my attempt at sort of a layman's explanation of that dynamic is that we are happily and aggressively pursuing expansions of solar technology and wind technology, et cetera, but I think the members of the Committee and members of the Senate have become familiar with intermittency issues. So we can talk about wind versus solar versus other sorts of fossil fuels versus et cetera, but we are sensitive to what happens when the sun is not shining and what happens when the wind isn't blowing and the role of—whether it's storage technologies or peaker plants or other things to make the system, as a whole, resilient, reliable, et cetera, while trying to minimize costs. So it's those interconnecting dynamics and factors that, I think, is the tension between an individual technology's per-unit cost versus system cost because we have holistic goals of reliability, cost containment, you know, rates, impacts, et cetera. So that is my attempt at normalizing that exchange of a few minutes ago.

But on the subject at hand, as you all know, I am proud to represent California, who we believe is the undisputed leader when it comes to fusion energy science. Besides having a large private startup ecosystem, California is also home to both the National Ignition Facility, the NIF, at Lawrence Livermore National Lab and the DIII-D at General Atomics in San Diego. NIF has been a tremendous success, and I think both the Chair and the Ranking Member acknowledged that earlier in their comments where they achieved fusion ignition five times in the last two years—less than two years. NIF experiments uniquely informed the foundational science of burning and ignited fusion plasmas needed for fusion energy. And additionally, DIII-D is about to celebrate its 200,000th experiment, and has also been instrumental in fusion R&D. So with sustained funding for operations, as well as refurbishment and plant upgrades, these fusion facilities will continue to provide the U.S. a singular advantage in advancing fusion energy.

My question is for Dr. Allain. How can we capitalize on this progress to develop a timeline for achieving commercial fusion and maintain this momentum? I think the question of timeline has come up before, but let's be clear in our objective here, not just clear in additional successful demonstrations, scaling up, but bringing it to commercialization.

Dr. ALLAIN. Yes, thank you, Senator Padilla, for that question. And as a proud alum of Cal Poly Pomona, I am glad that you mentioned California. Yes, the point about the relevance of leveraging existing assets is that it's not just, as you pointed out, ecosystems where we have, in fact, benefited tremendously from being able, for example, to benchmark a lot of the advanced modeling codes that in fact we are utilizing to be able to design the future fusion energy systems that would come in the private sector, but I think one important point about the objective of these investments is, it's clear that we have to now move from the science-alone questions to now the technology-focused questions. And to do that, the bridges of the public and private sectors, the public program also has to make sure it is aligned and part of—in my comments, what I shared was this public-private consortium frameworks approach, where we are looking at not just the labs that are engaging and taking advantage of these tools and assets and universities, but also have partnerships with local and state governments and in fact other investment participants to be able to then identify where is the near-term infrastructure that we have to invest.

This is part of our conversation right now. In fact, I have daily conversations with the private sector about the possibilities of partnerships. And this is an aspect, in fact, in the Building Bridges vision that I laid out earlier this year to ensure that we are converging both the public and private—both the interests and also priorities that have to be aligned. The Fusion Science and Technology Roadmap that we unveiled this year, or at least that we unveiled the plan toward that roadmap, is precisely to your point, Senator, is looking at targeting, with metrics, input from the industry how much progress are we making every year. And that is a question that we will be asking every investment we make in our program.

Senator PADILLA. Yes. A follow-up question for Ms. Siebens, actually, because I appreciated your remarks earlier about it's not just the breakthrough technologies and successful demonstrations once or twice, but when we get to the point of scaling up and commercialization, looking at the supply chain, strategic positioning, and investments that we should be thinking about today. Do you have any thoughts or comments on not just coordination/collaboration between the public and private sector but what the right balance is and what we should be doing?

Ms. SIEBENS. Yes, thank you for that question, Senator, and I will just start by saying that at Helion we are delighted to have Dr. Allain in the position that he is in at Department of Energy. It has been really exciting to see, really, for the first time ever, the conversations about how to support commercialization taking place, and really more focus on partnerships with industry.

I am going to focus on the supply chain piece of the question here for just a minute because I do feel like there are sectors of our government that have never been activated to support fusion before, and that now is the moment to quickly and thoughtfully put together a plan to do so. I think, in large part, when we think about how to support a supply chain for a fusion industry, it's about activating existing programs and existing funding. I think ultimately we will need to look at new programs, but in the near term, we can look at, particularly, Department of Commerce, thinking about how can we activate CHIPS to support building out a domestic supply chain of chips specific to fusion. That would be huge for us as a company because we use thousands of them for one machine.

Also, at our company right now, our headquarters, we have built in-house a capacitor manufacturing capacity because we need to actually have around 15 percent of the capacitors we need for our seventh prototype built in-house to meet the need, otherwise, we would be even more reliant on China than we want to be. So I think that there is a lot we can do with the Department of Commerce and other agencies to think about that supply chain problem, and do it now so that when we hit that benchmark of electricity production, we have a plan to pick up and move quickly with.

Senator PADILLA. All right. Well, my time is up, maybe as a follow-up to today's hearing, I would love to pick each of your brains, also, not just on the workforce question, thinking ahead, but where our college and university systems are to prepare, educate, and train that workforce that we will need when the time comes.

Thank you, Mr. Chairman.

The CHAIRMAN. Let me say one thing before I go on to the next speaker, and I think Senator King has really led the charge on this, and we have it in our permitting bill. It is reconductoring—reconductoring, basically, the capacity on the lines.

[Photo of advanced conductor displayed by the Chairman follows:]


CTC GLOBAL
ACCC®

The CHAIRMAN. This will double the amount of electrons that can be carried.

Senator KING. Without building new poles.

The CHAIRMAN. Without building anything, but I know that maybe the utilities aren't crazy about it because they can't have the capital expenditure to charge more higher rates. This would be the way for us to get into the game quicker, to put more electrons on, to have more capacity for you all. So this is in our permitting bill and it would really, really, accelerate what we need to do in our country.

Senator Cortez Masto.

Senator CORTEZ MASTO. And you even had a prop. That was good. I like it.

Let me continue on the supply chain buildout because I think this is crucial as part of us maintaining an economic advantage here. My understanding is the high-performance magnets are crucial for fusion energy, and China controls, what, 90 percent of our global rare-earth mineral processing and rare-earth magnet manufacturing. Last year, China announced an export ban of rare-earth extraction and separation technologies. Between this action and its recent export ban on other minerals, like graphite, gallium, and germanium, it's clear they are threatening to weaponize this area, right?

And so, what steps can we do to secure that supply chain? We have talked a little bit about it, but I want to get very specific and just throw this out here. You know, Senator Mullin and I, we introduced the Rare Earth Magnet Manufacturing Production Tax Credit Act to incentivize more of this manufacturing and bring those supply chains back here, similar to what we did with solar, geothermal, all of the above, to give opportunities for bringing the manufacturing back here. Does that make sense? Should we be doing things like that in Congress or other things to incentivize building out that chain that we need here to protect?

Ms. SIEBENS. Thank you for that question. We talk about this a lot—every day at Helion as we look to build out that supply chain. For us, we are mainly thinking about right now our biggest pain points being the production of those high-voltage capacitors and the semiconductors for our machines.

Senator CORTEZ MASTO. Okay.

Ms. SIEBENS. One thing that would be transformational for us would be to actually amend the 45X Manufacturing Tax Credit to make sure that fusion supply chain pieces are eligible for that. I would love to talk with you more about other things we can be doing, but when we think about existing programs, existing incentives that simply need to be activated for fusion, this is a really good example.

Senator CORTEZ MASTO. Okay.

Dr. White.

Dr. WHITE. Thank you. Yes, I think building on that last comment, really, this idea of having technology-inclusive policies that incorporate the fusion energy supply chain into the broader clean energy supply chain are critical. There is a wide variety of different engineering concepts currently underway for fusion energy. Some may require high-performance capacitors and other electronics.

Some may require high-temperature superconducting magnets. Some may require laser technology. And so, trying to focus on any one technology may make the process of trying to build an entire industry challenging, but if we can make sure that the policies that are out there to enable either tax credits, production incentives, or other types of benefits for any fusion energy technology, I think that is a really easy way to help the entire space flourish and really allow companies to explore, maybe, other novel, innovative technologies that otherwise wouldn't be covered under any specific umbrella of one tax credit.

Senator CORTEZ MASTO. That is helpful.

Dr. Allain.

Dr. ALLAIN. Yes, thank you, Senator.

I think another aspect of this in the supply chain also is innovation, and that is why, in my remarks, I talked about building a robust fusion technology manufacturing network. And the reason why I brought up that point is, we have to make sure that the bridges that we build with public and private are not only in developing those energy systems. That is an important part, but it is also supporting the growth of that supply chain that you indicated, Senator. And to that, the international partnerships with like-minded nations is really, really important because this is the place where we are seeing, for example, right now, companies that are coming from abroad to come here to the United States, and even U.S.-based companies that are finding an opportunity in the manufacturing sector and regional hubs all across this country, all across the United States. The program needs to make sure that we are supporting the growth of those interests by ensuring that as we think about fusion, science, and technology, the technology aspect of it is prioritizing on a lot of what has been mentioned already—advanced materials.

If you look, for example, forward looking at what are some of these technologies that need, you know, some closure of gaps, we find that bridge also to the private sector and those industrials, let's say, that are providing supply chain, that is an aspect that we have to pay attention to now, not wait while the fusion developers are ready to put energy on the grid, but right now be able to do this in this timeline.

Senator CORTEZ MASTO. Yes, and I agree. I think we just need to be very strategic about what we are trying to achieve now, but also five, ten years down the road, what we need because we have to start working on it now, for that reason.

The other thing I want to touch on, and Senator King and I have this conversation all the time—nuclear waste, right? Yucca Mountain. I am from Nevada. I will just put it out there.

Senator KING. She is against Yucca Mountain.

Senator CORTEZ MASTO. I am against Yucca Mountain, but I am not against fusion, and here is why I think it's important for us to start educating the general public. This idea, the difference between fission and fusion and the waste material, because besides having an economic impact that we are having for society, there is a societal impact, right, between the two, and there is a difference about the environment and the impact to the environment. So I don't know who would want to touch on it, Dr. Allain, but can you talk about the difference between the two and the waste material—the difference, and how we, as a Congress should also be looking at the societal impacts?

Dr. ALLAIN. Yes, thank you, Senator, for that question, and let me speak from the context of what I believe is one of the key issues on waste streams for any technology that's not only energy-dense, but in this particular case, you know, you referred to fission and fusion. And these are, indeed, you know, quite different in terms of how we have to manage waste streams, and what I would like to focus on is that in terms of waste streams for fusion, I believe that there is a lot in that aspect where it's going to take innovation around fusion materials—how you design these materials, how you think about the way the materials are responding to, of course, earlier it was mentioned, you know, we are generating neutrons. They are going to be activating, and even though it's low-level waste, we still have to be very cognizant of how to manage it.

I think it's a terrific opportunity for a lot, in fact, of our performers—in fact, a lot of the expertise around fusion materials. We have over four decades of leadership in this space that we can leverage, and in fact, be able to, when speaking about supply chains, take advantage of this as an opportunity for the United States in being able to manage this waste stream properly.

Senator CORTEZ MASTO. Well, and let me just say, and I hope that is the case—I hope there is this collaboration with Congress and our brilliant minds, our scientists, around this and the future and how we manage the waste because Congress was not successful back in 1982, and still to this day, dealing with some of the nuclear waste that is out there.

Dr. ALLAIN. Right.

Senator CORTEZ MASTO. So there has to be this collaboration, and I am just hoping my colleagues, we come to the table and we work with all of you to do that.

Dr. ALLAIN. Absolutely.

Ms. SIEBENS. I just want to give, sort of, a very specific example for our company at Helion because this really stood out to me and sort of amazed me, coming from the fission space looking at our fuel cycle and our waste streams. So as I mentioned earlier, we use deuterium, which is heavy water, and helium-3 as our fuel. Tritium's half-life is only 12.3 years, and that is compared to around 24,000 years for fission waste. So when you think about something like—we never want to say this word—but Yucca, right? When we think about something like that, the reason that is necessary is because of those 24,000 years you have to think about managing this. So that is a huge shift when you talk about 12.3 years. And the best thing for us, as a company, is that the tritium that is a byproduct of our process is actually a commodity for us because in about 12.5 years, it actually decays into helium-3, which is one of our fuels. So when we think about our fuel cycle as a company, it's the most sustainable I have ever seen.

Senator CORTEZ MASTO. Thank you.

Yes, Dr. White.

Dr. WHITE. I think, really, when we talk about the difference between fission waste and fusion waste, the number one characteristic with fusion is that we will not have the spent nuclear fuel. And that is the kind of waste that was ultimately destined for Yucca Mountain. But I think as we think about different fusion technologies, there will be other waste produced during operation. And so, I think one thing that is going to be very important for the private fusion industry and collaborators around the world to really think about is, what are the disposal pathways for that waste, trying to understand what type of waste will be produced, how can we minimize those through operation, how can we think about things like material recycling to maybe reduce or reuse some of the materials that are coming from fusion machines for future machines, and then, how are ways that we can potentially process and package waste for disposal.

We already have a lot of facilities around the United States that can handle, essentially, nuclear waste that is not spent nuclear fuel. And these are facilities that are already capable of handling what we call in the industry Class A, Class B, and Class C waste, different ways of classifying material that is contaminated with radioactive material. The question will be, as we think about scaling up a commercial fusion industry, how can they make choices on advanced materials, on the way they are operating the machines, on the way they are maintaining their machines, and on their entire maintenance and decommissioning strategy to make sure that fusion waste is not a burden and is not a barrier for fusion energy moving forward. And I think that is going to be a really exciting, innovative place over the next few years as we think about commercializing the industry.

The CHAIRMAN. Senator, the only thing I would say about Yucca Mountain, they could have picked a better name.

[Laughter.]

The CHAIRMAN. But the Yucca plan, I understand that they could have figured something out.

Anyway, with that being said, we are going to go to Senator Cassidy.

Senator CASSIDY. Thank you all.

Dr. Allain, I have a lot of—I am from Louisiana, and I have a lot of petrochemical refineries. They have a real interest in decarbonization. And I gather that some of the industry in my state are actually—like Dow, and I think Air Liquide—are looking at fusion as a way to decarbonize. Any comment upon that? If somebody was watching from back home? Speak to that please.

Dr. ALLAIN. Thank you, Senator, for the question. So you know, we have a number of different private-sector entities that are pursuing fusion in different ways and different approaches to fusion energy. I think what is exciting right now is what you are seeing as this—the beginning of convergence between the public and private sector, which is enabling us to be able to leverage the public sector know-how and expertise to be able to truly accelerate our pace toward fusion energy.

Now, of course, as you talk about timelines, you know, I mentioned this in my remarks earlier, you know, for us to reach fusion energy at the decadal timeframe, we do have to close out the remainder of science and technology gaps that do exist. There are aspects of the technology, for instance, that the private sector is aggressively going after. And in fact, there are designs and prototypes that are being built at a rate of one and a half to two years, which is an incredible pace to see that in the private sector. And so, I see that the question in terms of the timeline is one where as long as we can build that bridge between the public and private, we are going to be able to get the expertise needed on some of these outstanding gaps that are needed for us to get there in a decadal timeline.

Senator CASSIDY. So let me ask—by the way, your name would fit right at home in Louisiana.

Dr. ALLAIN. I know. Allain. It's a French name, yes, Senator.

Senator CASSIDY. Allain and Jean Paul, you know what I'm saying?

Dr. ALLAIN. That's right. Thank you very much for pronouncing it like that.

Senator CASSIDY. So we are talking about USG investment, but I am hearing from you that there is significant private investment. And so, and everybody is nodding their head. So, to what degree is that private investment supplanting—no, augmenting—again, if we are looking at how do we invest, we want to do it wisely.

Dr. ALLAIN. Yes, right.

Senator CASSIDY. And so, to what degree is that private investment, that public-private—I mean, Dow really wants to do this. Air Liquide really wants to do this, et cetera. Can we take that into account to say well, wait a second, in competing priorities, we know the private sector is really stepping up—that sort of thing?

Dr. ALLAIN. Let me maybe answer this question this way, Senator, and I think this is a great question that, you know, like my colleagues here, also to address, it's a question of being very thoughtful, methodical, and strategic as to how those investments are made. The question we are asking right now in our public program is precisely this, in a dialogue with the private sector—where are the common gaps that many of, for example, our private sector, companies are, in fact, stepping up and saying here is a common gap that, right now, our investments are very much focused on the development of our technology, specifically, but there are common gaps where we need help.

And this is where the government is coming in, very aggressively, to say, look, let's look at our program. Let's make sure we are realigned toward those gaps and make sure we aggressively invest——

Senator CASSIDY. So there is some concern that China might be spending more on this, but that would be CCP—they are China Inc., okay, my understanding is that there is no public-private, it is China Inc, whereas, in our case, we are speaking about USG but we are also having public investment, and then, I think I know that we are a part of that French initiative in which there are other countries that are there.

Dr. ALLAIN. Yes.

Senator CASSIDY. So put that all together, and how much should we be concerned that China Inc. is spending more than we, as opposed to know if you put it all together, we are, you know, hitting it right?

Dr. ALLAIN. Yes, this is a great question. There is a significant investment needed to translate fusion technology. There is no question about that.

Senator CASSIDY. That's not my question because the private sector is helping to translate, right?

Dr. ALLAIN. That's right, but the question is more of how you prioritize those investments, right? And the key piece here is, again, making sure we take advantage of that public and private exchange and connection that says——

Senator CASSIDY. But my question—I get that.

Dr. ALLAIN. Okay.

Senator CASSIDY. My question is, if X amount of money is spent, and let's assume that we are actually wise and we use our federal dollars to fill in the gap between what the private sector is doing.

Dr. ALLAIN. Sure.

Senator CASSIDY. And we know that we are part of this multinational initiative in France, which we all share the technology. I think we want to know how to prioritize our spending.

Dr. ALLAIN. Sure.

Senator CASSIDY. We don't want to fall behind, but wait a second, between the private sector and our international partners, plus what we are doing, we are doing okay, but no one ever says we are doing okay.

Yes, ma'am.

Ms. SIEBENS. I think this is a fantastic topic to bring up because I will say that what matters the most for us right now, when you talk specifically about a race with China, is the amount of money that China is spending on commercially relevant programs, right? And so, for us, I can speak for Helion, specifically. We are looking at the race that begins after we demonstrate, and that is building out the supply chain here in the United States and with our allies to make sure we can deploy it to scale to actually win this race with China, but also, looking at how we can utilize the funding that already exists within the Department of Energy to focus more on applied materials research and development, again, commercially relevant R&D that is going to help these machines that we are trying to deploy now.

And the Fusion Industry Association has done some fantastic work on actually breaking down what the spending looks like——

Senator CASSIDY. So I think what I am hearing from you is that it's not only that, you know, of course everybody always wants more money authorized.

Ms. SIEBENS. Right.

Senator CASSIDY. And everybody always wants more appropriated.

Ms. SIEBENS. Yes.

Senator CASSIDY. But our oversight could also be directed toward making sure that the money is spent wisely.

Ms. SIEBENS. Precisely. I think that we—certainly, as you say, more money is always nice. But yes, I think that there are ways that we could better strategically utilize what we already have, yes.

Senator CASSIDY. Sir.

Dr. WHITE. Yes, thanks, Senator.

I think another really important thing to think about when it comes to federal funding and the private fusion industry is really the multiplicative effect of federal investment into private fusion companies. Early-stage grants can help take innovative fusion concepts that otherwise might struggle in private markets and help them get to the level of demonstration where they can go out and actually get VC funding for their ideas or help them demonstrate early-stage technologies that then can enter into the national lab program for other grants. And also, getting a grant from a DOE program like the DOE's Milestone Program for Fusion can have a huge impact on companies to really give private investors some confidence that the experts at DOE have looked at this technology. They think there is something there worth investing in. So it can have a huge impact in helping to bring even more private capital, I think, into the private fusion space.

Senator CASSIDY. So you are adding nuance to what Dr. Allain said, which is that—I had to put a little French inflection on it—Dr. Allain said, in terms of doing the common gap and what Ms. Siebens said, okay, we have got to commercialize, and you are putting a little bit more of a drill down—here is a specific place to plant that seed corn more effectively.

Dr. WHITE. Exactly, Senator.

And I think the other thing is really identifying those cross-cutting issues, like materials research, like fusion fuel cycle, like tritium handling, these things that are going to be needed for almost every company in the fusion sector that might be too large of a lift for any one company to do alone, but if we can really use——

Senator CASSIDY. But—I'm sorry, one more question.

Dr. WHITE. Yes.

Senator CASSIDY. But we have this international consortium that is doing it in France. I assume that they are all doing this sort of thing. Do we need to reinvent that?

Dr. WHITE. So the international consortium is really going to be focused on scientific demonstration of kind of a net fusion energy machine. It very much is a scientific demonstration device. It might not necessarily go as far into some of the advanced materials research and commercially relevant technology development that are needed.

Dr. ALLAIN. If I may add to this point, Senator. To realize fusion energy, it's going to take multiple, multiple actions in parallel, not just, for example, that particular consortium you are talking about, but multiple ways for us to leverage international partnerships. This is why in an international partnership plan and strategy for the U.S., we are engaging like-minded nations to, in fact, address the very topics that we just talked about, but to do it in a way where we can invest together and basically make sure that we are multiplying the resources that we already have.

Senator CASSIDY. Got it. Thank you very much for your forbearance, Mr. Chairman. I yield.

The CHAIRMAN. Thank you.

Senator Hickenlooper.

Senator HICKENLOOPER. Thank you, Mr. Chair, and thank all of you for your work and for being here today.

The CHAIRMAN. Turn your speaker on.

Senator HICKENLOOPER. I turned it on.

The CHAIRMAN. Now it's on. Well, speak into it then.

[Laughter.]

Senator HICKENLOOPER. He is obviously in a finicky mood.

The CHAIRMAN. No, he is my dear friend. I can speak to him that way.

[Laughter.]

Senator HICKENLOOPER. Dr. Allain, recently DOE funded three laser fusion research hubs—$42 million over four years—to bring together researchers from academia, national laboratories, and from industry to begin to address all the technical challenges that are being discussed already to this path for commercializing fusion. Colorado State University is breaking ground soon on a $150 million facility that will house three very high-power lasers. And this will be, obviously, a unique facility, but really trying to build on those public-private partnerships. How will DOE work with Colorado State University to help commercialize this process?

Dr. ALLAIN. Yes, thank you very much, Senator, for that question.

A little over a year ago, in fact, I was in the State of Colorado celebrating our IFE hubs with the community of over 500 scientists and engineers, very excited about the prospects of these new programs that we have established in FES. So as I mentioned earlier, I think the bridge between the public and private sectors is key for us to be able to advance and support commercialization. Inertial fusion energy is one example of this, of what we are doing today. You know, historically, of course, as you know, with the facilities at NIF at Livermore, you know, the NNSA has a very specific mission, right? And we have seen that we have been able to leverage all the great strides that have been made in that science to now really focus on the engineering of realizing fusion, in this case, from inertial fusion energy sources.

Part of the activity now with these hubs is, in fact, to identify, as we mentioned earlier, these common gaps that are coming up—you know, we keep talking about things like materials and fuel cycle, et cetera. The activity that is happening at Colorado State is also reflecting on this other message that I talked about, which is the engagement of state-level government—local and state governments, academia, national labs, and the Federal Government. This partnership with the private sector, in this case, Marvel Fusion and some of the other actors there in Colorado, is just another example of what is happening here in the United States, which is that we are seeing this catalyst of investments that are really driving the move from just science-centric questions more to technology development. So it's very exciting.

Senator HICKENLOOPER. Right, and I think we can argue that that process of that high-level integration and collaboration is very different than what happens in China, you know, our rival.

Dr. ALLAIN. And I will add also, Senator, that that activity in Colorado is uniquely tied right now with another like-minded nation-partner of ours, in Germany.

Senator HICKENLOOPER. Right.

Dr. ALLAIN. We were just there last month. We took a U.S. delegation of ten scientists and engineers there that represented basically the whole landscape from our program because we are really focused on making sure we identify the ecosystems that will support not just the science, but the technology development. In fact, the supply chains related to laser systems—a lot of the components, you know, that go into development of these high-powered lasers, that was the central piece of our discussions in our partnership with Germany.

Senator HICKENLOOPER. Yes, you are right, that is just an added dimension that goes beyond the rivalry of what China has.

Ms. Siebens, let me ask you a question—in this critical race with China—sometimes I wonder what we would do without China. Where would we get the sense of urgency that is usually necessary to these kinds of achievements? But we are in a critical race in this great transition of global energy to a cleaner future. And fusion really does have the potential to revolutionize this in so many different ways, and especially as we get toward affordability, enhanced not just environmental safety, but security increases. And yet, by some measures we are still falling behind China, as you guys have pointed out. So can you elaborate a little more in detail on some of the investments China is making in fusion and how Congress and the Administration can take steps to regain the advantage?

Ms. SIEBENS. Thank you for the question, Senator. So I will start with two very specific examples that Helion has been watching closely. The first is that ENN Energy Research Institute's Helong experiment announced a program pretty much right after we announced that our last machine, Trenta, had reached 100 million degree temperatures, and they actually published a schematic that was identical to Helion's concept. So they are not shy about this, right? Another example is that China's HHMAX recently acknowledged Helion's approach is the fastest to commercial power and then publicly stated its intent to replicate our design. So again, not shy about it, right out front.

But the other piece that I want to keep coming back to, to really hone in on, is once again on that supply chain. They have a track record of success in really locking down supply chains for things that we innovate here and really demonstrate first in the United States. And so, I think that that is a very important area that we need to be thinking about now and working together to put together a policy framework that we can really kick off quickly after we demonstrate so that we can make sure that we aren't relying so heavily on China as we move to scale.

Senator HICKENLOOPER. Yes, Dr. White.

Dr. WHITE. Yes, Senator Hickenlooper, if I can just provide a little bit of additional context—I think it's important, if we think about those different phases of technology development, what does it mean for a scientific demonstration, an engineering demonstration, commercial demonstration? China has a plan for each one of those phases. The BEST tokamak, which is the Burning Plasma Experimental Superconducting Tokamak that they call "BEST," is currently under construction in China, and that will serve as both a scientific and engineering demonstration for their technology. And they have already announced plans for their China Fusion Engineering Test Reactor, or CFETR, that is essentially going to be a demonstration fusion machine. In addition to that, they have their CRAFT facility, which is kind of a cross-cutting technology R&D facility that is going to address many of the materials science, enabling technologies, and fusion fuel cycle issues that are really cross-cutting for all technology concepts. So it is really seeing that they have a plan for scientific demonstration, engineering demonstration, and commercial demonstration at a federal level as part of a plan.

Senator HICKENLOOPER. Right.

Dr. WHITE. And so, that's, I think, what we are really trying to compete against to make sure that we have a matching plan to get to commercialization.

Senator HICKENLOOPER. I agree, and that is where our collaboration gets a little bit—makes that more of a challenge. Anyway, I appreciate that.

The supply chains, we see the same thing in critical minerals, that they are building supply chains that are more cohesive and become the determinative, they make it harder for us to build our supply chain.

The CHAIRMAN. Senator Murkowski.

Senator MURKOWSKI. Thank you, Mr. Chairman. Good discussion this morning. Thank you all for being here today.

You know, we are talking collaboration, we are talking partnerships, and these are key, these are great. They are all important, really, an essential part of driving our nation's success and leadership in so many of these emerging technologies. But now, let's talk about China and how it fits into the picture to make sure that we have appropriate safeguards that are in place while we engage in these partnerships. And the ITER project has been referenced. The fusion facility in the south of France gets support from a number of nations, including China. So as we are participating in this, contributing funds, the research, the hardware components, how are the U.S. technologies and resources being safeguarded against program partners that may be adversarial to certain of our interests? How do you manage that aspect of it? And I think this is to you, Dr. Allain.

Dr. ALLAIN. Yes, thank you so much, Senator, for the question. And indeed, as mentioned earlier, it is important, not only to be, you know, not only to safeguard, in fact, the innovation and know-how and expertise of our performers, but make sure that we have instruments and elements for us to be able to safeguard that.

The reference to ITER is that it is an international project that indeed is engaging seven nations, seven countries. The way that we have worked toward this is, you know, the focus is all on the in-kind hardware and contributions that we provide that project. That is one aspect of it, right? And the nature of the—let's say, the contracts that go in, in terms of that hardware and in terms of the know-how behind that, of course, as IP, that is protected. There are aspects, of course, of ITER, since it is still and remains a scientific project, that that is open. For example, there are aspects, for instance, in terms of, you know, know-how or technical expertise that could be shared. And that is all under very specific, you know, agreement between, of course, those that are engaging the project—in this case, the ITER organization and those contracts and the language around those contracts.

But I can tell you and assure you that, you know, the aspect that has to do, for example, with the impact on U.S.-side supply chains, that is very much protected by, you know, again, agreements that protect IP of those that are engaging and delivering the in-kind hardware to this project, and also those that may be interested in accessing that information. It's not information that is readily available unless they are going through a very specific step and process to access that data and that information.

Senator MURKOWSKI. So you feel relatively comfortable in the safeguards.

Let me ask you, Ms. Siebens, because your testimony highlights China's efforts to replicate some of Helion's own prototypes. And as you are aware of this, can you share if they have been successful in engineering their own versions of these technologies based off this information?

Ms. SIEBENS. Thank you for the question, Senator.

As of this time, I do not believe that is true.

Senator MURKOWSKI. Okay.

Ms. SIEBENS. But they are working very hard to try and replicate. One thing I can say is that, when we think about how do we protect our IP as a private company, one of the ways that we do that is by focusing on building and demonstrating a machine versus sort of writing about what we are doing and sharing it on a constant basis, right? And I think this has been sort of a paradigm shift that we have seen happen in the fusion ecosystem after really just the past ten years, where predominantly this has been a science taking place in academia and in an environment where it is absolutely the culture to share across country boundaries and really have this be collective efforts, whereas, now that we are shifting to—this is very near-term and we are bringing something to the grid soon. That is where you sort of shift into a place where we are going to be nose-to-the-grindstone focused on actually demonstrating this and not necessarily sharing everything that we are working on, yes.

Senator MURKOWSKI. So let me ask about that because that is where I see things with excitement. It has been talked about how fusion can make a difference when we are looking at increased energy demands. We have talked about clean power to areas like manufacturing, mineral processing, data centers. We all see that. Can any of you share with me what you think the potential is to address energy and reliability challenges when we are in remote and very rural areas? Obviously, I come from a state where we are very challenged with how we are able to provide for energy resources in remote places, say for instance, say a mine that is out in, literally, the middle of most nowhere. Can you speak to that? Dr. White.

Dr. WHITE. Great, thank you, Senator Murkowski.

So I think this is where we start talking about how to set up that clean energy grid of the future, especially in remote locations. How do we think about balancing the intermittent or the variable and renewable sources that are there, storage, and then firm clean energy? And I think fusion energy has the potential to be a very effective firm clean energy source that can help power those communities. The question will really end up becoming how do private companies develop machines of different sizes, of different capabilities that match up with the needs for those different customers? What does it mean to provide heat and electricity to a small community versus trying to provide and meet the energy needs for a large industrial user, like a mine?

And so, I think this is an opportunity for the private industry to really work with different stakeholders and different potential customers, like those in Alaska, to really identify what are the energy products they should be prioritizing and they should be working on. In some cases, we may want a fusion machine that produces 500 megawatts of electricity and power half a million homes. Sometimes, you might want one that can power five megawatts and really meet the needs of a small community. And I think that is something that we are seeing the private fusion industry really try to identify and develop.

Senator MURKOWSKI. So Helion, let's use you as an example here. Would Helion look at opportunities to demonstrate certain technology in specific areas in Alaska, and what would you be looking for in terms of being able to site something?

Ms. SIEBENS. Absolutely. Thank you for that question, Senator.

So our machines, our systems, are very well-suited for siting in remote communities. And there are a couple reasons for that. The first is that we have a very small external power demand. We have a pulsed system. That is what we use in our machine. And all we need external power for is to draw in and create that first pulse before we sort of keep that machine running. And that is not a lot of power. We could actually use solar panels on the roof of one of our buildings to kick-start that, or a small generator, if it's attached to the building.

The other thing to mention is the actual small footprint of our facility. So for a 50-megawatt plant, you are looking at around, under 30,000 square feet for the entire facility, and that is about the size of a football field. So small community small.

Senator MURKOWSKI. Did you say 15 or 50?

Ms. SIEBENS. Fifty-megawatt.

Senator MURKOWSKI. Fifty-megawatt.

Ms. SIEBENS. And then the other thing is, 24/7 power, so you have that consistent, reliable electricity. And the actual fuel that we use is, again, very small amounts that we actually need onsite. So we would not need, you know, a lot of land for extra fuel storage either. So I think we are very well-suited and very interested in looking at applications in Alaska.

Senator MURKOWSKI. Good, very interesting.

Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator.

Senator Hoeven.

Senator HOEVEN. Thank you, Mr. Chairman.

Where is your sidekick today?

The CHAIRMAN. He knew you were coming.

[Laughter.]

Senator HOEVEN. Scared him off? Well, when Senator Murkowski leaves that means I am the ranking Republican.

The CHAIRMAN. You can take over. You could be Chairman, if you want.

[Laughter.]

Senator HOEVEN. Maybe we can do some serious business.

The CHAIRMAN. We are just so happy to have you.

Senator HOEVEN. You are a good man.

Thanks to all of you for being here. I guess my question is, you know, we talk about fusion being the energy source of the future. What's to say it's not always going to be the energy source of the future, right? You have heard that before, meaning, gee whiz, it seems to be a long time in coming. I mean, I can remember as a little kid, my dad talking about fusion being better than fission and you know, reading stories about the supercollider and the effort in Texas and you know, this has been going on for a long time. So I guess my question is, you know, is it really going to happen? When is it going to show up, commercially? And is it going to show up in these smaller applications or the larger applications? And you can—you all get a shot at this one in any order you want.

Dr. ALLAIN. All right, thank you, Senator, for the question, and of course, you know, I am sure there will be very good answers for this one.

We have to remember that many of the major novel technologies that we live in today took a long time to get there and translate. I mean, this is a reality. I will say that what is wonderful that is happening today, as opposed to even just ten years ago, you can go to, you know, Devens, Massachusetts and go over to Everett, you know, Everett, Washington and watch what is happening in the private sector. It's a daily grind, it's a daily race, if you will, in building prototypes toward fusion energy demonstration. That is exciting.

Our program, in fact, now that I have been in this position now for a little bit over a year, as a material scientist and engineer myself—a nuclear engineer—it's also exciting to see the fact that in our program, we are also trying to really rethink how we are thinking about fusion. And you are right, it has always been this 20- to 30-year outlook on when is fusion going to be ready. What gives me confidence and comfort, actually, is seeing all of the technology developments outside fusion that are impacting fusion energy development today. I mentioned earlier AI/ML. There are advances, for example, in high-temperature materials also that we are taking advantage of.

So what you are seeing, Senator, is a convergence of a lot of these technologies that is helping accelerate many of the approaches, that we are seeing the over $7 billion investment in the private sector realized.

Senator HOEVEN. So that means we are going to be actually using it in a commercially viable way when? Next year? Two years? Five years?

Dr. ALLAIN. So the timeline, I think, that we are really focused on right now, it's making sure that the science and tech gaps that we do have on some of these approaches are addressed right now, right? In a decadal time frame, that has been the focus. We are looking at, you know, in the 2030s, for us to be able to see those fusion pilot plants, which are demonstrating that all of the integration of these technologies that are on the path toward realizing, let's say, electricity on the grid, but there are some approaches, in fact, that can get there even faster, and I will——

Senator HOEVEN. But when you say the 30s, that still sounds like we are ten years away.

Dr. ALLAIN. Well, you know, again, so the question is technology development and translation. It does take time, right? And so, the question is, and your question is alluding to what timescale that is.

Senator HOEVEN. I am not alluding to it. I want you to tell me specifically when we are going to be using fusion because that is the same answer you could have given five years ago——

Dr. ALLAIN. Right.

Senator HOEVEN. Ten years ago, 15 years ago.

Dr. ALLAIN. What I can tell you is that in the last decade we have made significant strides to be able to close a lot of these science——

Senator HOEVEN. But you are still not telling me that within five years we are going to have a commercially viable pilot project and it's going to look like this. That is what I am asking.

Dr. ALLAIN. Sure.

Senator HOEVEN. And if you can't tell me that, I understand, but that is the specific question I am asking.

Dr. ALLAIN. Sure.

Senator HOEVEN. Because your answer could have been given—we could have been sitting here ten years ago and you could have given that answer.

Dr. ALLAIN. Yes. No, I appreciate the question, Senator. I think the answer, at least the way I would like to respond to this is—the fact that we are making strides in being able to close those gaps and we see that in the next half-decade to decade.

Senator HOEVEN. Yes.

Ms. SIEBENS. I would love to give you a very precise answer to this question. We are on track to have the first-ever commercially operating fusion plant in 2028, providing power to Microsoft. We have a firm power purchase agreement with Microsoft.

Senator HOEVEN. What is that going to look like?

Ms. SIEBENS. What is it going to look like? So for us, the actual fusion machine itself is something called a pulsed system, and I am happy to go after the hearing and dive into all the tech weeds on that, but essentially, it's a machine——

The CHAIRMAN. Just explain, if you will.

Ms. SIEBENS. Yes.

The CHAIRMAN. The magnet that we have seen in ITER versus the pulsed system, just, it might help Senator Hoeven and help me too.

Ms. SIEBENS. How we are different?

The CHAIRMAN. Different—how is the pulsed different from what the ITER——

Ms. SIEBENS. Right, sure. I love talking about this, yes.

So back in the '40s and '50s, when fusion was really emerging as a concept, there were pulsed concepts were actually already under consideration back then, along with the tokamak design, which is what you are seeing out in ITER. And so, the main difference here is that you have a steady-state design, which is what ITER is, where you are trying to actually contain long-lived plasma that needs to be contained for a long period. Whereas, a pulsed system is actually saying no, let's actually just do small amounts of fusion in very quick increments, repeatedly. And so, that is really the difference. And it helps reduce the size of the machine significantly.

The CHAIRMAN. Does the pulsed—I'm so sorry.

[Laughter.]

Senator HOEVEN. No, I am good with it as long as you are.

The CHAIRMAN. I just want to know, does the pulsed enable you to ramp up and ramp down, basically?

Ms. SIEBENS. Yes.

The CHAIRMAN. More so, because when ITER, when she is—it has got to produce.

Ms. SIEBENS. Yes, so precisely. So for our machine, we could pulse one time every minute. We could pulse ten times per second——

The CHAIRMAN. So basically, you could operate on the demand.

Ms. SIEBENS. Yes, and we can do that in real time, so it doesn't take long for us to ramp up.

The CHAIRMAN. You have already perfected that technology?

Ms. SIEBENS. Yes, so with our last prototype that we called Trenta, we had over 10,000 fusion pulses with that machine. And that is really what is giving us the confidence that we are going to be able to demonstrate electricity production with our seventh machine, which is on track to be completed this year.

Senator HOEVEN. So when you say 2028, are you talking about a pulsed system?

Ms. SIEBENS. That is correct.

Senator HOEVEN. Okay. So, but keep going now.

Ms. SIEBENS. Yes. Okay.

[Laughter.]

Senator HOEVEN. I know the Chairman is going to give me a little more time now because it's a collaborative——

Ms. SIEBENS. Yes.

[Laughter.]

Senator HOEVEN. This has turned into a collaborative process.

The CHAIRMAN. I was going to commend you on a great question.

Senator HOEVEN. Yeah, which I think is really good because I really—you said, okay, you said 2028. Good for you. Now, it may happen. It might not happen, but at least it starts to give us a feeling of okay, we can look toward something.

Ms. SIEBENS. Right.

Senator HOEVEN. Now we want to know what you think it's going to—so, you are thinking 2028?

Ms. SIEBENS. Yes.

Senator HOEVEN. And we want to know what it looks like.

Ms. SIEBENS. Right, yes.

Senator HOEVEN. So just elaborate a little bit more on what this looks like.

Ms. SIEBENS. Right. So——

Senator HOEVEN. And I mean, you know, what it looks like in terms of how it works and what it's going to do.

Ms. SIEBENS. Sure.

Senator HOEVEN. Like, it's going to run some guy's lawnmower or whatever.

Ms. SIEBENS. Right. So in this instance, we are thinking about the power needs of Microsoft, our customer, largely for data centers. And this first plant is going to be 50 megawatts, and the footprint of the facility will be approximately the size of a football field, just under 30,000 square feet, and that is the full perimeter of the site. And when we turn the machine on, we will be able to, as Senator Manchin alluded to, we will be able to actually ramp up or down depending on what the needs are for our customer.

Senator HOEVEN. Wow.

Ms. SIEBENS. And then, ultimately, we also have an agreement with Nucor, the largest steel producer in North America, to deploy a 500-megawatt facility.

Senator HOEVEN. Okay, but before you get beyond it, okay, you are talking, so a facility the size of a football field. It's a 50 megawatt?

Ms. SIEBENS. Correct.

Senator HOEVEN. And you can ramp up and down how much of that megawattage you provide, so it's variable?

Ms. SIEBENS. Correct.

Senator HOEVEN. And once you have built it, does it just run? Is it like nuclear fission, where it essentially, you don't have that ongoing fuel cost? I mean, it costs beaucoup to build the thing, right? We get that. But at that point then, does that sucker just, I mean, run until Manchin is like 250 years old, or, I mean?

[Laughter.]

Ms. SIEBENS. So we will need to——

Senator HOEVEN. You know, I mean like—and that is the promise of this stuff——

Ms. SIEBENS. Right.

Senator HOEVEN [continuing]. Is that if you put it in a spaceship and you go to, you know, Neptune and back, you never need to refuel it, right?

Ms. SIEBENS. Right. So we do have, I mean, so because it's a pulsed system, and with any system, you are still going to eventually add more fuel to the system. For us, we are puffing our fuel—the deuterium, the heavy water, and the helium-3 into either side of our machine.

Senator HOEVEN. Well, but that is part of my question is——

Ms. SIEBENS. Yes.

Senator HOEVEN. Do you have to keep refueling because the promise of this——

Ms. SIEBENS. Right.

Senator HOEVEN. Is that it powers forever, basically, once you build it.

Ms. SIEBENS. Right.

Senator HOEVEN. So that is my question.

Ms. SIEBENS. So for us, yes. We do need more fuel to——

Senator HOEVEN. And that would be what?

Ms. SIEBENS. But, so, for us it's the deuterium heavy water—very cheap—and helium-3, which is kind of funny—it's not widely available naturally on Earth, so we get some pretty crazy questions about folks that want to go mine the moon for us. But actually, we can create helium-3 right here on Earth.

Senator HOEVEN. But see, this is the part of the question that really matters because otherwise you might as well be putting in gasoline or something else, if you have to keep refueling, right? That diminishes the applications that we are trying to develop this for.

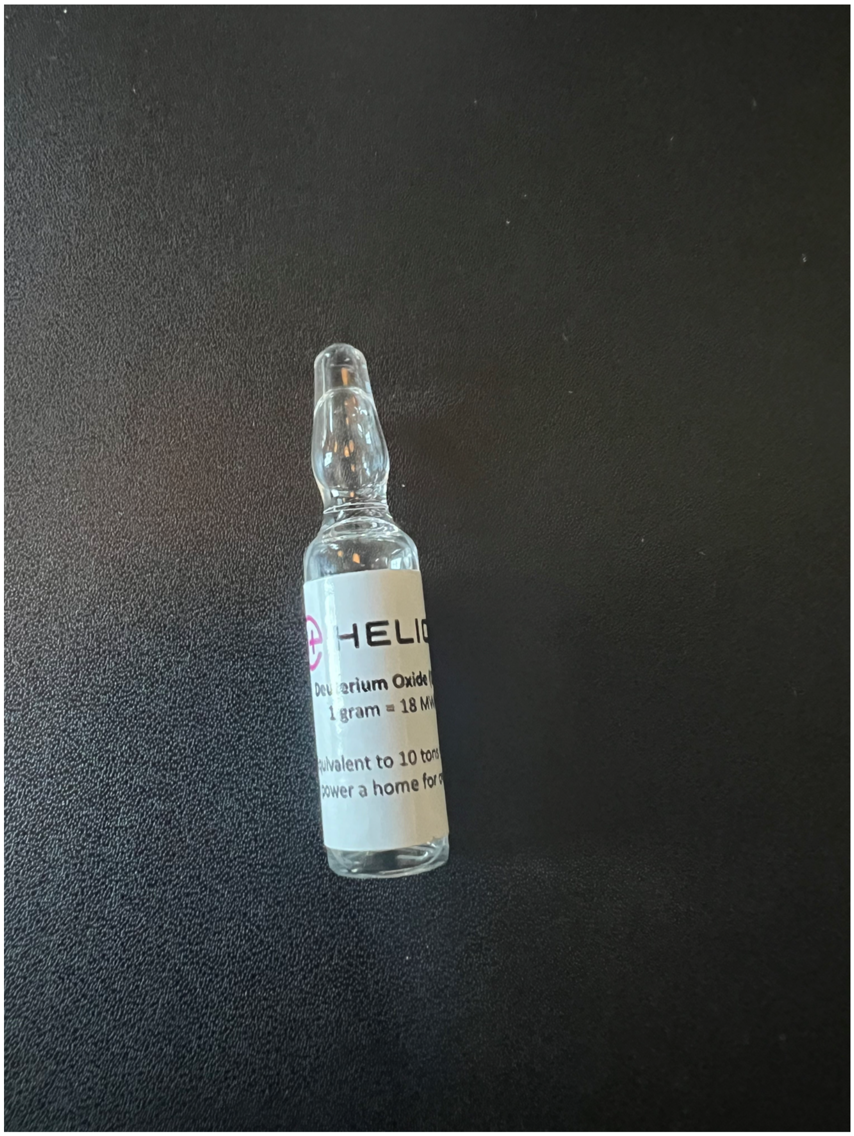
Ms. SIEBENS. Right.

Senator HOEVEN. For example, a rocket ship that will fly all over, you know, to galaxies beyond, you know?

Ms. SIEBENS. Right.

So I don't actually see it as a challenge when it comes to our fuel, and there are a couple reasons why. It's widely abundant and very cheap. So deuterium, for example, I am holding some right here.

[Photo of deuterium sample follows:]


HELI
Oxide
1 gram = 18
to 10
power a home

Ms. SIEBENS. So it's heavy water. You could even drink it if you wanted to. I don't really want to, but you could. And so, the reason I mention this is because water is readily available and abundant on planet Earth, and we don't see any time frame in the future where we will run out.

Senator HOEVEN. So when you say heavy water, it's kind of like it's available almost like water.

Ms. SIEBENS. Precisely. That's right.

Senator HOEVEN. Okay. Good.

Ms. SIEBENS. And then for the helium-3, actually, helium-3 is a by-product, first of all, of our fusion—our system. And so, we are actually creating more of the fuel we need just by running our machine. We can also create a separate machine that is just deuterium and deuterium fusing, and the by-product of that is helium-3. So all of this is very cheap and provides a very sustainable fuel source.

Senator HOEVEN. So fission has the problem of the by-product, you know, that you create nuclear radioactive material.

Ms. SIEBENS. Correct.

Senator HOEVEN. And what the hell do we do with it, right? If you can't completely reprocess it, nobody wants to store it, right? We think of Yucca Mountain as a great example. But the nice thing about it is, if you have it in your nuclear carrier, you drive all over the world for a long, long time and you don't have to refuel anywhere, nor do you have to carry any fuel, right? That would be an advantage of fission over fusion.

So again, as you develop this new energy source, for folks that are more into common sense because they were not good enough in math to be an engineer or a scientist, like me, I am trying to understand, okay, why is it we are spending a lot of money on this thing? When are we going to see a benefit? And how is that going to be more beneficial than other energy sources? And that's why what you are telling us now, I think, is really important compared to all this kind of theoretical stuff. This is the stuff where the rubber hits the road.

Ms. SIEBENS. Yes, and I would just say that the fuel itself is actually significantly cheaper for, at least for our system, than when you think about uranium that is used or high-assay low-enriched uranium for some of these advanced reactors, but the fact of the matter is, is that regardless of whether you are using a fission system or fusion system, you do have to refuel. So even in our existing nuclear power plants, you are usually looking at about a year-and-a-half refueling cycle there. Same thing with our submarines that used high-enriched uranium. You still ultimately have to refuel those.

Senator HOEVEN. After how many years?

Ms. SIEBENS. So right. So I think that is still a challenge. I would say that our fuel amount that we use for just a month in one of our systems can essentially be held in a canister the size of a bowling ball. So very small amounts.

The CHAIRMAN. Let me just say one thing. You mentioned that a 50-megawatt is the size of a football field—50 megawatts. What is the size of 500 megawatts?

Ms. SIEBENS. So we are currently working on the design for the Nucor facility, but not significantly larger. The actual fusion machine itself won't increase in size that much. What will is the footprint of the power electronics that support the direct electricity capture that we have that then puts that electricity to our customer.

The CHAIRMAN. Nucor is the new plant they are building in West Virginia.

Senator HOEVEN. Oh.

The CHAIRMAN. Yeah, that's where it is, and they have a contract with them now, partnering up to see if they can basically run their steel mill off of fusion.

Senator HOEVEN. Chairman, that is why it's important we pin these guys down on when we are going to get this. You and I aren't going to be around that much longer.

The CHAIRMAN. Right.

Senator HOEVEN. We're on the clock here.

The CHAIRMAN. I'm just saying, I think you'd like to have some of the heavy water to get to Neptune. Where did Neptune come in?

[Laughter.]

Senator HOEVEN. Well, I was trying to think of Pluto, but Neptune came to mind quicker.

The CHAIRMAN. Okay.

Senator HOEVEN. I was actually looking for a Star Trek reference, but——

The CHAIRMAN. Neptune was good.

Senator HOEVEN. Yeah.

The CHAIRMAN. Let me just say to all three of you, this has been extremely helpful for all of us. We know it's something that is coming. It's something that is needed. We are looking everywhere we can to energize our country for the demand we are going to have with the new data centers and everything, and we have had hearings on the constraints we are going to have if we don't, basically, have this new technology. We have invested, I think, in so many ways. The IRA and the Bipartisan Infrastructure bill have given us more opportunities to bring things to fruition that we share with the rest of the world. So I want to thank you for that.

All members are going to have until the close of business tomorrow to submit additional questions that we haven't asked today.

I want to thank you again for coming, and with that, we are adjourned.

[Whereupon, at 11:56 a.m., the hearing was adjourned.]

APPENDIX MATERIAL SUBMITTED

EPRI

TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

A Review of Fusion Confinement Types

INTRODUCTION

Increasing global energy demand and aggressive decarbonization goals are driving innovation throughout the energy sector. Fusion, long sought after as a source of sustainable, non-emitting, scalable, firm energy, is experiencing a surge in private investment and media coverage due, in part, to a number of recent advancements in both public and private efforts [1].

What is fusion? Does the taunting phrase "fusion is always 20 years away" still apply, or is it truly nearing commercialization? After a three-decade hiatus, EPRI is returning with a new strategic focus on fusion energy that includes technology scouting and assessment. Addressing questions on the viability of fusion as a future commercial energy option is one of the primary goals of this new EPRI fusion energy strategic program. In this briefing, three broad categories of fusion energy technologies are reviewed. Specifically, magnetic, inertial, and magneto-inertial confinement are common confinement methods used to manage and control the fusion fuel and reactions to produce a sustained net energy output.

FUSION EXPLAINED

Fusion is the process by which lighter elements such as hydrogen combine to form heavier elements, releasing energy (Figure 1). Because the process of fusion involves the nucleus of the atom, not just the electrons as in chemical processes, fusion is a nuclear process. As lighter elements combine, there is a tiny mass difference (Δm) between reactants and products. This mass difference is converted into released energy according to the famous equation $E=\Delta mc^2$, where c is the speed of light in a vacuum (a very large number). Fusion occurs across the universe every day, powering the sun and other stars for billions of years.

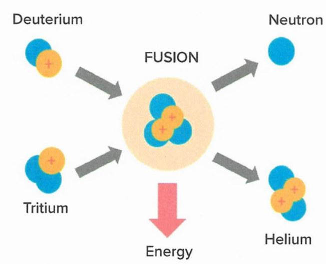


Figure 1. Fusion of deuterium and tritium, two isotopes of the element hydrogen, forming a helium nucleus and releasing a high energy neutron.

While fusion reactions are readily achievable in the laboratory and even in industrial neutron sources [2,3], self-sustaining fusion reactions in which more energy is released than is consumed by the overall facility (engineering gain) have yet to be achieved on earth. Fusion is challenging because it requires positively charged nuclei that normally repel one another to come in close enough contact for the strong nuclear force (that binds the nucleus together) to take over. Therefore, special conditions must be satisfied.

WHO'S WHO OF HYDROGEN

Atoms with the same number of protons that differ in the number of neutrons are called isotopes. Generally, isotopes of the same element exhibit similar chemical behavior but can have very different nuclear properties. For example, some isotopes of lead (Pb) can be stable and others radioactive. For fusion, the lightest element hydrogen plays an important role as a fuel, but that role varies by isotope. Hydrogen has three isotopes:

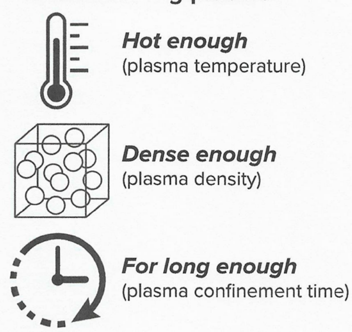
^{1}H (Protium): "light" or "ordinary" hydrogen. Protium consists of just one proton and no neutrons.
^{2}H (Deuterium): "heavy" hydrogen. Deuterium consists of one proton and one neutron.
^{3}H (Tritium): a radioactive form of hydrogen. Tritium consists of one proton and two neutrons.

The first condition is that the outer clouds of electrons that shield the inner nucleus must be stripped away through a process called ionization, typically achieved by adding heat to the system. Once nuclei are separated from their electrons, plasma is formed. Plasma, a fourth state of matter (beyond solids, liquids, and gases), is this state at which electrons are freed from their nuclei [4].

Second, suitable environmental conditions must be provided to allow the now bare nuclei to approach one another for long enough to combine. For simplicity, these conditions can be reduced to a product of three factors: density, temperature, and confinement time [5].

Stars like the sun create the confinement conditions suitable for fusion with the enormous force of gravity present in their interior. Creating these conditions on earth requires application of alternative methods that must yield temperatures in excess of 100 million degrees Celsius [7], over six times hotter than the center of the sun [8]. Three general classes of confinement methods to achieve anthropogenic fusion are described below.

Fusion requires keeping a fuel bearing plasma:



The Fusion Triple Product

Achieving sustainable fusion reactions that would support commercial energy generation requires producing and maintaining conditions that keep the plasma hot enough, dense enough, for long enough. These conditions allow positively charged nuclei to approach close enough to one another to overcome electrostatic repulsion and allow the strong nuclear force to take over. The strong nuclear force then pulls the nuclei together to form a new, heavier element. There are many different technological fusion approaches being pursued to achieve conditions to support sustained fusion reactions that can yield more energy out than goes in.

CONFINEMENT METHODS

Confinement methods are the mechanisms employed to create the conditions under which controlled fusion can occur. Three general methods are commonly used to categorize fusion approaches and are described below.

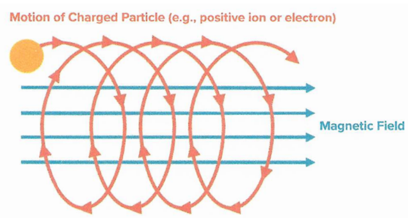


Figure 2. Spiraling motion of a charged particle in a magnetic field.

Magnetic Confinement

Charged particles, like those present in plasma, travel in spiral paths around magnetic field lines (Figure 2). Therefore, magnetic fields can be used to steer and confine plasmas. Magnetic Confinement Fusion (MCF) takes advantage of this behavior to squeeze and shape plasmas, heating them in the process, over relatively long confinement times in order to generate and maintain temperatures and plasma densities needed for fusion [9,10]. Magnetic fields can be generated externally using magnetic coils or self/internally induced as the result of electrical currents.

Externally generated MCF concepts, i.e., those reliant on one or more sets of powerful magnetic coils for plasma confinement, are the most common fusion approaches. Among these, the tokamak (Figure 3) and the stellarator are two prominent examples. Self-generated (or self-ordered) MCF concepts, i.e., those predominately reliant on magnetic fields induced by internal electric currents, include the field-reversed configuration (FRC) and the z-pinch.

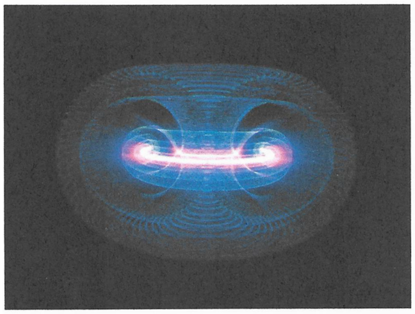


Figure 3. Illustration of plasma confined in the "doughnut-shaped" tokamak.

Magnetic fields are useful for limiting thermal losses caused by escaping ions; however, many concepts still require some form of external heating, such as through injection of radiofrequency energy or neutral ion beams, to maintain fusion conditions [11].

Inertial Confinement

In contrast to MCF, Inertial Confinement Fusion (ICF) approaches achieve confinement conditions for fusion through physical compression. As with magnetic confinement, there are multiple approaches to achieving inertial confinement [12]. The most common approach, laser ICF, employs lasers to drive the compression of a spherical fuel pellet directly or indirectly through the heating of the outer layer of the fuel pellet. This heating results in rapid outward expansion of the fuel pellet, and an equal and opposite implosive force to generate the densities and temperatures needed to initiate fusion. ICF approaches trade the longer confinement times offered by MCF approaches for much higher fuel densities.

In direct drive systems, the laser energy is focused directly on the fuel pellet surface. For indirect drive systems (Figure 4), the laser energy is focused onto the inner surface of a hohlraum, or a hollow cylindrical container, where it is converted to X-rays which then irradiate and heat the surface of the fuel pellet [13].

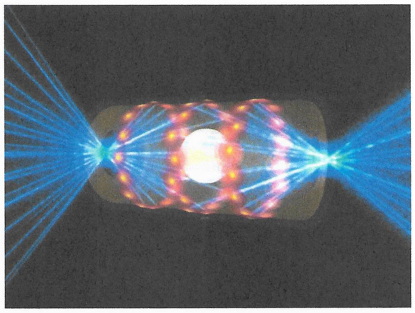


Figure 4. Illustration of indirect drive inertial confinement fusion. Here, the spherical fuel pellet lies at the center of a cylindrical hohlraum and is heated by X-rays produced following absorption of the intense laser light by the inner walls. Source: Lawrence Livermore National Laboratory. Used with permission.

Magneto-Inertial Confinement

Magneto-Inertial Confinement (MIC) combines aspects from both MCF and ICF to provide confinement conditions suitable for fusion. This confinement type takes advantage of magnetic heating and confinement concepts from MCF and compressive driver forces from ICF [14]. In some cases, magnetized target fuel is compressed via a liner material [15]. Solid liners, plasma liners, magnetized liners, laser liners, and liquid metal liners driven by pistons have been under investigation as methods to compress the target fuel [14,16]

In addition to magnetic, inertial, and magneto-inertial confinement fusion, other fusion confinement methods, such as electrostatic confinement and muon-catalyzed fusion exist and are currently under development [1]. These other approaches may offer alternative pathways to controlled fusion should they prove viable upon future exploration.

PATH FORWARD

Today, there is a large diversity of potential fusion concepts under investigation across magnetic confinement, inertial confinement, magneto inertial confinement, and other confinement approaches. Beyond being able to confine plasma and create a fusion reaction, fusion systems must be as efficient as possible to accommodate losses during energy conversion and delivery. Thus, as fusion stakeholders are still identifying viable fusion technologies, it is beneficial to explore many concepts that may provide different benefits and circumvent challenges.

EPRI continues to engage the fusion community and is working to support and accelerate commercialization of fusion technology via collaborative research and development to better align technology attributes with end-user and market needs. Current focus areas include requirements and guidance, advanced materials and manufacturing, testing and qualification, economic analysis, practical operations, and technology development and transfer. More information on EPRI's fusion efforts can be found here: https://www.epri.com/fusion.

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TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

Fuel Options for Fusion Energy

INTRODUCTION

Occurring every day across the universe, fusion releases the energy that make stars shine. It is currently being pursued on earth as a future supply of sustainable, non-emitting, scalable, and firm energy. Fusion occurs when lighter nuclei combine at sufficiently high temperatures and densities to form a heavier nucleus. The sun and other stars rely on the enormous force of gravity at their centers to provide the high temperatures and densities required. However, earth-bound fusion systems rely on confinement approaches other than gravity that provide the right combination of temperature, confinement time, and density to achieve a self-sustaining fusion reaction.

While there are many combinations of elements that can be used to fuel fusion reactions, not all are created equal with respect to energy yield and the conditions required to achieve fusion. Therefore, fusion systems under development on earth have a limited choice among practical fuel options or fuel cycles.

Common isotopes (elements with the same number of protons, but different number of neutrons in their nucleus) and particles used in fusion energy systems are:

- **Deuterium (D)**: ^{2}H. Stable hydrogen isotope that contains one neutron. Deuterium is abundant in seawater.
- **Tritium (T)**: ^{3}H. Short-lived, radioactive, and anthropogenic isotope of hydrogen with two neutrons. Tritium has a 12.3-year half-life. Global supplies include quantities produced in heavy water CANDU fission reactors as well as those produced and stored for defense applications [1].
- **Helium-3 (^{3}He)**: A stable, lighter helium isotope. While ^{3}He is less abundant on Earth, it is an end product of fusion reactions fueled by deuterium isotopes and is also a decay product of tritium.
- **Protons (p)**: A common subatomic particle occurring in familiar forms of matter.
- **Boron-11 (^{11}B)**: The stable, most abundant isotope of boron in nature.

Of these isotopes and particles, researchers and private fusion developers are currently using four fuel options in fusion systems [2] [3]:

- **Deuterium – Tritium** (D-T), producing helium and a neutron.
- **Deuterium – Deuterium** (D-D), producing ^{3}He, tritium, neutrons, and protons.
- **Deuterium – Helium-3** (D-^{3}He), producing a helium-4 (^{4}He) nucleus (the form of helium with equal number of protons and neutron), and a proton.
- **Proton – Boron-11** (p-^{11}B), briefly forming carbon-12 before decaying into three alpha particles (which are identical to a ^{4}He nucleus with two protons and two neutrons).

The choice of fusion fuel is a fundamental decision as it dictates the conditions required to achieve fusion, systems needed to maintain practical fusion energy production, and, therefore, the technology design requirements. For example, D-T fusion produces higher output energy at lower plasma temperatures (Figure 1). However, as explored in detail below, other fuel options may circumvent challenges that D-T fusion presents, such as the requirement for tritium breeding in the fusion system. This brief explores benefits and challenges for the four fuel options introduced above.

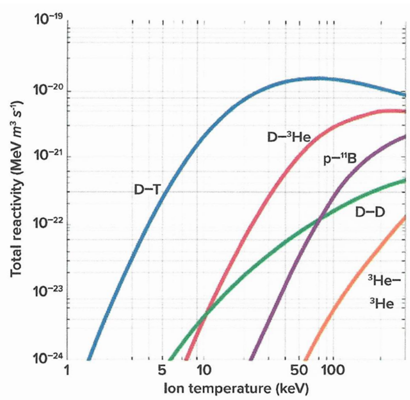

Figure 1. Reactivity rates vs. ion temperature for different fusion fuels [2]. Note that while fusing two ^{3}He nuclei is shown in this figure as a potential fuel option, high required ion temperatures and low reactivity makes it a less popular choice of fusion fuel and will not be explored in this report.

DEUTERIUM-TRITIUM FUSION

Due to its ability to reach fusion conditions and release more energy at lower plasma temperatures, deuterium and tritium (Figure 2) is the most common fuel pair across the current landscape of public research efforts and private fusion developer companies [4] [5]. Deuterium is abundant in sea water and is extracted through proven distillation, chemical exchange, and electrolytic processes [6]. Tritium, a radioactive isotope of hydrogen with a 12.3-year half-life, poses challenges due to low global inventories and considerations for proper handling and storage.

As the two hydrogen isotopes combine, helium is produced and diverted to exhaust, and a high energy, 14 megaelectron volt (MeV) neutron is released. 80% of the energy released in the fusion reaction is carried by the neutron, which is captured in a lithium-based "blanket", the first layer outside the vacuum vessel that houses the fusion reaction (Figure 3). The neutron's kinetic energy is transferred to the blanket, heating a working fluid in the and driving a traditional thermodynamic cycle for power conversion (e.g., heating water that then drives a steam turbine) [2].

In addition to the challenge of power conversion, the required blanket used in D-T systems serves two other functions that align with key barriers for D-T fusion: tritium breeding and neutron shielding. Given that the current available global tritium supply is on the order of what a D-T fusion plant will consume in a year, exacerbated by a relatively short, 12.3 year half-life, there is a need to breed tritium within the fusion system at the same rate at which it is consumed in the fusion reaction [2]. Tritium breeding is accomplished in the blanket as the fusion neutron reacts with lithium contained in the blanket. The tritium can then be recovered and fed through a closed loop fuel cycle to continue powering the fusion system [7].

Despite being useful for transferring energy away from the plasma and breeding tritium, the 14 MeV (high-energy) neutrons bombard plasma-facing materials and components in the system, resulting in material damage and activation [8]. Given their proximity to the fusion plasma, the structural and functional materials present in the blanket play an important role in neutron shielding. Due to the aggressive irradiation environment, development and use of low-activation materials that can withstand neutron damage are important for practical fusion systems.

Developing blanket technologies that can effectively provide power conversion, tritium breeding, and neutron shielding capabilities may pose barriers to the commercialization of D-T fusion. However, research efforts are ongoing to address these materials and engineering challenges. Work focused on completing the fuel cycle, such as tritium extraction systems, tritium storage, and gas fueling systems is in progress.

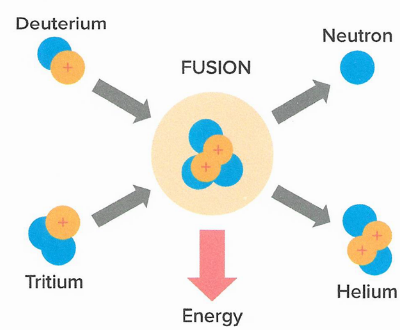

Figure 2. Fusion of deuterium and tritium, producing helium and a neutron.

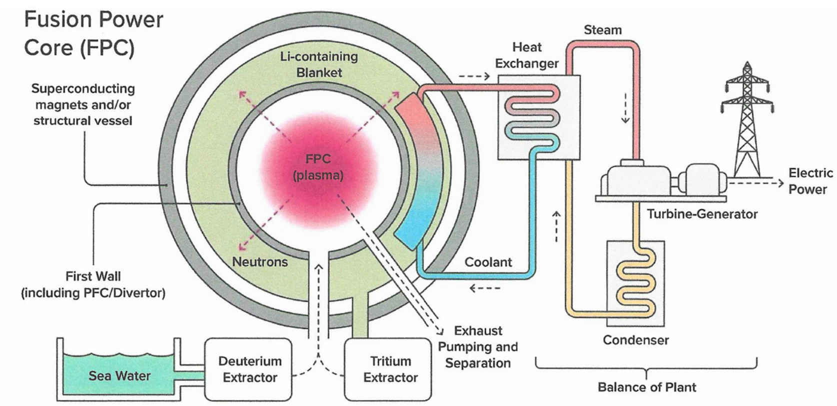

Figure 3. *Illustration of a fusion power core, including a representative lithium (Li)-containing blanket system.*

DEUTERIUM-DEUTERIUM FUSION

The fusion of two deuterium nuclei proceeds in two ways: (1) fusion yielding ^3He and a 2.45 MeV neutron or (2) fusion yielding tritium and a proton (Figure 4) [3]. D-D fusion has benefits of non-radioactive reactants, high abundance of deuterium in natural sources, and no need to breed tritium. However, for nuclei with the same kinetic energy, the probability of two deuterium nuclei fusing is less than that of a deuterium and a tritium nucleus [9]. Thus, D-D fusion requires higher plasma temperatures of up to or over 400 million degrees Celsius to achieve fusion compared to 100 million degrees Celsius required for D-T fusion [10]. These high temperature requirements to achieve fusion, coupled with lower energy output may be prohibitive for D-D fusion to be an optimal fuel source. However, many fusion developers choose to operate with deuterium only in initial stages to delay needing to manage a supply of radioactive tritium as fuel for experimental devices, avoid the associated increase in regulatory and management requirements, and reduce activation of materials and components compared to that resulting from the 14 MeV neutrons production in D-T fusion.

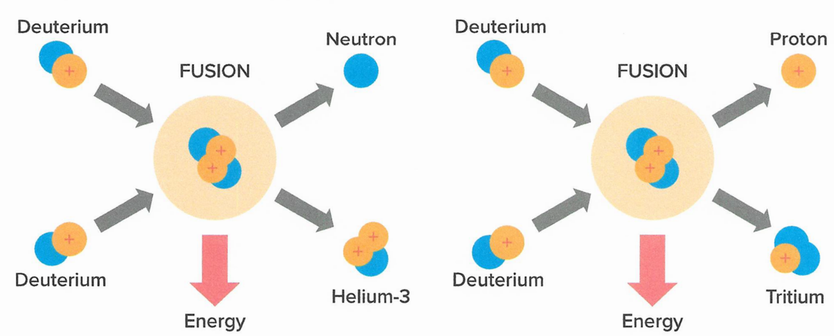

Figure 4. *Illustration of the two pathways for D-D fusion reactions, which can yield either a ^3He nucleus and a neutron or tritium nucleus and a proton.*

DEUTERIUM – HELIUM-3 FUSION

The fusion of deuterium and ^{3}He yields a helium nucleus and a proton. This pair of isotopes is another candidate fuel for fusion (Figure 5). Despite lower possible energy output compared to D-T fusion at similar plasma temperatures, the D-^{3}He fusion reaction is aneutronic, meaning no neutrons are produced in the process, reducing material activation and damage from neutrons (although side reactions of D-D can yield neutrons). D-^{3}He fusion also does not require radioactive tritium. Since tritium breeding, neutron shielding, and capturing the kinetic energy of neutrons for power conversion are not applicable to this fuel choice, a blanket system is unnecessary, potentially simplifying the pathway to practical power generation.

D-^{3}He fusion is challenged by the low availability of naturally occurring ^{3}He on Earth. While extracting ^{3}He from the moon's crust has been proposed [11], more pragmatic pathways for ^{3}He production are under investigation. ^{3}He is a product of D-D fusion [2], meaning it can potentially be sourced from fusion systems running on deuterium-only operations. ^{3}He is also a decay product of tritium [12], offering another possible fuel production pathway. However, this pathway of relying on tritium decay to recover ^{3}He imposes requirements for long-term tritium storage and processing.

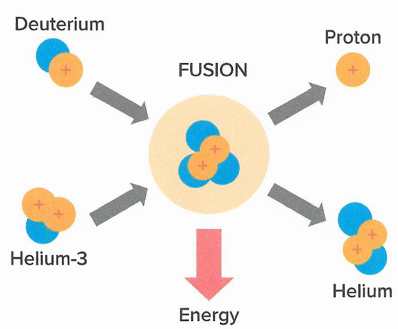

Figure 5. *D-^{3}He fusion, resulting in a ^{4}He nucleus and a proton.*

Instead of power conversion via a typical thermodynamic cycle, aneutronic options like D-^{3}He will likely need to rely on direct energy conversion methods, which propose harnessing the kinetic energy of charged particles to generate electricity without intermediate conversion, such as through a steam cycle.

Direct Energy Conversion (DEC) concepts do not rely on heating fluids to drive a turbine. They instead generate electricity directly from the energy releasing reactions. In fusion systems, one prominent DEC approach proposes to take advantage of the movement of charged particles and changing magnetic fields to induce a current outside of the plasma. DEC concepts are especially relevant for aneutronic fusion concepts that do not transfer significant amounts of energy via neutrons.

In D-^{3}He and p-^{11}B fusion, charged particles are generated. This charge can be collected to produce a voltage, or their movement can be used to create changing magnetic fields, which in turn induces a current [3]. In other concepts, ions may spiral past electrodes, which collect energy and feed a circuit [14].

PROTON – BORON-11 FUSION

p-^{11}B fusion offers another path to aneutronic fusion, also forgoing the need for complex blanket systems or tritium handling (Figure 6). Compared to D-^{3}He, p-^{11}B fusion requires higher temperatures and has lower theoretical possible energy output. However, protons (hydrogen) and ^{11}B isotopes are abundant on earth, reducing fuel scarcity concerns ^{3}He may present [13]. This type of fusion is also expected to rely on direct energy conversion for power conversion due to lack of neutrons for energy transfer.

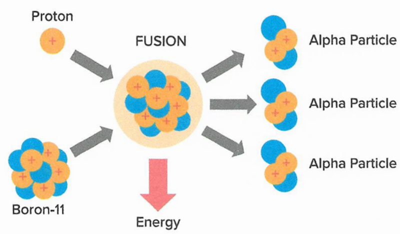

Figure 6. *p-^{11}B fusion, which briefly forms carbon-12 before decomposing and releasing three positively charged alpha particles.*

CONCLUSIONS

As fusion technology developers pursue a wide variety of fusion technology concepts, the choice of fuel can present benefits and trade offs for the viable performance of the full systems. D-T concepts, which potentially can fuse at lower temperatures with a higher energy output face the challenge of implementing blanket systems for tritium breeding, neutron shielding, and power conversion. These complex blankets introduce potential inefficiencies and engineering barriers. Aneutronic concepts, such as D-^{3}He and p-^{11}B fusion, require higher temperatures to achieve fusion and may require the development of direct energy conversion technologies. However, these fuel options offer attractive benefits by eliminating the need for tritium breeding and neutron shielding. As developers choose a fusion fuel, challenges in plasma performance, fuel supply, power conversion, and other engineering systems specific to the fuel choice will need to be addressed in parallel to advance toward commercialization.

EPRI continues to engage the fusion community and is working to support and accelerate commercialization of fusion technology via collaborative research and development to better align technology attributes with end-user and market needs. Current focus areas include requirements and guidance, advanced materials and manufacturing, testing and qualification, economic analysis, practical operations, and technology development and transfer. More information on EPRI's fusion efforts can be found here: https://www.epri.com/fusion

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2024 TECHNICAL UPDATE

Fusion Fuel Cycles Research Objectives

Results from the 2023 Fusion Fuel Cycles Workshop

Fusion Fuel Cycles Research Objectives

Results from the 2023 Fusion Fuel Cycles Workshop

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Technical Update, May 2024

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All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product. YES ~~NO~~ (NO circled)

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This report summarizes fusion fuel cycle research objectives identified during the 2023 Fusion Fuel Cycles Workshop, convened and hosted by EPRI on May 22–23, 2023, in Charlotte, NC. Any views, opinions, and recommendations expressed in this report do not necessarily state or reflect those of EPRI. Any references to specific design information in this report is intended for illustration purposes only and does not imply endorsement.

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ABSTRACT

In May 2023, representatives from the global fusion technology community participated in a two-day Fusion Fuel Cycles Workshop. During this workshop—and in the months leading up to it—participants worked to identify the key research objectives that are required to bring fusion fuel cycle technology to a sufficient level of maturity so that it can be deployed successfully in deuterium-tritium (D-T)-fueled fusion pilot plants. The U.S. Bold Decadal Vision for fusion calls for commercially relevant fusion technology in the 2030s. To realize this, significant strides must be made to develop robust, safe, and efficient technologies pertaining to tritium fueling, storage, and extraction.

The research objectives (ROs) resulting from the Fusion Fuel Cycles Workshop fall into two broad categories. First, the overarching ROs are general and multidisciplinary. They call for the generation of relevant property data, the identification of target performance metrics, techno-economic evaluation of fusion fuel cycles, and assessments of workforce and safety requirements. The overarching ROs specifically highlight the need for scalable exhaust processing and detritiation methods.

Second, the topical ROs address three primary categories:

1. **Fueling and exhaust processing.** Subcategories include:
   - Fueling
   - Vacuum pumping
   - Exhaust processing
2. **Isotope processing, rebalancing, and storage.** Subcategories include:
   - Isotope separation, rebalancing, storage, and handling
   - Tritium extraction
   - Tritium compatibility with materials
3. **Confinement processing and tritium accountancy.** Subcategories include:
   - Tritium removal and recovery
   - Management of tritiated waste
   - Modeling
   - Analytical tools
   - Regulation and nonproliferation concerns
   - Demonstration facilities

The community identified 85 specific topical ROs in total. Taken together, the topical ROs form a goal-oriented research plan to enable robust fuel cycles in fusion pilot plants. The community makes no recommendation as to what the specific design of a fusion fuel cycle should be; instead, the ROs are intentionally generalizable to many different fusion pilot plant concepts.

Importantly, the community emphasized the leadership of the private fusion sector with regards to fusion pilot plant design and overall commercialization efforts. During workshop discussions, it was observed that partnership and communication between the private sector, federal agencies, national laboratories, and university research centers is required to ensure that publicly funded fuel cycle research will be commercially relevant.

Keywords

Confinement processing
Fueling and exhaust processing
Fusion fuel cycle
Isotope processing
Tritium
Tritium accountancy

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

COP28	28th Conference of Parties to the United Nations Framework Convention on Climate Change
D	deuterium
DIR	direct internal recycling
DOE	U.S. Department of Energy
FLiBe	lithium fluoride/beryllium fluoride
FPP	fusion pilot plant
H	hydrogen
HT	tritiated hydrogen gas
IFE	inertial fusion energy
IP	intellectual property
JET	Joint European Torus
MFE	magnetic fusion energy
PPP	public private partnership
R&D	research and development
RAMI	reliability, availability, maintainability, and inspectability
RO	research objective
T or ^3H	tritium
T_2	tritium gas
TF	tritium fluoride
TRL	technology readiness level
U.S.	United States

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1 INTRODUCTION

A safe, efficient, and reliable fuel cycle is important for the commercialization of fusion energy. Many fusion concepts under development will require a robust deuterium-tritium (D-T) fuel cycle, and alternative fusion fuel cycles also have isotope processing needs. Both the U.S. Bold Decadal Vision and multiple private fusion programs envision fusion pilot plants (FPPs) operational by the early 2030s. The requirements of the associated fueling systems will require the evolution of fuel handling technologies, in particular regarding tritium, to assure reliable and sustained operations.

Tritium (^3H) and fuel systems present a unique set of design considerations for a D-T fusion power system, with safety, performance, and environmental implications. Tritium is radioactive and has properties similar to, but distinct from other hydrogen isotopes such as protium (^1H). Tritium gas (T_2) undergoes isotope exchange with common hydrogen compounds, such as hydrogen gas (forming HT), and water (forming HTO), both of which can enter the biosphere if not fully contained or recovered. Hydrogenic gases (Q_2 i.e.: H_2, D_2, T_2 HD, HT, DT) can be challenging to contain due to their ability to diffuse through and accumulate within pressure boundary materials. Ensuring worker and public safety as well as minimizing environmental impact in fuel cycle operations and waste disposal are critical requirements to achieve at the outset of commercial fusion.

Existing tritium handling systems have been developed for the small number of tritium-fueled fusion energy sciences experiments (such as JET and ITER), and as a waste management system in certain fission installations, particularly in heavy water reactors. The tritium handling systems required for fusion power plants will represent an evolution and major innovation of these systems. Operations will be effectively continuous, with circulating flow rates on the order of kilograms of tritium per day, and total tritium inventories on the order of hundreds of grams.[1] These performance targets will be enabled by tritium pumping, handling, separation, purification, and accountancy technologies adapted for fusion power plants. Furthermore, to resupply fuel used in the fusion reaction itself, the requirement of tritium breeding in D-T systems necessitates tritium extraction from the blanket at a rate on the order of tens of grams of tritium per day.[2]

To accelerate the development of relevant fuel cycle technologies, the Fusion Fuel Cycles Workshop was held from May 22-23, 2023, at EPRI in Charlotte, North Carolina. Participants included representatives from federal agencies, private fusion companies, universities, and national labs from the U.S., Canada, the United Kingdom, Italy, France, Germany, Japan, and

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[1] Illustrative order of magnitude estimates are based on analysis presented in Samuele Meschini *et al* 2023 *Nucl. Fusion* **63** 126005 and Ferry *et al* 2023, PPPL Introduction to Fusion Energy and Plasma, "Introduction to fusion power plant fuel cycles and tritium breeding blankets."

[2] Order of magnitude estimates for tritium extraction from the blanket is based on a generic gigawatt-scale plant, an estimated 15 MeV of energy released per individual fusion reaction, and the approximate 3 grams per mole molar mass of a triton.

Korea. The goal of this workshop was to gather information from stakeholders in order to support fusion fuel cycle technology development that will enable the community to build a fusion pilot plant with a robust fuel cycle on the timescale of a decade. A full summary of this 2023 Fusion Fuel Cycle Workshop will be presented in the forthcoming EPRI report 3002029370. A related but separate workshop was held from on the following days on fusion blanket technologies, with tritium extraction form the blanket forming the scope delineation of the two workshops. Separate documents were prepared from that workshop and are:

- (Forthcoming): *2023 Fusion Blankets Workshop Summary: A Summary of the 2023 Fusion Blankets Workshop Hosted by EPRI in Charlotte, NC on May 24–25, 2023*. EPRI, Palo Alto, CA: 2024. 3002029372.
- *Fusion Blankets Research Objectives: Results from the 2023 Fusion Blankets Workshop*. EPRI, Palo Alto, CA: 2024. 3002029373.

This document provides general conclusions from the workshop, over-arching research objectives, proposed framework concepts for new Fusion Fuel Cycle Research and Development (R&D) Centers within the U.S. Department of Energy (DOE) Office of Science Fusion Energy Sciences program, and detailed topical research objectives. These conclusions and research objectives were drafted by organizing committee members and reviewed by workshop participants. Any views, opinions, and recommendations expressed in this report do not necessarily state or reflect those of EPRI.

2 FUSION FUEL CYCLE GENERAL CONCLUSIONS

The Fusion Fuel Cycle Workshop Research Objectives documented in this report represent observations and general conclusions drawn from structured and moderated sessions seeking input from subject matter experts on fusion fuel cycle R&D activities needed to support commercialization of fusion energy technology. General conclusions from the Fusion Fuel Cycles Workshop include:

- Private industry is driving the commercialization of fusion energy worldwide, and public-private partnerships (PPPs) have already been invaluable for private programs. In the space of fusion fuel cycle R&D, PPPs are expected to greatly accelerate the development of all fusion energy concepts.
- Early fusion fuel cycle technology development (proof-of-concept, prototyping, etc.) can be performed with protium and deuterium in standard laboratories, but validation in a relevant environment will require testing with tritium prior to deployment in a pilot plant to de-risk them and mature readiness levels.
- De-risking fusion fuel cycle technologies by demonstration with tritium will be necessary to support deployment of these technologies. Tritium facilities will require appropriate spatial, inventory, and throughput scales and the corresponding safety infrastructure to enable safe use of the required tritium inventories and chemical formats. These facilities should offer flexible testing configurations with both standalone and integrated fusion fuel cycle loop testing.
- Leverage pathways for partnerships with the U.S. National Laboratories and international laboratories. The tritium production, processing, and modeling expertise that reside at these institutions represents decades of investment and expertise, constituting a valuable resource for advancing fusion fuel cycle science and technology.
- In order to deploy fusion on a commercial scale as rapidly as possible, the U.S. DOE and other publicly funded fusion R&D efforts–both in the U.S. and internationally–should coordinate closely with one another and with the private fusion industry to make efficient use of limited public funds. International cooperative R&D agreements, like the one announced at COP28,[3] should be leveraged and investments that are necessary to close critical gaps should be prioritized.

[3] COP28 refers to the 28th Conference of Parties to the United Nations Framework Convention on Climate Change, held from November 30th-December 12th, 2023, in Dubai, United Arab Emirates.

3 FRAMEWORK CONCEPTS: DEVELOPING FUSION FUEL CYCLE TECHNOLOGIES

Framework Concepts are suggestions from the Fusion Fuel Cycle Workshop participants on developing the framework for a new Fusion Fuel Cycle R&D Center within the U.S. DOE Office of Science Fusion Energy Sciences program. Key Framework Concepts identified at the Fusion Fuel Cycles Workshop include:

- Develop fusion fuel cycle collaborations and partnerships that can address the challenges in fuel cycles used by inertial fusion energy (IFE), magnetic fusion energy (MFE), and other advanced fusion fuel cycles, including issues related to tritium processing technologies, nonproliferation, and export control.
- Support PPPs as part of DOE's milestone program and other funding opportunities. Organize workshops, knowledge seminars, industry days, and technical exchange meetings. Streamline partnering mechanisms and work with companies to alleviate concerns related to intellectual property (IP).
- Foster engagement with community partners, universities, and the private sector to promote domestic and international partnerships to recruit and develop the fusion fuel-cycle technology workforce. Workforce development should include a deliberate effort to build a more diverse and inclusive fusion community. Developing fuel-cycle technology for a fusion pilot plant requires expertise from many disciplines. This provides a pathway to include research groups that have not historically participated in fusion technology development in key research and funding opportunities.
- Periodically reevaluate fusion fuel cycle research opportunities to take advantage of the developments within public sector research, international collaborations, and the private sector.

4 OVERARCHING RESEARCH OBJECTIVES (ROs) FOR FUSION FUEL CYCLE TECHNOLOGIES DEVELOPMENT FOR FUSION ENERGY

Overarching Research Objectives address research gaps common across fusion fuel cycle topics and are of high importance to the advancement of fusion fuel cycle technologies for the deployment of fusion energy. These Overarching Research Objectives include the following:

- Experimentally characterize, review, and organize physical property data for relevant fusion fuel cycle materials across process relevant conditions for different concepts and designs. Make the physical property data including data related to behavior of materials with H, D, and T available to the community through publications, databases, and other relevant mechanisms.
- Identify and develop a set of nominal design elements and performance requirements common to multiple private designs that can be utilized to guide FPP-scale fusion fuel cycle development.
- Develop techno-economic studies to evaluate the various fusion fuel cycle concepts and key performance metrics, including requirements for reliability, availability, maintainability, and inspectability (RAMI). With input from the energy industry and fusion science and technology experts, identify the most promising concepts to guide technology selection and to inform directions of technological development.
- Develop exhaust processing and detritiation techniques that will enable fusion energy production to scale economically. Explore methods for regeneration or recycling of fusion fuel cycle materials such as getters, and adsorbents as well as advancing water detritiation systems.
- Perform risk and budget/planning assessments associated with technology deployment. These assessments would address workforce training needs, safety procedures, technology readiness assessment levels for technology deployments, supply chain, and other relevant areas.
- Assess how to optimally implement nonproliferation, export control, waste disposal, accident scenarios, and community engagement for the fusion fuel cycle.

5 TOPICAL RESEARCH OBJECTIVES

Topical Research Objectives are specific to processes within the fusion fuel cycle or specific considerations that need to be addressed related to the fusion fuel cycle or its operation. These research objectives are organized by topics and sub-topics to the greatest extent possible but may have some applicability across topics as well where complex interactions are expected.

5.1 Fueling and Exhaust Processing

5.1.1 Fueling

- **RO 1.1-1:** Develop fueling design requirements for an FPP-scale fusion fuel cycle.
- **RO 1.1-2:** Develop requirements for tritium R&D facilities to test and develop fueling components at FPP scale.
- **RO 1.1-3:** Develop and scale fueling technologies to FPP-relevant conditions and demonstrate reliability.
- **RO 1.1-4:** Develop synergistic target/fusion fuel cycle co-design to identify target materials and processing methods that have minimum impact on the fusion fuel cycle and allow for inventory reduction.
- **RO 1.1-5:** Optimize fuel delivery to achieve required fusion yield for FPP design requirements.
- **RO 1.1-6:** Design, develop, and demonstrate a fueling control system and any storage system needs for disruption mitigation or other off-normal operations.
- **RO 1.1-7:** Develop impurity removal and processing of tritiated impurities during fuel formation processes.
- **RO 1.1-8:** Develop survivable cryogenic fuel layer for IFE applications.
- **RO 1.1-9:** Study the coupling between plasma behavior and fueling requirements to better understand their interactions in advanced fueling systems.
- **RO 1.1-10:** Develop tritium sensing requirements for fueling that can provide information on process conditions in the fueling system as well as provide information about tritium inventory.
- **RO 1.1-11:** Based on needs and requirements for direct internal recycling (DIR), plan tritium R&D facilities that can develop, test, and demonstrate DIR technologies alone or in combination with other fusion fuel cycle systems.

5.1.2 Vacuum Pumping

- **RO 1.2-1:** Develop pumping design requirement for an FPP-scale fusion fuel cycle.
- **RO 1.2-2:** Study the tritium compatibility requirement for pumping technologies and develop solutions that can solve tritium compatibility related challenges within the pumping train.

- **RO 1.2-3:** Develop and optimize pumping systems that are more robust and that can handle high duty cycle and continuous operation.
- **RO 1.2-4:** Scale pumping technologies to the throughputs needed for an FPP-scale fusion fuel cycle.
- **RO 1.2-5:** Mature DIR pumping solutions.
- **RO 1.2-6:** Plan for a tritium R&D facility to test and develop pumping components at FPP scale.

5.1.3 Exhaust Processing

- **RO 1.3-1:** Characterize the physical properties, non-dimensional scaling relationships, validation curves, and system integration factors that will enable process model development to support chamber exhaust processing design and operation. Model the performance of components and develop process modeling frameworks relevant to FPP scale in processing rates and inventory.
- **RO 1.3-2:** Evaluate the need and requirements for DIR of hydrogen isotopes.
- **RO 1.3-3:** Develop a fusion fuel cycle architecture for DIR of hydrogen isotopes from exhaust.
- **RO 1.3-4:** To the extent possible, determine the separation efficiency of DIR technologies.
- **RO 1.3-5:** Demonstrate reduction in tritium inventory by integration of DIR technology.
- **RO 1.3-6:** Characterize anticipated impurities generated in different fusion concepts including IFE and MFE.
- **RO 1.3-7:** Develop improved impurity removal techniques (e.g., target debris, palladium membrane reactors, getters) that can purify gas streams while minimizing inventory for different fusion concepts.
- **RO 1.3-8:** Develop continuously operating, high throughput exhaust processing system at the scale needed for a fusion plant. Reduce the tritium inventory and increase processing rate. The development should demonstrate the feasibility of all technologies throughout the exhaust processing system.
- **RO 1.3-9:** Identify or develop real-time concentration monitoring, diagnostics, sensors, or devices for locations in exhaust processing critical to process monitoring, control, or tritium accountancy.
- **RO 1.3-10:** Develop an understanding of the needs for tritiated waste processing infrastructure and waste disposal pathways needed to support operation of fusion plants.

5.2 Isotope Processing, Rebalancing, and Storage

5.2.1 Isotope Separation and Rebalancing

- **RO 2.1-1:** Develop a fusion fuel cycle architecture for the integration of isotope separation/rebalancing with DIR, storage, and fueling to accomplish critical tasks like protium removal from the process and rebalancing the isotope mixture.
- **RO 2.1-2:** Investigate isotope separation methods that have the potential to reduce tritium inventory while rebalancing isotopes, pursuing multiple methods in parallel and de-risking any particular method.
- **RO 2.1-3:** Minimize tritium inventory in the isotope separation system through process intensification that improves heat and mass transfer, increases kinetics, and reduces system volume.
- **RO 2.1-4:** Scale-up the processing rates of low tritium inventory isotope separation technologies to meet the needs of a fusion fuel cycle.
- **RO 2.1-5:** Develop improved models for isotope separation systems that both help to guide system integration as well as assist with further technology development.
- **RO 2.1-6:** Define the sensing needs in the isotope separation and rebalancing system for tritium accountancy and process control.
- **RO 2.1-7:** Perform validation of the isotope separation methods with tritium at the required flow rates in a tritium R&D Facility.

5.2.2 Isotope Storage and Handling

- **RO 2.2-1:** Identify candidate materials that can achieve the process requirements for hydrogen isotope storage materials to be used in a continuously operating fusion fuel cycle (e.g., charging/discharging rate, capacity, thermal stability, degradation/aging effects). Utilize databases of existing materials from other DOE efforts such as the hydrogen storage material center of excellence.
- **RO 2.2-2:** Define detailed operating characteristics for hydrogen isotope storage beds such as required heat transfer rates, storage capacity, dead volume, material lifetime, acceptable heel quantity of tritium, regeneration requirements (if applicable), need to be able to perform tritium accountancy functions, etc.
- **RO 2.2-3:** Define the needs for structural materials used in hydrogen storage bed housing including resisting embrittlement, ability to operate for extended periods and cycles at elevated temperatures, and the ability to support regeneration of the hydride beds if needed.
- **RO 2.2-4:** Identify the waste streams and disposal pathways/processes for the hydrogen storage materials and detritiation requirements during maintenance and/or decommissioning.

5.2.3 Tritium Extraction from Breeder Materials

- **RO 2.3-1:** Define the operational requirements for the tritium extraction system including blanket material flow rates, extraction efficiencies, tritium concentration monitoring requirements, and other applicable performance metrics.
- **RO 2.3-2:** Identify primary tritium extraction methods and systems of interest and system architectures for fusion fuel cycle integration that have the potential to meet private-sector fusion pilot plant timelines or that could be viable alternatives for first-of-a-kind plants or future fusion plants.
- **RO 2.3-3:** Identify and measure fundamental properties (e.g., phase diagrams, solubilities, mass transport properties, heat transfer properties) of major blanket systems and dissolved species needed for engineering of tritium extraction systems. Standardize data collection methods and develop efficient methods (e.g., databases) to share property data throughout the fusion community.
- **RO 2.3-4:** Perform an architectural analysis of the blanket loop to understand the trade-offs in locating tritium extraction relative to other blanket components such as the primary heat exchanger. The analysis should consider the tritium permeability of the primary heat exchanger.
- **RO 2.3-5:** Characterize tritium extraction process efficiency and develop mass and energy balance models that can be used to evaluate tritium inventory, parasitic loads, and by-product. Examples of these byproducts include tritiated gas (e.g., HT, HTO, TF, T_2) or tritiated compounds (e.g., tritiated metals).
- **RO 2.3-6:** Characterize tritium extraction process material compatibility with liquid breeder materials through testing in static conditions, in flow conditions, with the presence of impurities, and during off-normal operations.
- **RO 2.3-7:** Develop tritium extraction models that both help to guide integration of the fusion fuel cycle and blanket as well as assist with further technology development.
- **RO 2.3-8:** Identify the waste streams and disposal pathways/processes for the tritium extraction process and component requirements during maintenance and/or decommissioning.
- **RO 2.3-9:** Create research infrastructure (labs, facilities, etc.) to enable more rapid development of tritium extraction technologies and where concepts can start with non-radiological testing and progress to testing with tritium. Testing should also progress from static testing to loop testing up to high TRL level demonstrations of tritium extraction systems.

5.2.4 Tritium Compatibility of Materials

- **RO 2.4-1:** Perform an analysis on existing data for tritium compatible materials related to fusion plant design and operation, and identify methods (e.g., databases) to compile and organize the information. Identify gaps between existing data and anticipated requirements for commercial fusion facilities and facilities with the potential to close the gaps.
- **RO 2.4-2:** Perform tritium compatibility analyses relative to fusion materials on materials joining methods, novel methods of material fabrication being developed (e.g., additive manufacturing), testing on samples in specific configurations and/or stress profiles. Compile and organize the data into formats that are useful for the community.
- **RO 2.4-3:** Define the needs for tritium permeation barriers as well as develop and characterize permeation barriers for various use scenarios and substrate materials.
- **RO 2.4-4:** Develop improved models for tritium permeation and retention in fusion relevant materials. Modeling should include both solids and fluid systems.
- **RO 2.4-5:** Characterize the interplay between neutronic damage and tritium trapping as well as how these factors impact tritium permeation.
- **RO 2.4-6:** Develop an understanding of tritium retention and recovery during different operating phases of a fusion plant.
- **RO 2.4-7:** Perform an assessment of facility and/or capability needs for tritium materials research including both assessments for operational and waste disposal and detritiation needs. Develop the facilities to support tritium materials research needs for all aspects of fusion energy.
- **RO 2.4-8:** Develop and demonstrate methods to recycle, regenerate, or reuse tritiated materials such as vacuum pump oil, hydrogen storage materials, isotope separation catalysts, equipment structural metals, or tritiated gasses within the fusion fuel cycle process in order to reduce waste streams of tritiated material produced within an FPP.

5.3 Confinement Processing and Tritium Accountancy

5.3.1 Tritium Removal, Tritium Recovery, and Tritiated Waste

- **RO 3.1-1:** Assess the ability of existing technologies to perform atmospheric detritiation and define the gaps in the technologies needed for detritiating room-temperature air. The assessment should include evaluation of technologies developed for ITER along with systems and operating experience at global tritium handling facilities. Investigate detritiation processes that do not generate tritiated water.
- **RO 3.1-2:** Develop specific technologies (e.g., columns, dehumidifiers) for removal of tritiated water vapor from the air in various spaces and/or scenarios during the operation of a fusion pilot plant.
- **RO 3.1-3:** Develop improved methods and technologies (e.g., adsorbents or molecules that preferentially bind to tritium) that can remove and/or recycle tritium at low concentrations from liquid water.

- **RO 3.1-4:** Identify and develop improved getter materials for use in fusion fuel cycle processes for removal of tritium or other process impurities. Identify potential pathways for waste minimization, recycling of materials, or other methods to reduce tritiated waste streams from the use of getters.
- **RO 3.1-5:** Perform an assessment of the set of available technologies for managing different waste streams during operation of fusion plants and identify gaps where technology development is needed for fusion plant operation.
- **RO 3.1-6:** Assess technology development needs in detritiation of solid materials that investigates lessons learned at JET, other fusion devices, and other global tritium handling facilities.
- **RO 3.1-7:** Develop improved methods for solid material detritiation and recycling of recovered tritium that minimize tritium levels in solid waste for disposal.
- **RO 3.1-8:** Develop improved techniques for quantifying tritium inventory in solid materials (including tritiated dust) that can be used in both short-term and long-term measurements including destructive and non-destructive assays.
- **RO 3.1-9:** Develop predictive models for tritium inventory in solid waste systems that are validated with experimental data and utilize state-of-the-art predictive technologies (e.g., artificial intelligence) to help improve predictions of relevant quantities such as tritium content or tritium concentration with time.
- **RO 3.1-10:** Develop a waste disposal pathway/methodology to handle tritiated waste from commercial fusion plants that can handle the volumes of waste materials of different types that are planned to be generated during the operation of a fusion plant. This would include coordination between regulators and disposal facilities to develop a fusion waste classification.
- **RO 3.1-11:** Communicate and engage with the public around issues of tritium management.

5.3.2 Modeling

- **RO 3.2-1:** Develop modeling resources (e.g., curated physical properties databases including uncertainties and meta-data) that have good validation of input data and that can be used by the community to develop more robust fusion fuel cycle modeling.
- **RO 3.2-2:** Develop integrated mass and energy balance process models that can be used to optimize process flow rates and to assess energy requirements, parasitic loads, minimize tritium inventory, assist in technology selection, and optimize fusion plant performance.
- **RO 3.2-3:** Develop modeling tools and methods to support real-time tritium accountancy and validate models with data on batch and flowing systems.
- **RO 3.2-4:** Develop fusion fuel cycle modeling tools to support discussions with regulators and can incorporate aspects relevant to regulation such as environmental transport of tritium and other considerations.
- **RO 3.2-5:** Develop accident scenarios modeling involving tritium transport and release to the atmosphere and improve modeling of tritium intake in the biological systems and food chain.

5.3.3 Analytical Tools

- **RO 3.3-1:** Perform an assessment and gap analysis of analytical tools for the fusion fuel cycle that can identify process requirements, available technologies, and can apply operating experience from global tritium facilities and fusion demonstration systems. Consider if the gaps are best addressed by advancing existing tritium technologies, incorporating existing technologies not yet applied to tritium, or developing entirely new technologies.
- **RO 3.3-2:** Develop a process monitoring toolbox that meets regulatory requirements and supports continuous operation of fusion plants. Integrate knowledge from batch testing, testing in other fields with similar problems, and consolidate material compatibility data. Assess the supply chain for sensors that would be needed in different parts of a fusion plant.
- **RO 3.3-3:** Develop improved spectroscopic or sensing methods (e.g., Raman spectroscopy) for detecting relevant species in process streams at relevant concentrations in real time.
- **RO 3.3-4:** Develop improved spectroscopic or sensing methods that can support real time tritium accountancy and quantification of material mass balances within the process at the required accuracy. Improvements may include higher sensitivity, speed, and reliability.
- **RO 3.3-5:** Develop, demonstrate, and validate the use of distributed sensor integration (e.g., sensor fusion) to improve the accuracy of sensing and measurements and calculated tritium accountancy frameworks that rely on these measurements.

5.3.4 Regulation, Nonproliferation, Supply Chain, Community Engagement

- **RO 3.4-1:** Provide technical support to regulators in providing materials property data, data on assumptions in accident scenario analysis, operating experiences or lessons learned, standard fusion fuel cycle configurations, or other information to support the development of a regulatory framework for fusion.
- **RO 3.4-2:** Develop guidance on nonproliferation risks for companies and lists of materials exclusions that would be necessary to ensure nonproliferation goals are met in terms of the potential for material irradiation, diversion of hydrogen isotopes (deuterium and/or tritium) that are export controlled, or other proliferation pathways that are identified to be potentially significant.
- **RO 3.4-3:** Perform a parametric relation study to reduce the uncertainty in how regulation, economics, and technology relate to fusion commercialization. This will involve understanding how technology development options will impact overnight cost of plant, lifecycle plant cost, and/or other relevant metrics.
- **RO 3.4-4:** Develop reference plants for MFE and IFE with a generic bill of materials that includes both functional and specific component requirements that can be used to develop the supply chain for fusion plants.

- **RO 3.4-5:** Analyze the tritium start up needs for fusion plants in the context of global availability and conduct cost-benefit and trade-off analysis for various methods of tritium production. Understand how potential new facilities for tritium production could supplement tritium availability from fusion plants to support the expansion of fusion energy.
- **RO 3.4-6:** Develop a model plan and resources to support community education, engagement, and acceptance around the fusion fuel cycle, fusion waste, and other topics that can be used in communities where fusion plants are being sited, constructed, and operated.
- **RO 3.4-7:** Create a screening tool for public acceptance, export control, and regulatory compliance that can help evaluate issues related to fusion plant permitting, construction, operation, decommissioning, or other issues.

5.3.5 Fusion Fuel Cycle Demonstration Facilities

- **RO 3.5-1:** Develop tritium R&D facilities that can help to understand fundamental tritium behavior and properties by leveraging experiments and simulations.
- **RO 3.5-2:** Create tritium R&D facilities that can demonstrate and validate the performance of components and subsystems as well as study interfaces. These facilities would also have capabilities for testing component durability and would deliver validated data that can provide confidence in fusion fuel cycle design for fusion plants.

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2024 TECHNICAL UPDATE

Fusion Blankets Research Objectives

Results from the 2023 Fusion Blankets Workshop

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All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product. YES NO ✓

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This report summarizes fusion fuel cycle research objectives identified during the 2023 Fusion Blankets Workshop, convened and hosted by EPRI on May 24-25, 2023, in Charlotte, NC. Any views, opinions, and recommendations expressed in this report do not necessarily state or reflect those of EPRI. Any references to specific design information in this report is intended for illustration purposes only and does not imply endorsement.

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ABSTRACT

In May 2023, representatives from the global fusion technology community participated in a two-day Fusion Blankets Workshop. During this workshop—and in the months leading up to it—participants worked to identify the key research objectives that are required to bring tritium breeding blanket technology to a sufficient level of maturity so that it can be deployed successfully in deuterium-tritium (D-T)-fueled fusion pilot plants. The U.S. Bold Decadal Vision for fusion calls for commercially relevant fusion technology in the 2030s. To realize this, significant strides must be made to develop robust, safe, and efficient blanket technologies.

Tritium is bred in the blankets when neutrons produced in the D-T fusion reaction interact with lithium. There are four main categories of breeder material proposed for fusion blankets: lithium ceramics, liquid lithium, liquid lead-lithium, and liquid (molten) lithium-containing salts. Each breeder choice presents unique advantages and challenges with regards to blanket geometry, breeding efficiency, chemistry, safety, tritium extraction, and the specific needs of an individual fusion pilot plant concept. Currently, the community makes no recommendation as to which breeder material should be prioritized.

The research objectives (ROs) resulting from the Fusion Blankets Workshop fall into two broad categories. First, the overarching ROs are general and multidisciplinary. They call for the generation of relevant property data, the development of frameworks by which that data can be efficiently shared, quantification of waste streams, and the development of software tools that can be engaged in design. Importantly, the community also highlights the need for experimental facilities in which breeder materials can be studied and blanket technologies assessed.

Second, the topical ROs address five primary categories:

1. **Tritium control.** Subcategories include:
   - Permeation barriers
   - Modeling needs
   - Measurement
   - Extraction systems
2. **Functional materials.** Subcategories include:
   - Flow phenomena
   - Modeling needs
   - Breeder materials
   - Neutron multiplier materials
3. **Structural materials.** Subcategories include:
   - Compatibility
   - Modeling needs

- Activation and waste
- Fabrication

4. **Blanket enabling technologies.** Subcategories include:
   - Thermal management
   - Corrosion protection
   - Lithium supply chains
   - Dual-coolant system needs
5. **Maintenance and integration.** Subcategories include designing for:
   - Safety
   - Integration
   - Maintenance
   - Reliability
   - Manufacturability

The community identified 87 specific topical ROs in total. Taken together, the topical ROs form a goal-oriented research plan to enable effective tritium breeding blankets in fusion pilot plants. During workshop discussions, it was identified that specific blanket designs and breeder choices are likely to be driven by the needs of the private fusion sector. As a result, it was observed that partnership between the private sector, federal agencies, national laboratories, and university research centers is required to ensure that publicly funded breeder-blanket research will be commercially relevant.

Keywords

Blanket enabling technologies
Functional materials
Fusion blanket
Maintenance and integration
Structural materials
Tritium control

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

Be	beryllium
CO_2	carbon dioxide
COP28	28th Conference of Parties to the United Nations Framework Convention on Climate Change
D	deuterium
DOE	United States Department of Energy
FLiBe	lithium fluoride/beryllium fluoride
FLiNaBe	lithium/sodium/beryllium fluoride
FPP	fusion pilot plant
H	hydrogen
He	helium
HF/TF	hydrogen fluoride/tritium fluoride
IFE	inertial fusion energy
IP	intellectual property
Li	lithium
MFE	magnetic fusion energy
MHD	magnetohydrodynamic
Pb	lead
PbLi	lead lithium
PPP	public-private partnerships
RAFM	reduced activation ferritic martensitic
R&D	research and development
SiC	silicone carbide
T	tritium
TBR	tritium breeding ratio
TPB	tritium permeation barrier
TRL	technology readiness level
UK	United Kingdom
U.S.	United States

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1 INTRODUCTION

An efficient, reliable, and safe fusion blanket is essential to the commercialization of deuterium-tritium (D-T) fusion energy (requiring tritium breeding) and also alternative fusion fuel cycles. Both the U.S. Bold Decadal Vision and multiple private fusion programs envision fusion pilot plants (FPPs) operational by the early 2030s that will require robust and operational fusion blanket technology. The requirements of the fusion core blanket will demand the evolution of materials, engineering, and technology to provide reliable and sustained operations.

In D-T fusion concepts, the typical fusion blanket almost entirely surrounds the fusion source, regardless of the specific fusion technology concept. The primary functions are to breed tritium for the D-T fuel cycle, absorb > 90% of the fusion neutron power for thermal conversion, and provide some level of shielding to components behind it. The blanket can also be a pressure vessel because it can reside in vacuum, it often has a plasma facing (or fusion source) component to it (first wall), and it must resist failure under accidents and plasma (or other) transients to the extent possible. The fusion technology concept under consideration (e.g., tokamak vs. stellarator or other magnetic confinement option vs. inertial or magneto-inertial confinement option) can alter the requirements of the blanket and potentially change its integration with other components in the fusion core. In general, fluids will need to flow into and out of the blanket to remove the energy deposited in the blanket, as well as tritium for the D-T fuel cycle. A blanket must be replaceable since it will receive the brunt of the fusion neutron flux and will most rapidly accumulate damage. In general, fluids and their circulation loops are absorbed into the blanket topical area despite being physically situated outside the blanket.

A full, operation-ready fusion blanket has never been built, let alone utilized in a fusion (or any) neutron environment. Notwithstanding, small benchtop D-T irradiations have been performed on some conceptual integrated blanket components. The development of the blanket for fusion energy applications will be a major element in creating a viable fusion energy source. Blanket research has been ongoing for decades, generally at low funding levels, and the global community has gravitated toward a set of blanket concepts for fusion reactors that are combinations of the following materials:

- Water or helium coolant
- Lead-lithium (PbLi) liquid breeder
- Molten salt liquid breeder, including lithium fluoride/beryllium fluoride (FLiBe) or lithium/sodium/beryllium fluoride (FLiNaBe)
- Lithium (Li) liquid breeder
- Lithium bearing solid ceramic breeders
- Reduced activation ferritic martensitic (RAFM) or advanced RAFM structural steel material
- Beryllium (Be) or lead (Pb) neutron multiplier
- Helium purge gas (with solid breeders)

- Functional materials (e.g., silicone carbide (SiC), alumina (Al_2O_3), etc.)
- Tungsten very thin layer on blanket first wall

To accelerate the development of blanket technologies for a range of fusion concepts, 2023 Fusion Blankets Workshop was held (following the 2023 Fusion Fuel Cycles Workshop) from May 24-25, 2023, at EPRI in Charlotte, North Carolina. Participants included representatives from federal agencies, private fusion companies, universities, and national labs from the U.S., Canada, the United Kingdom, Italy, France, Germany, Japan, and Korea. The goal of this workshop was to gather information from stakeholders in order to support fusion blanket technology development that will enable the community to build a fusion pilot plant with a successful breeder blanket on the timescale of a decade. A successful breeder blanket in a pilot plant will:

- Demonstrate tritium breeding, extraction, and integration with the plant fuel cycle at commercial-relevant scales.
- Use technologies and systems that can be scaled up to a commercial plant.

It is noted that for a fusion pilot plant, full tritium self-sufficiency is ideal but not required.

A full pilot plant design is unknown, nor is it know if there will only be one pilot plant design. It was not the role of this workshop to downselect which breeder material to focus on. A general observation from this workshop is that there is relatively little interest from the U.S. community in pursuing solid breeder concepts. Rather, most interest is concentrated on PbLi and molten FLiBe salt. Interest in liquid Li breeders is also driven by the UK fusion program.

This document summarizes the key research objectives developed at the two-day workshop. A related but separate workshop was held from on the preceding two days on fusion fuel cycle technologies, with tritium extraction form the blanket forming the scope delineation of the two workshops. A full summary of this 2023 Fusion Blankets Workshop will be presented in the forthcoming EPRI report 3002029372. Separate documents were prepared from that workshop and are:

- (Forthcoming): *2023 Fusion Fuel Cycles Workshop Summary: A Summary of the 2023 Fusion Fuel Cycles Workshop Hosted by EPRI in Charlotte, NC on May 22–23, 2023*. EPRI, Palo Alto, CA: 2024. 3002029370.
- *Fusion Fuel Cycles Research Objectives: Results from the 2023 Fusion Fuel Cycles Workshop*. EPRI, Palo Alto, CA: 2024. 3002029371.

This document provides general conclusions from the workshop, over-arching research objectives, proposed framework concepts for new Fusion Blankets Research and Development (R&D) Centers within the U.S. Department of Energy (DOE) Office of Science Fusion Energy Sciences program, and detailed topical research objectives. These conclusions and research objectives were drafted by organizing committee members and reviewed by workshop participants. Any views, opinions, and recommendations expressed in this report do not necessarily state or reflect those of EPRI.

2 FUSION BLANKETS WORKSHOP GENERAL CONCLUSIONS

The Fusion Blankets Workshop Research Objectives documented in this report represent observations and general conclusions drawn from structured and moderated sessions seeking input from subject matter experts on fusion blanket research and development (R&D) activities needed to support commercialization of fusion energy technology. General conclusions from the Fusion Blankets Workshop include:

- Tritium breeding blankets, while critical to the operation of future deuterium-tritium (D-T) fusion energy systems, have not been necessary to support short-pulse fusion research devices to date. This has led to the under-development of blanket technology in the U.S. compared to other countries.
- Related to the above finding, fusion blanket R&D has been primarily a design and simulation-focused research effort. New experimental facilities to address blanket R&D needs through prototypes which then provide critical design feedback are therefore urgently needed to advance this technology on a decadal timeline.
- A low level of sustained investment in fusion blanket R&D has resulted in knowledge gaps arising from lack of familiarity with early R&D work in the field. A concerted knowledge retention and transfer effort is needed to address this.
- Private industry is driving the commercialization of fusion energy in the United States, and public-private partnerships (PPPs) could greatly accelerate the development of all fusion energy concepts.
- In order to deploy fusion on a commercial scale as rapidly as possible, the U.S. Department of Energy (DOE) and other publicly funded fusion R&D efforts– both in the U.S. and internationally– should coordinate closely with one another and with the private fusion industry to make efficient use of limited public funds. International cooperative R&D agreements, like the one announced at COP28,[1] should be leveraged and investments that are necessary to close critical gaps should be prioritized.

[1] COP28 refers to the 28th Conference of Parties to the United Nations Framework Convention on Climate Change, held from November 30th-December 12th, 2023, in Dubai, United Arab Emirates.

3 FRAMEWORK CONCEPTS: DEVELOPING BLANKET TECHNOLOGIES

Framework Concepts are suggestions from the Fusion Blankets Workshop participants on developing the framework for a new Fusion Blanket R&D Center within the U.S. DOE Office of Science Fusion Energy Sciences program. Key Framework Concepts identified at the Fusion Blankets Workshop include:

- Develop a fusion blanket program and partnerships that can address the challenges in blankets used by inertial fusion energy (IFE), magnetic fusion energy (MFE), and other advanced fusion concepts.
- Support PPPs as part of DOE's milestone program and other funding opportunities. Organize workshops, knowledge seminars, industry days, and technical exchange meetings. Streamline partnering mechanisms and work with companies to alleviate concerns related to intellectual property (IP) through mechanisms that DOE recently made available such as 30-year IP protection in Cooperative Research and Development Agreements (for certain technologies).
- Foster engagement with community partners, universities, and the private sector to promote domestic and international partnerships to recruit and develop the blanket technology workforce. Workforce development should include a deliberate effort to build a more diverse and inclusive fusion community. Developing blanket technology for a fusion power plant requires expertise from many disciplines. This provides a pathway to include research groups that have not historically participated in fusion technology development in key research and funding opportunities.
- Periodically reevaluate fusion blanket research progress to take advantage of the rapid developments within public, private, and international research programs and focus future R&D efforts.

4 OVERARCHING RESEARCH OBJECTIVES (ROS) FOR BLANKET TECHNOLOGIES DEVELOPMENT FOR FUSION ENERGY

Overarching Research Objectives address research gaps common across fusion blanket topics and are of high importance to the advancement of blanket technologies for the deployment of fusion energy. These Overarching Research Objectives include:

- Determine a framework for collecting data and metadata from tritium breeding, tritium behavior, and materials compatibility experiments relevant to fusion blanket technology. Determine the necessary experimental metadata that must be collected in order for datasets from different experiments to be reliably combined.
- Collect, review, and organize physical property data for relevant blanket materials and technologies across process relevant conditions for different concepts and designs according to the framework determined above. Make the physical property data, including data related to behavior of materials with hydrogen (H), deuterium (D), and tritium (T) easily available via a standardized database.
- Conduct a domestic and global blanket test facilities gaps analysis, cross-referenced against final objectives output from the research objectives identified within this document. Closure of these gaps should focus on how to achieve component-level testing capabilities and identify the minimum set of acceptable environment/performance regimes needed in testing to move towards commercially viable fusion blankets.
- Identify and develop a set of nominal design elements, relevant environment, and performance requirements common to multiple private designs that can be utilized to guide FPP-scale blanket development.
- Quantify waste streams resulting from neutron activation, transmutation, and tritium absorption in blanket materials and their volumes that are anticipated to be generated during the process. Disposal pathways need to be identified and R&D is needed on methods for potential recycling and reuse of these materials.
- Perform risk and budget/planning assessments associated with technology deployment. Thes assessments would address workforce training needs, safety procedures, technology readiness assessment levels for technology deployments, and other relevant areas.
- Develop effective software tools for fusion blanket designs. This means low-fidelity models for rapid iteration, as well as high-fidelity, more computationally intensive models for detailed optimization. Design tools should be flexible, available, and straightforward to use, so that they are available to a wide subset of the fusion community and not just isolated teams.
- Assess how to optimally implement nonproliferation, export control, waste disposal, and community engagement for fusion blankets.

5 TOPICAL RESEARCH OBJECTIVES

Topical Research Objectives are specific to functional categories within the fusion breeder blanket system or specific considerations that need to be addressed related to breeder blankets or their operation. These research objectives are organized by topics and sub-topics to the greatest extent possible but may have some applicability across topics as well where complex interactions are expected.

5.1 Tritium Control

5.1.1 Permeation Barriers

- **RO 1.1-1:** Define performance requirements for tritium permeation barriers (TPBs), including durability in the thermochemical/mechanical/radiation environment along with anticipated service lifetime. Define where TPBs will be needed in an FPP.
- **RO 1.1-2:** Assess state-of-the-art and identify data gaps. Develop an R&D plan and facility needs so TPBs are ready for FPP deployment.
- **RO 1.1-3:** Develop fabrication/coating processes that enable robust TPBs at scale.

5.1.2 Data and Modeling Needs

- **RO 1.2-1:** Assess what data is needed to design an effective FPP blanket, to what extent existing data in the literature is usable, and to what extent existing fission irradiation and hot cell facilities can be leveraged. In particular, data regarding tritium solubility and diffusivity as a function of temperature and breeder chemistry is needed. Materials performance data in a fusion neutron spectrum is also needed.
- **RO 1.2-2**: Prioritize efficient data collection, data management, and data sharing from repeatable, standardized experiments. It should be possible to effectively combine data from multiple experiments.
- **RO 1.2-3**: Obtaining necessary data will require collaborations on experiments and facilities. Efficient IP standards should be developed which enable effective and mutually beneficial collaborations.
- **RO 1.2-4**: The data and modeling required to operate a plant, not just design it, must be considered. This means assessing what tritium detection and monitoring capabilities are required throughout the plant and assessing whether current technologies are adequate for the radiation environment in a fusion blanket.
- **RO 1.2-5**: Integral-scale tritium experiments and facilities are needed to provide tritium transport model validation data as it is expected that separate effect tests may not be fully predictive of plant-scale behavior.

5.1.3 Measurement and Control

- **RO 1.3-1:** The high radiation environment of fusion, and the resulting highly activated materials, will complicate tritium measurements within an FPP and make in situ measurements difficult. Improving tritium measurement performance should focus on measuring tritium in effluent streams. It should be assessed whether adequate technologies exist, and whether there are instances where in situ measurement of tritium (e.g., in the breeder material of the blanket) will be necessary.
- **RO 1.3-2:** Assess how different breeder materials affect tritium measurement. There is limited experience with liquid tritium breeders in general.
- **RO 1.3-3:** Engage with regulators to understand the likely standards that will be developed, and how much discrepancy will be allowed between the amount of tritium that is bred in theory and the amount of tritium that is measured and extracted.
- **RO 1.3-4:** Establish metrics and design criteria that maximize radiological safety to plant personnel, the public, and the environment.
- **RO 1.3-5:** Communicate and engage with the public around issues of tritium management. Fusion will be integrated in the larger energy market and society. Hence, it is prudent to assess the broader impacts of fusion design choices on economic, safety, environmental, and social factors.

5.1.4 Extraction Systems

- **RO 1.4-1:** There is a general lack of thermophysical data for tritium properties, behavior, and forms within blanket systems that needs to be addressed.
- **RO 1.4-2:** Tritium extraction system (TES) technologies are generally at low technology readiness level (TRL). The best-performing candidates need to be scaled up for the tritium processing throughput an FPP will require. Scale-up of some blanket concepts such as FLiBe, PbLi, and Li are likely to require facilities that can handle all relevant chemical hazards along with any radiation challenges associated with testing with tritium (if applicable). Appropriate facilities for tritium extraction testing scale-up will need to be identified or created and should be capable of handling relevant throughputs.
- **RO 1.4-3:** Assess how impurities and contamination impact the performance of various TES technologies.
- **RO 1.4-4:** *(Extraction from FLiBe)* Tritium's behavior in FLiBe is not well characterized. The data that exists is sparse with little agreement. Tritium breeding and extraction tests in FLiBe are needed; this requires facilities capable of working with beryllium, tritium gas, and tritium fluoride.
- **RO 1.4-5:** *(Extraction from Li)* Because lithium is an effective getter for tritium, efficient TES technologies must be developed that exploit different mechanisms than for the other liquids. There is very limited research on pure-Li breeder blankets, so it is necessary to scale up extraction and permeation testing. As with other lithium experiments, its high chemical reactivity requires careful chemistry control and fire safety systems.

- **RO 1.4-6:** *(Extraction from PbLi)* Additional data on tritium solubility and diffusivity in PbLi is needed. Extraction of tritium from PbLi will be difficult, and proposed technologies are low-TRL. Scaling tritium extraction technologies to FPP-scale is an engineering and materials challenge.

5.2 Functional Materials

5.2.1 MHD, Flow Phenomena, and Coolants

- **RO 2.1-1:** Address long-term stability of solid breeders in respective coolant systems (e.g., helium), including corrosion effects and thermomechanical degradation.
- **RO 2.1-2:** Research materials compatibility with liquid lithium, PbLi, and FLiBe, including both structural materials and thin films and coatings.
- **RO 2.1-3:** Research magnetohydrodynamic (MHD) effects in liquid breeders, especially PbLi and lithium, and how these effects may impact heat and mass transfer, corrosion, and wear within the blanket, manifolds and piping (noting that the higher density of PbLi will result in greater forces on materials). Model how these MHD effects will impact FPP performance. Build experiments capable of testing system behavior with variable geometry for a range of magnetic fields up to high magnetic fields (>5 Tesla).
- **RO 2.1-4:** Develop chemical purification/redox control/impurity removal systems for FLiBe, PbLi, and liquid lithium, leveraging research and development on similar fluid systems in fission.
- **RO 2.1-5:** Develop computational tools that enable liquid breeder blanket designs. These tools should account for conductive walls, MHD effects, heat and mass transfer, turbulence, and tritium behavior. These tools should be widely usable by the community (prioritize ease of access, good documentation, and flexibility).

5.2.2 Data and Modeling Needs

- **RO 2.2-1**: Better data is needed across the board for breeder materials. Data should be collected from repeatable, well-documented experiments. Important data categories include tritium transport, corrosion effects, and MHD effects.
- **RO 2.2-2**: Assess gaps in neutronics data for functional materials. Prioritize gaps based on what is needed for pilot plant design.
- **RO 2.2-3**: Assess gaps in data for neutron multiplier materials (thermophysical, corrosion, neutronics, irradiation stability). Prioritize gaps based on what is needed for pilot plant design.
- **RO 2.2-4**: Develop a framework for collecting MHD data in liquid breeder experiments, such that data from different experiments can be easily compared.

5.2.3 Breeder Materials

- **RO 2.3-1:** *(Developing solid breeder blankets)* There is a large body of research on solid breeder blankets. However, because solid breeders require more structural/functional materials than liquid blankets, a larger percentage of the blanket is non-breeding, and thus, the achievable tritium breeding ratios (TBR) may be too low. Improving TBR of solid breeder blankets is a key research priority. Long-term mechanical stability of solid breeders under irradiation requires more research.
- **RO 2.3-2:** *(Developing FLiBe blankets)* The thermophysical/chemical properties of FLiBe need to be better characterized; the data that exists is sparse with little agreement. Material compatibility with FLiBe needs further research. This requires facilities capable of working with beryllium and tritium. Redox control/chemistry control systems need to be developed for FLiBe. The FLiBe supply chain is also very constrained currently, adding to the difficulty of building FLiBe-based experimental programs.
- **RO 2.3-3:** *(Developing liquid Li blankets)* There is very limited research on pure-Li breeder blankets, so it is necessary to scale up extraction and permeation testing. Lithium is highly reactive, so blanket tests and scaled-up blanket systems will require careful chemistry control and fire safety systems. Sensitivity to impurities is not well understood.
- **RO 2.3-4:** *(Developing PbLi blankets)* MHD effects are central to the performance of PbLi blankets and require further study.
- **RO 2.3-5:** All blanket concepts would benefit from greater attention to engineering integration issues in their design, and measurement of tritium breeding rates under neutron irradiation.

5.2.4 Multiplier Materials

- **RO 2.4-1**: Beryllium poses a health hazard, so research into beryllium and beryllides requires access to specialized facilities. Institutions researching beryllium multiplier materials need access to such facilities.
- **RO 2.4-2**: Assess safety hazards and mitigation strategies associated with large volumes of lead and beryllium at an FPP. Determine needs for remote handling.
- **RO 2.4-3**: Strong supply chains for lithium-6 and/or beryllium are needed, as more lithium enrichment can reduce needs for lead and beryllium multipliers by improving overall TBR of the blanket. Whether enrichment, or use of multiplier materials, is a better strategy should be assessed.

5.3 Structural Materials

5.3.1 Materials Compatibility

- **RO 3.1-1:** Implement a program to understand materials compatibility between proposed structural materials (including lower-TRL fusion materials) and proposed coolants/liquid breeders at relevant temperatures and flow conditions. In situ irradiation during corrosion and tritium effects tests should be leveraged to understand materials durability in environments with multiple degradation mechanisms.
- **RO 3.1-2:** FLiBe corrosion data with structural materials appropriate for the fusion neutron spectrum is very limited. Hydrogen fluoride and tritiated hydrogen fluoride (HF/TF) from tritium breeding or water ingress and other aggressive species pose corrosion risks that must be mitigated with proper redox control, which must be demonstrated at larger scale. Corrosion testing in FLiBe requires beryllium-capable equipment and facilities. It is necessary to develop a good reference electrode for FLiBe to improve the corrosion data from these experiments.
- **RO 3.1-3:** PbLi compatibility may require specialized coatings of structural materials at high temperatures to ensure compatibility. This necessitates an R&D program to demonstrate the reliability and usability of these coatings (e.g., ability to coat a component with complex geometry, long-term radiation stability and adhesion of the coating to the structural material beneath).
- **RO 3.1-4:** There is limited corrosion data for liquid lithium and structural materials. Corrosion experiments need to take precautions regarding lithium's high reactivity with moisture and account for purity of lithium both before and during the testing process.
- **RO 3.1-5:** Develop the qualification requirements and implement a test program for cyclic electromagnetic loading of blanket structural materials and component prototypes.

5.3.2 Data/Modeling Needs

- **RO 3.2-1:** Assess the minimum dataset needed for effective lifetime analysis of how commonly proposed structural materials for fusion will perform in an FPP. Assess what can be addressed with existing data and where a program must be implemented to fill gaps. To the greatest extent possible, match new experiments with existing facilities. Assess when integrated tests are necessary; separate effect tests should be motivated by a clear data need.
- **RO 3.2-2:** Collect sufficient data to model joints and welds in components. Coupon-scale testing of weld fusion and heat affected zones may be performed on the way to full-scale component testing that more accurately represents behavior.
- **RO 3.2-3:** Develop a U.S. Fusion Prototypic Neutron Source, which is important for long-term data needs.

5.3.3 Activation and Waste Considerations

- **RO 3.3-1:** Materials and blanket concept choices have a large impact on activation and waste, and assessments of decay heat and waste generation should be performed early in FPP design processes and as a means of evaluating concepts.
- **RO 3.3-2:** Waste classification regulations need to be updated. Current waste classification regulations are specific to fission with fission relevant materials activated by fission relevant neutron fields. To support the development of fusion, the waste classification regulations will need to be updated to also include fusion relevant materials activated by fusion relevant neutron fields to provide clarity to fusion energy developers and operators so that appropriate selections, design, and end of life waste management can be thoughtfully undertaken.
- **RO 3.3-3:** D-T fusion will generate a large volume of radioactive waste. Significant R&D is needed to develop strategies and technologies to minimize this, through design, waste treatments, and recycling and reuse.
- **RO 3.3-4:** Implications of mixed waste disposal (e.g., activated materials containing tritium and/or beryllium) need to be evaluated.

5.3.4 Fundamental Properties and Fabrication

- **RO 3.4-1:** Promising novel materials (e.g., high entropy alloys, advanced silicon carbide composites) promise good thermomechanical stability under irradiation, low activation, and good materials compatibility. Advancing these materials from lab-scale to large-scale components requires a dedicated R&D program focused on fabrication and machining using these materials.

5.4 Blanket Enabling Technologies

5.4.1 Thermal Management (Heat Exchangers, Pumps)

- **RO 4.1-1:** Research and development into high temperature heat exchangers with tritium permeation barriers. Materials compatibility with primary coolant choices and low level of radiation tolerance.
- **RO 4.1-2:** Research into long term reliable pumps which function under harsh environments with primary coolant material compatibility, tritium compatibility and sufficient throughput scale.
- **RO 4.1-3:** Exploration of power generation cycles fit for fusion application to determine Brayton or Rankine configurations.
- **RO 4.1-4:** Facilities (e.g., experimental loops) for testing balance of plant equipment for different blanket concepts are needed.

5.4.2 Purification and Corrosion Protection

- **RO 4.2-1:** Develop baseline purity standards for liquid breeders. Current datasets from different experiments cannot be compared against each other because the as-received breeder purity varies greatly and is often unreported.
- **RO 4.2-2:** Understand how activation products will affect the chemistry of liquid breeders (e.g., Polonium-210 and Mercury-203 in PbLi).
- **RO 4.2-3:** Certain material/breeder combinations may require the development of robust corrosion-protective coatings.
- **RO 4.2-4:** All blanket concepts will require coolant purification systems to remove impurities and corrosion and activation products. These systems need to be developed and tested in prototypic environments (potentially including neutron activation), and facilities are needed to conduct this testing.

5.4.3 Li Enrichment and Supply Chain

- **RO 4.3-1:** Assess level of enrichment needed for a given FPP and set of operational targets. It is not a given that all FPP designs will require enrichment, or to what level they will require enrichment. Assessment of required Li enrichment level requires modeling of the fuel cycle, particularly neutronics (e.g., determining TBR).
- **RO 4.3-2:** Develop strategies and methods for obtaining Li-6 (e.g., work with molten salt fission companies who need to minimize tritium production in their coolant). Assess existing Li-6 stockpiles in the national lab system.
- **RO 4.3-3:** Understand possible challenges associated with Li-6 enrichment. This includes export control challenges and public perception surrounding use of Li-6 for defense applications.
- **RO 4.3-4:** Analyze the need for an existing supply chain for other potential bottleneck materials including enriched lithium, purified beryllium, reduced activation/neutron transparent structural material alloys, etc. Understand the supply chain development required to facilitate the expansion of fusion energy.
- **RO 4.3-5:** Characterization and mapping of lithium enrichment processes currently used and under development.

5.4.4 Dual Coolant System Needs

- **RO 4.4-1:** Conduct a comparative pumping power assessment for various dual coolants (e.g., helium (He), carbon dioxide (CO_2) and steam), considering the commercial availability or supply chain development required for the critical components (e.g., He/CO_2 compressors).

- **RO 4.4-2:** With the exception of water, dual coolants such as helium are likely to require some new component development and testing, and experimental facilities to enable this. Develop test articles, components and test stands to increase the heat removal capability of helium and other coolants.
- **RO 4.4-3:** With the exception of water-based dual coolant systems, a commercial supply chain for components must also be developed.

5.5 Maintenance and Integration

5.5.1 Design for Safety

- **RO 5.1-1:** Develop safety systems for liquid lithium blankets to prevent explosion or fire in the event of contact with air, water, and/or moisture.
- **RO 5.1-2:** Ensure that fusion researchers and companies follow beryllium safety standards if working with FLiBe or beryllium-based multiplier materials.
- **RO 5.1-3:** Safety implications of material choices and blanket concept selection need to be considered and analyzed early in the design process.
- **RO 5.1-4:** Design for decay heat removal and the installation of other safety systems should be a part of early design integration.
- **RO 5.1-5:** Development of codes, standard, and best practices is needed to address fusion safety issues.
- **RO 5.1-6:** Develop necessary monitoring and surveillance technology for safety, e.g., real-time beryllium detection.
- **RO 5.1-7:** Key safety analysis techniques need to be developed for and/or applied to fusion systems, including failure mode and effects analysis, accident identification and analysis, safety analysis systems models (i.e., software), and software reliability analysis.

5.5.2 Design for Integration

- **RO 5.2-1:** Work with FPP designers to develop draft models of the blanket to assess points of integration. Examples include the interface between the blanket and vacuum vessel; first wall and limiters; blanket and structural mounts; blanket and piping; blanket and diagnostics, etc. The plasma physics teams for FPPs should also be consulted to assess which components related to plasma control will need to be mechanically integrated into the blanket design. Assess challenge points: where does integrating the blanket into the plant raise other engineering challenges?
- **RO 5.2-2:** Ensure that the design of the blanket, and its integration with other components, allows for effective plant maintenance.

5.5.3 Design for Maintenance

- **RO 5.3-1:** Engage with the R&D community, private industry, and relevant vendors to develop efficient, flexible maintenance strategies that maximize learnings from the first of a kind pilot plant that will lead to maximizing commercial plant uptime.
- **RO 5.3-2:** To the extent possible, design pilot plants with maintenance strategies that are as potentially applicable to n^{th} of a kind plants.
- **RO 5.3-3:** Assess likely risk of tritium cross-contamination across interfaces during maintenance. Develop blankets/maintenance strategies that enable one sector or component to be sealed off from others during maintenance.
- **RO 5.3-4:** Assess and develop necessary remote handling maintenance strategies (e.g., to deal with highly activated or chemically toxic materials), which may be informed by existing strategies in other technology domains.
- **RO 5.3-5:** Design blanket components that will undergo minimal misalignment during their lifetime as a result of radiation damage instability, thermal expansion, or movement during maintenance. It should be determined if in situ metrology strategies are needed to detect dimensional changes early.

5.5.4 Design for Reliability

- **RO 5.4-1:** Reliability of fusion systems and components is critical to both the safety and availability of power plants, and therefore to the attractiveness of fusion energy. A greater knowledge of component reliability data is needed in order to ensure a successful demonstration on an FPP and beyond.
- **RO 5.4-2:** Determine the need for and the necessary capabilities to conduct in situ monitoring of structural components to provide suitable protection against structural failures.

5.5.5 Design for Manufacturability

- **RO 5.5-1:** Develop an understanding of the required manufacturing tolerances required for the various blanket system elements, and cross reference with existing manufacturing capabilities for the specific materials.
- **RO 5.5-2:** Develop a gap analysis for the manufacturing capabilities that already exist, compared the manufacturing requirements for the various blanket system elements.

5.6 Cross-Cutting Topics

- **RO 6-1:** Assess the shielding efficacy of the various blanket concepts and determine the need for additional shielding materials to provide sufficient margin.
- **RO 6-2:** Assess and develop the necessary blanket diagnostics systems for blanket system monitoring and control (pressure, temperature, flow, level, tritium accountancy, chemical assessments, etc.).

- **RO 6-3:** Support techno-economic studies to evaluate the various blanket concepts and key performance metrics. With input from the private fusion concept developers, the energy industry, and fusion science and technology experts, identify the most promising concepts to guide technology selection and to inform directions of technological development and concept downselection.
- **RO 6-4:** Advance the development of radiation-resistant sensors and instrumentation for FPP blanket systems. This is a cross-cutting topic with the diagnostics R&D community.

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Program on Technology Innovation: 2022 Fusion Prototypic Neutron Source (FPNS) Performance Requirements Workshop Summary

Washington, D.C., September 20–21, 2022

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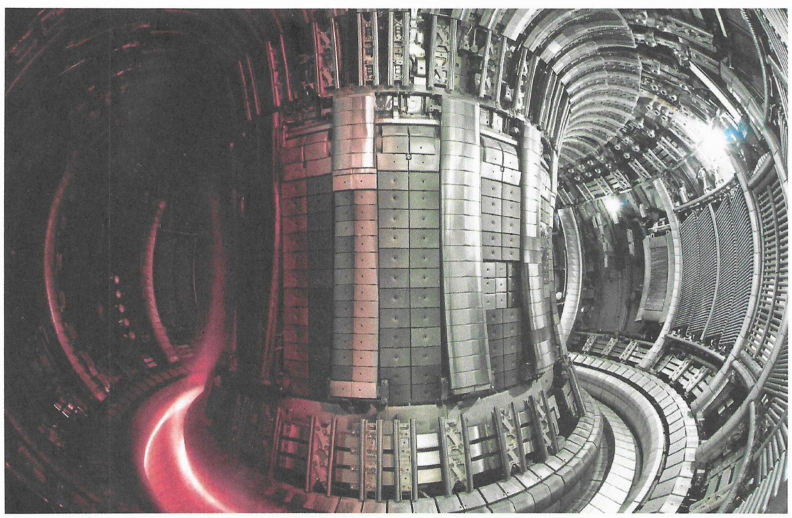

Cover image: Interior of the JET Tokamak with plasma superimposed.
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Program on Technology Innovation: 2022 Fusion Prototypic Neutron Source (FPNS) Performance Requirements Workshop Summary

Washington, D.C., September 20–21, 2022

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Technical Update, November 2022

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ACKNOWLEDGMENTS

EPRI prepared this report.

Principal Investigator
A. Sowder

This report describes research sponsored by EPRI.

The following individuals comprised the executive committee for the 2022 Fusion Prototypic Neutron Source Performance Requirements Workshop, convened and hosted by EPRI on September 20-21, 2022, in Washington, D.C., and prepared this summary report:

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ABSTRACT

The requirements for a fusion prototypic neutron source (FPNS) were initially developed by the fusion materials and technology community in 2018–2019, and in 2020 the American Physical Society Division of Plasma Physics further elaborated the need and priority, rating the FPNS as the most pressing need among potential activities for realization of fusion energy. In light of the significant changes and advancements within the private fusion industry, a two-part workshop was convened and hosted by EPRI comprising a half-day webinar on August 29, 2022, followed by a two-day hybrid workshop on September 20–21, 2022, to update the public and private fusion community consensus on FPNS requirements and development timeline. The workshop included presentation of the diversity of fusion concepts and material selections, and indicated a need to modify the performance requirements to eventually provide increased volume to allow high throughput testing of many different materials concepts, including composites, and an increased temperature window up to 1200°C.

The consensus reached among workshop participants was for delivery of an FPNS in 2028 (or earlier) meeting the following requirements: 5 to 11 displacements per atoms (dpa) per calendar year damage rate (Fe equivalent); neutron energy spectrum that will introduce gaseous and solid transmutants at generation rates consistent with 14 MeV fusion neutrons; ≥ 50 cm^3 sample volume in the high flux zone; ~300 to 1200°C temperature range; 3 independent temperature controlled and monitored regions; and ≤ 20%/cm flux gradient in the plane of the sample. A second consensus reached among participants was to ensure sufficient FPNS upgrade capacity to deliver increased performance capability by 2032 (or earlier) delivering the following enhanced requirements: 15 dpa per calendar year damage rate (Fe equivalent); ≥ 300 cm^3 sample volume in the high flux zone; and 4 independent temperature controlled and monitored regions.

There was also recognition of the importance that the FPNS neutron spectrum introduce appropriate levels of gaseous and solid transmutants within irradiated materials consistent with the fusion neutron environment. Commensurate with the U.S. government's Bold Decadal Vision for Commercial Fusion Energy announced in March 2022, workshop participants emphasized the need for a sense of urgency with respect to the timeline to design, build and operate an FPNS with an upgradeable path to improved performance. Following completion of the workshop, the Fusion Industry Association (FIA) surveyed its members to assess the extent of the consensus opinion developed at the 2022 FPNS workshop. Consistent with the workshop consensus, the FIA survey results indicate strong fusion developer support for FPNS, particularly among D-T fusion concept developers.

Keywords

Fusion

Fusion energy

Fusion pilot plant (FPP)

Fusion prototypic neutron source (FPNS)

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1
INTRODUCTION

The development of fusion energy requires structural and plasma-facing materials with sufficient dimensional stability and resistance to neutron degradation of thermal-mechanical and physical properties to support sustained operation. Use of these materials also will need to meet such environmental and safety requirements as low quantities of long-lived radioactivity, low concentrations of short-term volatile radioactive species and modest decay heat.

1.1 Need for a Fusion Prototypic Neutron Source (FPNS) Capability

The fusion materials science community has agreed that there is a shortage of relevant materials performance experimental data to support sufficient model development and design criteria, beyond the relatively high confidence for reduced activation ferritic-martensitic alloys up to a neutron wall loading of ~5 MW/year within the temperature range from approximately 400 to 550°C [1]. While data from existing neutron irradiation sources has been helpful for predicting materials performance at lower neutron energy fluences and temperatures compared to a deuterium-tritium (D-T) based fusion pilot power plant, there remains a significant need to develop advanced materials to enable improved performance of materials and manufactured components for reactors beyond the fusion pilot plant and first of a kind (FOAK), in addition to a need for experimental data at significantly higher temperature and higher neutron fluences with a 14-MeV peaked neutron spectrum to predict performance in structural and plasma-facing materials.

Significant materials research and development will be required to enable the design and function of all in-vessel and ex-vessel structural and functional materials in the fusion pilot plant environment. Functional materials include those for closing the fuel cycle (e.g., tritium breeding, including neutron multipliers and tritium permeation barriers), diagnostic materials, flow channel inserts, and shielding/insulating materials. For a deuterium-tritium (D-T) fusion reactor concept, the 14-MeV neutrons will interact with materials across a range of operating temperatures, from about 300 to 1200°C, and will produce both displacement damage (characterized in units of displacements per atom or dpa) and will induce transmutant impurities through (n, p) and (n, α) reactions. These transmutant reactions induce much higher hydrogen and helium production than occurs in fission reactors, in addition to the Z-1 and Z-2 impurities that result as daughter products from these reactions.

Figure 1-1 illustrates the materials operating environment challenge with respect to transmutant helium produced, in units of atomic parts per million (appm), and displacement damage, in units of dpa. In particular, the effect of the gaseous impurities of hydrogen and helium on the microstructure evolution at high dpa levels remains an active area of concern associated with materials degradation of performance-sustaining properties [2]. Thus, evaluation of fusion neutron irradiation effects requires simultaneous displacement damage and the introduction of appropriate levels of both gaseous (He, H) and solid (Z-1, Z-2, and subsequent radiation decay product) impurities in bulk samples. It is important to note that the use of both multiple beam ion irradiations and fission reactor irradiations are needed as part of the fusion materials and technology development in order to reduce risk, but neither can completely replicate the fusion neutron displacement and transmutant environment, and as such cannot replace the need for a dedicated fusion prototypic neutron source for materials testing and development.

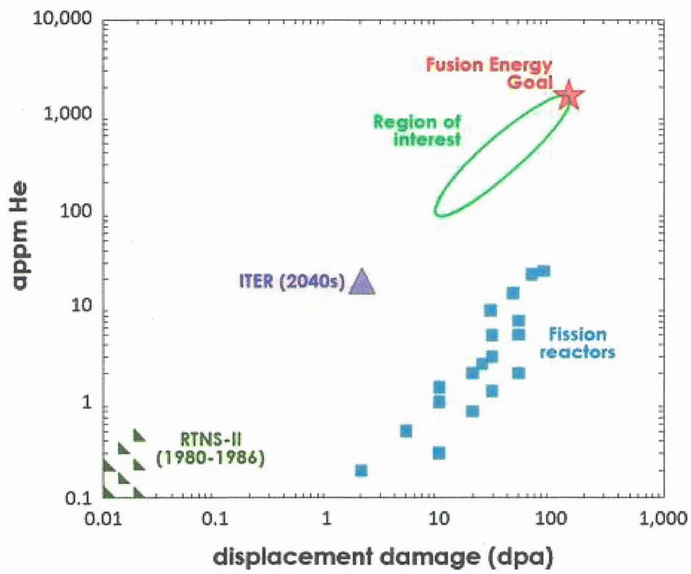

Figure 1-1
Region of interest for fusion structural and functional materials. Figure adapted from FESAC report DOE/SC-0149, February 2012 [3].

1.2 Workshop Context

A 2018 U.S. DOE Fusion Energy Science (FES) workshop evaluated the need for FPNS, the minimum high-level requirements and potential to position the U.S. in an internationally leading role in fusion materials and technology [4]. Subsequently, in 2020, the American Physical Society Division of Plasma Physics Community Planning Process (APS DPP-CPP) further elaborated the need and priority for an FPNS [5], with the FPNS ranking highest among potential new start activities within the recommendation to pivot the U.S. fusion activities towards a fusion technology and energy mission to support a fusion pilot plant. Further, the U.S. fusion materials program advisory group, also known as "*MASCO*", revisited the FPNS performance requirements in 2021 [6], resulting in the recommendation for the performance requirements shown in Table 2-1.

Table 1-1
Refined FPNS requirements resulting from the 2018 FES workshop [4], 2020 APS DPP CPP [5] and 2021 *MASCO* [6] reports

Parameter	2018 Workshop Guidelines [4]	2021 Augmented Recommendations [6]
Damage rate	~ 8–11 dpa/calendar year (Fe)	Time averaged rate during beam-on period. Integrated over irradiation time. Required for >70% of sample volume.
Spectrum	~10 appm He/dpa (Fe)	~40 appm H/dpa(Fe)
Sample volume in high flux region	≥50 cm3	Ability to accommodate in situ control and measurement capabilities
Temperature range	~300–1000°C	–
Temperature control	Three independently monitored and controlled regions	Ability to maintain within 5% of target temperature (Kelvin) at a reference point in each temperature zone.
Flux gradient	≤20%/cm in the plane of the sample	Spatial variation <10% along 6 mm length in beam-normal plane within at least 70% of all temperature zones.

Since the 2018 FES-sponsored FPNS workshop, significant changes have occurred with respect to: (1) development of fusion energy concepts; (2) private-sector investment; (3) convergence of the U.S. fusion community focus on smaller, lower capital cost fusion plant designs [7]; and (4) community recommended pivot of fusion technology research towards putting fusion electricity on the grid [8]. A recent 2022 Fusion Industry Association report highlights that there has been over $4.7B of declared private investment into the fusion industry to-date, and the past year investment into commercial fusion is in excess of $2.8 billion[1] [9], including $1.8 billion in private equity (series B funding) for Commonwealth Fusion Systems in its pursuit of commercial fusion energy [10]. This expanding private sector interest in fusion has been complemented by the White House Fusion Summit, held March 17, 2022, to launch a Bold Decadal Vision for Commercial Fusion Energy[2] and a June 2022 U.S. Department of Energy-sponsored workshop examining fusion public-private partnerships.[3] It is within this context that EPRI and the University of Tennessee partnered to organize a fusion community workshop to re-assess FPNS performance requirements and development timeline.

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[1] U.S. dollars (USD)

[2] Readout of the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy. April 19. 2022. https://www.whitehouse.gov/ostp/news-updates/2022/04/19/readout-of-the-white-house-summit-on-developing-a-bold-decadal-vision-for-commercial-fusion-energy/

[3] DOE Workshop on Fusion Energy Development via Public-Private Partnerships. June 1-3, 2022. Washington Hilton. Washington, D.C. https://science.osti.gov/fes/Community-Resources/Workshop-Reports/Fusion-Energy-Development-via-Public-Private-Partnerships

1.3 Workshop Organization

EPRI, working in coordination with the University of Tennessee, Knoxville, and an FPNS workshop executive and local organizing committee, hosted a two-part workshop on the Fusion Prototypic Neutron Source (FPNS), consisting of a half-day webinar on August 29, 2022, followed by a two-day hybrid workshop on September 20-21, 2022, to assess FPNS performance requirements and development timeline. Appendix A provides agendas for the webinar and hybrid workshop held in Washington, D.C.

2
WORKSHOP OVERVIEW AND DISCUSSION

The 2022 EPRI-sponsored workshop series on FPNS included extensive presentations from the fusion materials and technology community in addition to presentations from the fusion industry, including both fusion concept developers and fusion technology suppliers or vendors, and extensive discussion, as noted in the agenda provided in Appendix A. Both the webinar and workshops included presentations on the three most advanced concepts for an FPNS, including:

- The spallation neutron accelerator-based system available at the Los Alamos Neutron Science Center (LANSCE) facility
- A D-T fusion neutron concept developed by SHINE Systems and Manufacturing (formerly Phoenix, LLC)
- A D-Li stripping source, including the possibility for a linear accelerator or cyclotron driver for the necessary current of high-energy deuterium ions

Idaho National Laboratory (INL) discussed plans for a Boosted Energy Advanced Spectrum Test (BEAST), a dedicated fast neutron testing environment planned for development within the INL Advanced Test Reactor, and the University of Wisconsin presented on a gas dynamic trap volumetric neutron source concept.

The presentations also included extensive coverage of topics related to small-scale testing, the role of computational multiscale materials modeling, the role of post-irradiation examination and testing, and the use of both available fission reactor and ion beam irradiation facilities. It was noted that computational materials modeling is important for interpreting neutron testing results and extrapolating the conclusions to the 14 MeV fusion neutron environment.

The discussion on the role of ion beam and nuclear reactors noted that the use of both multiple beam ion irradiations and fission reactor irradiations are needed in order to accelerate the development timeline and reduce the risk of the fusion materials and technology development, but neither can completely replicate the fusion neutron displacement and transmutant environment. As such, neither fission reactor irradiation nor multiple ion beam irradiation can completely replace the need for a dedicated fusion prototypic neutron source for materials testing and development.

One important aspect of the discussions held at the September hybrid workshop was the sense of urgency felt within the fusion industry. This urgency is related to their desire to rapidly complete prototype fusion concept pilot plant designs and to deliver fusion energy to the grid, driven by the pace of innovation and the timelines developed with the investors. Thus, the fusion developers have an immediate sense of urgency towards these initial demonstrations, while the fusion vendors have a longer-term perspective associated with developing a viable commercial fusion sector.

Another observation from the fusion concept presentations was the need to consider many different types of structural and functional materials; it was apparent that a need exists to increase the potential operating temperature window to a maximum around 1200°C for commercial fusion energy.

During discussions, workshop participants recognized there are multiple possible development pathways for FPNS construction and operation, including siting the FPNS at a DOE national laboratory or via public-private partnership approaches. However, these topics were identified as being outside the workshop scope and purpose, which was to develop a clear fusion community consensus on (1) the need for an FPNS capability and (2) the associated performance requirements and development timelines.

It was noted that design, construction and operation of FPNS will require co-location of requisite hot cell facilities to handle the irradiation capsules, sort, remove and ship the material samples, and proximity to available post-irradiation examination facilities to perform the required testing and microstructural characterization. However, post-irradiation examination (PIE) could be performed at multiple facilities and locations throughout the fusion materials and technology community with appropriate shipment of irradiated materials.

Three key workshop outcomes regarding FPNS performance, timelines, and upgradability are:

1. The presentations and discussions at the September 2022 workshop led to the emergence of a consensus opinion for an FPNS delivered in 2028, or earlier, that would meet an updated set of requirements that are presented in Table 2-1.
2. The discussions highlighted both the desire for near-term development of capability to provide prototypic 14-Mev neutron data as soon as possible, and the requirement that the FPNS irradiation environment provide data with induced gaseous and solid transmutant impurity concentrations that are as close to the actual D-T fusion neutron environment as possible.
3. There was also strong consensus that the FPNS should be designed and built in a way to enable future upgrades in terms of irradiated material volume and operating temperature regimes, as noted in Table 2-2, and that this upgraded capability is desired by 2032, or earlier.

Table 2-1
Consensus performance requirements for an FPNS desired by 2028, or earlier

Parameter	Capability Requirement
Damage rate	5 to 11 dpa/calendar year (Fe equivalent)
Spectrum	Gaseous and solid transmutant impurity generation rates consistent with 14 MeV fusion neutrons
Sample volume in high flux zone	≥ 50 cm^3
Temperature range	~300 to 1200°C
Temperature control	3 independently monitored and controlled regions
Flux gradient	≤ 20%/cm in the plane of the sample

Table 2-2
Consensus performance requirements for an upgraded FPNS desired by 2032, or earlier

Parameter	Capability Requirement
Damage rate	15 dpa/calendar year (Fe equivalent)
Spectrum	Gaseous and solid transmutant impurity generation rates consistent with 14 MeV fusion neutrons
Sample volume in high flux zone	≥ 300 cm^3
Temperature range	~300 to 1200°C
Temperature control	4 independently monitored and controlled regions
Flux gradient	≤ 20%/cm in the plane of the sample

3
BROADER FUSION INDUSTRY INPUT

Following completion of the September workshop, the FIA surveyed its members in order to determine a broader, fusion industry-wide view of the support for the FPNS requirements and timeline developed at the workshop (shown in Tables 2-1 and 2-2). This survey included both the fusion industry members who are actively working to develop deuterium-tritium fusion power plant concepts, and members who are categorized as vendors or suppliers of fusion-relevant technology. The questions asked in the FIA survey are presented in Appendix B, and participants were asked to respond to each question on a 1 (strongly do not support) to a 5 (strongly support) numerical scale. No private fusion companies pursuing non-D-T fusion energy concepts responded to the survey after multiple reminders.

A few takeaways emerge from the FIA poll results. In general, there is strong support for the nearer term FPNS mission (Table 2-1) with a total average of 4.6 (out of 5) between all responses. It is worth noting that lower support exists among the private companies developing a D-T fusion energy concept for the longer-term mission (Table 2-2). There is also a unanimous preference among D-T fusion energy developers for a faster time to FPNS startup with reduced capability, and a preference for it to cost in the $250-750 million range.

For the FIA members who are vendors/suppliers or other affiliate member, priorities are flipped relative to developers, with a stronger preference for a longer-term FPNS mission and more capabilities at startup, even if this results in a longer FPNS deployment timeframe. This difference is understandable because vendors and suppliers are likely to be less strongly tied to aggressive timescales faced by private fusion developers on their path to commercialization of individual fusion energy concepts. The vendor/supplier community is also more supportive of higher estimated FPNS project costs.

The sixth and final question in the FIA poll related to the funding and operating model for FPNS. As noted in the recap of the September workshop, this question falls outside the workshop scope to determine mission need, performance requirements, and development timeline for an FPNS. Industry views are mixed on this question with no clear consensus on the funding and operation model for an FPNS.

The consistent divergence between the developers and the suppliers/vendors with respect to the speed of FPNS deployment and capability reinforces an important message from the workshop: Fusion concept developers prioritize speed given commercial pressures to achieve and maintain competitive advantage and investor confidence. Whereas the suppliers/vendors and the U.S. fusion material science and technology community have different priorities. This tension is natural and did not prevent development of a consensus opinion: An FPNS capability is an urgent and high priority for supporting the development of a commercial fusion power industry in the U.S. However, an FPNS facility is not necessarily on the critical path for near-term fusion concept demonstrations and pilot plant operation.

4
CONCLUSIONS

The consensus opinion of the 2022 workshop was for an FPNS facility (1) delivered in 2028 (or earlier) meeting the requirements described in Table 2-1, and (2) with sufficient capability for future upgrades to deliver increased performance capability by 2032 (or earlier) as shown in Table 2-2. There was also agreement that the FPNS neutron spectrum needs to introduce appropriate levels of gaseous and solid transmutant impurities into irradiated materials that are consistent with the fusion neutron environment. Further, commensurate with the U.S. government's Bold Decadal Vision for Commercial Fusion Energy, the workshop reiterated a strong sense of urgency in the timeline to design, build, and operate an FPNS, while also maintaining an upgradeable path to improved performance.

The 2022 EPRI-sponsored workshop series on FPNS featured technical presentations from the fusion materials and technology community, fusion technology developers, and fusion vendors/suppliers, followed by extensive discussion. The presentations included substantial coverage of topics related to small-scale material testing and characterization, the role of computational multiscale materials modeling for interpreting neutron testing results and extrapolating the conclusions to the 14 MeV fusion neutron environment, the role of post-irradiation examination and testing, and the use of available fission reactor and ion beam irradiation facilities.

The combined use of multiple beam ion irradiations and fission reactor irradiations is essential for fusion materials and technology development. However, neither can fully replicate the fusion neutron displacement and transmutant environment. Consequently, these capabilities do not and cannot replace the need for a dedicated fusion prototypic neutron source for materials testing and development.

Following completion of the workshop, the Fusion Industry Association surveyed its members to determine agreement among the broader fusion industry with the consensus developed at the 2022 workshop. The survey included both the fusion industry members who are actively working to develop deuterium-tritium fusion power plant concepts and members who are categorized as vendors or suppliers of fusion relevant technology. All eight of the D-T fusion developers participating in the survey unanimously communicated strong support for the rapid (2028 or earlier) delivery of an FPNS facility that fulfills the requirements captured in Table 2-1 above. Overall, the FIA survey results indicate solid community wide support for an FPNS deployed on a commercially relevant timeline to support private-sector development of safe, reliable, and cost-competitive fusion technology options for firm zero-carbon energy generation.

5
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A
WEBINAR AND WORKSHOP AGENDAS

Agendas are provided below for the August 29, 2022, pre-workshop webinar and the September 20-21, 2022, hybrid FPNS workshop hosted at EPRI Washington D.C. Office; 1325 G St., NW; Suite #530; Washington DC 20005.

A.1 August 29, 2022 Pre-FPNS Workshop Webinar Agenda

SESSION 1: CONTEXT FOR A US FUSION NEUTRON SOURCE, SESSION CHAIR: AHMED DIALLO (PPPL/ARPA-E)		
TIME	**TOPIC**	**PRESENTER**
12:00 p.m.	Welcome, Introduction of Objective	***Brian Wirth (UTK/ORNL)*** ***Andrew Sowder (EPRI)***
12:10 p.m.	FESAC Long-Range Plan	***Troy Carter (UCLA)***
12:35 p.m.	NASEM Pilot Plant Study Recommendations	***Rich Hawryluk***
1:00 p.m.	The Administration's Plan for a Bold Decadal Vision	***Scott Hsu (DOE)***
1:20 pm	Energy Justice Considerations	***Aditi Verma (U Michigan)***
1:45 p.m.	FES Perspective	***Gene Nardella (DOE)***
1:50 p.m.	Review of 2018 FPNS Workshop	***Daniel Clark (DOE)***
2:15 p.m.	The role of an FPNS on the CFS commercial fusion pathway	***Cody Dennett (CFS)***
2:40 p.m.	Discussion/Q&A on Context for a US Fusion Neutron Source	***Ahmed Diallo (PPPL/ARPA-E)***
3:05 p.m.	**Break**	

SESSION 2: STATUS OF RADIATION DAMAGE TESTING AND NEEDS FOR MATERIALS QUALIFICATION, SESSION CHAIR: JAIME MARIAN (UCLA)		
TIME	**TOPIC**	**PRESENTER**
3:20 p.m.	Materials Degradation and 14 MeV testing Needs	***Steve Zinkle (UTK/ORNL)***
3:45 p.m.	Infrastructure Needs to Support Materials Characterization	***Grace Burke (ORNL)***
4:10 p.m.	Approaches for 14 MeV Neutron Irradiation Capability	***Phil Ferguson (ORNL)***
4:35 p.m.	Review of fission reactor testing capability & approaches to utilize for fusion materials	***Lance Snead (Stony Brook/MIT)***
5:00 p.m.	Role of multi-beam ion irradiation	***Gary Was (U Michigan)***
5:25 p.m.	Discussion/Q&A on Status of Radiation Damage Testing and Needs for Materials Qualification	***Jaime Marian (UCLA), moderator***
5:45 p.m.	Overview of Agenda for in-person meeting and Homework Assignments to prepare for that meeting	***Brian Wirth (UTK/ORNL)*** ***Andrew Sowder (EPRI)***
6:00 p.m.	**Adjourn**	

A.2 September 20-21, 2022 FPNS Workshop Agenda

SESSION 1: PRIVATE FUSION COMPANY PERSPECTIVES ON FUSION PLANT CONCEPTS, MATERIALS AND DEVELOPMENT NEEDS FOR AN FPP 20 SEPTEMBER 2022		
TIME		PRESENTER
9:00 a.m.	**Session 1a: Private Fusion Presentations, Moderated by Sarah Ferry (MIT)**	
9:00 a.m.	Tokamak Energy presentation	Jim Pickles
9:20 a.m.	Xcimer Energy presentation	Michael Tobin
9:40 a.m.	Moderated discussion	Sara Ferry (MIT)
10:05 a.m.	Break/panel changeout	
10:25 a.m.	**Session 1b: Private Fusion Presentations, Moderated by Jaime Marian (UCLA)**	
10:25 a.m.	CTFusion presentation	Derek Sutherland
10:45 a.m.	Oxford Sigma presentation	Thomas Davis
11:05 a.m.	Kyoto Fusioneering presentation	Richard Pearson
11:25 a.m.	Moderated discussion	Jaime Marian (UCLA)
11:55 a.m.	**Lunch Break**	

SESSION 2: PUBLIC (UNIVERSITY/NATIONAL LABORATORY) PERSPECTIVES ON FUSION PLANT CONCEPTS, MATERIALS AND DEVELOPMENT NEEDS FOR AN FPP 20 SEPTEMBER 2022		
TIME	TOPIC	PRESENTER
1:10 p.m.	**Session 2a: Public Fusion Presentation, Moderated by Andrew Sowder (EPRI)**	
1:10 p.m.	ORNL presentation	Mickey Wade
1:30 p.m.	PPPL presentation	Jon Menard
1:50 p.m.	Moderated discussion	Andrew Sowder (EPRI)
2:10 p.m.	Break/panel changeout	
2:15 p.m.	**Session 2b: Public Fusion Presentation, Moderated by Derek Sutherland (CTFusion)**	
2:15 p.m.	UW Stellerator presentation	Benedikt Geiger
2:35 p.m.	Moderated discussion	Derek Sutherland (CTFusion)
3:00 p.m.	**BREAK**	

SESSION 3: PRIVATE FUSION COMPANY PERSPECTIVES ON FUSION PLANT CONCEPTS, MATERIALS AND DEVELOPMENT NEEDS FOR AN FPP 20 SEPTEMBER 2022		
TIME	TOPIC	PRESENTER
3:15 p.m.	**Session 3a: Private Fusion Presentations, Moderated by Mary Alice Cusentino (SNL)**	
3:15 p.m.	CFS presentation	Cody Dennett
3:35 p.m.	Zap Energy presentation	Ryan Umstattd
3:55 p.m.	Moderated discussion	Mary Alice Cusentino (SNL)
4:20 p.m.	Break/panel changeout	
4:30 p.m.	**Session 3b: Private Fusion Presentations, Moderated by Caroline Sorenson (CFS)**	
4:30 p.m.	General Atomics presentation	Tyler Abrams
4:50 p.m.	Moderated discussion	Caroline Sorensen (CFS)
5:15 p.m.	General Discussion	Andrew Sowder (EPRI) and Brian Wirth (UTK/ORNL)
5:45 p.m.	Adjourn Day 1	

SESSION 4: NEUTRON SOURCE TECHNOLOGIES AND CAPABILITIES AS POTENTIAL OPTIONS FOR AN FPNS 21 SEPTEMBER 2022		
TIME	TOPIC	PRESENTER
8:30 a.m.	**Session 4a: Neutron Source Capability Options, Moderated by Brian Wirth (UTK/ORNL)**	
8:30 a.m.	ORNL D-Li stripping source presentation	Phil Ferguson
8:50 a.m.	MIT/Stony Brook cyclotron presentation	Lance Snead
9:10 a.m.	UW mirror based neutron source	Cary Forest
9:30 a.m.	Moderated discussion	Brian Wirth (UTK/ORNL)
9:50 a.m.	Break/panel changeout	
10:00 a.m.	**Session 4b: Neutron Source Capability Options, Moderated by Wahyu Setyawan (PNNL)**	
10:00 a.m.	Shine/Phoenix nuclear source presentation	Ross Radel
10:20 a.m.	LANL nuclear source presentation	Eric Pitcher
10:40 a.m.	Moderated discussion	Wahyu Setyawan (PNNL)
10:50 a.m.	Break	

SESSION 5: PERSPECTIVE ON MATERIALS TESTING CAPABILITIES AND NEEDS 21 SEPTEMBER 2022		
TIME	**TOPIC**	**PRESENTER**
11:00 a.m.	**Session 5a: Perspectives on materials testing capabilities and needs, Moderated by Mary Grace Burke (ORNL)**	
11:00 a.m.	UK STEP presentation	Amanda Quadling
11:30 a.m.	Modeling perspective on data needs, benchmarking and extrapolation	Jaime Marian
11:50 a.m.	Moderated discussion	Mary Grace Burke (ORNL)
12:00 p.m.	**Lunch break**	

SESSIONS 6 & 7: DISCUSSION SESSIONS ON NEUTRON TESTING FACILITY NEEDS, AND TIMELINE/STAGING ON DEVELOPMENT PATH FROM FPP TO FIRST-OF-A-KIND FUSION REACTOR ON THE GRID 21 SEPTEMBER 2022		
TIME	**TOPIC**	**PRESENTER**
2:25 p.m.	**Session 6: Moderated discussion on neutron data needs for FPP design and operation, Moderated by Jaime Marian (UCLA) and Mary Grace Burke (ORNL)**	
3:40 p.m.	Break	
3:55 p.m.	**Session 7: Moderated discussion on neutron data needs FOAK and Commercial Fusion, Moderated by Mary Alice Cusentino (SNL) and Caroline Sorensen (CFS)**	
5:25 p.m.	Break	
5:40 p.m.	Summary of consensus opinion on FPNS performance requirements	Brian Wirth (UTK/ORNL) and Andrew Sowder (EPRI)
6:00 p.m.	**Adjourn Workshop**	

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FUSION INDUSTRY ASSOCIATION MEMBER SURVEY QUESTIONS REGARDING DEVELOPMENT TIMELINE AND PERFORMANCE REQUIREMENTS FOR A FUSION PROTOTYPIC NEUTRON SOURCE

1. Please indicate the most applicable information for your entity below that will assist in organizing information from the poll. *

- ○ Developing a D-T fusion energy concept
- ○ Developing a non-D-T fusion energy concept
- ○ Affiliate members who are vendors/suppliers
- ○ Other affiliate member

2. On a scale of 1 - 5, with 1 being "strongly do not support," and 5 being "strongly support", please indicate your level of support for delivering an FPNS with the features listed in Table 1 by 2028 or earlier (independent of cost). *

	1	2	3	4	5	
Strongly do not support	○	○	○	○	○	Strongly support

3. On a scale of 1 - 5, with 1 being "strongly do not support," and 5 being "strongly support," please indicate your level of support for delivering an FPNS with the features listed in Table 2 by 2032 or earlier (independent of cost). *

	1	2	3	4	5	
Strongly do not support	○	○	○	○	○	Strongly support

4. Based on your responses to question 2, please indicate which modifications (if any) would increase your level of support for the FPNS with the capabilities listed in Table 1: *

- ○ Faster time to startup, but with reduced capability (e.g. lower dpa rate/volume)
- ○ More capabilities at first startup, but longer timescale (e.g higher dpa rate/volume)
- ○ Other:

5. For the FPNS with capabilities listed in Table 1, please indicate the threshold for the projected cost that would cause your level of support you indicated in question 2 to decline *

- ○ $100M
- ○ $250M
- ○ $500M
- ○ $750M
- ○ $1B+
- ○ Other:

6. Please indicate your preference for how an FPNS is funded and operated. *

- ○ Publicly funded and operated (i.e. on or near national lab facility)
- ○ Public-Private Partnership (PPP) and publicly operated/managed
- ○ Public-Private Partnership (PPP) and privately operated/managed
- ○ Contracted private facility and privately operated/managed
- ○ Other:

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