Enabling Commercial Fusion

Venture & Technology Opportunities for a Growing Fusion Industry

PROTO VENTURES

PSFC Plasma Science and Fusion Center
Massachusetts Institute of Technology

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Fusion has entered the commercial era. New supply chain opportunities abound for entrepreneurs, researchers, investors, and corporations.

For decades, the idea of fusion energy has captured our collective imaginations as the energy source of the future, providing firm electricity without operational carbon emissions. In recent years, possible fusion has come closer and closer to probable, with major breakthroughs by top research institutions complemented by billions of dollars of investments supporting a burgeoning private fusion sector, all racing to build the first fusion power plant in the next decade.

Fusion is now entering the commercial era. Major technical and cost milestones remain, and success will also require a network of partners, vendors, and technology providers to form a robust industrial supply chain. We are in a moment that offers rich possibilities for new entrants who can offer unique products and services to fill critical gaps. This report offers a roadmap for navigating the exciting landscape of a potential future commercial fusion ecosystem, helping investors, entrepreneurs, researchers, and corporations alike capitalize on the immense potential of this transformative technology.

All mature industries need a robust and sophisticated supply chain, and fusion will be no exception. Drawing from interviews with private fusion power plant companies, extensive research, and building upon the expertise of both the Plasma Science and Fusion Center and Proto Ventures, this reports outline some key opportunities for first movers to secure a valuable foothold in a future fusion industry as providers of materials; components and consumables; subsystems; and software, services, and facilities.

We believe that fusion energy has the potential to revolutionize the way the world produces energy. Through this report, we invite you to join us on the journey towards a cleaner, brighter future powered by the stars.

PROTO VENTURES

Proto Ventures is MIT's venture studio, the first of its kind within any university. Proto Ventures combines translation and technology expertise to identify, build, and launch impactful startups inspired by MIT research and technology. In 2019, Proto Ventures founded its first effort in AI and Healthcare, which worked with 200+ members of the innovation ecosystem around MIT and resulted in the creation of two startup companies.

In 2023, Proto Ventures launched the Fusion & Clean Energy channel in partnership with MIT's Plasma Science and Fusion Center; the groups are collaborating to create groundbreaking new startup opportunities in clean energy by leveraging MIT's top-tier talent and core competencies, including superconducting magnets, robotics, machine learning, and advanced materials.

PSFC Plasma Science and Fusion Center Massachusetts Institute of Technology

The MIT **Plasma Science and Fusion Center** (PSFC) provides research and educational opportunities that expand our understanding of fusion science, plasma physics, its applications, and magnet technology. As a multidisciplinary lab, the PSFC uses translational science to create real-world solutions, with a focus on developing magnetic fusion as a carbon-free energy source.

The PSFC is affiliated with seven academic departments at MIT: Aeronautics and Astronautical Engineering, Chemistry, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Science and Engineering, and Physics. Approximately 250 people conduct and support the PSFC's research, including faculty and senior academic staff, research scientists and engineers, graduate and undergraduate students, visiting scientists, research affiliates, technical support personnel, administrative and support staff.

The PSFC is housed in seven buildings on MIT's main campus and encompasses more than 150,000 sq. ft. of diverse lab space, along with infrastructure that accommodates energy storage, power conversion, radio frequency sources, nuclear magnetic resonance magnets, and accelerators.

A NOTE ON SCOPE:

Our focus is on opportunities for external providers. For example, if fusion power plants are Boeing, the opportunities in this report are the equivalent to the role of Rolls Royce in providing aircraft engines. We presume that fusion plant developers will handle issues such as plasma control systems or high-field magnets in-house. Furthermore, because deuterium-tritium (D-T) fusion is widely viewed by fusion experts as the most commercially relevant at present, we primarily feature opportunities for D-T fusion.

OPPORTUNITIES ON WHAT TIMESCALE?

Private fusion plant developers and government programs are collectively spending billions of dollars today, meaning that some opportunities described in this report could make for a successful venture immediately. At the same time, there is significant uncertainty about when — and whether — fusion will grow into a major industry delivering a meaningful fraction of the world's energy. Therefore, other opportunities in this report are best suited to R&D groups for the time being, and are likely too early for commercial ventures. All are crucial to the industry's success, but some will need to rely on additional beachhead markets (e.g. aerospace, or other forms of power generation) until fusion provides a meaningful customer base.

CONTENTS

Fusion materials

Plasma-facing materials · Structural materials · Superconducting materials · Tritium permeation barriers

Components & consumables

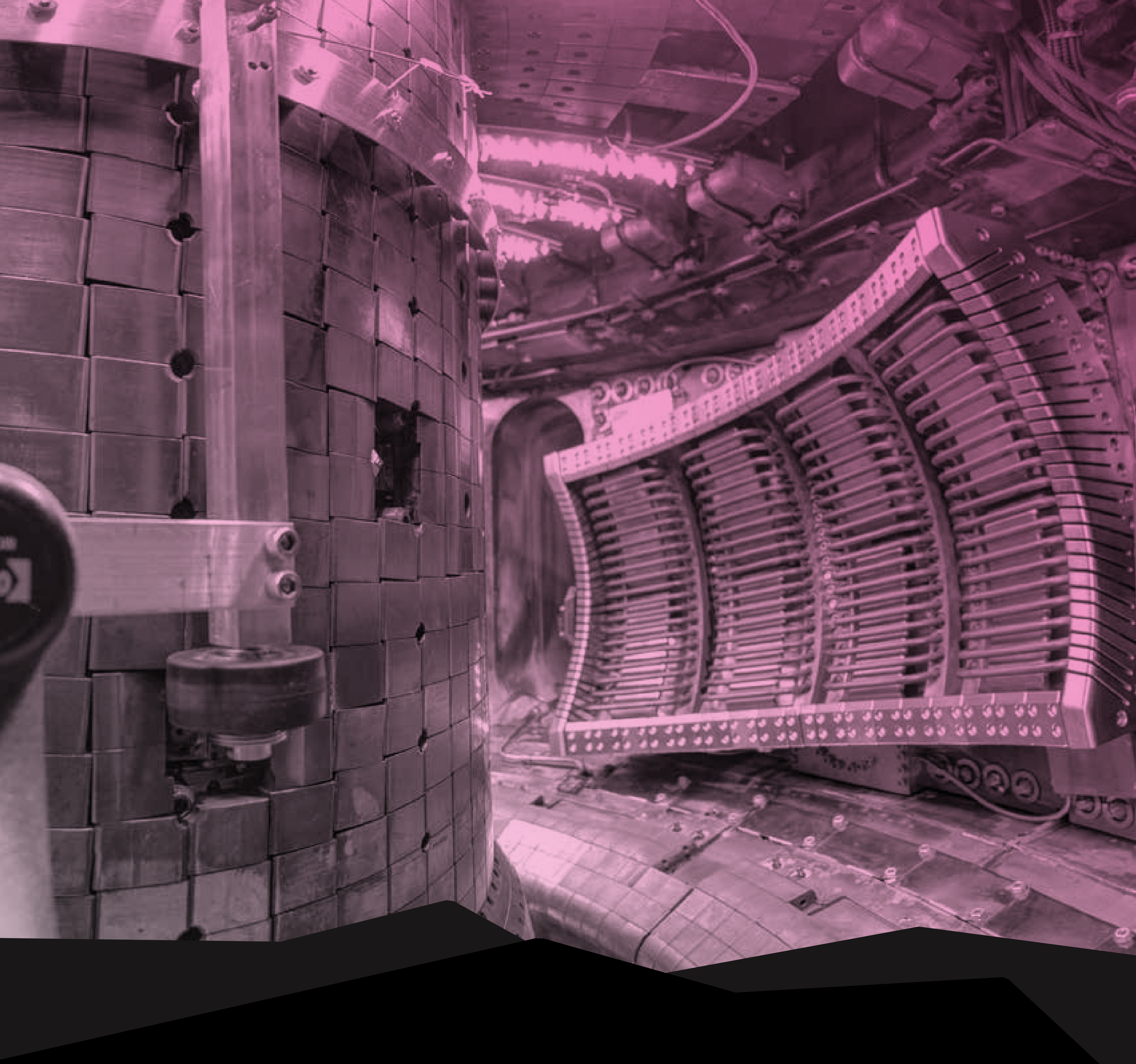
Enriched lithium supply · Radiation-hard sensors and electronics · Vacuum pumps · Isotope and element selectivity · Tritium marketplace · Molten salt supply · Solid-state plasma heating components

Subsystems

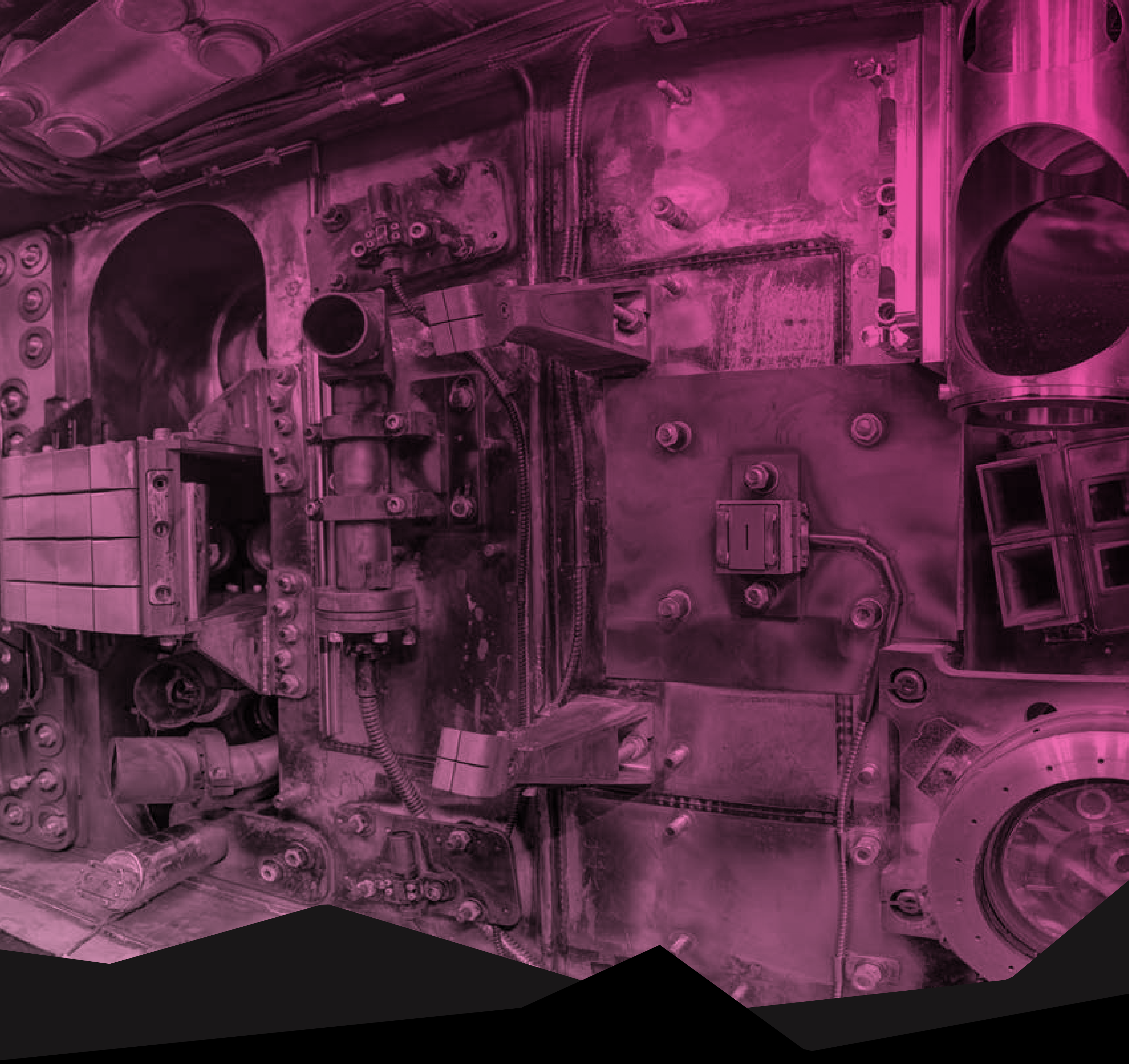
Tritium fuel cycle · Integrated plasma heating and current drive actuators · Cryogenics · Heat exchangers · Thermal storage

Software, services & facilities

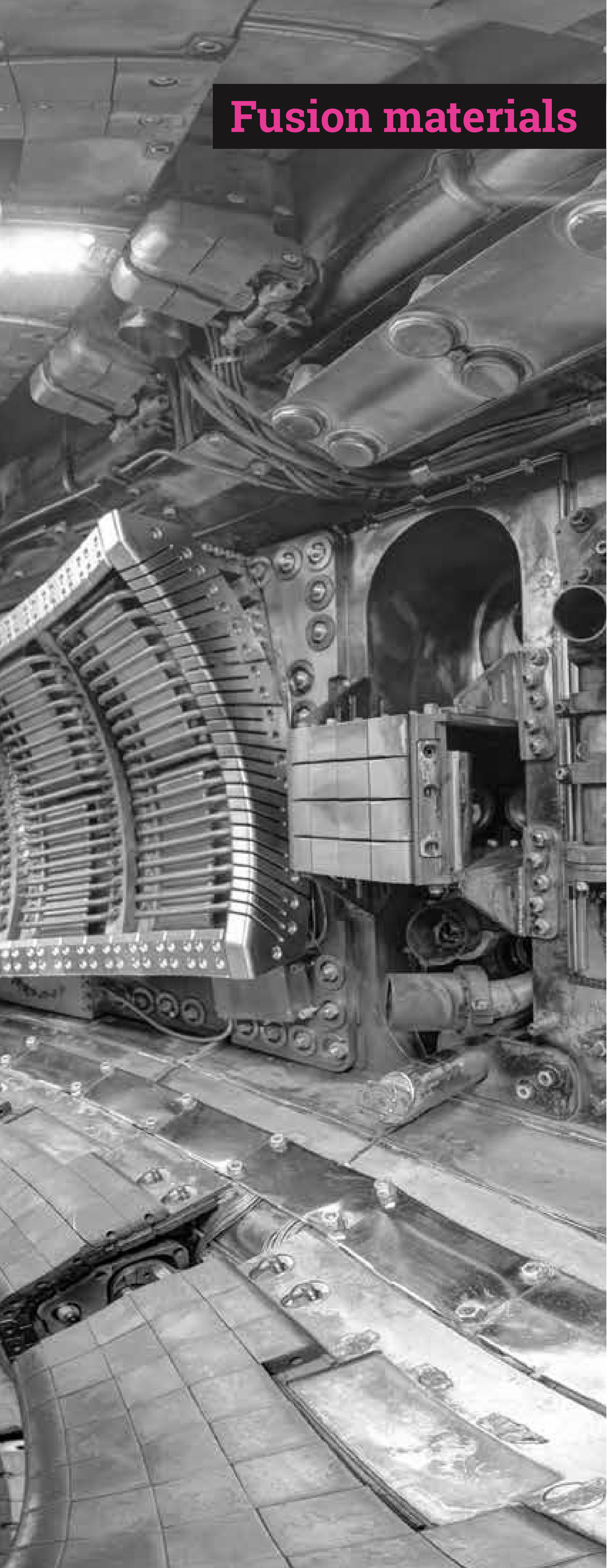
Materials testing · Commercial-grade plant design software · Robotic maintenance · Liquid waste technologies · Component qualification and integrity testing · High-precision engineering and component manufacturing · Third-party standards & ratings for fusion milestones · Workforce training and recruiting · Legal services for fusion developers · Community engagement and communications



Fusion materials



Fusion promises a bright future, and the goal is in sight, but reaching the commercial fusion finish line calls for the development of a host of materials that are not commercially available at this time. Here we share a selection of key opportunities for materials vendors to create and capture tremendous value in the fusion industry.



Fusion materials

PLASMA-FACING MATERIALS

Engineer materials that can withstand a fusion environment on commercial timescales.

STRUCTURAL MATERIALS

Provide advanced structural materials needed to construct vacuum vessels, molten salt blankets, and piping.

SUPERCONDUCTING MATERIALS

Develop electromagnets that maintain their performance under irradiation.

TRITIUM PERMEATION BARRIERS

Improve the industry's safety and productivity by preventing leakage of tritium across components.

Currently, no mass-manufacturable materials can withstand the extremely high temperatures, mechanical loads, and radiation fields that are expected in a commercial fusion power plant[1]. Further challenges with today's materials include material erosion under the effect of the plasma, retention of tritium inside solid materials, and manufacturability. This current lack of appropriately durable and manufacturable materials, however, represents a unique opportunity for companies and laboratories to develop the needed materials and play a crucial role in the emerging fusion industry.

Fusion plant operation calls for the use of materials that exhibit high yield strength, ductility, and thermal conductivity at high temperatures (~750 ºC) while being bombarded by high-energy neutrons. Some of these structural materials (e.g. for liquid immersion blankets) will also need to be highly resistant to corrosion.

The fusion industry will need vendors capable of fabricating large, strong, complex-shaped, and vacuum-tight structures using these advanced structural materials; in many cases, working with these materials to produce said structures will require the creation of new manufacturing techniques.

Superconducting electromagnets are used to confine plasma and are thus an essential ingredient of any fusion power plant pursuing a magnetic confinement fusion (MCF) concept. However, the microstructures that lend these magnets their superconductivity are susceptible to the radiation damage produced by fusion reactions that decreases their capabilities. Radiation can also degrade the electrical insulation and high-conductivity copper that is ubiquitous in these magnets, jeopardizing the entire structure's functionality. An opportunity exists for materials providers that can supply new or enhanced superconducting materials that maintain their performance under radiation, as well as for vendors who can test the performance and usable lifetimes of candidate magnet materials.

Tritium, a radioactive isotope of hydrogen, is the fuel source for D-T fusion. Because of its scarcity and because it can degrade components, tritium must not be allowed to diffuse across solid materials in a fusion plant. To prevent this, the development of tritium permeation barrier (TPB) materials for use in components such as coolant channel piping and heat exchanger surfaces represents an enormous opportunity for commercialization. Currently, R&D efforts are underway for several types of ceramic and metal TPB coatings, however that is only half the challenge; TPB suppliers must also develop a reliable and durable application process. A solution to both aspects of TPB will assure an extremely secure place in the commercial fusion market.

Components & consumables

From vacuum pumps to transistor chips and molten salts, the commercial fusion industry will rely on third-party vendors to supply a host of components and consumables, many of which have yet to be adapted or made for fusion energy. Researchers, entrepreneurs, and established equipment manufacturers alike can fill these emerging needs.

Components & consumables

ENRICHED LITHIUM SUPPLY

Provide lithium for fusion blankets with a higher concentration of ^{6}Li.

RADIATION-HARD SENSORS AND ELECTRONICS

Deliver sensors and maintenance systems that can withstand irradiation to enable plasma monitoring and control.

VACUUM PUMPS

Provide durable and tritium-compatible vacuum pumps for plasma exhaust.

In D-T fusion systems, lithium is used in blanket technology to produce tritium. Two isotopes, ^{7}Li and ^{6}Li, make up ~92% and ~8% of naturally-occuring lithium respectively, and 6Li is responsible for the majority of tritium production. There is a significant opportunity for commercial providers who are able to supply the fusion industry with enriched lithium that contains a higher concentration of ^{6}Li.

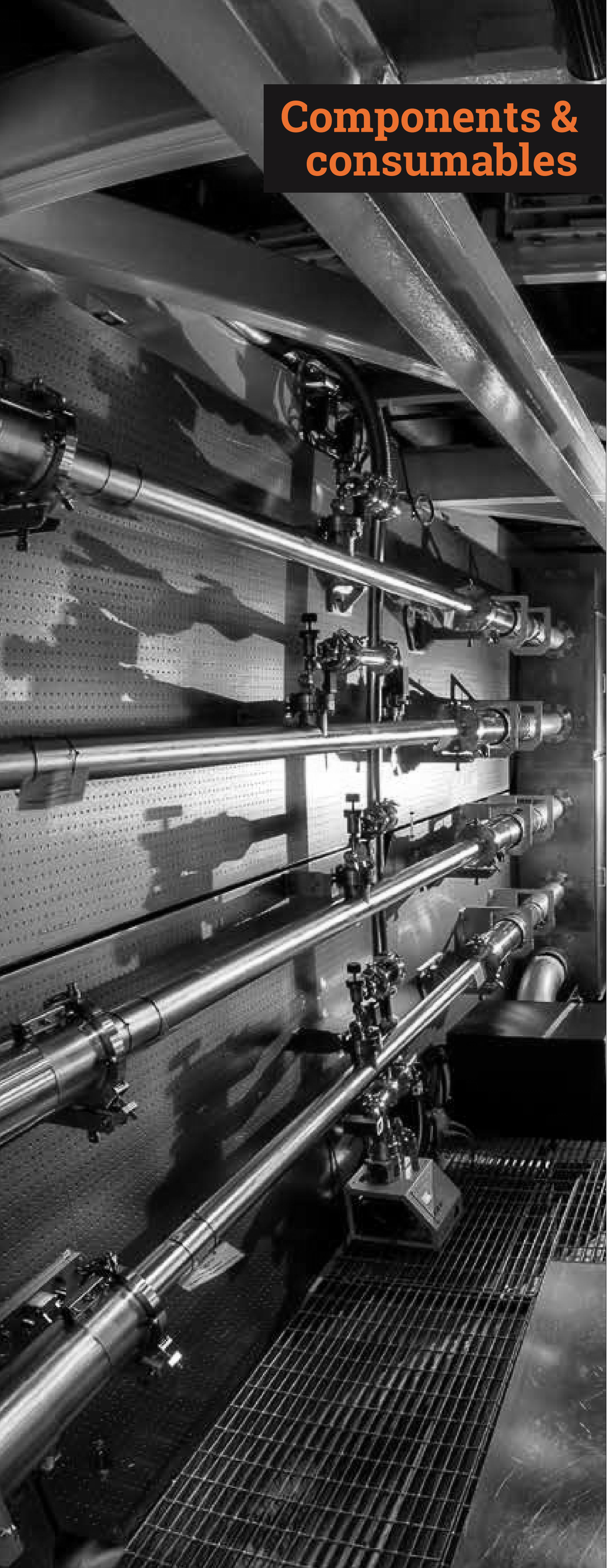
Fusion plants will be controlled and monitored using a fleet of electronics and sensors with delicate parts that can quickly fail when exposed to radiation. Creating durable components will require testing to ensure they meet performance thresholds as measured by three key parameters: Total Ionization Dose (TID), Displacement Damage (DD), and Single-event Effects (SEEs)[2]. To design radiation-hardy (or rad-hard) electronics, alterations must be made to the components' internal layout, circuits, and system-level approaches. For both analog and digital electronic devices, layout design is generally the most effective approach against TID, DD, and SEEs. Circuit and system design can also improve radiation tolerance[3], though typically at the expense of performance.

Semiconductors are foundational to electronics, and the space industry has developed more radiation-tolerant semiconductors using silicon carbide and gallium nitride rather than the standard silicon. New semiconductor manufacturing techniques such as Silicon-on-Insulator and fin field-effect transistors have improved resilience in the face of TID effects[4], and there have been significant investments by US-based groups to spur the development of other rad-hard semiconductors appropriate for nuclear applications[5].

Despite these advances, rad-hardness is still a major unsolved issue for commercial fusion. In D-T experimental tokamaks for example, electronics embedded in the toroidal magnets can become damaged within mere minutes. Developing rad-hard sensors and electronics will require extensive collaboration between the fields of semiconductors and nuclear materials; the advent of these components would be significant to the fusion industry and many other established industries as well.

Unlike many conventional methods of power production, fusion's emissions are not carbon-based but rather helium; expelling accumulated helium and other impurities is essential to maintaining stable fusion, and necessitates the use of pumps that can expel the plasma exhaust and maintain a high vacuum. Due to tritium accumulation in pump components and fluids, and to leakage through clearances, existing pump designs are not sufficiently tritium-compatible for a commercial fusion plant. Additionally, pumps that are located on the interior of fusion devices must also be resistant to the effects caused by high magnetic fluxes, extreme temperatures, and radiation.

The pumps that are currently available aren't designed for use in fusion devices; they aren't durable enough, they can't withstand tritium infiltration, and it's difficult to effectively modify them to overcome these issues. Scroll pumps that are used in tritium systems need improved durability, though liquid ring pumps may be an alternative once the technology is further developed. Vapor diffusion pumps are suitable for high vacuum applications and perform moderately well in the presence of tritium. For ultra-high vacuum applications, non-evaporable getter pumps meet requirements for through-put, as do cryopumps, which, while effective, have high energy demands that could limit scalability. One particularly promising technology is metal foil pumps capable of separating tritium from plasma exhaust for Direct Internal Recycling. These pumps' high performance and low technological maturity make them ripe for collaborations between academia and industry.



ISOTOPE AND ELEMENT SELECTIVITY

Commercialize new technologies to separate hydrogen isotopes and other species in pumping particle streams.

TRITIUM MARKETPLACE

Manage the production, storage, transportation, and trading of tritium across national boundaries

MOLTEN SALT SUPPLY

Supply and manage challenging molten salts like FLiBe for fusion blankets.

Plasmas can be unstable and difficult to sustain; any introduction of foreign materials, no matter how small, can induce instabilities and heat loss. Unburnt fuel, helium exhaust, and impurities intentionally injected for plasma control must be filtered out using isotope separation systems that ensure a balance between deuterium and tritium (in the case of D-T fusion) to maintain optimal plasma performance. These technologies are essential to ensuring the success of fusion power, but research and development is still nascent.

To isolate deuterium and tritium from one another, separation systems utilizing thermal diffusion, fractional absorption, cryogenic distillation, Thermal Cycling Absorption Process (TCAP), and Thermal Swing Adsorption (TSA) have been explored, with TCAP and TSA currently regarded as holding the most commercial promise.

To separate hydrogen from other elements including helium, palladium-silver (Pd-Ag) membranes and metal foil pumps are likely candidates. Pd-Ag membranes have been shown to work, though they would require adaptation for use in fusion plants because the limited availability of Pd could make the manufacturing process prohibitive; a substitute for Pd would likely be needed. As in the previous opportunity, metal-foil pump technology represents a potential major breakthrough for the commercial fusion supply chain, however it likewise requires additional R&D, which makes it an excellent entry in the fusion opportunity canon.

Tritium fuels D-T fusion, however naturally-occurring tritium is extremely rare, and as the fusion industry grows, so will demand for fuel. D-T demonstration plants continue to proliferate, showing that the industry could be revolutionized by the creation of a comprehensive infrastructure for tritium commerce, transport, and startup inventory.

Establishing a global tritium marketplace would enable the trade of tritium inventories between power plants, allowing those with surplus to meet demand, fostering resource optimization and industry-wide cooperation.

Strategic collaborations with companies specializing in advanced materials and logistics could help address the challenges associated with tritium storage and transport. Likewise, developing secure transport methods and advanced containment technologies, including anti-permeation coatings, could enhance the reliability and safety of the tritium supply chain. By tackling these critical aspects comprehensively, the fusion industry can ensure a stable and efficient tritium ecosystem for future fusion power plants.

Both nuclear fission and fusion projects are exploring the use of liquid molten salt blankets to convert radiation into heat. When used in D-T fusion applications, liquid molten salt blankets are also able to produce tritium, essentially creating self-fueling fusion devices. Currently, the top candidate for fusion blankets is a 2:1 mixture of lithium fluoride (LiF) and beryllium fluoride (BeF_2) called FLiBe.

There are, however, complex challenges associated with creating and handling FLiBe: beryllium is highly toxic and readily absorbs moisture from its environment, which makes its transport and storage very difficult. Lithium is extremely reactive and combusts in the presence of air and water. Large-scale FLiBe storage and transport is also challenging due to the materials' toxicity and hygroscopic properties. Furthermore, FLiBe for fusion must have the right ratio of ^{7}Li to ^{6}Li, since this ratio greatly impacts the plant's tritium breeding ratio.

Finally, FLiBe for commercial fusion must be free of impurities, since these can lead to corrosion, proliferation risks, and other undesirable consequences. Because mixing FLiBe is complex, fusion companies will likely purchase the mixture from vendors rather than producing it in-house, which creates an opening for enterprising groups to continue developing a technology that could be very valuable to both fission and fusion industries.

Components & consumables

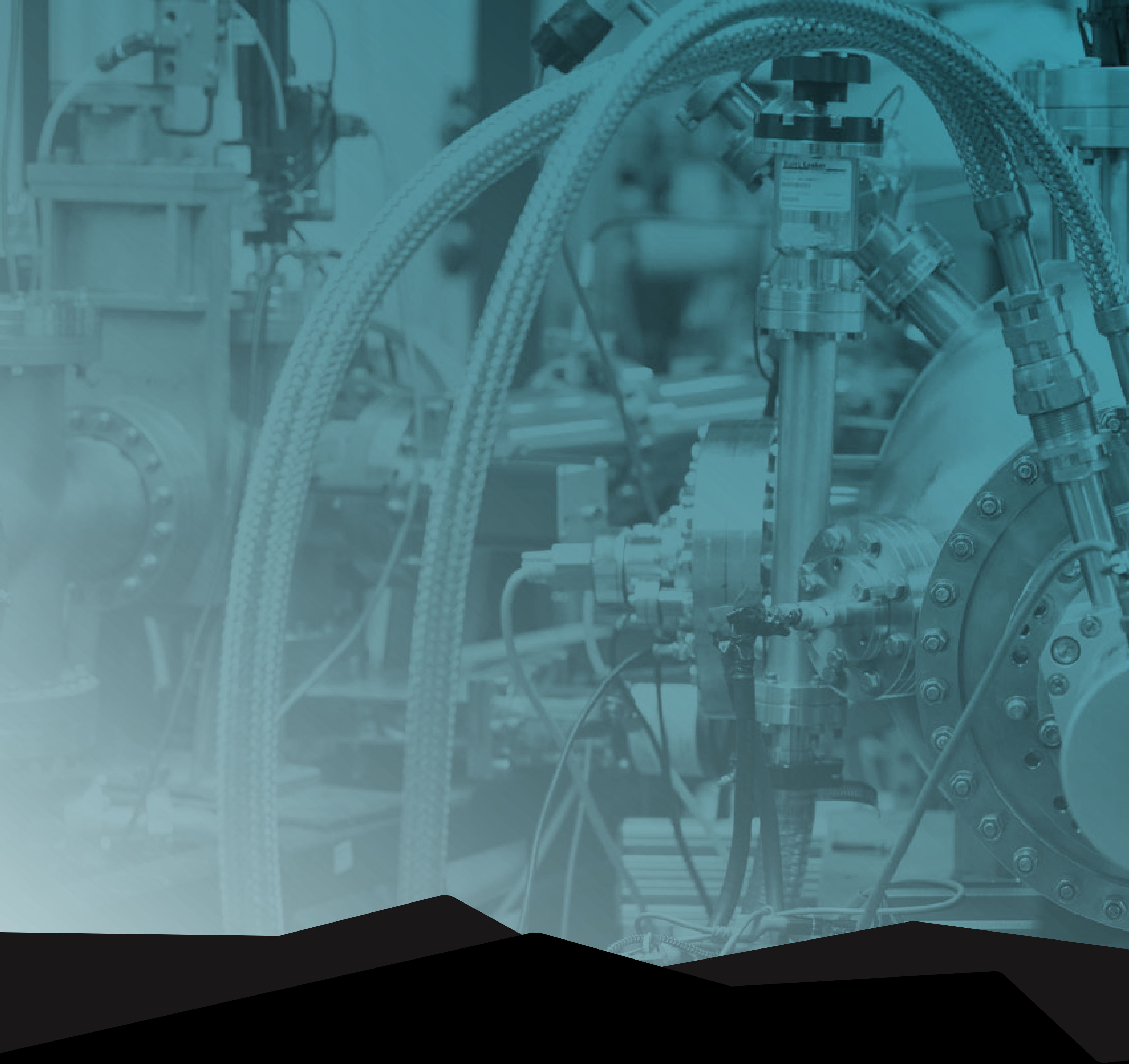
SOLID-STATE PLASMA HEATING COMPONENTS

Deliver next-generation transistor chips for plasma heating

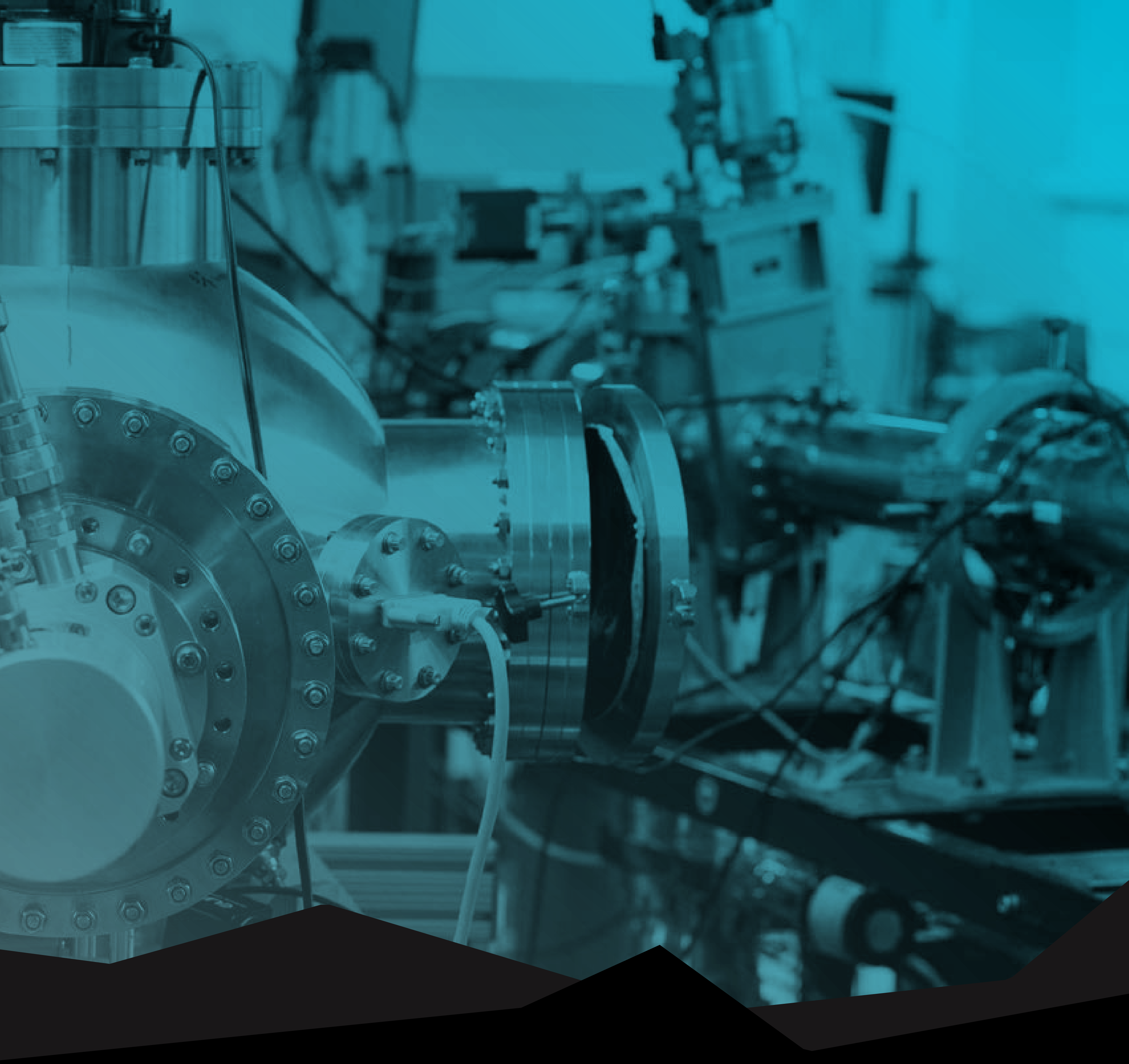
In many fusion device designs, plasma must be heated using external sources to achieve and sustain fusion conditions. Radiofrequency (RF) heating is often used because it is energy-efficient and supplies the electrical current essential to stabilizing plasmas. RF sources amplify power using either traditional vacuum tube systems or newer solid-state technologies; vacuum tube tetrodes, klystrons, and gyrotrons provide effective heating at higher frequencies, while today's more advanced solid-state systems could potentially outcompete vacuum tube tech at lower frequencies.

Solid-state systems based on integrated circuits offer reliable and stable heating. An arrangement of these chips in parallel can heat the plasma and keep functioning even if a few chips fail. Additionally, chips require lower voltage than vacuum tube systems, making them easier to electrically insulate. Improvements in chip technology are now focusing on increasing their breakdown voltage and lowering their 'on' resistance, ultimately improving their efficiency.

Increasing chip breakdown voltage will likely require using different materials for the chip's substrate. Substituting diamond for the usual silicon holds promise, but producing large enough diamond wafers at scale remains an unsolved challenge. Advancing the performance of chips used in solid-state plasma heating systems will meet an important need in the fusion industry, and more advanced chips will also have multiple applications beyond fusion.



Subsystems



While the plasma-producing heart of a fusion power plant will typically be developed in-house by fusion power plant companies, there are several major subsystems that are excellent fits for third-party providers. These ancillary subsystems, such as the fuel cycle or heat exchange, will be integral for plant operation, and can likely be standardized across multiple fusion concepts and plant designs. At present, subsystems have received relatively little attention and thus are fertile ground for organizations ready to develop and supply them to the fusion industry.

Subsystems

TRITIUM FUEL CYCLE

Provide a fuel cycle subsystem that achieves tritium self-sufficiency and minimizes tritium inventories.

INTEGRATED PLASMA HEATING AND CURRENT DRIVE ACTUATORS

Make more cost-effective, high-power, high duty cycle, high-efficiency plasma heating and current drive actuators.

CRYOGENICS

Modernize cryogenic cooling systems to complement the efficiency of new high-temperature superconducting fusion magnets.

Achieving tritium self-sufficiency is a key challenge for the D-T fusion industry. Power plants must produce enough tritium for continuous operation and surplus for starting new plants, while an effective fuel cycle minimizes tritium inventories, enhancing safety and regulatory compliance. Essential components in D-T fuel cycles include vacuum pumps, separators, tritium extractors, breeding blankets, storages, fueling systems, and instrumentation for tritium accountancy.

Efficiency and fast processes in components are vital for both objectives. Some fuel cycle components, like storage systems, have a high technology readiness level, and/or are implemented in experimental tokamaks (vacuum pumps, element and isotope separators, fueling systems), while others, such as tritium extractors, have smaller-scale demonstrations, and breeding blankets remain untested. In a broader context, the need for licenses, dedicated spaces, and trained personnel hampers fuel cycle R&D.

Fuel cycles intersect with other fields like process engineering, energy engineering, and vacuum systems. Deuterium-tritium concepts necessitate a fuel cycle, making most components applicable across the broader fusion industry, regardless of the confinement approach[6].

Radio frequency (RF) and microwave systems are likely to be the most suitable heating and current drive (H&CD) actuators for a fusion power plant because they do not require line-of-sight access to the plasma. The technological readiness level for many H&CD subsystems is relatively high, but equipment developers must still address significant gaps before these components are ready for a commercial fusion plant.

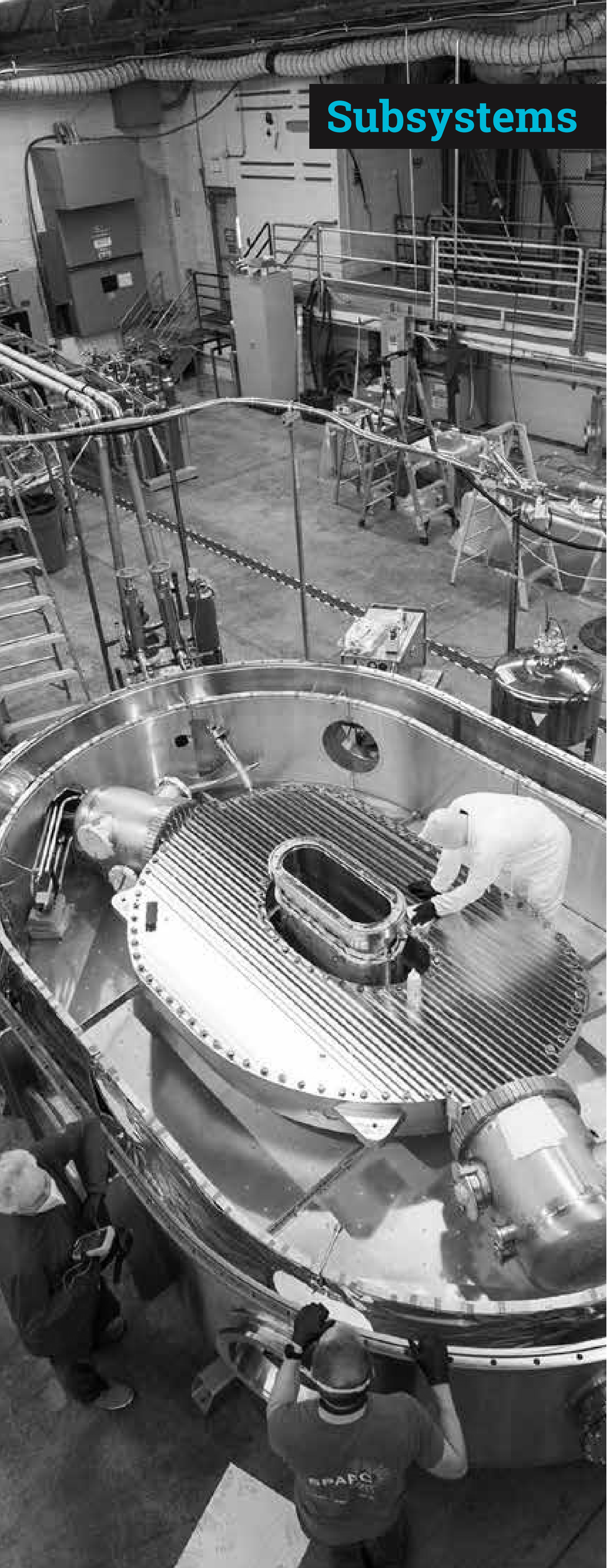
Cost reductions are necessary. H&CD systems can cost up to $50 per watt today, which drives up operating expenses and necessitates more efficient systems for converting electrical power to RF/microwave power. Improving high voltage direct current (HVDC) power supplies, RF/microwave amplifiers, and transmission line components could help increase the overall efficacy of these systems.

Increasing the lifetime of H&CD components is also important, as systems operating near the limits of performance typically have short lifetimes and require frequent, costly rebuilding. Integrating H&CD actuators into the first wall/blanket of the fusion device is one approach that could extend component lifetimes. However advanced manufacturing methods would be needed to create large-scale components in order to prevent disruptions to the blanket's neutron shielding and tritium production (for DT concepts) capabilities. Additionally, H&CD antennas must be built using materials that are both highly conductive and durable under extreme heat and neutron loads.

Fusion magnet technology has greatly advanced in the last two decades, as high-temperature superconducting (HTS) tape has become widely available. In contrast to low-temperature superconducting (LTS) magnets, HTS magnet temperatures for fusion applications can instead perform efficiently at 20 K, which does not require liquid helium and thus offers significant energy savings. New magnet designs can also withstand much greater nuclear thermal loads than designs utilizing LTS magnets.

With the advent of HTS magnet technology, industry is no longer tied to a liquid helium regime. There is an opening to develop more compact, reliable, commercial-grade cryogenic systems dedicated to 20 K+ cooling for the fusion industry. These commercial-grade systems should emphasize thermodynamic and spatial efficiency. Higher operating cryogenic temperatures also raises the possibility of developing alternate coolants beyond helium and hydrogen.

Subsystems



HEAT EXCHANGERS

Design heat exchange subsystems capable of withstanding the effects of radiation and high temperatures.

THERMAL STORAGE

Enable fusion plants to work seamlessly within a grid populated by other power sources by developing integrated thermal energy storage systems.

High-temperature, corrosion-resistant heat exchangers will likely play an important role in determining the efficiency of fusion power plants[7]. Regardless of the liquid medium, heat exchangers must be compatible with corrosive liquids at high temperatures. In deuterium-tritium plant concepts, they must also prevent tritium from leaking from the blanket to a secondary coolant loop[8]. Designing a heat exchanger to satisfy these tasks is a multi-faceted challenge involving materials, manufacturing, and component design.

Heat exchangers today use stainless steels and/or nickel superalloys. Unfortunately, stainless steels cannot survive blanket operating conditions, whereas nickel superalloys suffer from tritium absorbance and permeation issues[9]. For salts, tungsten alloys are ideal, but suffer from manufacturing and cost issues.

Several technical directions show promise, including new printed circuit heat exchangers based on tungsten/zirconium carbide composites[10], vanadium alloys and SiC/SiC composites for lead-lithium concepts[11], and the plating of corrosion-resistant coatings (such as tungsten, molybdenum, and nickel) onto stainless steels and nickel superalloys that have already certified by the American Society of Mechanical Engineers' Boiler Pressure Vessel Code[12]. In summary, heat exchangers that excel in several of the required performance metrics exist today, and the possibility of modification for use in fusion liquid blankets represents an opportunity for entrants to the fusion industry.

Renewable energies like solar and wind are and will continue to be important sources of clean electricity for today's grids, however their high penetration rate will pose a competitive challenge to commercial fusion power. The marginal cost of renewable production is hard to beat, leading renewable production to supply most of the demand when renewables are producing, but the intermittency of solar and wind power means that we often need backup power from other sources. Gas power plants can idle when not in use, but that strategy will be less effective for a fusion power plant because of high capital costs and low variable costs.

Thermal energy storage offers a solution: instead of idling during periods of high renewable energy availability, the fusion system can continue to run and divert its output to store in the form of heat. When renewables produce less and the price of electricity rises, the plant can convert this stored heat to sell as electricity. Modeling suggests that integrated thermal storage will be an important component of any economically competitive fusion power plant[13]. Thermal storage systems optimized for fusion plants are a key supply chain gap that will require specialized development to fill, and as such they represent a major opportunity for equipment providers.

Software, servic
& facilit

ces

ties

It’s not just about hardware. All industries rely on a network of providers for software, services, financial products, testing facilities, plus other so-called soft goods, and fusion is no exception. In the next few pages, we go beyond hardware and highlight key opportunities to serve a maturing fusion industry.

Software, services & facilities

MATERIALS TESTING

Provide access to facilities that approximate a fusion environment to enable testing and qualification of candidate materials.

COMMERCIAL-GRADE PLANT DESIGN SOFTWARE

Create integrated, easy-to-use software to dramatically simplify the task of commercial teams developing new fusion plants.

ROBOTIC MAINTENANCE

Develop robust robotic tools to replace plasma-facing components and perform system maintenance.

Designing a durable fusion power plant requires selecting the correct materials to build it, and making an informed selection requires extensive testing. When it comes to fusion, today's materials testing facilities are sorely lacking. The current gold standard of nuclear materials testing is fission neutron irradiation and post-irradiation examination (PIE), however these expensive irradiation campaigns can last a decade. Research devices are available, but they lack high-energy neutrons, so the radiation damage they cause is almost an order of magnitude lower than in a fusion plant.

Ion or proton irradiation offers a promising alternative to high-energy neutrons. Ion irradiation can match fusion damage levels, though in a more localized and less penetrative manner, and it does not perfectly mimic transmutation. On the other hand, high-energy protons cause transmutations in materials with less activation, albeit at shorter penetration depths than neutrons. Still, service providers have an opportunity to offer high-energy proton materials testing facilities that provide a reasonable facsimile of fusion neutron damage, eliminating the industry's reliance on nuclear research devices and expensive PIE facilities. There are additional openings to develop testing facilities with tritium capabilities for the fusion industry, as well as facilities that can subject materials to coupled effects, including high temperature, irradiation, and tritium.

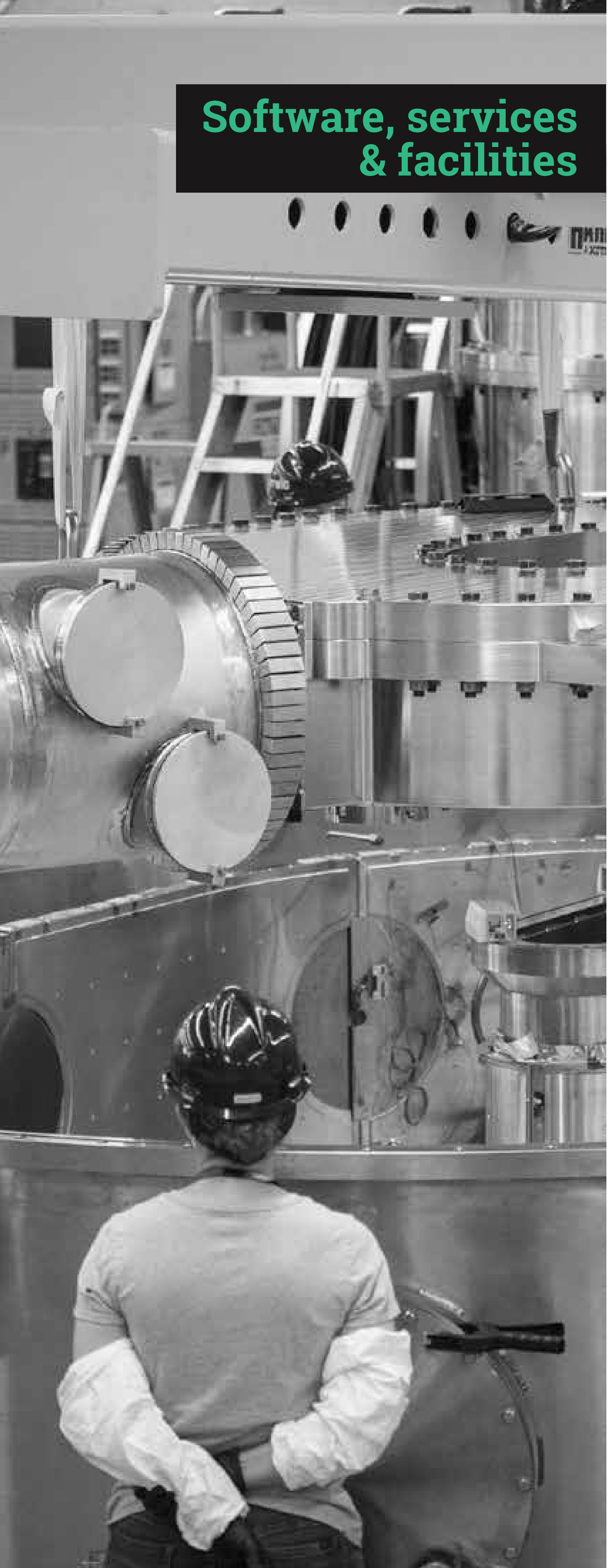
At present, the teams developing and evaluating fusion plant designs face major challenges due to to the complexity of the individual systems, the importance of many different kinds of physics across multiple time and length scales, and the necessary integration of the various systems into a performant, reliable, coherent design. There is a secondary challenge in earning the trust of plasma scientists and other technologists who have a stated preference for slow, clunky software whose results they trust over a new, unproven software, even if it is better integrated and runs more efficiently.

There is an opportunity to take inspiration from other highly complex industries, such as aerospace, and build commercial-grade fusion plant design software.

The life cycle of system maintenance and component replacement is an important consideration in fusion plants. In particular, plasma-facing components (PFCs) will be exposed to intense radiation fields, which may require them to be frequently maintained or replaced. The disposal of used PFCs, which will be radioactive and may be permeated with tritium in D-T concepts, must be carefully coordinated to ensure human and environmental safety. Commercial-scale solutions for PFC handling and recycling are only just being explored, and opportunities to make a difference in this area are plentiful.

Similarly, fusion plants need autonomous systems that can perform maintenance and inspection inside fusion devices, where residual radiation and high temperatures preclude human intervention even long after the system has been turned off[14]. This requires radiation-resistant electronics [p.15] but also the development of robotic tools that can navigate the layout of supporting structures, magnets, and diagnostic systems. Today's nuclear-capable robotic systems have significant limitations, and their functionality must improve for use in both fission and fusion plants. While remote inspection systems have been successfully deployed in experimental fusion devices, these systems are not suited for the much more radioactive and complex environment of a commercial fusion plant. Thus, more robust and faster-working systems suitable for fusion plant use is essential, and there are opportunities for both researchers and commercial players to meet these industry needs.

Software, services & facilities



LIQUID WASTE TECHNOLOGIES

Improve fusion's sustainability with liquid waste management and disposal systems capable of removing tritium.

COMPONENT QUALIFICATION AND INTEGRITY TESTING

Taking cues from the existing aerospace and nuclear fission industries, create a robust market for rapid compound stressor component qualification and testing.

HIGH-PRECISION ENGINEERING AND COMPONENT MANUFACTURING

Exploit the production potential of additive manufacturing to construct intricate components out of metal alloys.

Fusion plants will likely produce liquid waste, primarily tritiated water from air de-tritiation systems as well as from tritium permeation through coolant channels and heat exchanger surfaces. There is a significant opportunity to integrate cutting-edge technologies and novel processes for liquid waste de-tritiation and disposal. Implementing smart monitoring systems to continually assess tritium levels in various components could allow for real-time adjustments and ensure that the process of decommissioning and component replacement is based on identified need rather than a potentially inefficient fixed maintenance schedule.

Collaboration with the waste management and recycling industries opens avenues for sustainable practices in handling tritiated waste, aligning with the fusion industry's commitment to environmental responsibility. Exploring advanced filtration and separation technologies can further refine de-tritiation processes, setting new standards for safety and environmental stewardship. Recovering tritium during the de-tritiation process not only ensures safe disposal but also presents opportunities for recycling and utilization in other fusion devices, adding an extra layer of efficiency and sustainability to the fusion power sector.

Thanks to the speed at which technological breakthroughs have occurred over the past several years, the arrival of fusion pilot plants is nearing even as many significant questions of plant operation and design remain unanswered; if innovation continues at a similar pace, launch timelines will match up with the commercial availability of essential plant components. To ensure the needed progress, fusion component qualification and integrity testing must not let perfect be the enemy of the good, and also seek to learn more, faster.

Single-effect studies must be eschewed for combined effects facilities that reproduce combinations of stressors present in fusion plants, so more broadly applicable results can be arrived at more quickly. Using light or heavy ion beams, combined with simultaneous magnetic fields, corrosive fluids, and high stresses will down-select materials for faster funneling, and quickly reveal unanticipated disqualifiers in materials and design. This multi-pronged approach can conserve precious space and time for final qualification that allows for fleet-scale component testing and regulatory approval.

Conventional machining isn't able to produce components with complex internal structures, such as fusion plant cooling channels and waveguides. Additive manufacturing (AM), which leverages 3D printers, can build components with intricate internal geometries by depositing extremely thin layers of metal in three-dimensional configurations. The rapid melting and cooling of AM acts as an annealing process to produce stronger structures, and eliminates the need for secondary operations such as welding and brazing, which also reduces possible points of structural failure.

A single AM platform can switch between materials to create alloys, and be used to fabricate multiple components based on different designs, a useful feature in the experimental field of fusion. Moreover, AM reduces production time, streamlines logistics, and is less energy- and resource-intensive than traditional manufacturing processes. AD represents an opportunity to service multiple industries and especially fusion, which relies on many elaborate systems and components to operate.

Software, services & facilities

THIRD-PARTY STANDARDS & RATINGS FOR FUSION MILESTONES

Improve confidence of capital markets and lend credibility to private fusion companies by providing standardization and rating services.

WORKFORCE TRAINING AND RECRUITING

Solve the challenge of human capital with fusion industry training and recruitment tools.

LEGAL SERVICES FOR FUSION DEVELOPERS

Streamline legal and administrative processes for fusion companies.

COMMUNITY ENGAGEMENT AND COMMUNICATIONS

Tell the story of fusion power and shape public perception through savvy engagement and communications strategies.

Today, private capital markets have no good way to assess the relative progress of various fusion power plant startups. This is in part due to a lack of objective, harmonized, and mutually agreed-upon milestones that can apply to any fusion concept, and in part because no third-party organization is active in independently verifying the claims and results of individual fusion companies. A ratings company for fusion — similar to credit rating agencies like Moody's for financial institutions — would be a lucrative and impactful addition to the fusion sector[15].

The fusion workforce requires subject matter experts and skilled employees in a variety of fields beyond plasma physics. Mechanical, electrical, and materials engineers, especially those with prior experience in nuclear science, will be in progressively higher demand. Fusion companies will need increasing numbers of project managers, manufacturing experts, systems engineers, and safety specialists as well.

While PhDs and highly technical hires are essential to fusion's development and innovation, workers from all educational backgrounds will be required to support the industry. There is tremendous potential for organizations dedicated to training a skilled fusion workforce, and also significant demand for fusion-tailored employee recruitment tools able to capture candidates with relevant skills.

Fusion companies are already reporting several legal pain points that are slowing industry development and distracting from their core competencies. The challenges of developing cooperative research agreements with partner entities like research universities, navigating immigration services to bring on skilled workers, and handling import/export of highly-regulated materials all require specialized legal expertise. Streamlining legal and administrative processes would solve important challenges fusion developers are currently facing and that will only continue to grow in complexity.

Fusion's relative newness in the cultural consciousness, its scientific complexity, and its potential associations with nuclear fission make controlling the popular narrative of fusion power imperative. An unfavorable public perception could greatly hurt or even halt the implementation of fusion by causing overly burdensome regulatory practices or misinformed "not in my back yard" protestations.

As such, several fusion companies already have active communications initiatives ranging from grassroots community engagement programs to government lobbyists. The need for communications specialists to represent the industry will only continue to grow, as will demands for tools that can collect metrics on public engagement with the fusion sector.

CONCLUSION

The arrival of fusion power and the growth of its supporting industry is following a truly unique trajectory, as it must.

Scalable fusion power has not yet arrived, and myriad technical and non-technical challenges remain. Yet the critical need to decarbonize the global economy, the breakneck pace of major technological advancements, and the proliferation of well-funded fusion companies speak to our collective sense that fusion could put power on the grid sooner than previously expected — and these factors are combining to form a perfect storm of opportunities for bold investors, entrepreneurs, researchers, and corporations.

Three motifs from this report resonate at a macro level; one of the most significant cross-cutting themes is that of developing robust materials. Every subsystem is composed of components that must maintain their properties and perform as intended when exposed to the compound stressors of a fusion environment, and do so over commercial timescales. Unlocking the materials challenges associated with fusion will open a remarkable beachhead market, triggering a cascade of possible advances that will affect every part of the fusion plant development, design, and build process.

The fusion industry is established enough to reveal vital supply chain needs, but not stable enough to accurately estimate a timeline for product saleability and profit. However, several of this report's opportunities would appeal to customers in already-established industries, in addition to providing critical services for the budding fusion industry's needs. Radiation-hard electronics, cryogenics, robotic maintenance systems, and high-precision additive manufacturing are some of the technologies that will find places in today's markets and tomorrow's fusion industry.

Finally, while many opportunities speak to pressing hard tech needs, investors and entrepreneurs should not discount the importance of a solid non-technical framework able to buttress fusion's technical activities. Enabling access to a skilled workforce and ensuring streamlined regulatory procedures will be as critical as the most indispensable supply chain elements. The many non-technical (yet essential) niches that must be filled widen the field of opportunity to a vast group of players, and leave room for a great deal of creativity.

Fusion power could change the course of human history. Accomplishing this vision will require a massive buildout of a new industry with plenty of room for innovation and value creation from established corporations, capital providers, researchers, and entrepreneurs alike. Those willing to pursue the opportunities afforded by this fast- growing industry have a chance to form the base of a world-changing endeavor.

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