KYOTO FUSIONEERING

ADVANCING FUSION TECHNOLOGY

Kyoto Fusioneering's Approach to Accelerating Commercial Viability

Kyoto Fusioneering's Role

Established in 2019 as a spin-out from Kyoto University, Kyoto Fusioneering (KF) complements global fusion development programs ("fusion developers"), who focus on demonstrating sustainable, net-energy producing fusion reactions using a variety of confinement concepts – magnetic confinement (MCF), inertial confinement (ICF), magneto-inertial (MIF).

KF provides fusion power plant **design** and **engineering** services, and designs and supplies fusion-grade **technology** and **integrated systems** to fusion development programs, enabling a path to a commercially viable fusion power plant.

KF develops and integrates technology in three key systems: **Fusion Fuel Cycle System (fuel cycle)**, needed for all fusion concepts to ensure the safe and reliable supply of fuel to the reaction, **Fusion Thermal Cycle System (thermal cycle)**, needed for all fusion concepts to translate heat into useful energy, and **Plasma Heating (Gyrotron) System**, required in many MCF concepts to heat and stabilize the plasma. Figure 1 shows the conceptual coupling of these systems in a fusion power plant.

For commercial success, it is imperative to design and engineer a fusion power plant holistically and iteratively from the outset, considering the interdependencies of the confinement, fuel cycle, thermal cycle, and other key systems. Fusion developers who overlook the necessity of an integrated and sophisticated design for the fuel and thermal cycles, alongside their confinement concept, risk facing significant challenges that could impede the realisation of a commercially viable power plant.

Those who partner with KF are on a faster, more capital-efficient, and lower-risk path to commercial fusion.

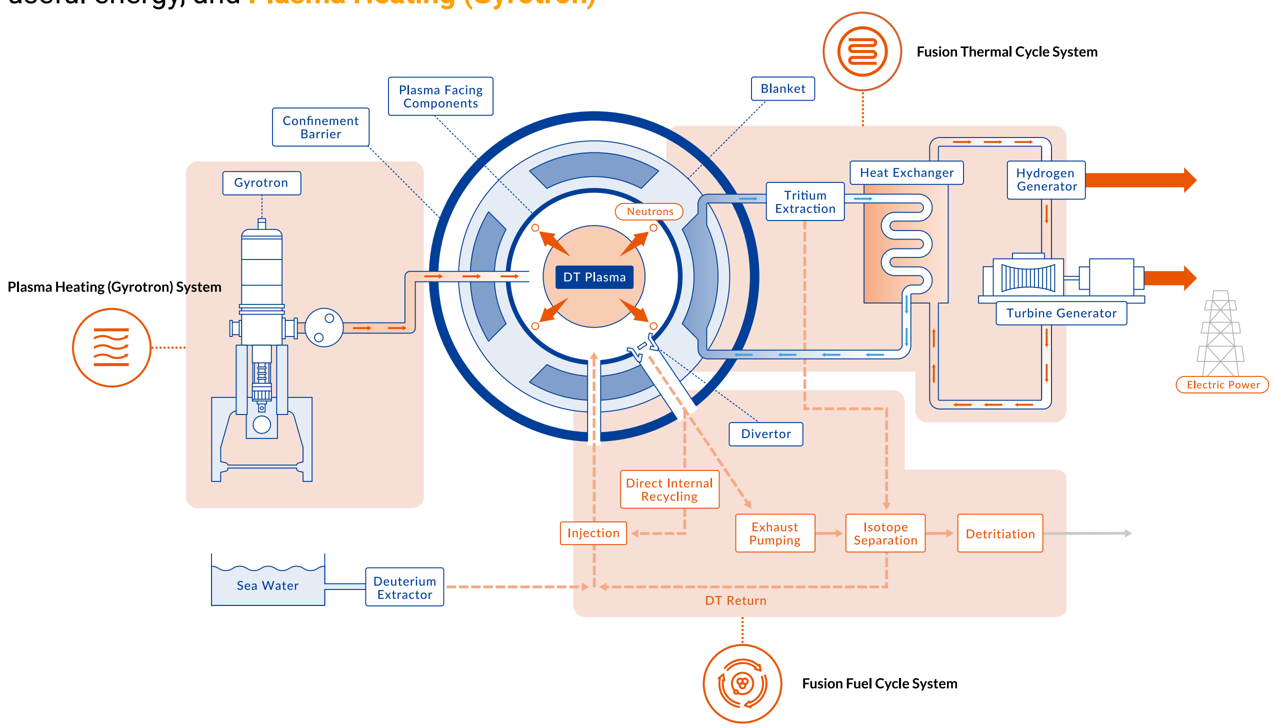

Figure 1: Conceptual Coupling of Systems Developed by Kyoto Fusioneering

This diagram illustrates the integration of key systems necessary for a fusion power plant. It shows the interaction between the plasma confinement system, powered by gyrotrons and superconducting magnets, and other critical components such as the blanket for tritium breeding and heat extraction, and the thermal cycle for converting fusion energy into electricity.

In this document, we consider KF's approach to developing these systems and incorporating them in a target fusion power plant.

A-FNS	Advanced Fusion Neutron Source
ADS	Air Detritiation System
APS	American Physical Society
BB	Breeding Blanket
BCTF	Blanket Component Test Facility
BDV	Bold Decadal Vision
CAD	Computer-Aided Design
CNL	Canadian Nuclear Laboratories
CNSC	Canadian Nuclear Safety Commission
CPP	Community Planning Process
CRL	Chalk River Laboratories (Canada)
D-T	Deuterium-Tritium
DEMO	Demonstration Power Plant
DIR	Direct Internal Recycling
DOE	The U.S. Department of Energy
DPP	Division of Plasma Physics
dU	depleted Uranium, uranium with a lower content of the fissile isotope 235U than natural uranium.
ECCD	Electron Cyclotron Heating and Current Drive
ECH	Electron Cyclotron Heating
ECR	Electron Cyclotron Resonance
ECRH	Electron Cyclotron Resonance Heating
EM	Electromagnetic
EMP	Electromagnetic Pump
EPMA	Electron Probe Micro-Analysis
FCTF	Fuel Cycle Test Facility
FCUS	Fuel Clean-Up System
FES	Fusion Energy Sciences (U.S.)
FESAC	Fusion Energy Sciences Advisory Committee (U.S.)
FFC	Fusion Fuel Cycles Inc. (Canada)
FIB	Focused Ion Beam
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode and Effects and Criticality Analysis
FOAK	First-Of-A-Kind
FPNS	Fusion Prototypic Neutron Source
FPP	Fusion Pilot Plant
GC	Gas Chromatography
HAZID	Hazard Identification Study
HAZOP	Hazard and Operability Study
I&C	Instrumentation & Control
ICF	Inertial Confinement Fusion
IFMIF	International Fusion Materials Irradiation Facility
IFMIF-DONES	IFMIF-Demo Oriented Neutron Source (Europe/Spain)
IFMIF/EVEDA	IFMIF/Engineering Validation and Engineering Design Activities (Japan)
INFUSE	Innovation Network for Fusion Energy
ISS	Isotope Separation System
ITER	International Thermonuclear Experimental Reactor
JAEA	Japan Atomic Energy Agency
JET	Joint European Torus
JT-60	Japan Torus-60
JT-60SA	Japan Torus-60 Super Advanced
JT-60U	Japan Torus-60 Upgrade
KF	Kyoto Fusioneering Ltd.
KFA	Kyoto Fusioneering America Ltd.

KFEU	Kyoto Fusioneering Europe GmbH
KFUK	Kyoto Fusioneering U.K. Ltd.
KIT	Karlsruhe Institute of Technology (Germany)
LANL	Los Alamos National Laboratory (U.S.)
LHD	Large Helical Device
LNG	Liquefied Natural Gas
LOPA	Layer of Protection Analysis
LRP	Long Range Plan
MCF	Magnetic Confinement Fusion
MHD	Magnetohydrodynamic
MIF	Magneto-Inertial Fusion
MOU	Matching Optics Unit
NASEM	National Academies of Sciences, Engineering, and Medicine (U.S.)
NB	Neutral Beam
NBI	Neutral Beam Injection
NIFS	National Institute for Fusion Science (Japan)
ODS	Oxide Dispersion Strengthening
P&ID	Piping and Instrument Diagram
PFC	Plasma Facing Components
PFD	Process Flow Diagram
PIRT	Phenomena Identification and Ranking Table
PIS	Pellet Injection System
Q	The Q notation is used for H, D, and T in this report in cases of undefined mixtures of the three hydrogen isotopes. Q_2 for example stands for all six hydrogen isotopologues (H_2, HD, D_2, HT, DT and T_2), CQ_4 represents all 15 possible methane isotopologues labelled with H, D and T
QMS	Quadrupole Mass Spectrometer
QST	National Institutes of Quantum Science and Technology
RAFM	Reduced-Activation Ferritic/Martensitic
RAMI	Reliability, Availability, Maintainability, and Inspectability
RF	Radio Frequency
SCM	Superconducting Magnet
SCS	Self-Cooled Yuryo Lithium-Lead Advanced Concept Study
SCYLLA©	Self-Cooled Yuryo Lithium-Lead Advanced
SEM	Scanning Electron Microscope
SiC_f/SiC	Silicon Carbide Fiber-Reinforced Silicon Carbide
SIS	Safety Instrumented System
SRL	System Readiness Level
SUS	Stainless Steel
TAS	Tritium Accountancy System
TBR	Tritium Breeding Ratio
TCAP	Thermal Cycling Absorption Process
TEM	Transmission Electron Microscopy
TES	Tritium Extraction System
TEU	Tritium Extraction Unit
TMP (plan)	Technology Maturation Plan
TMP (pump)	Turbo Molecular Pump
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
UKAEA	United Kingdom Atomic Energy Authority
UNITY	UNique Integrated Testing facilitY
VST	Vacuum Sieve Tray
WDS	Water Detritiation System
XRD	X-ray Diffraction

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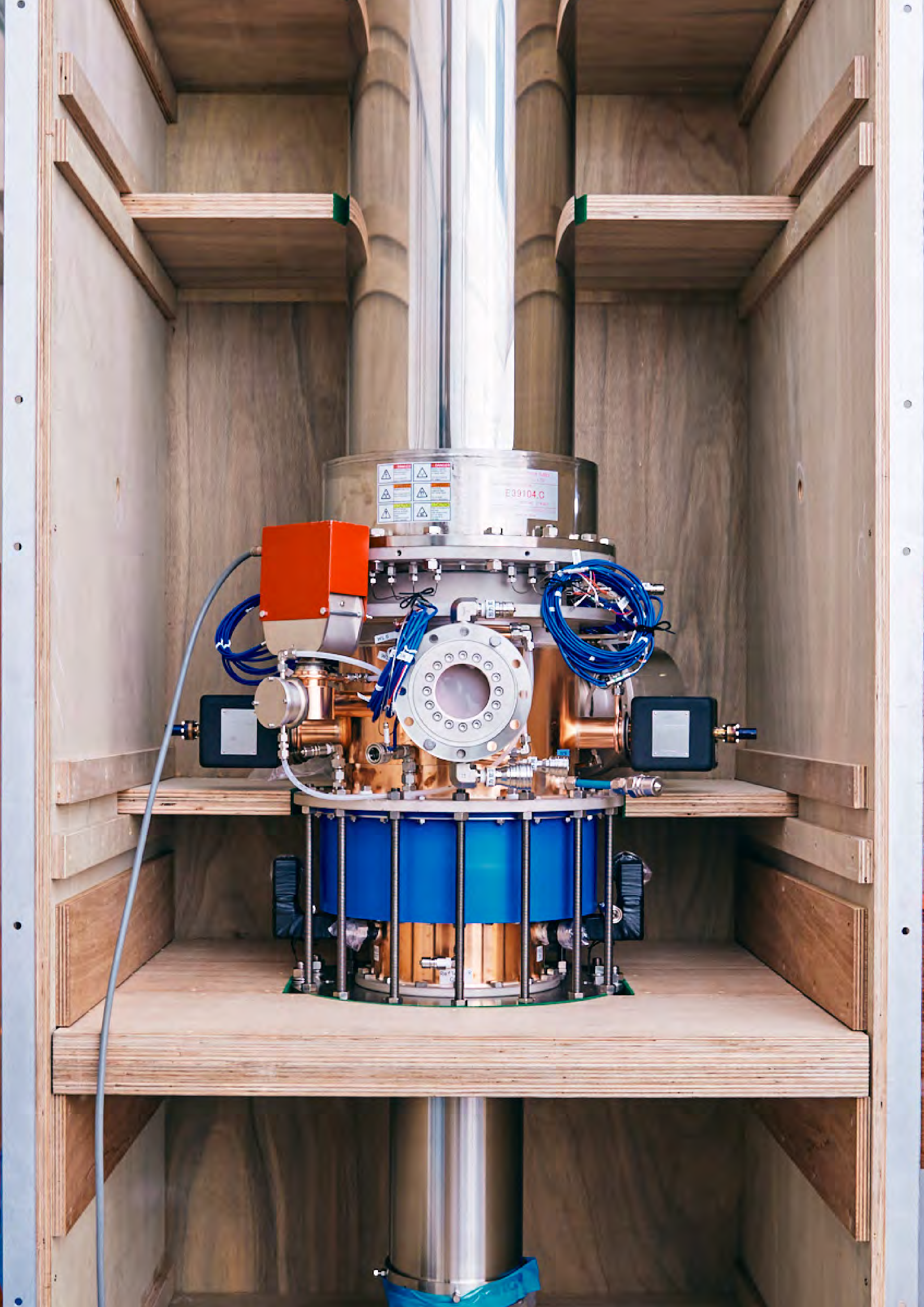
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FUSION for the FUTURE.

Approach to Development

The development and optimization of the key systems mentioned in Figure 1 requires the acquisition of knowledge and experience at different scales, from the atomistic understanding of materials under irradiation, to the experience of building large integrated facilities. KF therefore operates in parallel at multiple levels, as described here and presented in Figure 2. Activities at each level are supported by specific drivers of success that are critical to achieving our goals.

1 Plant Design & Development

With an emphasis on design safety and alignment with regulatory developments, we work closely with fusion developers from the outset to design integrated fusion experimental and commercial plants. During the delivery phase, we supply integrated systems.

Drivers of success:

Early and deep engagement with **fusion development** programs, and delivery in partnership with specialized **delivery organizations**.

IN PRACTICE

- UKAEA and Kyoto Fusioneering Collaborate to Develop Fusion Energy Projects
- THE FUSION ERA – Exporting Kyoto Fusioneering's Gyrotrons to the UK | NEWS | Kyoto Fusioneering
- Kyoto Fusioneering to Supply Advanced Gyrotron Systems to General Atomics
- Kyoto Fusioneering and General Fusion Sign MOU to Accelerate Commercialization of Magnetized Target Fusion
- THE FUSION ERA – Introduction of KF'Safety & Regulation Team | NEWS | Kyoto Fusioneering

2 Integrated Testing

We build test facilities to demonstrate technology in an integrated, prototypic environment to elevate the system readiness level (SRL). Furthermore, we make these facilities available to other stakeholders in the global fusion community, enabling external researchers and developers to test their technologies in an comprehensive environment, fostering innovation and accelerating the overall progress in fusion energy.

Drivers of success:

Robust partnerships with our **co-developers**, such as Canadian Nuclear Laboratories (CNL), as well as specialized **delivery organizations**.

IN PRACTICE

- Canadian Nuclear Laboratories and Kyoto Fusioneering Form Strategic Alliance to Advance Critical Path Fusion Energy Technology
- Full article: UNITY: Kyoto Fusioneering's Unique Integrated Testing Facility for Fusion Power Generation
- World-first Integrated Testing Facility for Fusion Power Plant Equipment to be Constructed in Japan

3 Technology Development

We design fusion-grade components, and work with our global supply chain to manufacture the parts, before assembling them into functional subsystems ourselves.

Drivers of success:

Relationships with an intricate supply chain consisting of nearly 100 specialized, fusion-relevant **manufacturers** and **suppliers**, as well as with other technology developers interested in co-development.

IN PRACTICE

- Kyoto Fusioneering Collaborates with Leading Vacuum Pump Manufacturer MIKUNI JUKOGYO to Co-Develop Advanced Fuel Exhaust Vacuum Pumps

4 Scientific Discovery & Experimentation

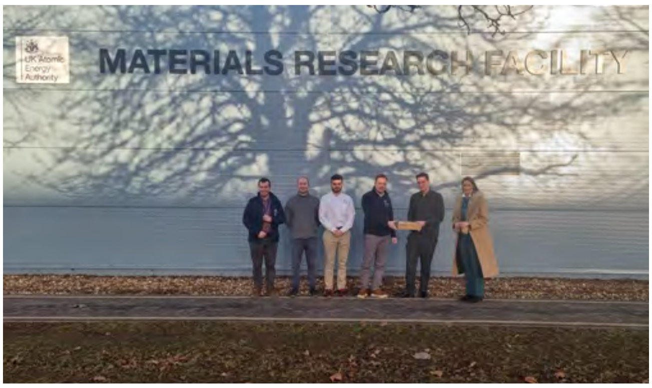
One of our core activities involves in-house experimentation and materials research aimed at developing innovative materials, components, and tools. This work is crucial to understand and manipulate the nuclear and chemical processes necessary for fusion.

Drivers of success:

Collaborations with **national laboratories** and **universities** around the word, including those in the US, the UK, Japan, Canada, and Germany.

IN PRACTICE

- Kyoto Fusioneering Partners with KIT to Accelerate the Development of Fusion Energy
- UKAEA awards contract to Kyoto Fusioneering Advancing Initiatives with Fujikura Ltd. on High-Temperature Superconducting Magnets
- Kyoto Fusioneering America Secures Three INFUSE Awards from the U.S. Department of Energy
- UKAEA and Kyoto Fusioneering sign agreement to advance materials for commercial fusion energy



Plant Design & Development

- **Support feasibility studies, scheduling, and costing during project initiation.**
- **Design the plasma heating, fuel cycle and thermal cycle systems for experimental to commercial fusion plants.**
- **Engineer and supply components and systems during construction.**
- **Continually supply consumable components (e.g., blanket) throughout operations.**
- **Provide onsite support during operations**
- **Enhancement to plant safety via safety assessment and hazard scenario analysis, which feeds back into our engineering process**
- **And more**

Integrated Testing

UNITY-1 in Kyoto for thermal cycle:
- **1000°C working fluid operating temperature**
- **Blanket testing**
- **4T MHD testing with SiC_f/SiC insulators**
- **Electricity gen from prototypic fusion heat**
- **450 L LiPb loop**

UNITY-2 in Ontario for fuel cycle:
- **~30 g of T, ~50 L LiPb loop w/ VST T extraction**
- **Dual storage system (dU, ZrCo)**
- **ISS (CD), outer cycle (WDS, ADS)**
- **Pellet Injection**
- **DIR system**

Plasma heating system test facility:
- **Gyrotron**
- **Power Supply**

Technology Development

- **High performance gyrotrons**
- **Self-cooled lithium-lead blanket modules**
- **Tritium compatible metal diffusion, roughing, turbo molecular pumps**
- **Proton conductor pumps, metal foil, palladium diffuser for DIR**
- **ZrCo tritium storage beds**
- **Isotope separation systems**
- **Atmospheric and water detritiation systems**
- **Vacuum sieve tray for tritium extraction**
- **Liquid metal and molten salt loops and technology**
- **And more**

Scientific Discovery & Experimentation

- **New grade of SiC_f/SiC with liquid phase sintering and particle dispersion composite manufacturing process.**
- **New joining methods for similar and dissimilar material bonding with SiC_f/SiC**
- **Mo alloys for novel heat exchangers**
- **FLiBe purification techniques & compatible materials**
- **Proton Conductor Pump for DIR and selective pumping**
- **RAFM steels (F82H) as structural materials**
- **New alloys for storage beds**
- **V alloys for blankets**
- **Impurity and cold trapping studies for Li-Pb**
- **And more**

Figure 2: Kyoto Fusioneering's Multilevel Approach to Fusion Power Plant Development.
This figure illustrates the four levels of KF's comprehensive development strategy: Plant Design & Development, Integrated Testing, Technology Development, and Scientific Discovery & Experimentation. Each level showcases specific activities, capabilities, and facilities that contribute to the design, engineering, and supply of key systems for fusion power plants. By operating at multiple levels simultaneously, KF ensures a holistic and integrated approach to advancing fusion technology and supporting fusion developers from conceptual design through to operational support.

Next, building on the description of level 4, we elaborate on how we integrate with global fusion development programs

Integrating with Fusion Development Programs

KF is actively involved in the design and engineering of fusion power plants from the very beginning, ensuring that all critical systems are meticulously considered and seamlessly integrated. Our iterative approach, combining scientific discovery, technology development, and integrated testing, allows us to collaborate closely with fusion developers and align our advanced technologies with their specific needs. This close partnership extends through the supply of hardware during the build and delivery phases, guaranteeing that fusion plants are equipped with state-of-the-art systems that drive performance and reliability.

By partnering with KF, fusion developers can access a comprehensive suite of design, engineering, and testing services that not only reduce technical risks but also significantly accelerate the path to commercial fusion. This strategic tech-to-market approach accelerates innovation and pools the collective expertise and resources of the fusion community in a focused manner. Our diverse and expert team, spanning Japan, the U.S., the U.K., Germany, and Canada, brings together centuries of cumulative, domain-specific expertise in fusion technology. Our extensive global network includes strategic partners, suppliers, and mission-driven backers who recognize and support the transformative potential of fusion energy.

By leveraging our comprehensive design and engineering capabilities, we ensure that fusion developers can achieve their goals efficiently and effectively, positioning KF as a crucial partner in the journey towards a sustainable fusion-powered future.

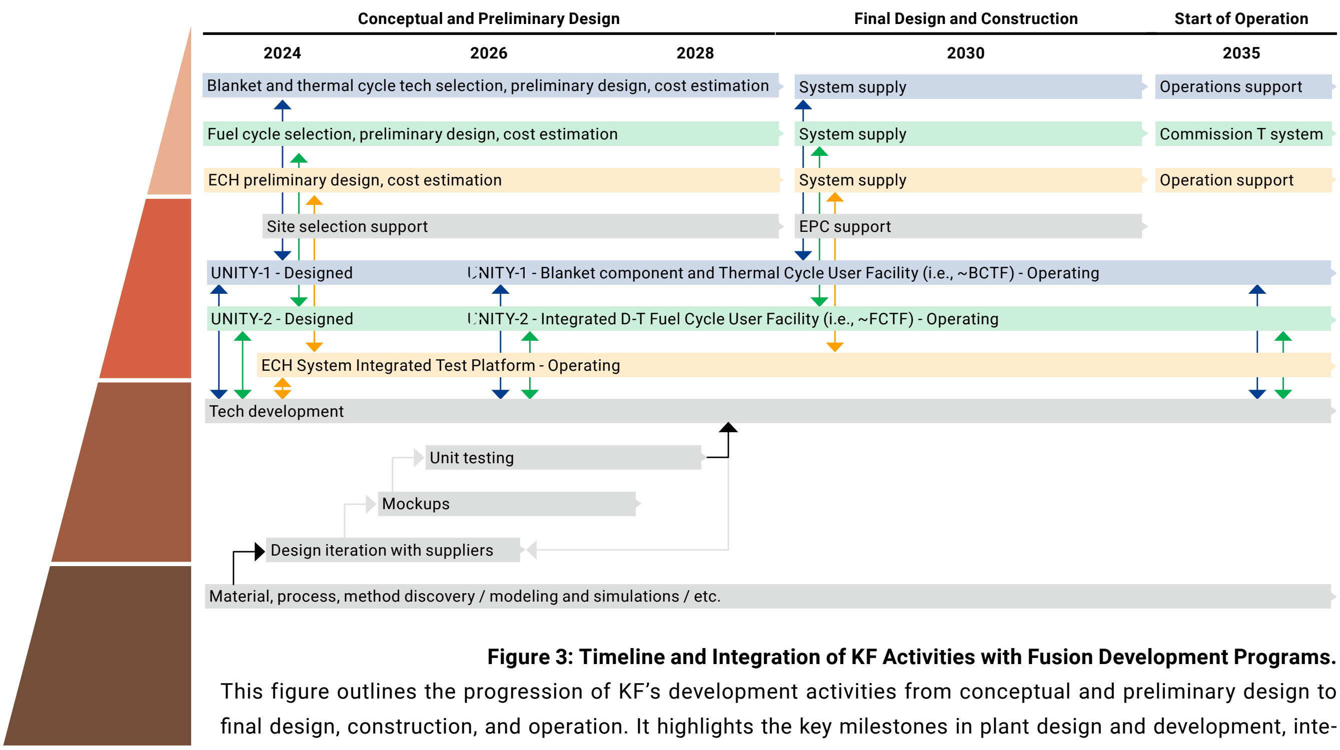


Figure 3: Timeline and Integration of KF Activities with Fusion Development Programs. This figure outlines the progression of KF's development activities from conceptual and preliminary design to final design, construction, and operation. It highlights the key milestones in plant design and development, integrated testing, technology development, and scientific discovery & experimentation. The timeline demonstrates how KF's capabilities and facilities, such as UNITY-1 and UNITY-2, align with and support the requirements of fusion development programs and the BDV, emphasizing the importance of early and continuous engagement in the design and engineering processes to ensure the successful commercialization of fusion power plants.

Building a Diverse Workforce

The journey to commercial fusion energy hinges on both technological innovation and a diverse, inclusive workforce. We are dedicated to fostering a workplace environment that values diversity in all its forms. By celebrating a wide range of experiences and viewpoints, we can drive greater creativity, innovation, and problem-solving capabilities.

To achieve this, we ensure that our workplace culture empowers all employees to contribute to the full extent. Our commitment extends beyond our office to education and outreach programs that inspire future fusion scientists and engineers.

Overview and Goals

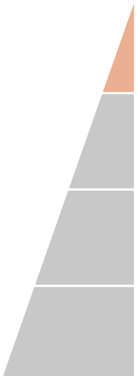
Harnessing fusion energy on Earth promises to address global energy challenges and usher in a new era of human prosperity. Increased energy consumption is directly linked to economic growth [1], yet it also corresponds to higher CO_2 emissions [2]. The solution to our energy needs lies in a source that is clean, dense, safe, dispatchable, geographically independent, and economically viable: fusion energy. By providing a sustainable and powerful energy source, fusion energy will drive economic growth while significantly reducing carbon emissions.

For fusion to significantly impact the transition to a low-carbon emission energy system by 2050, a fusion pilot plant (FPP) should be operational and net power-producing within the 2030s [3] and derisk the design of a first-of-a-kind (FOAK) fusion power plant. However, despite recent scientific breakthroughs, decades of government-funded research into science and technology, and over $6 billion in private investments into commercially-oriented fusion development, a successful FPP on the above mentioned timescale is not a foregone conclusion – many scientific, technical, and systemic challenges remain.

With that said, the current era of fusion industry is marked more so by engineering and demonstrating the practical viability of fusion technology, rather than relying on serendipitous scientific breakthroughs. Thus, continued investment and coordinated effort across nations, governments, and the private sector, is essential to realize commercial fusion on an accelerated timeline.

This Document

In this document, we provide an overview of KF's role in realizing an FPP on a decadal timeframe and a commercially viable FOAK thereafter. It is divided into four subsections that align with a functional requirements hierarchy, from the facility-level requirements to the scientific.



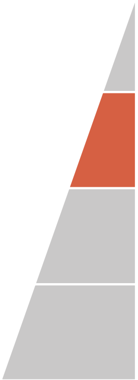
1. Goals of a Fusion Pilot Plant

Derived from the National Academies of Sciences, Engineering, and Medicine's (NASEM) 2021 report [3][1], this section outlines the critical criteria for the technological and economic feasibility of fusion energy. By aligning our technological developments with these overarching goals, we ensure that every step is directed towards the ultimate success of the FPP. Key question addressed is:

- What are the key criteria for a successful FPP?

[1]Despite the U.S.-centricity of this report, the FPP requirements prescribed in it are appropriate for aligning the global fusion community's efforts.

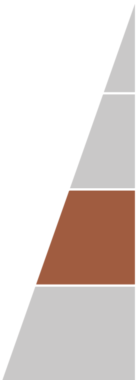
2. Primary Pilot Plant Systems



This section focuses on the three primary systems of an FPP: **Plasma Confinement and Control**, **Thermal Cycle**, and **Fuel Cycle**. We detail the functional requirements of each of these systems, and KF's activities and developments in them. This includes an overview of our blanket component and fuel cycle test facilities, UNITY-1 and UNITY-2, respectively. We focus on issues such as:

- What systems are involved in achieving each of the plant-level criteria defined at level 1?
- What functional requirements must each system satisfy to enable a successful FPP?
- What role does KF play in closing the technology gaps and elevating SRL in each of the primary systems?
- How can fusion developers, researchers, and technologists take advantage of KF's efforts?

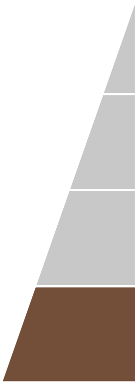
3. Technology Development



Here, we discuss the technologies being developed to meet the stringent requirements of a fusion plant. KF's specific contributions and advancements are highlighted, demonstrating our role in pushing the boundaries of fusion technology. Questions addressed include:

- What specialized components are KF developing to satisfy the functional requirements and withstand the harsh environments of a fusion power plant?
- How can fusion developers, researchers, and technologists take advantage of KF's technology development efforts?

4. Science & Technology Challenges



This section details the research and development activities currently underway to meet the outlined criteria, emphasizing KF's efforts to tackle these challenges. We provide examples of our current projects and collaborations, exploring key questions such as:

- What are some key challenges in achieving commercially viable fusion energy?
- How is KF and the broader fusion community contributing to solving them?

Together, these sections describe the multiscale challenges of fusion energy and outline the approach KF is taking to address them. By providing insights into our goals, systems, technologies, and ongoing research, this document serves as both a roadmap and a call to action for the global fusion community. It underscores the importance of collaboration, innovation, and sustained effort in making fusion a viable and transformative energy source for the future.

Note to Readers

In many cases throughout this assessment, we assume a Deuterium-Tritium (D-T) fusion reaction. Despite this, many of the solutions described in the sections below are agnostic or adaptable to alternative fusion fuel cycles, including $D\text{-}^3He$.

01

Goals of a Fusion Pilot Plant

We base our goals for an FPP on the criteria put forth in the NASEM report [3]. These criteria, important for the technological and economic feasibility of fusion energy, are summarized in Table 1 and expanded upon in Table 2 to showcase our activities in tandem with the criteria

Category	Criteria
Fusion and electric power performance	1. 100-500 MW net fusion time-averaged thermal power
	2. ≥50 MWe peak electricity generation
	3. $Q_e > 1$
	4. Operate for several environmental cycles[2]
Components	5. Strategy, cost, and timescale of removing and replacing degraded components as a design feature
Fuel and ash	6. Ash removal concept can be scaled up to FOAK fusion power plant
	7. Plasma-facing components that can withstand damage caused by helium ash in an environment representative of a FOAK fusion power plant
	8. Tritium breeding ratio >0.9
	9. Tritium inventory ≤1 kg
	10. Innovations in boundary plasma science, fueling technologies, and gas processing
	11. Tritium accountability clearly defined along with analytical methods that can satisfy accountability requirements
Reliability and availability	12. Perform remote maintenance and replacement
	13. Modular, replaceable components
Environmental and safety considerations	14. Mitigation of tritium release
	15. Minimizing waste volume and hazard overall and avoiding greater than Class C waste as much as feasible
	16. Decommissioning of activated waste
Economics	17. Overnight construction cost of less than $5-6 billion

Table 1: Criteria for a Successful Fusion Pilot Plant

[2] An environmental cycle in a fusion power plant includes installing core components, operating the plant until these components degrade, and then performing maintenance to continue operations. Although the duration of this cycle isn't precisely defined and can differ by design, it typically spans about a year of full power operation before maintenance or repair is needed in an FOAK fusion power plant [3].

These plant-level requirements are expanded to lower hierarchical levels in the ensuing sections.

KEY FINDING

Satisfying these requirements necessitates an integrated design of the full power plant from the outset, across all key systems. Fusion developers who overlook the necessity of an integrated and sophisticated design for the fuel and thermal cycles, alongside their confinement concept, risk facing significant challenges that could impede the realization of a commercially viable power plant.

02

Primary Pilot Plant Systems

CONTENTS

Most FPP concepts can broadly be divided into three primary systems, which are described here and visually illustrated in Figure 4:

Plasma Confinement and Control

The Plasma confinement and control system is responsible for containing and maintaining the plasma within the fusion device under conditions that allow fusion to occur. Plasma confinement technologies typically involve MCF, ICF, or MIF methods to achieve sufficiently high products of density, confinement time, and temperature.

Thermal Cycle

The thermal cycle system converts the energy produced by the fusion reaction into usable energy, in the form of heat. It includes the blanket, which not only captures high-energy neutrons to heat the primary coolant but also plays a vital role in breeding tritium from lithium, and thus integrates the thermal and fuel cycle systems. The heat from the primary coolant is transferred to a secondary working fluid via heat exchanger, typically water or helium, which then drives turbines to generate electricity. This system effectively bridges the gap between energy generation in plasma and useful power output.

Fuel Cycle

The fuel cycle system manages the supply, injection, recycling, and processing of the fusion fuel, which varies depending on chosen fuel mix, but is typically made up of the light hydrogen isotopes such as deuterium and tritium. It includes handling the extraction and purification of these isotopes, their introduction into the reaction chamber, and the efficient management of by-products from the fusion process, notably helium.

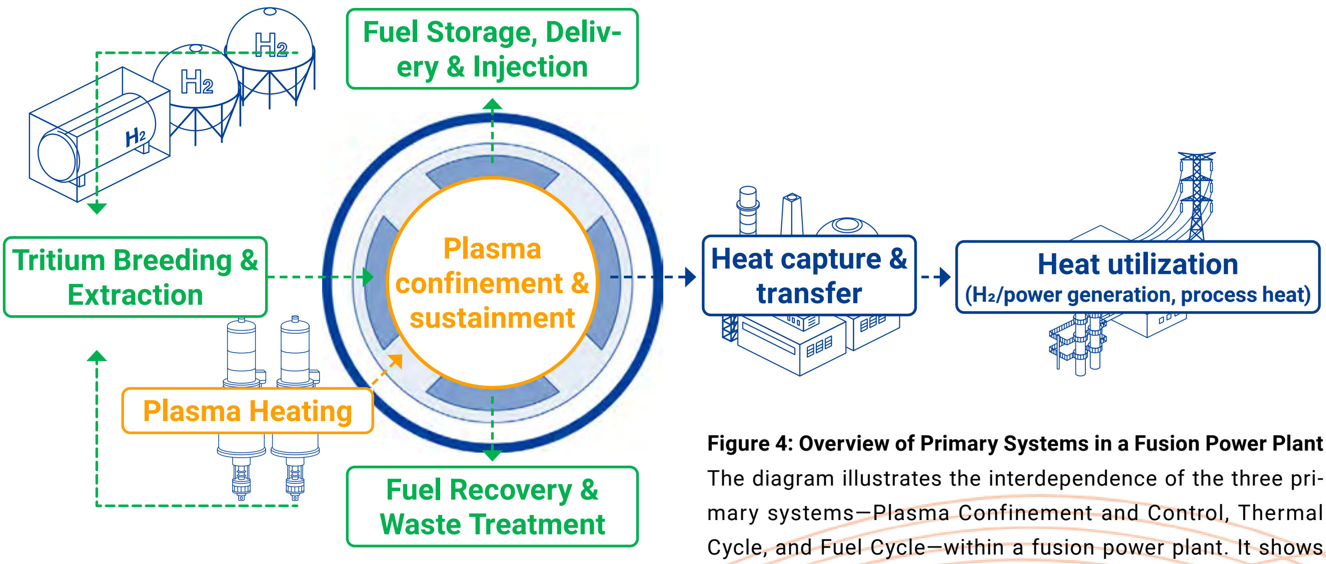


Figure 4: Overview of Primary Systems in a Fusion Power Plant
The diagram illustrates the interdependence of the three primary systems—Plasma Confinement and Control, Thermal Cycle, and Fuel Cycle—within a fusion power plant. It shows how plasma confinement and sustainment are central to the process, supported by plasma heating and fuel storage, delivery, and injection. The thermal cycle is represented by the heat capture and transfer system, leading to heat utilization for power generation and other applications. The fuel cycle is depicted through the tritium breeding and extraction, fuel recovery, and waste treatment processes. This integrated approach highlights the need for a holistic design to achieve commercial viability.

2.1 Primary Systems' Criteria

Continuing to draw largely from the NASEM report, Table 2 below expands upon each of the criteria from Table 1 and describes the key requirements and technology gaps for each of the three primary systems. Furthermore, it summarizes KF's role in addressing these requirements and technology gaps. The subsections that follow the table describe KF's experimental and developmental activities, to advance these systems towards realizing a commercially viable fusion power plant.

Note to Readers

The authors recognize that the blanket has overlap with both the fuel and thermal cycles and is sufficiently complex and significant to warrant being treated as an independent system responsible for heat capture, tritium breeding, and shielding of components outside of the vacuum vessel. However, it has been captured as a component of the thermal cycle in our analysis for the sake of simplicity.

Table 2: Criteria for primary fusion power plant systems

<table>
<tr><th>Category</th><th>Criteria</th><th>Plasma Confinement</th><th>Thermal Cycle</th><th>Fuel Cycle</th></tr>
<tr><td rowspan="4">Fusion and electric power performance</td><td>1. 100-500 MW net fusion time-averaged thermal power</td><td colspan="2" rowspan="4">Technology Requirements
a. Triple product of roughly 4–10 x 10^{21} keV s m^{-3} for D-T devices operating with a plasma temperature in the range of 8 – 20 keV (or equivalent for alternative fuels).
b. Uninterrupted operation of burning plasma in a high-performance confinement concept.
c. For long pulse and sustained concepts: values of plasma energy gain should be sustained for at least several characteristic plasma times including energy confinement times.
d. For sustained tokamak: high bootstrap current fraction.
e. Plasma-facing components (PFC), armor and first wall to accommodate high heat exhaust requirements to enable a high-power density plasma core.
f. Demonstrate high efficiency energy conversion technologies (for electricity and equivalent process heat application).

KF Contribution
• Plasma confinement and control (KF involvement: Support): High efficiency and performance Electron Cyclotron Heating (ECH) system for plasma heating and current drive (see 2.2).
• Thermal cycle (KF involvement: High): High temperature and efficiency integrated thermal cycle system design and demonstration – UNITY-1 (see 2.3).
• KF's power plant systems play a critical role in the overall plant economics.</td><td rowspan="4"></td></tr>
<tr><td>2. ≥50 MWe peak electricity generation</td></tr>
<tr><td>3. $Q_e > 1$</td></tr>
<tr><td>4. Operate for several environmental cycles</td></tr>
<tr><td>Components</td><td>5. Strategy, cost, and timescale of removing and replacing degraded components as a design feature</td><td colspan="2">Technology Requirements
g. Establish lower bound on mean time to failure of structural components and blanket materials.
h. Demonstrate remote maintenance/ replacement of components.

KF Contribution
• Thermal cycle (KF involvement: High): Materials testing at prototypic fusion temperatures with flowing liquid metal in UNITY-1; remote maintenance and replacement regimes being explored.</td><td></td></tr>
<tr><td rowspan="2">Fuel and ash</td><td>6. Ash removal that can be scaled up to FOAK fusion power plant</td><td colspan="2"></td><td>Technology Requirements
i. Exhaust pumping system that can handle large gas throughputs at high pumping speeds.
j. Exhaust gas transported to tritium plant for cleaning.

KF Contribution
• Fuel cycle (KF involvement: High): High performance and tritium compatible vacuum pumping and fuel cleanup system to be demonstrated in UNITY-2 (see 2.4).</td></tr>
<tr><td>7. Plasma-facing components that can withstand damage caused by helium ash in an environment representative of a FOAK fusion power plant</td><td colspan="2">Technology Requirements
k. Demonstrate ability to successfully remove heat flux for durations on the order of hours/days for compact fusion pilot plant power densities.
l. Demonstrate net erosion yield ≤1 mm/ effective full power year.
m. Demonstrate sufficiently low tritium losses in PFCs such that external tritium inventory is maintained for power operations and effluents remain within regulatory limits.
n. Demonstrate robustness to expected fast and thermal helium ion implantation in PFCs.
o. Demonstrate heat removal, material erosion, and tritium loss can be sustained for an environmental cycle.
p. Demonstrate structural integrity for neutron wall loading on the order of 1 to 3 MW-year m^{-2}.

KF Contribution
• Thermal cycle (KF involvement: High): KF is developing coating techniques for Silicon Carbide Fiber-Reinforced Silicon Carbide (SiC_f/SiC) blanket modules and exploring liquid FW systems (see 4.2). Furthermore, KF is engineering blankets for target fusion concepts. Blanket component testing will be conducted under prototypic conditions in UNITY-1.</td><td></td></tr>
</table>

<table>
<tr><th>Category</th><th>Criteria</th><th>Plasma Confinement</th><th>Thermal Cycle</th><th>Fuel Cycle</th></tr>
<tr><td rowspan="4">Fuel and ash</td><td>8. Tritium breeding ratio >0.9</td><td colspan="3" rowspan="4">Technology Requirements
q. High-fidelity understanding of all processes involving tritium
r. High tritium burnup fraction
s. Low tritium processing time
t. Low tritium release
u. High tritium extraction efficiency
v. Demonstrate tritium generation with tritium breeding ratio (TBR) > 0.9 averaged over an environmental cycle.
w. Demonstrate tritium losses <1 percent of tritium consumption averaged over an environmental cycle.
x. Demonstrate ability to generate and recover tritium with sufficiently low tritium losses such that external tritium inventory is maintained for power operations and remain within regulatory limits.
y. Low losses from and low inventory in all fusion power plant systems.
z. Minimize tritium migration through materials and across interfaces, tritium retention in bulk solids and liquids, and tritium retention and behaviour in plasma-facing materials.
aa. Systems and processes to process tritium efficiently and safely continuously at flow rates and quantities.
ab. Understanding of many interconnected phenomena including permeation, radiolytic chemistry, surface science and kinetics, liquid metal magnetohydrodynamics, and mass transfer.
ac. Direct internal recycling system.
ad. Rapidly recover tritium and keep out of collateral materials to minimize inventory within breeding loop.
ae. For pellet injection: pellet velocity of ~1000 $m\ s^{-1}$ [4].

KF Contribution
• Fuel cycle (KF involvement: High): High performance tritium processing plant (inner and outer fuel cycle) design and demonstration in UNITY-2 (see 2.4).
• Thermal cycle (KF involvement: High): Modelling and designing blankets to ensure TBR > 0.9 for FPP/mock-up testing and tritium inventory is low, while also ensuring high thermal performance (see 2.3 & 3.2).</td></tr>
<tr><td>9. Tritium inventory ≤1 kg</td></tr>
<tr><td>10. Innovations in boundary plasma science, fueling technologies, and gas processing.</td></tr>
<tr><td>11. Tritium accountability clearly defined along with analytical methods that can satisfy accountability requirements.</td></tr>
<tr><td rowspan="2">Reliability and availability</td><td>12. Perform remote maintenance and replacement.</td><td>See 5</td><td colspan="2"></td></tr>
<tr><td>13. Modular, replaceable components</td><td colspan="3">KF Contribution
• Plasma confinement and control (KF involvement: Support)
• Thermal cycle (KF involvement: High)
• Fuel cycle (KF involvement: High)
• ECH, UNITY-1 and UNITY-2 systems are designed to be modular and relatively independent subsystems with maintenance regimes aimed at minimizing impact to the overall plant.</td></tr>
<tr><td rowspan="3">Environmental and and safety considerations</td><td>14. Mitigation of tritium release</td><td></td><td colspan="2">See 8 – 11</td></tr>
<tr><td>15. Minimizing waste volume and hazard overall, and avoiding greater than Class C waste as much as feasible.</td><td colspan="3">Technology Requirements
af. Use of low-activation materials
ag. Minimize tritium permeation

KF Contribution
• Thermal cycle (KF involvement: High): Low activation structural and blanket materials being developed and used in blanket/thermal cycle system (see 2.3).
• Fuel cycle (KF involvement: High): D-T fuel cycle design aiming to minimize tritium inventory; tritium compatible components and permeation barriers to be demonstrated in UNITY-2 (see 2.4).
• Developing capability to minimize hazard by ensuring safety design, such as through safety assessment and accident scenario analysis (e.g., Failure Mode and Effects Analysis (FMEA), Phenomena Identification and Ranking Table (PIRT), Hazard and Operability Study (HAZOP), etc.) (see 2.3.3 , 2.4.3, and blog post).</td></tr>
<tr><td>16. Decommissioning of activated waste.</td><td colspan="3">Key Requirements
ah. Decommissioning plan in line with regulatory requirements.
ai. Facility operation in a manner that minimizes contamination to reduce decommissioning complexity.
aj. Recover tritium for use in other plants, and manage and dispose of tritium waste safely.
ak. Dispose or store activated waste per local regulations.

KF Contribution
• Fuel cycle (KF involvement: High): Decommissioning plan developed for tritium-containing UNITY-2 facility (see 2.4). Tritium recovery from waste methods being explored.</td></tr>
<tr><td>Economics</td><td>17. Overnight construction cost of less than $5 to $6 billion.</td><td colspan="3">KF Contribution
• Plasma confinement and control (KF involvement: Medium)
• Thermal cycle (KF involvement: High)
• Fuel cycle (KF involvement: High)
• Cost estimates for power generation, ECH, and tritium plants based on actual data, including UNITY-1 and UNITY-2 data.
• Prioritising building resilient, global supply chain from the outset.
• Optimizing UNITY-1 for high-temperature operations to enable a smaller, more cost-effective device.
• Optimizing UNITY-2 for low tritium inventory and high throughput to minimize plant size and safety requirements.
• Pursuing high efficiency and power gyrotrons to reduce cost per unit power delivered to plasma.
• Developing modular sub-systems that can be assembled on-site.</td></tr>
</table>

2.2 KF Electron Cyclotron Heating System

Directly supports criteria 1-3, 13, 15.

2.2.1 Overview

ECH offers a technically and economically attractive solution to the challenges associated with plasma heating in MCF concepts [5]. ECH utilizes millimeter waves generated via electron cyclotron resonance (ECR), serving multiple functions required for magnetic confinement:

1. Achieving initial ionization and ignition
2. Producing plasma and heating it to fusion temperatures
3. Sustaining and stabilizing the plasma by electron cyclotron heating and current drive (ECCD)

1 Plant Economics and Balance of Plant Implications

The ECH system's impact extends beyond the realm of plasma operations. By supporting high-efficiency energy conversion technologies (criterion 1f), ECH also directly contributes to improving the overall plant economics compared to other methods. Achieving higher power and wall-plug efficiency (criteria 1-3) reduces operational costs, minimizes space requirements, and enhances the plant's economic viability. Additionally, the modularity and replaceability of ECH components (criterion 13) minimize downtime and maintenance costs, aligning with maintenance strategies to further optimizing the plant's economic performance.

2 Technical Overview

The millimeter waves are oscillated by gyrotrons. A gyrotron is the vacuum tube that serves as an efficient MW-power millimeter-wave source. The gyrotron system consists of several auxiliary components including a superconducting magnet (SCM), a matching optics unit (MOU), and a high-voltage power supply system. In addition to the gyrotron, KF is trusted in the design of the SCM, MOU, transmission lines, power supply systems, cooling systems, and support systems.

One of the technological focal points of KF is designing and producing gyrotrons and its auxiliary systems, which are a key component in most MCF configurations.

The high demand for gyrotrons with higher performance and efficiency motivates our R&D program. Future goals for gyrotron development include:

1. **Higher power** to reduce the number of gyrotrons and simplify the ECH systems and the fusion device, therefore reducing the cost and space requirements
2. **Higher wall-plug efficiency** to reduce the heat load on the gyrotron by millimeter-wave loss and further enhance reliability, improving performance and cost profile.

3. **Advanced multi-frequency** gyrotrons to allow flexible operation and optionality for fusion experiments, and system simplification, reducing risk and cost.

4. **Higher frequencies** are interesting for commercial and scientific reasons. They are required for very high field devices and to deliver scientific impact for exploring the potential of millimeter-wave technology. KF is developing a 236 GHz gyrotron and plans to go higher in the future.

5. **Simplified gyrotron system packages** for mass-production of any devices from small systems to very large commercial fusion plants.

Additional technical details are outlined in section 3.1 and digital gyrotron catalogue here.

IN PRACTICE

Delivery Experience

KF has experience designing and delivering gyrotrons to public and private fusion programs globally, including nine active supply contracts as of May 2024.

- Exporting Kyoto Fusioneering's Gyrotrons to the UK
- Kyoto Fusioneering to Supply Advanced Gyrotron Systems to General Atomics

KF Gyrotron Specs

Table 3: Specifications of KF's Gyrotron Systems

Frequency	236 GHz*	203.1 GHz**	170 GHz**	137 GHz**	104 GHz**	35 GHz***	28 GHz***
Oscillation Mode	$TE_{43,15}$	$TE_{37,13}$	$TE_{31,11}$	$TE_{25,9}$	$TE_{19,7}$	$TE_{10,6}$	$TE_{8,5}$
Output Mode	Gaussian Beam						
Magnet	9.2 T	7.98 T	6.63 T	5.32 T	4.08 T	--	--
Power (>1s)	1 MW (to be tested)	1 MW	1.2 MW 1 MW (>300 s)	1 MW			

***Under development with QST**
****R. Ikeda, et al., Journal of Infrared, Millimeter, and Terahertz Waves 38 (2017) 531-537. [6]**
*****T. Kariya, et al., Nuclear Fusion 59 (2019) 066009. [7]**

Multi-frequency gyrotrons are available to allow operational flexibility.

For more information on KF's ECH development and commercial offering, please contact KF at www.kyotofusioneering.com/en/contact.

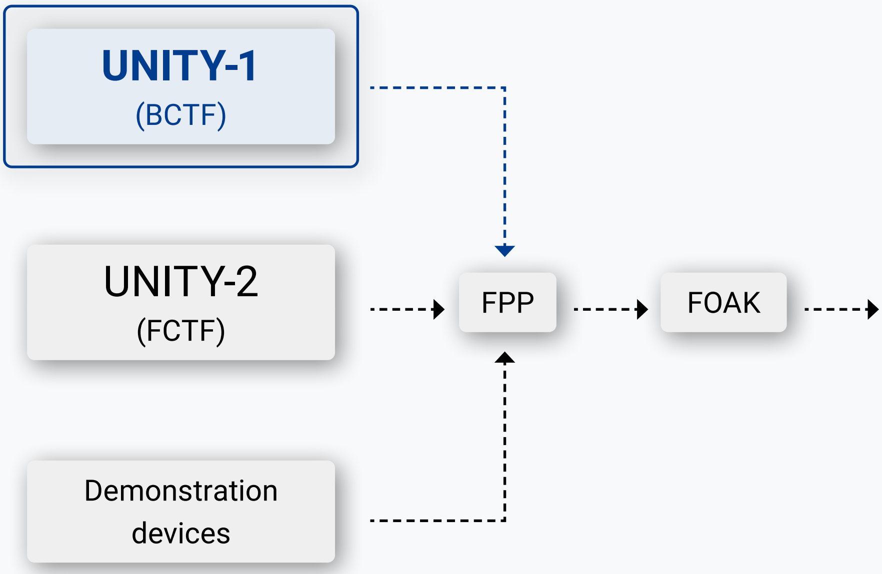
2.3 Unique Integrated Testing Facility 1 (UNITY-1): Blanket Component and Thermal Cycle User Facility

Directly supports criteria 1-5, 7-13, 15-17

2.3.1 Overview

UNITY-1 is a non-radiological blanket component and thermal cycle test and user facility at KF's Kyoto Research Center (KRC) in Kumiyama, Kyoto, Japan. **Early operations have begun** while the full-scale testing campaigns are expected to commence in 2026.

UNITY-1 will directly contribute to world-leading science and close critical fusion technology gaps for an FPP within the decade. It will serve as a flexible test platform to support many users in engineering science.



Aligned with the recommendations and timelines prescribed in the American Physical Society Division of Plasma Physics Community Planning Process (APS-DPP-CPP) [8], Fusion Energy Sciences Advisory Committee (FESAC) Long Range Plan (LRP) [9], the 2021 NASEM report, and the Bold Decadal Vision (BDV) [10], UNITY-1 "integrates all non-nuclear features of a fusion blanket and its ancillary systems (prototypic, at-scale complex structures and coolants) under prototypic conditions of temperature, pressure, magnetic field, and mechanical stress, with surrogate surface and volumetric heating and injected hydrogen [and] deuterium in place of tritium." [9]

UNITY-1 will elevate the technology readiness level (TRL) of fusion blanket and power generation technologies and perform non-nuclear qualification to close technology gaps and enable a risk-reduced path to an FPP. It will do so by demonstrating:

1. **Containment and circulation of high temperature and pressure prototypic breeder and coolant fluids (LiPb)** coupled to first wall and blanket prototypes. Blanket modules to be tested are in the range of full-scale for those planned in many of the magnetic confinement plasma devices such as tokamaks and stellarators. Typically, 1 m^2 at the relevant heat extraction from 1 MW/module energy density.

2. **High temperature heat extraction and power generation** from a ~1000°C circulating LiPb loop for high thermal efficiency and to demonstrate driving other high-temperature processes using this thermal energy. Intermediate heat exchangers will also be developed and tested to meet the specifications of the blankets and fluids. Heat extraction from wet-wall chambers typically considered for inertial confinement concepts can also be tested with adequate interface.

3. **Structural integrity and longevity of components** under FPP-relevant conditions, including stability under 4 T magnetic fields, MHD pressure drop caused by a flow of conductive fluid, mechanical stresses, and temperature gradients, as well as demonstrating material compatibility with coolants.

4. **Performance of blanket components and safety systems** across accident scenarios, such as loss of flow, coolant loss, and blackout. Actual operation experience and possible off-normal events and deviations will be facilitated to identify the operational risks and their mitigations, which will be essential for safety analysis and licensing processes. To meet the BDV, integrated testing of the fusion plant model is essential, and it is likely that only UNITY-1 will meet the expected timeline.

UNITY-1's contributions extend beyond technical demonstrations; they are pivotal for the economic feasibility of fusion power plants. By elevating the TRL of blanket and thermal cycle technologies, UNITY-1 ensures that key components meet stringent performance and reliability standards (criteria 1-3, 7-13). This minimizes downtime, maintenance costs, and overall operational risks (criteria 13, 15-17). Additionally, the facility's emphasis on non-nuclear qualification aids in reducing the costs and complexities associated with radioactive materials handling and regulatory compliance.

KEY FINDING

The relative sophistication of the integrated thermal cycle design in the form of UNITY-1 is applicable to target fusion demonstration and pilot plants. Fusion development programs should leverage the work done on UNITY-1 to design their own systems, accelerating their path to commercialization.

To learn how you can adapt the UNITY-1 design, please contact KF at www.kyotofusioneering.com/en/contact.

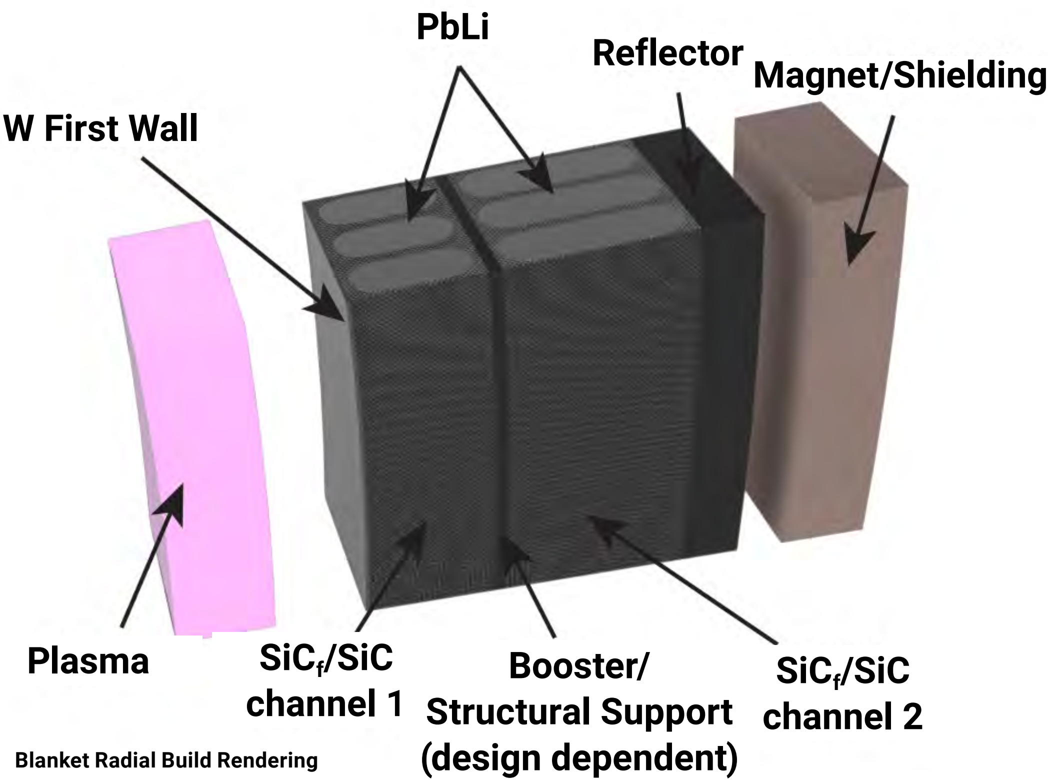
IN PRACTICE

KF's Blanket Design and Development Activities

UNITY-1 provides a prototypic environment for the characterization and qualification of small-scale breeding blanket mock-ups. This facility enables testing of various fusion-relevant aspects, including thermal behaviour under surface and volumetric heating, structural integrity, MHD effects, and more.

Within this framework, KF is developing a novel breeding blanket design based on the Self-Cooled Yuryo Lithium-Lead Advanced (SCYLLA©) concept for application in a spherical tokamak [11]. The fil rouge connecting UNITY-1 and the breeding blanket design activity is a fully integrated design philosophy.

The project, known as the SCYLLA© Concept Study (SCS), focuses on developing a self-cooled lithium-lead breeding blanket design that includes its main ancillary systems. These entail, but are not limited to, the lithium-lead loop, the tritium removal system, and the corrosion product removal systems. SCS's comprehensive approach ensures that the design considers the most relevant aspects, such as neutronics, thermo-mechanical analyses, tritium transport, remote handling, remote maintenance, and so on.



Blanket Radial Build Rendering

Areas of development

KF is undertaking development in five key areas within the SCS to advance the design of a commercially viable breeding blanket:

1. Technology Readiness Assessment (TRA) and Technology Maturation Plan (TMP):
TRA and TMP are crucial for determining the current state of blanket technology development and identifying areas requiring further advancement to achieve commercial and technological reliability.

2. Safety Analysis:
KF prioritizes the implementation of safety analysis from the initial design stages. This includes PIRT, FMEA/FMECA, RAMI (Reliability, Availability, Maintainability, and Inspectability) analysis, HAZOP, HAZID (Hazard Identification), risk analysis, tritium transport modelling studies, and compliance with all relevant safety regulations.

3. System Engineering:
KF has extensive experience in defining of system requirements and their propagation, functional analysis, functional architecture definition, as well as interface management and analysis, and risk management.

4. Design of Breeding Blanket and Ancillary Systems:
A multi-physics approach forms the foundation for breeding blanket design. This approach couples the most significant and complex effects, such as MHD, with other important effects like the non-uniform distribution of the thermal field within the blanket. These analyses, referred to as magnetoconvection, are the basis for the design of the SCYLLA© breeding blanket. The design encompasses a broad range of activities, including thermo-hydraulics analyses, thermo-mechanical and structural analyses, neutronics, computer-aided design (CAD) development, Process Flow Diagram (PFD) and Piping and Instrumentation Diagram (P&ID) development, design and optimization of tritium extraction technologies, Instrumentation and Control (I&C) development, and much more.

5. Manufacturing and Fabrication:
A strong connection exists between the design activities in the SCS and the mock-up to be tested in the UNITY-1 experiment. Manufacturing and fabrication aspects are considered one of the most critical foundations upon which breeding blanket design is built. This translates into a robust collaboration between design, manufacturing, and materials teams to ensure the resulting design is both realistic and manufacturable, paving the way for the commercialization of fusion energy.

To learn more about our blanket development program and how you can leverage it, please contact KF at www.kyotofusioneering.com/en/contact.

UNITY for the Community

UNITY-1 as an International User Facility

Flexible | Well-Diagnosed | Digital Twin | Workforce Development

UNITY-1 will be open to the international fusion community as a user facility, allowing users to test their own blanket and power generation technologies in an FPP-relevant environment.

Potential use cases

- Testing of diagnostic tools
- Thermomechanical and fluid dynamics analysis of blanket mockups
- MHD effects studies
- Hydrogen transport and extraction experiments
- Material corrosion and compatibility assessments
- High temperature auxiliary technologies
- Advanced energy conversion technology (electricity generation or other high-temp application)

Well-Diagnosed

Comprehensive analytical instrumentation will be available at UNITY-1 for accurate and detailed data collection during experiments. This includes advanced sensors, pressure indicators, temperature measurement technologies, and continuous monitoring systems for LiPb levels and conditions.

Digital Twin Vision

While UNITY-1 currently focuses on creating a 3D model of the entire plant layout to ensure accessibility and maintainability, plans are underway to integrate advanced multi-physics modeling. In the near future corrosion and deposition modeling, thermohydraulic, mechanical stress analysis, and irradiation damage predictions will be available at this facility. This vision invites collaboration and ideas from the international fusion community to enhance and realize the full potential of a digital twin for UNITY-1. One of the most important roles of digital twin technology for liquid breeder concept is the description of the 3D flow pattern and the transport of energy as well as bred tritium fuel. Because of the complicated behavior of the conductive liquid flow under the magnetic field, only digital twin technology can analyze it. However, no experiments have ever benchmarked the codes and calculations due to the lack of relevant testing with adequate instrumentation. UNITY-1 will provide this benchmarking role through the developed digital twin.

Workforce Development

UNITY-1 will also serve as a platform for workforce development, providing training and educational opportunities for future fusion engineers and scientists. By engaging with the facility, users can gain hands-on experience and deepen their understanding of fusion technology and its applications.

For more information on UNITY-1, to arrange a tour of the facility, or to register to use the facility, please contact KF at www.kyotofusioneering.com/en/contact.

2.3.2 Facility Attributes

UNITY-1 will allow users to mount scaled blanket test articles (integrated blanket modules, manifolds, and components) between 4 T superconducting magnets, connected to a flowing LiPb loop that is heated to 1000°C via surface heating. Further details on UNITY-1's subsystems are provided in this section.

Coolant loop

- 450 L inventory LiPb
- Flow rate: base loop 50 L/min, blanket loop 10 L/min (limited by heating power)
- Deuterium as a stable proxy isotope for radio-active tritium
- 500°C and 1000°C induction heaters

UNITY-1 has a LiPb loop with a 450 L inventory. The loop contains 2 sections: the base loop, which operates between 300-500°C, and the blanket loop, where temperatures reach up to 1000°C in the blanket test section and heat exchanger. The base loop has a gas injection point with deuterium used as a proxy for tritium and provides a test section for analysis of samples under flowing LiPb conditions.

Parameter	Value
Footprint	12 m x 25 m
Piping size	1½ inch
Coolant	Li17-Pb83
Inventory	450 L
Magnetic field	4 T
Temperature	300 – 1000°C
Flow rate	50 L/min
Design pressure	0.5 MPa
Piping materials	SS316 (up to 500°C), SiC_f/SiC (up to 1000°C)
Other materials	SiC_f/SiC, Mo
Pump specification	EMP, 91 kVA, ~0.5% efficiency
Impurity control	Cold trap

Table 4: UNITY-1 Main Facility Parameters

Blanket test section

- Blanket test module 30 x 30 x 70 cm
- 1000°C LiPb
- 4 T niobium-titanium (NbTi) magnet for MHD testing

The modular nature of the blanket test section allows for various blanket modules to be tested to determine optimal blanket design for selected fusion device configurations. For the initial configuration, a blanket testing module (30 x 30 x 70 cm) will be incorporated into the LiPb blanket loop in the blanket test section. The module is made from KF's fusion-grade silicon carbide and is placed between superconducting NbTi magnets generating magnetic fields of up to 4 T to investigate MHD effects within the blanket and associated piping. The blanket will be surface heated with an induction heater up to 1000°C, yet volumetric heating of the blanket is a future option.

Heat transfer

- Molybdenum heat exchanger
- High temperature helium loop

A molybdenum-based heat exchanger will be included in the blanket loop to demonstrate heat extraction from 1000°C LiPb, with the development of a high temperature helium loop in a closed Brayton cycle. A second 500°C heat exchanger made of SS316 will be installed downstream of the high temperature heat exchanger to demonstrate power generation via an air Brayton cycle using industrial steam turbine technology. This will be a world-first demonstration of electricity generation from a high-temperature, fusion-relevant liquid metal loop.

Process heat utilization

High-temperature heat recovery enables exploration of auxiliary applications, such as carbon capture and hydrogen production through biomass pyrolysis.

KF is developing biomass technologies using a lab-scale microwave heating system at Kyoto University to investigate carbon capture and hydrogen production from bamboo and cellulose. Data collected will inform the design of biomass systems for integration into fusion thermal cycles, and UNITY-1 offers an opportunity to demonstrate these biomass technologies in the future.

Hydrogen isotope extraction

- Vacuum Sieve Tray: height 3.3 m x diameter 0.5 m
- Flow rate: 5-20 L/min

Tritium extraction from a breeder is a requirement for D-T fusion concepts. UNITY-1 will demonstrate the extraction of deuterium injected into the LiPb coolant as a proxy for tritium. One technology that will be tested is the Vacuum Sieve Tray (VST), which will extract deuterium from falling LiPb droplets under vacuum. The VST has 3 stages that will process 5-20 L/min of LiPb at 500°C. The VST testing program will provide valuable information related to extraction efficiencies and rates, vacuum pumping requirements, and optimal sieve tray design, with considerations of scalability to an FPP.
Testing with tritium will be performed in UNITY-2 (see 2.4).

Diagnostics

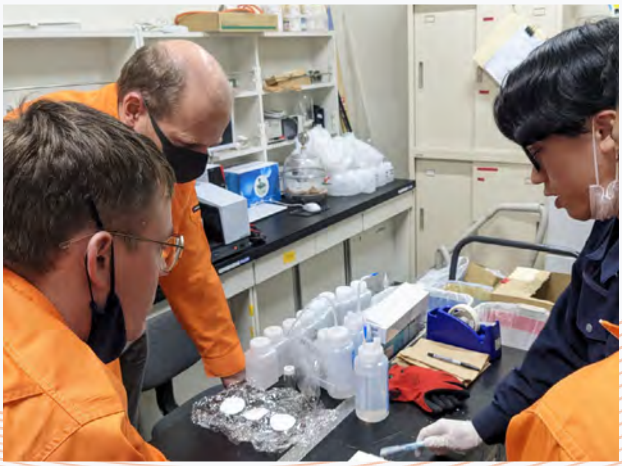
KF's diagnostic technologies will be included in the LiPb loop such as the ceramic hydrogen sensor for analysis of hydrogen concentrations in LiPb, pressure indicators made of molybdenum and silicon carbide for indirect pressure measurements at high temperature, temperature measurement technologies for piping and components, and continuous measurements of LiPb using level indicators.

2.3.3 Safety Engineering

UNITY-1 is a demonstration facility consisting of numerous process systems, and differences in the design condition of each system and its interfaces may contain potential hazards to personnel, assets, and the environment.

KF focuses on a fundamental risk management approach for the process plant, i.e., Hazard Identification and Risk Assessment.
As the project progressed from the conceptual design to the construction and operation phases, we performed the following activities referring to the common methodologies for nuclear fission and process industries to ensure safety in design and operation.

- HAZID based on PFDs to identify generic hazards.
- HAZOP based on P&ID to identify the facility and process specific hazards for all operating modes.
- Layer of Protection Analysis (LOPA) to identify the needs of protection layers, such as Safety Instrumented System (SIS) as an independent protection layer.
- Pre-commissioning procedure review to ensure all operations are performed with safety considerations.



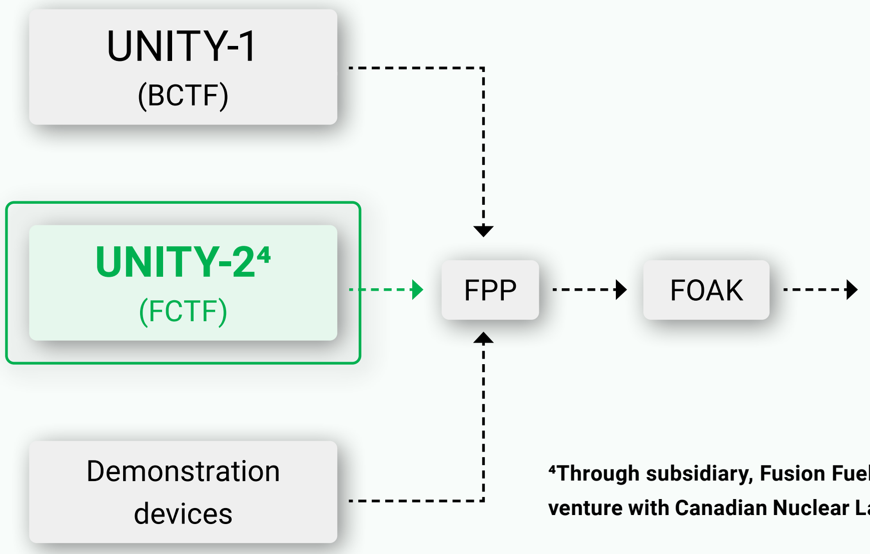
See Appendix B to learn more about KF's thermal cycle experts and to see a list of publications.

2.4 Unique Integrated Testing Facility 2 (UNITY-2): Integrated D-T Fuel Cycle User Facility

Directly supports criteria 6, 8-11, 13-17

2.4.1 Overview

UNITY-2 is a radiological fuel cycle test and user facility to be constructed in an existing tritium-licensed building at Chalk River Laboratories (CRL), a 9,100-acre nuclear site in Ontario, Canada in a 50:50 collaboration with Canadian Nuclear Laboratories (CNL). Full commissioning and operations are expected by mid-2026. As of this writing, initial testing of some of the components has already started in Japan, as visitors to Kyoto can see, in preparation for shipment and installation.



[4]Through subsidiary, Fusion Fuel Cycles Inc. (FFC), a joint venture with Canadian Nuclear Laboratories.

UNITY-2 directly supports key criteria for fusion plant development, addressing effective tritium handling and safety (criteria 6, 8-11). By minimizing tritium inventory and reducing processing times, UNITY-2 enhances the economic and operational feasibility of fusion power plants (criteria 13-17).

The facility's advanced diagnostics and simulation capabilities provide essential data for optimizing fuel cycle processes and ensuring regulatory compliance.

For fusion concepts using tritium as fuel, a sophisticated fuel cycle is essential. This cycle handles tritium safely while minimizing inventory and processing time, involving processes like pumping tritium into the plasma chamber, recycling unburnt tritium, recovering tritium from by-products, safely storing tritium, separating tritium from other hydrogen isotopes, and accurately accounting for all tritium used and produced. The goal is to maintain a secure tritium supply while minimizing potential risks to workers, the public, and the environment.

Few tritium-capable R&D facilities exist globally, leading to a significant gap in tritium research for fusion, hindering progress toward commercialization. A tritium fuel cycle facility is critical to advance necessary systems and demonstrate their feasibility for future larger-scale systems. Such a system must be capable of operating continuously for 24 hours a day, 365 days a year, for decades, safely. Even if the initial FPP experiments were to be conducted in a pulse mode or, for inertial confinement devices, with repeated pulses, the tritium plant will still be required to detritiate continuously, to protect workers and the public from the release of tritium. Similarly, even while plasma performance is low and fusion reactions are sparse, the device must be fueled, and the unburnt exhaust must be processed.

A continuously operating integrated tritium fuel cycle system, like the one at UNITY-2, needs to be tested and verified prior to the initial operation of any FPP.

To fill this gap, KF is building a fully integrated tritium fuel cycle facility through a joint venture with CNL, Fusion Fuel Cycles Inc. (FFC). The test facility, UNITY-2, aims to achieve the following key objectives:

1 **Enabling Tritium Research and Closing of Technology Gaps**

By developing a facility capable of handling and processing tritium, UNITY-2 seeks to fill the existing research gap by providing a platform for the development, testing and demonstration of mid-TRL technologies within the tritium fuel cycle, to advance them to the point that they are ready for use in an FPP.

2 **Advancing Tritium Safety**

The facility will contribute to the development of tritium management practices and establish comprehensive tritium accountancy systems specific to D-T fusion fuel cycle systems. UNITY-2 is undergoing thorough risk analyses and environmental impact assessments to ensure regulatory compliance and provide safety engineering blueprints for future fusion plants.

The conceptual design phase of UNITY-2 was completed at the beginning of 2024 and the detailed design phase will be completed in 2025, with the procurement of key components and systems beginning soon thereafter. Testing of some of the key components such as tritium compatible vacuum pumps has already started. Integration of these systems at CRL and commissioning of the facility is expected in 2026.

KEY FINDING

The advanced design of the integrated fuel cycle system in UNITY-2 is crucial for fusion demonstration and pilot plants, particularly those using tritium. Fusion development programs should leverage the extensive work done on UNITY-2 to enhance their own fuel cycle systems, expediting their journey towards commercialization.

To learn how you can adapt the UNITY-2 design, please contact KF's subsidiary, FFC at info@ffc.inc.

UNITY for the Community

UNITY-2 as an International User Facility

Flexible | Well-Diagnosed | Digital Twin | Workforce Development

UNITY-2 will be accessible to private, public, and academic partners for testing and demonstrating their technologies in an FPP-relevant environment. Operating with tritium, UNITY-2 provides opportunities to test in a prototypic fusion fuel cycle environment.

Potential use cases

- Tritium permeation analysis, tritium uptake for components
- Testing the fusion fuel cycle for various D-T operational scenarios, including re-evaluation of integrated systems to ensure reliability and safety
- Evaluation of material corrosion in tritiated LiPb
- Demonstration of tritium extraction technologies
- Alternative fueling, such as pellet injector, and Direct Internal Recycling (DIR) technology
- Alternative pumping technologies
- Alternative fuel cleanup systems, such as PERMCAT
- Alternative isotope separation such as Thermal Cycling Absorption Process (TCAP)
- Testing of tritium tracking and accountancy technologies
- Instrumentation and software
- Operational scenario testing for private fusion companies

Well-Diagnosed

UNITY-2 will feature advanced diagnostic tools and instrumentation, enabling precise monitoring and analysis of tritium handling and processing. Techniques such as Raman spectroscopy, quadrupole mass spectrometry (QMS), and gas chromatography (GC) will be utilized for gas concentration analysis and tritium accountancy.

Digital Twin Vision

A comprehensive process simulation of the entire UNITY-2 system will be developed, allowing users to simulate tritium processes, optimize experimental setups, and predict outcomes with high accuracy before physical implementation. A particularly important need is for real time tritium inventory and distribution monitoring. Currently, no practically accurate evaluation of the tritium inventory and its control is available for a continuously running systems. Benchmarking a digital twin to evaluate its accuracy is important for fusion fuel cycle operation.

Workforce Development

UNITY-2 will play a crucial role in training and educating the next generation of fusion scientists and engineers. The facility will provide hands-on experience in tritium handling and fuel cycle technologies, fostering the development of a skilled workforce ready to tackle the challenges of commercial fusion energy. Internationally applicable safe tritium handling procedures will be developed for training purposes for FPPs and initial D-T experiments.

For more information on UNITY-2, to arrange a tour of the facility, or to register to use the facility, please contact KF's subsidiary, FFC at info@ffc.inc.

2.4.2 Facility Attributes

UNITY-2 is designed to be a state-of-the-art tritium fuel cycle facility, essential for developing and demonstrating the critical processes involved in managing tritium fuel in fusion power plants. This section outlines the key parameters and capabilities of UNITY-2, showcasing its role in advancing tritium handling technologies.

Fueling and Pumping

- Fueling flow rate: 2.6 Pa·m³/s
- Vacuum pumping: < 1 Pa
- Tritium compatible

UNITY-2 is equipped with a vacuum vessel, acting as a fusion device, where vacuum conditions (<1 Pa) will be achieved using a tritium compatible exhaust pumping system that includes high vacuum pumps along with KF's reciprocating pumps for rough pumping. A steady-state fueling rate of 2.6 Pa·m³/s of D-T gas will be supplied to the vessel and continuous operation of the UNITY-2 system will be demonstrated.

Storage and Rebalancing

- Storage capacity (Depleted Uranium (dU)/ZrCo): 30 g of tritium
- DT, D_2, T_2 buffer tanks

Hydrogen isotope storage systems must be able to safely and reliably provide and store tritium when required in order to maintain steady-state conditions within the fuel cycle. It also must provide sufficient storage in case of emergency procedures. UNITY-2 contains two types of storage beds: metal hydride beds, and depleted uranium beds which will have a combined capacity that exceeds the UNITY-2 tritium limit of 30 g. Rebalancing of D and T will be facilitated by buffer tanks and careful control of flow rates into the vacuum vessel.

Parameter	Value
Footprint	**15 m x 15 m**
Tritium inventory	**< 30 g[5]**
Tritium release limit	**< 1.9 x 10^{11} Bq/year**
Fueling rate	**> 2.6 Pa·m³/s**
Breeder	**LiPb**
Breeder inventory	**50 L**

Table 5: UNITY-2 Main Facility Parameters

[5]Building license allows for 100 g of tritium; current UNITY-2 design uses <30g.

Inner Cycle

- Impurity gas: CQ_4, NQ_3, He, Q_2O vapor, noble gases
- Q_2 separation: ~99%

Hydrogen isotopes that are not removed by DIR along with the other exhaust gases are processed in the inner cycle. While the actual exhaust gas composition of a fusion device is not known precisely and will be strongly device dependent, UNITY-2 takes a conservative approach by including a range of predicted impurity gases including CQ_4, NQ_3, Q_2O vapor, He, Ar, and Xe so that all potential requirements for exhaust gas processing can be demonstrated. As the composition of gases in the exhaust stream will vary between steady-state and transient operational conditions, the inner cycle is designed to process the stream under both scenarios. The inner cycle separates the majority of the remaining hydrogen isotopes from the exhaust gas and sends them to the refueling system or for isotope separation, while converting the tritiated gases (CQ_4, NQ_3) into Q_2. The remaining exhaust gases are sent to the outer cycle for further processing.

DIR/Pellet Injection

- DIR: 80% reduction in flow to outer cycle
- Pellet injection rate: steady state 1.4 Pa·m³/s; maximum 15 Pa·m³/s

UNITY-2 includes a DIR system that is designed to extract hydrogen isotopes directly from the vacuum vessel's exhaust gas stream and divert them straight back to the fueling system. The system will separate up to 80% of hydrogen isotopes and send the remaining 20% through the fuel cycle for processing along with the other exhaust gases. DIR technology will reduce the tritium inventory of the fuel cycle, reduce tritium processing times, and minimize the overall size and complexity of fuel cycle systems. The recovered isotopes will be sent directly to the Pellet Injection System (PIS), a refueling technique that propels pellets at high-speed into the plasma to breach the confinement barrier and achieve plasma penetration. This PIS of UNITY-2 is designed to maintain a steady-state fueling rate of 1.4 Pa·m³/s, with the potential to demonstrate peak rates up to 15 Pa·m³/s.

Outer Cycle

- Isotope Separation System (ISS) efficiency: 80-99% depending on requirements
- Water Detritiation System (WDS) detritiation factor: ~200,000
- Air Detritiation System (ADS) tritium release: < 1.9 x 1011 Bq/year (5 Ci/year)

The outer cycle recycles any tritium that could not be retrieved by DIR and the inner cycle, as well as tritium that escapes from process equipment into the secondary confinement systems that are used throughout the facility. It consists of three main sub-systems: ADS, WDS, and ISS. The ADS receives tritiated gas streams and converts them to tritiated water. The water is then sent to the WDS. Subsequently, the tritiated water is concentrated in the WDS and turned into a gaseous mixture of H, D and T before being sent to the ISS where purified streams of D_2 and T_2 are returned to the refueling system and H_2 is vented. The efficiency of ISS purification can be altered depending on requirements. The outer cycle is the only part of the fuel cycle that vents gas to the environment, and this will be strictly monitored and controlled to keep tritium release rates below 5 Ci/year.

LiPb Loop and Tritium Extraction

- SS316 loop, 50 L, 300-500°C, 400 kPa
- Test cell section for online tritium measurements in LiPb

UNITY-2 contains a LiPb loop that will be used for the first demonstration of tritium extraction from a breeder. The tritium extraction technology implemented in the loop is the VST as adopted in UNITY-1. The loop also has a test section for KF's tritium accountability technologies such as Q_2 sensors and online sampling points for LiPb analysis.

Diagnostics

In all areas of UNITY-2, tritium concentrations will be monitored for accountancy and to ensure safe operation of the facility. Raman spectroscopy is a technique that allows for continuous, online analysis of gaseous mixtures of H, D, and T. KF is developing this technology for fuel cycle applications and will be demonstrated in UNITY-2. Other techniques such as QMS and GC will be used throughout UNITY-2 for gas concentration analysis.

2.4.3 Safety Engineering

UNITY-2 falls under the licensing process of CNSC. Compliance with Canadian regulations and development of the engineering design with safety considerations are important objectives of the project.

KF performed a conceptual hazard assessment to identify coarse hazards in the UNITY-2 facility. As the project progresses, the following activities are planned to ensure the safety in design and licensing basis for the facility:

- P&ID review for each system from safety and operability perspectives.
- Detailed HAZOP based on the mature design.
- 3D model review to ensure safe access, operation, and maintenance.

See Appendix B to learn more about KF's fuel cycle experts and to see a list of publications.

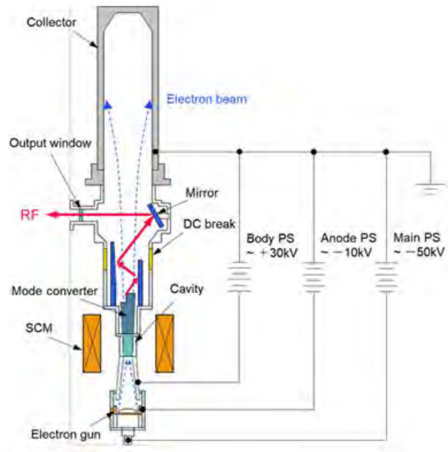
03

KF’s Pilot Plant Technologies

CONTENTS

KF is at the forefront of developing cutting-edge technologies essential for the successful operation of an FPP. These technologies are designed to meet the stringent requirements of fusion energy systems, focusing on efficiency, reliability, and safety. We provide an overview of KF's technologies, highlighting their critical roles and contributions to fusion power generation.

3.1 KF's Electron Cyclotron Heating Technology



ECH is a type of plasma heating method that uses a phenomenon called electron cyclotron resonance and is essential for a wide range of operational phases in fusion reactors: from pre- ionization, plasma ignition, the production of high-temperature plasma required for fusion reactors, and to the suppression of plasma instabilities by non-inductive current drive called electron cyclotron current drive (ECCD). ECH is made possible by a MW-class electromagnetic wave source device called a gyrotron.

KF's Electromagnetic (EM) Team designs the gyrotron and its ancillary systems, including the superconducting magnet system and high-voltage power supplies, with core components provided by Japan's leading manufacturers in this field, such as Canon Electron Tubes & Devices.
The specifications of KF's gyrotron and its auxiliary systems are listed below (digital catalogue here):
KF has the capabilities to design a gyrotron system over a wide parameter space for multiple requirements.

These can be split into the following classes of gyrotrons:

- **1 MW, 28/35 GHz dual frequency gyrotron.** This is based on the design developed at the University of Tsukuba [7]. The world's first MW-power several-second operation at low frequency range has been achieved during testing.
- **1 MW, 104 - 203 GHz range gyrotron.** This is based on the design developed at National Institutes of Quantum Science and Technology (QST) for ITER [6]. The frequency can be selected from a range of 104 - 203 GHz. Multiple (2 or 3) frequency oscillation is also possible by parameter control depending on the combination of frequencies and modes. *Note: A 1 MW oscillation at 236 GHz with the same class of gyrotron is scheduled for testing.*

Product Index	
Output power	**1 MW**
Frequency	**selectable from 28 – 203 GHz. Multi-frequency gyrotrons can be designed**
Pulse width	**from millisecond-order pulse to continuous wave operation (depending on the oscillation frequency)**
Efficiency	**over 50%, from input power to output millimeter wave**
HE_{11} Mode purity	**over 90% at MOU output**

KF's gyrotrons can be utilized as a millimeter-wave source not only for fusion devices but also in other industrial applications. Ultradeep geological boring is one example. As a high-power millimeter-wave source, our gyrotron can contribute to efficient geothermal energy extraction, where conventional drilling technologies may not be applicable.

See Appendix A to learn more about KF's ECH experts and to see a list of publications.

3.2 Thermal Cycle Technologies

KF's thermal cycle technologies are designed to optimize the process of converting the energy produced by the fusion reaction to generate electricity. With our technology, the thermal cycle system can be ensured for high efficiency and reliability.

Table 6: Thermal Cycle Subsystems and Technology

Subsystem	Technology	Description
Base loop	Heat Exchanger (500°C)	Facilitates the transfer of heat from the coolant to a working fluid, crucial for maintaining optimal operating temperatures. KF Contribution: • Technology is available from KF • Demonstration in UNITY-1
	Vacuum Sieve Tray	Utilized for hydrogen isotope extraction from the coolant, enhancing fuel recycling efficiency. KF Contribution: • Technology is under development at KF with testing ongoing at KRC. Computational models of the VST are also being developed to inform the VST design for TEE optimization and VST scalability. See section 2.3.2 for more details. • Demonstration in UNITY-1 and UNITY-2
	Cold Trap	Cools and condenses impurities from the coolant, maintaining the purity and effectiveness of the cooling system. KF Contribution: • Technology is available from KF • Demonstration in UNITY-1 and UNITY-2
	Electromagnetic Pump (EMP)	Ensures the circulation of the liquid metal coolant, vital for maintaining consistent thermal performance. KF Contribution: • Technology is available from KF • Demonstration in UNITY-1 and UNITY-2
	Induction Heater (500°C)	Provides precise heating control to simulate fusion reaction chamber conditions for testing and development purposes. KF Contribution: • Technology is available from KF • Demonstration in UNITY-1

Subsystem	Technology	Description
Blanket loop	Blanket Module	Captures high-energy neutrons and contributes to tritium breeding, integrating thermal and fuel cycle systems. KF Contribution: • KF is deeply involved in the development of blanket technologies. See section 2.3.1 for details on KF's blanket activities • Demonstration in UNITY-1
	Heat Exchanger (1000°C)	Transfers high-temperature heat to a secondary working fluid, enhancing overall thermal efficiency. KF Contribution: • A molybdenum-based heat exchanger is under development at KF, along with computational models to increase heat exchange efficiency by design optimization. See section 2.3.2 for details. • Demonstration in UNITY-1
	Superconducting Magnet	Provides the necessary magnetic field for plasma confinement and control within the blanket module. KF Contribution: • Technology is available from KF • Demonstration in UNITY-1
	Induction Heater (1000°C)	Simulates operational conditions for testing high-temperature components. KF Contribution: • Technology is available from KF • Demonstration in UNITY-1
Power generation	Heat Exchanger (He/H_2O)	Facilitates the transfer of heat from helium to water, driving turbines for electricity generation. KF Contribution: • Technology is available from KF • Demonstration in UNITY-1
	High-Temperature Helium Closed Brayton Cycle	Utilizes helium as a working fluid in a high-efficiency power cycle, optimizing energy conversion. KF Contribution: • Technology is available from KF • Demonstration in UNITY-1

3.3 Fuel Cycle Technologies

The fuel cycle system manages the supply, injection, recycling, and processing of fusion fuel.

Our fuel cycle technologies are designed to ensure the efficient and safe use and management of fusion fuels, particularly the isotopes deuterium and tritium.

Table 7: Fuel Cycle Subsystems and Technology

Subsystem	Technology	Description
Direct Internal Recycling	Metal Foil Pump	A pump that utilizes superpermeation of hydrogen isotopes through a thin metal foil to separate isotopes from impurity gases. The MFP will be key to DIR systems and reducing tritium processing times and inventory. KF Contribution [12]: • Under development at KF • Demonstration in UNITY-2
	Proton Conductor Pump	A pump that electrochemically transports hydrogen isotopes across a conductive membrane for separation of isotopes from impurity gases. The PCP will be integral to the DIR system of the fuel cycle for an FPP. KF Contribution [13]: • Under development at KF • Demonstration in UNITY-2
Pumping	Metal Diffusion Pump	A high-vacuum pump that uses vaporized fluid to transfer gas molecules from high to low pressure areas through diffusion processes. KF Contribution [14]: • Under development at KF • Demonstration in UNITY-2
	Cryogenic pump	A type of sump vacuum pump. By installing a cryogenic surface in the vacuum vessel, residual gases are condensed and trapped on the surface. KF Contribution: • Technology is available from KF
	Turbo Molecular Pump {TMP (*pump*)}	A high-speed rotating pump that efficiently removes gas molecules by mechanical collision, suitable for achieving ultra-high vacuum levels. KF Contribution: • Under development at KF • Demonstration in UNITY-2
	Roughing Pump	A preliminary vacuum pump that removes bulk gases at lower pressures, preparing a system for fine vacuum pumps to achieve higher vacuums. KF Contribution [15]: • Developed at KF with a range of pumps available, please see the KFRP catalogue for details. • Demonstration in UNITY-2
	Metal bellows Pump	A vacuum pump that utilizes a flexible metal bellow to compress and transfer gases, providing a leak-tight seal for consistent and reliable operation. KF Contribution: • Technology is available from KF • Demonstration in UNITY-2

Subsystem	Technology	Description
Tritium Storage	ZrCo-based	Advanced ZrCo alloys are used for absorbing and storing tritium. This material forms stable hydrides with hydrogen isotopes and has desirable desorption characteristics. KF Contribution [16]: • Under development at KF • Demonstration in UNITY-2
	Depleted uranium	Uranium with a lower content of fissile isotopes is used for tritium storage due to its ability to form stable hydrides with hydrogen isotopes. KF Contribution: • Technology is available from KF
	Transport containers	Specialized containers designed to ensure the safe and secure transport of tritium gas, complying with regulatory standards. KF Contribution: • Under development at KF
Separation	Pd Diffuser	Separates hydrogen isotopes from impurity gases via selective isotope diffusion through a Pd/Ag membrane, reducing the required size of the fuel clean up system. KF Contribution [17]: • Under development at KF • Demonstration in UNITY-2
	Cryogenic Distillation	A technique that separates hydrogen isotopes at extremely low temperatures by exploiting their difference in boiling points, providing purified streams of D and T for the refueling systems KF Contribution: • Technology is available from KF • Demonstration in UNITY-2
	Thermal Diffusion	Separates hydrogen isotopes based on their different rates of diffusion in a temperature gradient. KF Contribution: • Under development at KF
Fuel Clean Up	Nickel bed	A high temperature reactor that cracks methane gas into hydrogen over a nickel catalyst bed. KF Contribution: • Technology is available from KF • Demonstration in UNITY-2
	Catalytic Reactor	A reactor that oxidizes tritiated gases within the exhaust gas stream to tritiated water while producing tritium-free gases that can be vented. KF Contribution: • Under development at KF • Demonstration in UNITY-2
	Molecular Sieve	A porous material that selectively adsorbs tritiated water from the exhaust gas stream. KF Contribution: • Technology is available from KF • Demonstration in UNITY-2

Subsystem	Technology	Description
Fuel Clean Up	Electrolysis Cell	The cell electrochemically splits tritiated water and generates separated streams of hydrogen isotopes and oxygen. KF Contribution [18]: • Under development at KF • Demonstration in UNITY-2
Outer Cycle	ADS	A system that converts tritiated gases into tritiated water, and vents tritium-free gases to the atmosphere. KF Contribution: • Technology is available from KF • Demonstration in UNITY-2
	WDS	A system designed to remove tritium from tritiated water via electrolytic and catalytic processes. KF Contribution: • Technology is available from KF • Demonstration in UNITY-2
Tritium Extraction	Vacuum Sieve Tray	KF's innovative VST is designed for efficient hydrogen isotope extraction from LiPb coolant. By optimizing extraction, it will ensure maximum utilization of fusion fuel by reducing processing times and operational costs. KF Contribution: • Technology is under development at KF with testing ongoing at KRC. Computational models of the VST are also being developed to inform the VST design for TEE optimization and VST scalability. See section 2.3.2 for more details. • Demonstration in UNITY-1 and UNITY-2
	Electrochemical extraction	Techniques for extracting tritium from FLiBe and liquid Li coolants via electrochemical methods. KF Contribution [19]: • Under development at KF
Analysis Instrumentation	Hydrogen (Q_2) sensor	A sensor to measure tritium concentrations in coolant via an electrochemical process using proton conductor technology. KF Contribution: • Under development at KF • Demonstration in UNITY-1 and UNITY-2

Subsystem	Technology	Description
Analysis Instrumentation	Raman Spectroscopy	A light scattering technique that allows for online, continuous analysis of hydrogen isotope concentrations in a gas stream facilitating online tritium accountancy. KF Contribution: • Under development at KF • Demonstration in UNITY-2
	Gas Chromatography	A technique where gases are separated based on their interaction with a stationary column and concentrations are analysed at the column outlet. KF Contribution: • Technology is available from KF • Demonstration in UNITY-2
	Ionization Chamber	A device that measures ionizing radiation to detect tritium concentrations KF Contribution: • Technology is available from KF • Demonstration in UNITY-2
	QMS	A sensitive mass spectrometer that can distinguish between and measure the concentration of hydrogen isotopologues. KF Contribution: • Technology is available from KF • Demonstration in UNITY-2

By leveraging these advanced technologies, KF is not only pushing the boundaries of what is possible in fusion energy but also preparing our systems are ready to meet the demands of a commercially viable FPP.

For more details about KF's technologies, please contact us at www.kyotofusioneering.com/en/contact.

04

Science & Technology Challenges

The following section explores some of the key hurdles to develop an FPP and the potential pathways being pursued to accelerate fusion technologies towards commercialization.

CONTENTS

4.1 Advanced Materials

Achieving commercially viable fusion power plants hinges on conquering an array of extreme material challenges. The extreme temperatures, high radiation environments, and thermal stress arising from continuous operation of the systems push the limits to what materials can withstand. Fusion's extreme conditions represent conditions no material have been qualified for. In this section, we unpack these specific conditions and the cutting-edge innovations that our team proposes to bring fusion material research to new heights.

Problem 1 Extreme environments

High-energy neutron collisions with structural materials cause microstructural changes, leading to degradation of physical and mechanical properties. Neutron irradiation-induced damage primarily involves two mechanisms:

1. **Collision displacement**, where atoms are knocked off their lattice sites, creating material defects.
2. **Transmutation reactions**, where neutron absorption changes the material composition and produces helium and hydrogen gases trapped within components.

These effects, compounded by environmental factors like temperature and mechanical stress, can trigger various degradation mechanisms in materials such as radiation hardening, embrittlement, volumetric swelling, irradiation creep, phase instabilities, and helium embrittlement. Such mechanisms limit the operating range, lifetime, and chemical composition of materials used in fusion devices.

Fusion machines operate at extremely high temperatures, with the plasma core reaching millions of degrees Celsius. While structural materials are not exposed to these extremes, they face significant thermal loads that can lead to degradation. Thermal stress and fatigue may be induced by high temperatures and repeated heating and cooling, leading to microcracks and structural degradation. Varying coefficients of thermal expansion among adjacent materials can cause interface stresses and mechanical failure. Creep, or slow deformation under constant stress, is a critical concern at high temperatures, affecting the integrity of components over time.

Reactive coolants can cause substantial corrosion of structural materials, necessitating the use of protective coatings or alloying strategies. Additionally, plasma-wall interactions lead to sputtering, which degrades the material and contaminates the plasma. Hydrogen isotopes like tritium and deuterium permeate materials, causing hydrogen embrittlement and making them brittle. The high-temperature environment further accelerates corrosion, exacerbating these effects and posing significant challenges to the integrity of reactor components.

Solution 1: Degradation resistant materials

The development of materials that can withstand the extreme and unique environment of an FPP is ongoing within the fusion community. KF works hands-on in materials development with efforts currently being focused on two sets of materials:

Silicon Carbide Composites

Silicon carbide fiber-reinforced silicon carbide (SiC_f/SiC) composite is a promising candidate material, particularly for applications in the blanket and high-temperature coolant piping systems. This ceramic material offers relatively high thermal conductivity, low neutron activation, resistance to radiation damage, and high strength at high temperatures. Furthermore, its improved resistance to crack propagation relative to monolithic silicon carbide makes it well-suited for long-term application in the dynamic mechanical loads present in fusion environments.

Mock-up SiC_f/SiC “blanket module”

SiC_f/SiC plate-type heat exchanger

The development of SiC_f/SiC composites faces several challenges, including creating reliable and durable joining techniques and managing thermal stresses from repeated thermal cycling. Additionally, ensuring compatibility with reactive coolants like liquid metals and overcoming the material’s brittleness under extreme conditions are significant issues.

KF is developing a proprietary fusion-grade SiC_f/SiC, engineered and adapted to meet the demands and specifications of an FPP, collaborating closely with industrial partners and academic institutes to develop advanced manufacturing methodologies. Our collaborations encompass research into optimized prepreg formulations, innovative joining technologies, and weaving silicon carbide fiber. Additionally, efforts are being made to scale these innovations, ensuring they align with the specifications of future fusion power plants.

Molybdenum Alloys

Molybdenum (Mo) and its alloys possess desirable thermal properties that make them an attractive choice for a heat exchanger in an FPP. Their high melting points provide a significant safety margin to avoid thermal creep at operations around 1000°C, and they are compatible with LiPb coolants at high temperatures, potentially eliminating the need for costly and complex anti-corrosion coatings. With high thermal conductivities along multiple crystallographic planes, Mo alloys are efficient in heat transfer. Moreover, their low thermal expansion coefficients at high temperature reduce stresses which can lead to deformation or cracking within the heat exchanger.

On the other hand, the characteristics that makes Mo alloys an attractive option for heat exchanger also marks them with distinct manufacturing challenges. Namely, the high melting point of Mo alloys necessitates specialized techniques for joining them in a manner that maintains gas hermeticity and avoids recrystallization. Collaborating closely with manufacturers, KF is developing advanced methods for joining Mo alloys and for ensuring their adaptability to the geometries and specifications demanded by thermal cycle heat exchangers.

Alongside the projects related to SiC_f/SiC and Mo alloys, KF is also working on the development of vanadium alloys in conjunction with the National Institute of Fusion Science (NIFS) in Japan. This work aims to demonstrate the feasibility of a blanket module made from a low-activation vanadium alloy that is of fusion grade with low impurities such as oxygen.

Corrosion of Mo alloy samples in LiPb

Problem 2 Replicating fusion neutrons

One of the significant challenges in the development of fusion energy is the difficulty in replicating the neutrons within a fusion device for materials testing. Fusion reactors produce neutrons with an average energy of 14.06 MeV, which is substantially higher than the 1-2 MeV neutron energies typical of current Gen IV fission reactor concepts [20]. Although these advanced fission reactors may encounter similar levels of collision displacement damage (measured in displacement per atom, or dpa) and operate within comparable temperature ranges [21], neutron irradiation damage will be higher in fusion due to the higher energy neutrons. These neutrons will lead to higher rates of transmuted helium production—up to 100 times higher for a given irradiation displacement dose [20]. Although progress has been made, using fission test reactors, computational modeling, and ion beams, to explore material suitability for fusion environments, more pragmatic testing facilities are required.

Solution 2: Development of irradiation facilities

The establishment of research facilities relevant to FPP conditions are imperative for testing, validation, and qualification of fusion materials. This requires the development of a Fusion Prototypic Neutron Source (FPNS) with sufficient neutron intensity and irradiation volume to be able to replicate fusion neutrons in an FPP. A comprehensive database of test data for fusion materials is necessary to investigate material feasibility, provide data for licensing and safety assessments, and to instruct the design and construction of future FPPs.

The development of facilities such as the International Fusion Materials Irradiation Facility – Demo Oriented Neutron Source (IFMIF-DONES) in Spain [22] and the Advanced Fusion Neutron Source (A-FNS) in Japan [23] will enable more relevant conditions for fusion material testing. KF is currently not directly involved in this space and is observing the development of FPNS facilities with great interest.

Problem 3 Material activation

Activation occurs when materials within a fusion machine become radioactive due to exposure to the intense neutron flux generated by fusion reactions. When high-energy neutrons interact with structural materials, they may induce nuclear reactions that transmute nuclei into different isotopes, some of which are radioactive. Material activation is problematic as it generates radioactive waste, presenting challenges for waste management and decommissioning of fusion plants. The presence of radioactive materials necessitates handling, treatment, and storage solutions to protect public health and the environment, and the safety risks associated with managing radioactive substances impose regulatory requirements.

Solution 3: Low activation materials

To minimize the number of long-lived radioactive isotopes and the associated waste disposal burden and safety considerations, several materials have been developed specifically for fusion applications using certain favorable elements in place of problematic ones. However, these so-called "reduced-activation" materials minimize the production of long-lived radioisotopes when subjected to fusion neutrons [24].

Reduced-activation ferritic/martensitic (RAFM) steels are the most technologically mature class of fusion structural materials that have been demonstrated to be functional after high irradiation dose exposure. However, these are limited to relatively low operating temperatures of ~550°C which reduces the thermal efficiency that can be achieved and therefore the economic attractiveness. A more advanced variety of RAFM steels utilizing oxide dispersion-strengthening (ODS) have a potentially higher operating temperature limit (up to ~800°C) [25], but suitable manufacturing and joining methods remain as gaps [26]. Other advanced fusion materials, such as vanadium alloys and fusion-grade SiC_f/SiC, also show promise for high-temperature operation under high irradiation conditions, up to 750°C and 1000°C respectively, but remain at somewhat lower technology maturity levels. KF is not currently involved in RAFM steel but has direct links to the material supply chain.

Problem 4 Material compatibility

Compatibility issues between structural materials, components and coolants can induce degradation mechanisms such as corrosion, erosion, or embrittlement which can lead to failure.

Joining dissimilar materials also presents challenges, particularly if the properties of adjoining materials are significantly different. For example, dissimilar rates of thermal expansion between adjoining structural materials can lead to build up of strain and ultimately failure of joints.

Furthermore, uncertainties remain around the chemical stability of joints under the influence of synergistic effects of high temperatures, neutron irradiation and magnetic fields.

Solution 4: Material testing facilities

UNITY-1 and UNITY-2 provide testing grounds for material compatibility studies in conditions relevant to an FPP with a selection of studies provided below:

UNITY-1

The long-term durability of SiC_f/SiC piping within the LiPb coolant loop of UNITY-1 will be evaluated, with a focus on demonstrating the manufacture of complex geometries like the blanket module. The stability of joints between SiC_f/SiC piping, as well as its connections to other materials, will also be examined along with the effectiveness of coatings designed to reduce corrosion and prevent material degradation. This analysis will be particularly targeted at regions of the LiPb coolant loop where flow acceleration and perturbations occur, such as the blanket module and molybdenum heat exchanger. Furthermore, the temperature gradient between the hot leg (~1000°C) and cold leg (~500°C) offers a chance to examine material mass transfer, which is expected to lead to pipe thinning in the hot leg and blockage in the cold leg. UNITY-1 includes a dedicated test section where material samples can be evaluated under conditions relevant to an FPP.

UNITY-2

UNITY-2 will serve as a platform for analyzing material stability and compatibility in environments with tritium exposure. Tritium permeation through structural materials will be studied, particularly in high temperature components where permeation rates are expected to increase. Tritium incorporation into materials and the subsequent generation of solid waste will also be investigated, a key concern for waste management and decommissioning. Additionally, the solubility of tritium in LiPb will be analyzed under FPP relevant conditions, offering insights into the implications for permeation and material integration. Material compatibility studies with tritiated LiPb can be conducted in the test section of the LiPb loop.

KF’s relationship with both academia and industry means that it has access to a wide range of materials fabrication and testing techniques both on the laboratory scale and on the industrial scale. These include, but are not limited to:

- bulk sample mechanical testing (fatigue, tensile strength, fracture toughness)
- SiC fiber mechanical testing
- specimen preparation techniques (FIB, arc melting, milling, electric discharge machining)
- manufacturing and joining
- ion irradiation testing
- electron microscopy techniques (TEM, SEM, EPMA, AES)
- spectroscopic techniques (Raman, IR, EDS, GD-OES, SXES)
- diffraction techniques (XRD, HT-XRD)
- oxidation testing
- hydrogen permeation testing
- corrosion testing (liquid Li, LiPb, FLiBe; static and flowing loops)
- coating preparation (CVD, pack cementation)

4.2 Harnessing Fusion Power

In pursuit of harnessing fusion power, we must face a range of intricate technical hurdles. Central to these challenges is the development of resilient and efficient systems for converting the intense heat produced. Transitioning fusion from experiments to an economically-competitive energy source relies on striking a balance between operational costs and system performance. Solutions must not only withstand the extreme environments of a fusion reactor but do so in a manner that maximizes power output while minimizing expense over the plant lifetime. In this section, we examine our paths to realize plant solutions that are marked by both technical superiority and economic feasibility.

Problem 1 High heat flux and power density

Both the intensity (energy per neutron) and fluence (number of neutrons per unit area) of the neutron radiation from a D-T fusion device are unprecedented, exceeding conditions found in fission reactors. In addition to neutron-induced heating, the device walls also experience intense radiative and conductive heat flux, ranging from several MW/m^2 to tens of MW/m^2. This combination creates an immense energy flow rate through individual surfaces, resulting in highly concentrated thermal power within a small volume, or high-power density, and leads to elevated temperatures posing significant challenges.

Solution 1: First wall and blanket design

The first wall is the interior surface of a fusion device that directly faces the plasma. It must absorb heat generated in the fusion device and transfer the heat to the blanket where it is captured by coolant for use in the power generation systems. KF is developing first wall/blanket systems applicable to the various fusion device concepts and their associated thermal cycles, an example being the SCYLLA© blanket [11]. The SCYLLA© blanket is made from KF's proprietary fusion grade SiC_f/SiC with a tungsten or tungsten alloy first wall. It is expected to be capable of operating at high temperature and carries the potential for high thermal efficiency with respect to electricity conversion.

Problem 2 Heat capture and tritium breeding

In a D-T fusion device, the blanket must simultaneously serve two critical functions: breeding tritium to sustain the fuel cycle while capturing heat generated for power generation. These requirements, coupled with multiple other functions the blanket must provide, makes the blanket one of the most important components of an FPP.

The key to enabling both heat capture and breeding is the coolant technology. This coolant must transport intense heat away from the fusion reactor to power generation system while capturing high-energy neutron to facilitate reactions with lithium.

Selecting the ideal blanket and coolant technology is therefore paramount, as it underpins the overall efficiency of the power plant and the self-sustaining fuel cycle. Getting this choice right is pivotal for any FPPs.

Solution 2: Coolant technologies

There is ongoing research into various blanket systems within the fusion community, including liquid breeder, solid breeder, and pebble bed designs. Of the materials being researched, LiPb is a promising candidate to meet all the requirements for a blanket. Our self-cooling lithium-lead technology at UNITY-1 will serve as a breeder, neutron multiplier, tritium carrier, and coolant in an FPP. In addition, tritium extraction efficiencies will be analyzed using deuterium at UNITY-1 and tritium at UNITY-2. These test results will inform the required TBR to ensure fuel cycle sustainability for an FPP ahead of the demonstration of tritium breeding.
Moreover, KF has dedicated lab-scale loops for liquid Li and FLiBe coolants. These loops facilitate research into coolant purification and compatibility with materials, material corrosion under flowing conditions, corrosion product analysis, tritium extraction technologies, tritium accountability technologies, as well as tritium permeation studies. Testing programs using the coolant loops will inform the development of various blanket and coolant systems to improve heat capture and tritium breeding for different fusion device designs.

Parameter	FLiBe Loop	Pure Lithium Loop
Footprint	2.8 m x 3.0 m	2.1 m x 1.7 m
Pipe size	½ inch	½ inch
Heating power	6.1 kW	3.1 kW
Coolant	FLiBe (Li2[BeF4])	Li
Inventory	4 L (dump tank), 0.7 L (pipe volume)	7 L (dump tank), 0.7 L (pipe volume)
Temperature	500 – 650°C	600°C (max)
Flow rate	50 L/min	10 L/min
Design pressure	0.4 MPa (gauge)	0.4 MPa (gauge)
Materials	Inconel 600 (piping) SS304 and SS316 (pump)	9Cr-1Mo (pipes), SS430 (small pipes) SS316 and SS304 (other components)
Pump specification	Vertical centrifugal pump (modified water pump), 2.2 kW	EMP, 2.6 kVA
Impurity control	Vapour trap	Vapour trap

Table 8: FLiBe Loop and Pure Lithium Loop Parameters

Problem 3 Techno-economic considerations

The high-power densities and temperatures encountered in a fusion device present a paradoxical set of challenges and opportunities: higher power densities can translate into more compact designs, potentially reducing capital costs and making fusion energy more economically attractive, while also intensifying the heat exhaust challenge.

Similarly, elevated temperatures in the working fluids can lead to increased electric power conversion efficiency, enhancing the economic viability of fusion energy economics, but can also impose more stringent material requirements and add complexity to the heat capture and conversion processes.

Solution 3: UNITY-1

UNITY-1 is a case study to address this paradox of the efficiency of the thermal cycle and the cost of building, operating, and maintaining the system. Demonstration of the blanket loop at 1000℃ and the associated heat exchange and power generation will show the feasibility of high-temperature heat extraction, reducing the required capacity and cost of the thermal cycle. Collection of operational data will inform further improvements to blanket design.

UNITY-1's modularity offers significant advantages to fine-tune parts of the system for optimization. It enables seamless integration to persistently boost high-temperature heat extraction efficiencies. Furthermore, its modular nature provides a scalable pathway: as the requirements of FPP thermal cycle system increase, the cost of UNITY-1 can be scaled up in line with it.

4.3 Tritium as Fusion Fuel

Ensuring an adequate tritium fuel supply represents a critical prerequisite for the realization of D-T fusion power plants. With limited natural inventories and uncertainties surrounding future production, bridging the gap between available tritium and the fueling demands of commercial plants is a relevant challenge for the fusion community today.

Problem 1 Tritium supply

Tritium is rare in nature due to negligible production or accumulation on Earth, which, combined with its relatively short half-life of 12.3 years, results in a small natural global inventory of about 4 kg. The current global commercial tritium supply comes instead primarily as a byproduct from heavy water type fission reactors.

Besides being considered an economically prohibitive source for commercial fusion purposes [9], the total current inventory procured from fission reactors over decades is estimated to be as low as 30 kg and its future supply is uncertain [10].

A fusion pilot plant of 500 MW_{fus} output would consume up to 28 kg of tritium annually at full power, an amount nearly equivalent to the entire current commercial tritium inventory.

This highlights a significant mismatch between available supply and fusion consumption needs even for experimental or demonstration plants, underscoring one of the key feasibility challenges for commercial D-T fusion.

Solution 1: Tritium breeding and extraction

The leading solution to bridge the tritium supply gap is the in-situ breeding of tritium within the fusion plant. This can be achieved within the blanket by reacting Li with neutrons generated from the fusion reaction to form tritium. The TBR, defined as the ratio of tritium bred in the blanket to the rate of tritium burned in the plasma, must be greater than one by a margin sufficient to ensure the generation of enough tritium to meet consumption demands, account for losses, and provide enough for new fusion plant startup while maintaining reserve inventories. Despite the need for tritium for the majority of current fusion concepts, breeding of tritium within a blanket has not yet been demonstrated.

Tritium bred in the blanket must also be extracted from the coolant so that it can be recovered and used as fuel. For LiPb coolant, the VST can extract tritium under reduced pressure facilitated by the low solubility of tritium in LiPb. UNITY-1 will demonstrate the extraction of hydrogen isotopes from LiPb coolant under fusion plant conditions, while UNITY-2 will demonstrate the first extraction of tritium using VST technology developed within KF. For other coolants such as Li and FLiBe, tritium solubilities are higher and alternate methods of extraction are required such as electrochemical techniques and extraction via permeation of tritium through a membrane under vacuum. These techniques currently have low TRL levels and will initially be developed at our lab-scale coolant loops.

Problem 2 **Low tritium burn rate**

The use of tritium as a fuel is complicated by the fact that the burn fraction of the fuel in the plasma ranges from 1% to 30% depending on the plasma confinement method and fusion device [9], [11].

This means that a significant proportion of the fuel injected into the fusion device is unused, posing additional challenges to self-sustaining power plants.

Solution 2: Tritium recovery

Unburnt tritium must be recovered and recycled for it to be feasible as a fuel source, necessitating the development of technologies capable of recovering tritium from the exhaust stream of the fusion device. The role of the Fuel Clean Up System (FCUS) is to recover tritium from the exhaust gas and direct the extracted tritium back to the refueling systems to ensure a steady supply of fuel.
KF is developing a range of FCUS technologies such as the Pd diffuser which selectively separates Q_2 from impurity gases, catalytic reactors that contain Pt catalysts to oxidize tritium containing gases to tritiated water, technologies to remove water from exhaust gas streams such as molecular sieves, and electrochemical cells capable of splitting water into gas.
Combinations of such technologies provide a means to recover unburnt tritium as well as tritium that has integrated into impurity gases.

Proton Conductor Pump

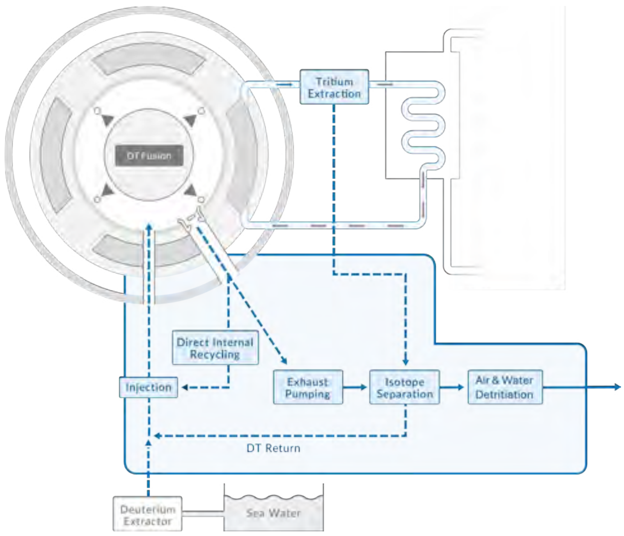
Palladium Diffuser

Problem 3 Minimizing tritium inventories

Minimizing the required tritium inventory in a fusion plant is essential due to tritium supply challenges, and safety and regulatory considerations [9], [10]. The processing time needed to extract and recover tritium has a substantial impact on the inventory required; longer processing times directly lead to larger tritium inventories.
Currently, the most advanced technologies for tritium purification and separation from the fusion device exhaust operate on a timescale of hours, while tritium extraction from the blanket may take several days depending on the concept and the removal efficiency of the mechanism of removal. The challenge of minimizing inventories is further exacerbated by the permeation of tritium through structural materials, leading to retention of tritium within the reactor structural materials and potential losses to the environment [9], [10].

Solution 3: Direct Internal Recycling

The DIR system directly extracts tritium from the exhaust of the fusion device and directs it back to the refueling systems, thus reducing the total tritium inventory of the fusion plant and the required capacity of the tritium recovery systems in the fuel cycle. A technology option for the DIR system is the proton conductor pump (PCP) which selectively pumps hydrogen isotopes across a solid-oxide proton conductor via electrochemical means to extract the isotopes. Another option for DIR is the metal foil pump (MFP) that is based on superpermeation where hydrogen atoms/ions generated by a plasma directly permeate through a specific metal membrane to separate hydrogen isotopes from the exhaust gas stream. These DIR technologies are currently at low TRL levels and will be implemented into UNITY-2 to advance their development and demonstrate DIR as a feasible system for an FPP fuel cycle.



Outlook

In this new era of fusion energy commercialization, KF stands at the forefront, not merely as a participant but as a catalyst and an enabler in the fusion sector.

The complexities and challenges of developing a fusion power plant are immense and require more than isolated efforts; they demand a concerted, collaborative approach leveraging advanced, specialized infrastructure and deep technical expertise.

KF's contribution through our engineering and technology development program, reinforced by the establishment of unique facilities, UNITY-1 and UNITY-2, and our open invitation for partnership, represent a critical nexus for these efforts.

We extend a strategic call to action to fusion developers, researchers, technologists, and innovators across the globe to engage with us. By utilizing our specialized facilities, you gain access to the forefront of fusion technology testing and development. For those developing plasma confinement systems, our UNITY-1 and UNITY-2 facilities offer unprecedented opportunities to test and refine technologies under real-world conditions, accelerating the path from experimental to operational.

We also invite academic institutions and research organizations to join us in pioneering studies that could shape the future of energy. Our facilities are designed not just for commercial testing but as hubs of learning and innovation. Here, theoretical knowledge meets practical application, offering a rich ground for doctoral research, scientific publications, and groundbreaking discoveries.

Moreover, KF is eager to collaborate on designing subsystems that integrate seamlessly with various fusion technologies, enhancing their efficiency and commercial viability. Our approach is holistic and integrative, ensuring that solutions developed are not only technologically sound but also economically and environmentally sustainable.

The fusion community is on the brink of a new energy era, and through collaboration, we can overcome technological hurdles more swiftly and effectively. Let's turn the potential of fusion energy into a reality, creating a sustainable, safe, and prosperous future for all. Through strategic partnerships, we not only accelerate our own advancements but also contribute to a robust, dynamic industry capable of meeting the world's growing energy needs sustainably.

Your engagement is essential; your expertise, invaluable. Together, let's define the future of energy. We look forward to embarking on this exciting journey together, pushing the boundaries of what is possible – resulting in a new epoch for humankind.

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KF's ECH Expertise

Keishi Sakamoto (CTO)

Keishi was formerly Director of Fusion Reactor Material Division at QST, Japan.

He has 40 years of experience and involvement in fusion technology development, with a primary focus on RF plasma heating and gyrotrons, serving as the Head of the RF Heating Technology group, at Japan Atomic Energy Agency (JAEA) from 2004 to 2015.

In addition to his core expertise on gyrotron technology, Keishi served as the Director of the Department of Fusion Reactor Material Research, and Project Manager of IFMIF/EVEDA Japan from 2016 to 2021, for the development of a fusion neutron source and fusion material development.

Shinichi Moriyama (Principal Engineer)

Shinichi has played a significant role in the field of plasma physics and nuclear fusion research for 40 years. At GAMMA10, he was involved in the measurement of high-energy particles, also serving as an operator for Neutral Beam Injection (NBI). His expertise was further showcased at JT-60U, where he contributed to the development and experimental operation of Ion Cyclotron and Electron Cyclotron Heating apparatus. Shinichi's skills were instrumental in the assembly, operational planning, and testing of the JT-60SA, and he is now a Principal Engineer at KF, overseeing our EM Technology Department.

Shigeyoshi Kinoshita (Principal Engineer)

Shigeyoshi's 45-year tenure in fusion energy research is marked by his significant contributions at Hitachi Ltd. And NIFS. Initially engaged in the control system studies and plasma experiments for magnetic confinement fusion energy devices at Hitachi's Energy Research Laboratory, he later took charge of designing fusion devices, accelerators, and superconducting coils at the Hitachi Works. Post-Hitachi, Shigeyoshi continued his work at NIFS, contributing to major fusion projects such as Kyushu University's TRIAM-1M, Kyoto University's Heliotron J, NIFS's Large Helical Device (LHD), and QST's JT60.

Kenichi Hayashi (VP, Head of EM Technology)

Kenichi developed gyrotrons at Toshiba Corporation and was the Head of Business Unit at Toshiba Electron Tubes & Devices (currently Canon Electron Tubes & Devices). He was also in charge of RF for the IFMIF accelerator at QST Rokkasho Lab. M.Sc. from Osaka University.

Yosuke Hirata (Head of EM Development)

Yosuke started his R&D career at Toshiba Corporation in the gyrotron division. He has been involved with the high-power mm-wave transmission development followed by various simulations and mechanics for nuclear power plants. He was also Involved in the IFMIF project at QST in developing the central control system. He is a visiting scientist at UC Davis and joined KF in 2021. M.Sc. from Kyoto University.

Yasuhisa Oda (Tech Advisor)

With a PhD from University of Tokyo, Yasuhisa participated in the CubeSat project while still a student. Participated in the ITER project at QST and worked on the gyrotron operation system design. Member of the Joint Special Team for DEMO Design at QST. Joined Kyoto Fusioneering in April 2021.

Tsuyoshi Imai (Tech Advisor)

Tsuyoshi led the Microwave Heating and Current Drive in JT-60, Head of RF Heating Lab. Developing ITER gyrotron at QST and served as a professor and director of Plasma Research Center in University of Tsukuba, and a director of the Japan Society of Plasma Science and Nuclear Fusion Research. Led the development of NIFS (77GHz and 154GHz) and university (28/35GHz) gyrotrons at the University. PhD from Osaka University.

Toru Tsujimura (Senior Researcher)

Toru researched high-beta confinement configuration heated by torus plasma merging via magnetic reconnection and neutral beam injection at the University of Tokyo. He worked on the Large Helical Device Project and was involved in the development of the electron cyclotron heating system and plasma heating research at NIFS. He is currently engaged in development work for gyrotron systems at Kyoto Fusioneering. PhD from Tokyo University.

Selected Publications from KF Experts on ECH Technologies

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KF's Thermal and Fuel Cycle Expertise

Satoshi Konishi (CEO, Chief Fusioneer)

Satoshi has 4 decades of fusion engineering experience and spent 22 years at JAERI (now JAEA in Japan), 5 years at LANL in the USA and 5 years leading the ITER TBM Project Steering Committee. After researching fusion plant components at the respective tritium laboratories, he was appointed as Professor at Kyoto University.

His research topics spanned various fusion plant components for fuel and thermal cycles. This included a program to develop a SCLL liquid metal blanket and many effects were analyzed regarding the liquid metal/wall interaction, MHD effects, pumping power and thermal analyses backed by experimental data taken in his group in specifically designed lithium-lead and pure Li loops. Now as co-founder, CEO, and Chief Fusioneer, he leads the technology division of Kyoto Fusioneering.

Christian Day (Senior Vice President)

Christian has PhD in Process Engineering from the University of Karlsruhe, Germany. He has spent nearly three decades at Karlsruhe Institute of Technology (KIT), Germany, working in all areas of tritium, fueling and vacuum technologies for ITER and other fusion devices. He developed the concept of Direct Internal Recycling to arrive at an attractive reactor scale fuel cycle architecture and was responsible for the EUROfusion fuel cycle program for 10 years prior to joining KF.

Colin Baus (Co-VP of Plant Technology)

Colin co-leads Kyoto Fusioneering's plant technology division. He received his PhD from the Karlsruhe Institute of Technology (KIT), Germany for his work at the Large Hadron Collider (CMS experiment at CERN) on heavy-ion cross sections and astroparticle physics. Having co-authored the simulation tool, CRMC, he carries deep knowledge in nuclear physics.

He is author of the high-temperature fusion blanket concept SCYLLA© and oversees the technical development of the UNITY-1 project for the fusion thermal cycle. As a visiting researcher at Kyoto University, he has worked with liquid metals and hydrogen addition and extraction from lithium-based coolant loops. He has also worked on numerous projects with UKAEA for breeding blankets and tritium systems.

Yoshifumi Kume (Co-VP of Plant Technology)

Yoshifumi specializes in fusion plant process engineering and supply chain management, and drives fusion fuel cycle and thermal cycle technology advancements at KF.

Formerly with Mitsubishi Corporation, he orchestrated investments and industry-academia partnerships in decarbonizing chemical technology across the European region in London office and led commodity physical and derivative trading in Singapore office.

Richard Pearson (Chief Innovator)

Richard is a co-founder of and serves as Chief Innovator at KF. He has an MSc in Nuclear Engineering, and a PhD in fusion engineering and innovation.

Richard has a broad knowledge of blanket technology with a specific focus on aspects associated with commercialization, from materials, safety and waste, to cost, resource availability, and manufacturing. He has been involved in developing KF’s single-cooled SiC_f-SiC lithium-lead blanket concept.

Keisuke Mukai (Principal Researcher)

Keisuke worked for academic fusion research for more than 10 years with >30 peer-reviewed publications. He studied crystal structure analysis and characterizations of high temperature chemical properties of non-stoichiometric breeder materials in his PhD thesis. He carried out neutron transport and activation simulations for the HCPB blanket at INR of KIT. He studied corrosion of EUROFER RAFM steel by breeder materials at IAM-KWT of KIT. As an Assistant Professor at Kyoto University, he conducts ab-initio simulations for beryllium neutron multiplier, material synthesis/processing, neutron measurement, neutronic calculations, hydrogen permeation, and corrosion. He currently also holds the position of Associate Professor at the National Institute of Fusion Science (NIFS).

Satoshi Ogawa (Manager of Thermal Cycle)

Satoshi has experienced in Japanese engineering company as a mechanical engineer on a wide variety of international process plants and offsite facilities in the fields of petroleum refining, gas processing and natural gas liquefaction plants.

Satoshi has been leading the UNITY-1 project such as organize UNITY-1 project member and vendor status control, and construction field work by vendor.

Kyosuke Namba (Senior Engineer)

Kyosuke, with a Master of Energy Science from Kyoto University, brings a wealth of expertise to his role at KF. His academic journey included an in-depth evaluation of the environmental performance of fusion energy systems, laying a strong foundation for his career in the energy sector. Transitioning to the industry, Kyosuke honed his skills as a mechanical engineer at Japanese engineering company. During his tenure, he played integral roles in various refinery, liquefied natural gas (LNG), and chemical plant projects, specializing in combustion equipment such as boilers, heaters, flares, and incinerators. Joining KF in 2023, Kyosuke's has been contributing to the development of the UNITY-1 lithium-lead loop facility. His diverse skill set encompasses process modeling, piping and layout engineering, structure design, and instrument and control system development. He also played a key role in the advancement of power generation systems in UNITY-1.

Luigi Candido (Senior Engineer)

Luigi, a distinguished nuclear engineer, serves as the technical lead of the fusion blanket team at KF. His role involves spearheading the development of advanced blanket systems. Before joining KF, Luigi played a pivotal role in ITER's European Test Blanket Modules, focusing on the Tritium Extraction System (TES) and the Tritium Accountancy System (TAS) for both the Water-Cooled Lithium-Lead and Helium-Cooled Ceramic Pebble Test Blanket Modules. This experience has given him an in-depth understanding of the critical components in fusion plant technology. His research interests span across tritium technologies, magnetohydrodynamics, and multiphysics modeling, contributing significantly to the fusion energy sector.

Yoshinao Matsunaga (Manager of Fuel Cycle)

Yoshinao specializes in chemical engineering. He previously worked at Mitsubishi Chemical and engaged in operations management and improvement of facilities at an ethylene production plant for 10 years. Currently, he is working on R&D for Exhaust Pumping Train, DIR, FCUS, and other systems, and is spearheading the overall R&D of KF's Fuel Cycle Team. On the UNITY-2 project, he performed overall process and equipment studies.

John McGrady (Senior Engineer)

John, holding an Engineering Doctorate in Nuclear Engineering from the University of Manchester, has rich research experience in radiation chemistry for nuclear waste disposal, notably at the University of Tokyo and JAEA. Proficient in handling radioactive materials like uranium, he joined KF in April 2023. Currently, he collaborates with the fuel cycle team, emphasizing detritiation technologies.

Suneui Lee (Engineer)

Suneui, holding a PhD in Energy Science from the University of Toyama, has investigated non-destructive tritium detection methods. The technique was applied to determine tritium retention in plasma-facing components retrieved from large fusion devices, Joint European Torus (JET) ITER-like wall in the U.K. and LHD of NIFS in Japan. Currently, Suneui's main work at Kyoto Fusioneering is improvement of metal hydride hydrogen storage bed.

Naoko Ashikawa (Fusion Engineer)

Naoko holding a PhD in Fusion Engineering from the Graduate University of Advanced Studies, has investigated a plasma diagnostic for total radiation loss using infrared camera. The current major research topics are tritium engineering, for quantitative tritium analytical method for remained tritium in the vacuum vessel.

Selected Publications from KF Experts on Thermal Cycle Technologies

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