# The Path to a Fusion Materials Roadmap

## Revision of advances in materials development and challenge areas for fusion to identify critical gaps in technical disciplines

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# Foreword

The aim of this fusion materials roadmap initiative is to investigate materials technologies with potential use in fusion power plants.

The path forward is to work together with industry, labs, big science organizations and academia to identify critical technology gaps. Setting priorities for innovation driven development in the most critical areas to provide guidelines and support to stakeholders setting up funding and investment schemes for fusion materials projects.

Workshops supported by a network of experts will be the main tool to facilitate the evolution of a fusion materials roadmap.

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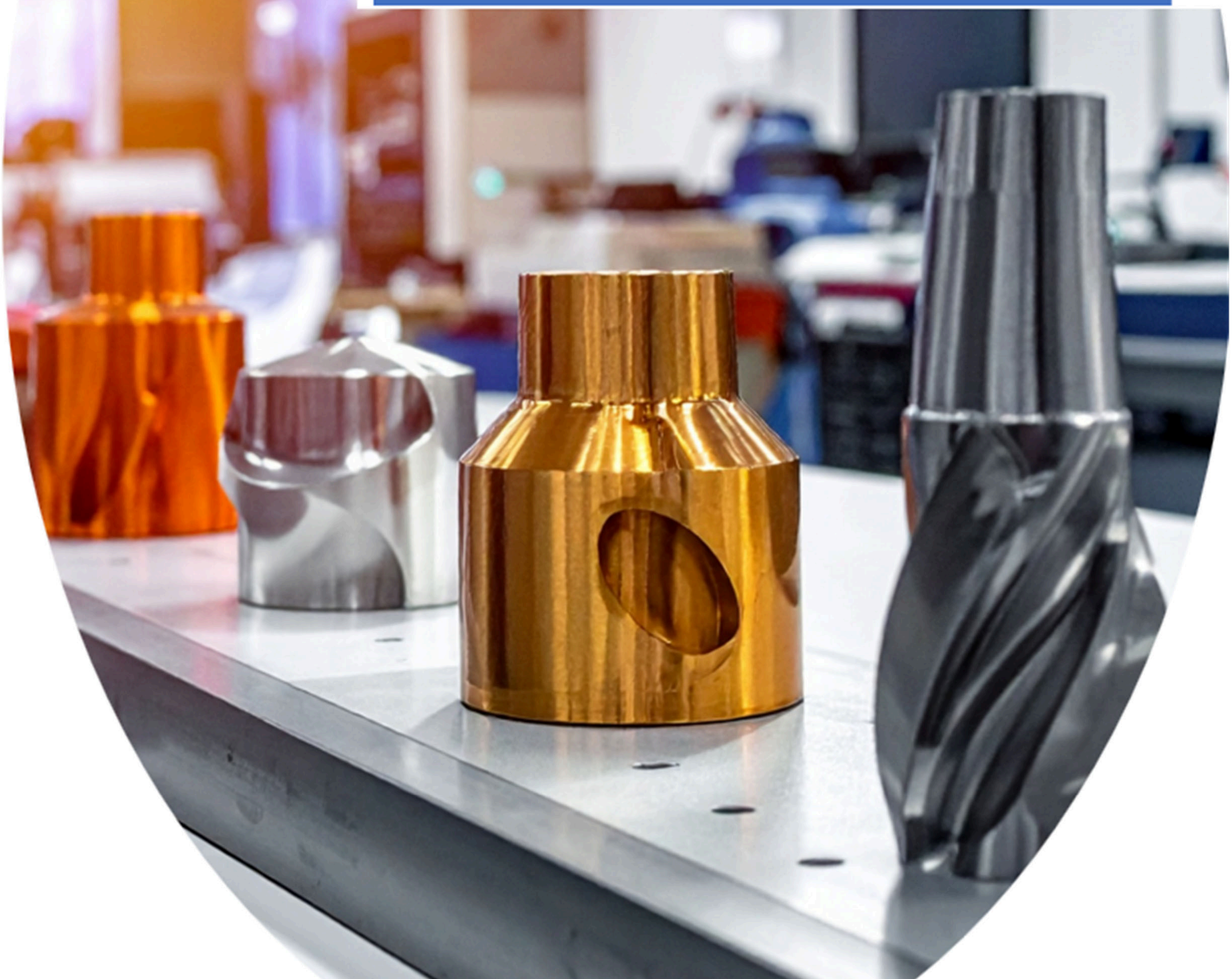

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# 1. Introduction to this fusion materials road map

Recently, there have been significant efforts to develop fusion energy, and globally the research landscape is evolving with introduction of new fusion projects. For experimental fusion reactors, the materials development has generally evolved from conventional materials to avoid the tedious work qualifying and introducing new materials in Nuclear Codes and Standards. Such approaches can be considered compromise solutions that work well for test reactors. However, there are significant engineering challenges to resolve to obtain commercial fusion materials that can sustain the extreme operational conditions in a fusion power plant.

Illustration of high energy particles passing through 3 layers of materials affecting microstructures. From the top: plasma facing material, heat sink, and structural material.
*Illustration by S. Wikman.*

High energy particles produced by the burning plasma, such as neutrons, ions, helium, hydrogen fuel isotopes, and various impurity ions will collide with the surrounding materials. The collisions will first generate several surface reactions such as electron and gamma emission, sputtering, erosion, and reflections to name a few possibilities. There will be dramatic changes to the materials due to the large number of incoming particles generating damage and changing the internal structure along with chemical composition due to transmutation into new elements.

Neutrons passing through the materials will generate a cascade of chain collisions resulting in dislocations, vacancies, and formation of trapped helium gas. Over time these effects change the performance of all the exposed materials.

There are also functional materials for different purposes and tritium breeding materials to produce needed tritium fuel and much more that require further development.

**Innovation driven development** is necessary to bridge the gaps when it comes to delivering commercial fusion materials. For successful outcome, it is also important to evaluate spin-off synergies for other fields.

It is essential to connect talent and expertise in the private and public sector with critical infrastructure and test facilities.

**The purpose of the Fusion Materials Roadmap** is to transition priorities to coordinated Technology Development Actions with defined objectives and milestones.

Engineers investigating materials solutions to increase the plasma facing components lifetime exposed to the artificial sun.
*Illustration by S. Wikman.*

# 2. Materials development challenges for nuclear components

Even materials with superior properties that are commercially available may need several years to be taken in consideration. This is due to the process of inclusion in codes and standards (ASTM, EN, ISO, RCC-MRR etc).

The nuclear licensing authorities in the country where a facility is planned will request evidence that the materials properties correlate to respective standards. Standards and regulations dedicated to fusion applications do not exist yet (initiatives are taken in this direction as RCC-MRx). To introduce a new material into a standard requires comprehensive testing and assessment where the materials properties need to be demonstrated with reproducible statistical data. For conceptual design this also include the manufacturing processes, qualification campaigns, and acceptance testing.

On a positive note, the additive manufacturing processes have so many advantages for commercially competitive applications and many materials are being adopted for inclusion in nuclear codes and standards. The renewed interest in fission SMR's and fusion is also positive as it increases the capacity to rationalize the qualification processes.

**Possible scope of work and challenges**

| **Materials Database** | **Challenges** |
|---|---|
| Coordinated effort for a nuclear materials database to support new fusion and fission projects. | Difficult for individual companies and labs as materials data is vast and spread.<br>National agencies, governments, Big Science Organizations and international entities as EU, IAEA need to support the activities. |
| | |
| **Introduction of Materials in Codes & Standards** | **Challenges** |
| Establish routines and processes to introduce new materials in the relevant codes & standards. | National agencies, governments, Big Science Organizations and international entities as EU, IAEA need to support the schemes to accelerate inclusion in relevant codes & standards. |

Materials are globally developed for different disciplines with variations depending on purpose, but may not be readily available for fusion and to meet nuclear requirements on impurity control. Well known materials may need to be manufactured with strict contamination control that is difficult to comply with for large materials manufacturers who need handle smaller batched separately.

## 2.1 Materials manufacturing

Materials manufacturing processes are constantly developed with new technological leaps every year. Additive manufacturing presents the highest relevant growth area today, demonstrating materials properties that can match or even be superior to what is achieved by conventional manufacturing. Today's challenge is, like materials themselves, to implement the new manufacturing processes into codes & standards for each application (nuclear codes and standards in particular) as proper demonstration and assessment is necessary. This process can be both lengthy and costly for the industry or big science projects leading to prioritization issues. Traditional manufacturing solutions are often selected as compromise, due to resources and time constraints, over the most suitable options.

**Examples of manufacturing processes with gaps in nuclear codes & standards**

| Manufacturing Method | Pro's and Con's |
|---|---|
| **Powder HIP** (hot isostatic pressing) processing is well known to produce materials with properties superior to what can be obtained by conventional manufacturing. Used for decades in oil & gas for the most demanding and complex drill heads. Developed for ITER blanked modules qualification program, as one fusion relevant example, and with potential for many nuclear applications. | + Complex near net geometry shape manufacturing limiting waste by machining.<br>+ High materials properties.<br>- Cost (HIP is not cost efficient for simple structures).<br>- Not covered in all aspects by codes and standards |
| **Diffusion bonding by HIP** as joining method has several advantages. Flat surfaces of similar or dissimilar materials can be joined with joint properties as good or better than the base materials. This joining process is today the superior joining method of flat surfaces, like plasma armour tiles. | + Reproducible properties of large quantities of joints.<br>+ Efficient method joining dissimilar materials.<br>+ Minimizing residual stresses as the whole component is subject to heat treatment in the HIP furnace.<br>- Complex setup with specialized facilities. Experienced technicians necessary as the preparation for HIP can be described as tailored craftmanship. |
| **Additive Manufacturing** has evolved into several branches such as powder bed fusion, direct deposition of materials via wires or spray methods and binder-based powder 3D printing etc. Each technology evolves rapidly. Tailor-made processes can achieve full density materials with properties superior to what is achieved by standard conventional manufacturing (with complex shapes).<br>AM technologies have potential to simplify and pave the way for more commercial solutions for complex shaped nuclear components. | + Efficient use of raw materials for complex shape manufacturing.<br>+ Materials properties can be tailor-made by controlling energy, raw material sizes and building directions.<br>+ High savings due to less need for machining of final components.<br>- Not covered in all aspects by codes and standards.<br>- Supply chain for some variants of raw materials is falling behind, as new wire materials for direct energy deposition.<br>- Component sizes achievable by some processes for different applications with different materials are limited. |

# 3. Neutron Irradiation Facilities and Materials Test Facilities

Materials in a fusion reactor are exposed to a varied flux of neutrons with fast moving 14 MeV neutrons hitting the plasma facing components and thereafter the neutron energy (speed) is subsequently moderated passing through materials and coolants. Neutron irradiation generates different effects such as transmutations into new elements and helium production. The collisions knock atoms out of their positions in the material lattice with cascade effects that are magnified determined by the speed of the neutrons. This leads to hardening, embrittlement, swelling and different defects.

In this critical phase to develop fusion materials the availability of fast neutron irradiation facilities is limited in EU. To move forward with any fusion reactor concept, it is necessary to irradiate material specimens for mechanical and perform physical characterization.

## 3.1 The European Spallation Source

The European Spallation Source will be a facility with high potential to support characterization of materials being developed for fusion and fission power plants. ESS is well equipped for materials characterization and fundamental mapping of nuclear materials. It is important that scientists and engineers working with nuclear materials development are aware of the capacity and possibilities of ESS.

A materials specimen exposed to flux of particles.

*Illustration by S. Wikman.*

To be further relevant for fusion materials development, a good proposal is to investigate the possibility to place material specimens closer to the target area over a period to accumulate crystalline structural changes due to influence of neutrons and thereafter extract the specimens for investigation at the analysis target area. Influence of the faster non-moderated neutrons on materials gives the most useful data for fusion materials development.

The beam hitting the ESS target wheel generates a probability distribution of the neutron flux energy (speed). The neutron energy close to the wheel is much higher than in a conventional test reactor with potential to provide key materials data.

**ESS, possible scope of work and challenges**

| Standard Materials Testing | Challenges |
| --- | --- |
| Standardized testing and evaluation of materials structures. | No challenge (priorities of what materials to assess) |
| | |
| **Characterization of irradiated material** | **Challenges** |
| Characterization of materials structure irradiated elsewhere to different dpa levels. | Transport, storage and remote handling of activated material (however, will be thin slices).<br>Transmutation mapping. |
| | |
| **Irradiation to neutrons and characterization** (most valuable to materials development) | **Challenges** |
| Exposure to neutrons as close to the target area as possible in an ESS channel (prevent neutron moderation). Materials sample (with dedicated sample holder) that can be exposed to neutrons and retrieved to assess effects of neutrons on material microstructure. Possibility to progressively map damage mechanisms and transmutations over time in a unique way. | Requires tailor made experimental setup (rig allowing back and forth movement of sample from exposure location to assessment location). |

## 3.2 IFMIF-DONES

IFMIF-DONES will be dedicated neutron sources with a calibrated steady neutron flux of 14 MeV to determine operational lifetime under operational conditions. Materials exposure testing in these facilities will provide precision data to nuclear licensing authorities to approve operation under actual conditions. IFMIF is nearing completion in Rokkasho, Japan, while DONES is expected to take additional 10 years to be completed in Granada, Spain.

**IFMIF-DONES, possible scope of work and challenges**

| 14 MeV Irradiation of Materials | Challenges |
| --- | --- |
| The facilities will play an important role to qualify materials for operation under fusion operational conditions. Unique opportunities to test neutron breeding components. | Limited volume for neutron exposure.<br>Irradiation of materials test specimens (tensile, fatigue etc etc) need careful planning with priority.<br>Mock-ups connected to coolant or breeding loops require complex experimental setup. |
| | |
| **Characterization of irradiated material** | **Challenges** |
| Characterization of irradiated materials. | Transport, storage capacity and remote handling of activated material. |

## 3.3 Conventional Fission Test Reactors

**Conventional Fission Test Reactors** have provided most of the irradiation of materials up to present date. The irradiation campaigns have been performed by allocating materials samples between fuel assemblies in the nuclear cores. The drawback is that the materials are exposed to moderated thermal neutrons that are much slower and may not be representative to actual fusion materials in operation.

**Fission Test Reactors, possible scope of work and challenges**

| Irradiation of Materials | Challenges |
|---|---|
| Possibilities to irradiate materials in existing facilities, such as in-pile testing of materials in fission test reactors. | Availability of facilities.<br>Requires careful planning and experimental setup in test rigs is complex.<br>Slow fission neutrons that may provide results with different damage mechanisms on materials compared to 14 MeV neutrons. |
| | |
| **Characterization of irradiated material** | **Challenges** |
| Characterization of materials structure irradiated to different dpa levels. | Transport, storage and remote handling of activated material. |

## 3.4 Post Irradiation Examination – PIE Facilities

Hot Cells with advanced PIE capabilities are available in several EU member states. High temperature materials testing capacities up to 600°C will be necessary.

**PIE Facilities, possible scope of work and challenges**

| Standard Materials Testing | Challenges |
|---|---|
| Standardized testing and evaluation of materials structures. | No challenge (priorities of what materials to assess) |
| | |
| **Characterization of irradiated material** | **Challenges** |
| Characterization of materials structure irradiated elsewhere to different dpa levels. | No challenge (priorities of what materials to assess).<br>Availability of facilities. |

## 3.5 Coolant Media Exposure – Corrosion and Erosion Test Facilities

Neutron exposure will alter the chemical composition of any coolant media. For example, water molecules alone can split and generate 34 different products via radiolysis. Liquid metals and molten salt require tailor made autoclaves to test unique conditions. The effect of neutrons on coolant media can be experimentally simulated, and actual neutron exposure is in most cases not necessary (with exception of Tritium Breeding liquid media, but such testing is likely only possible in IFMIF-DONES).

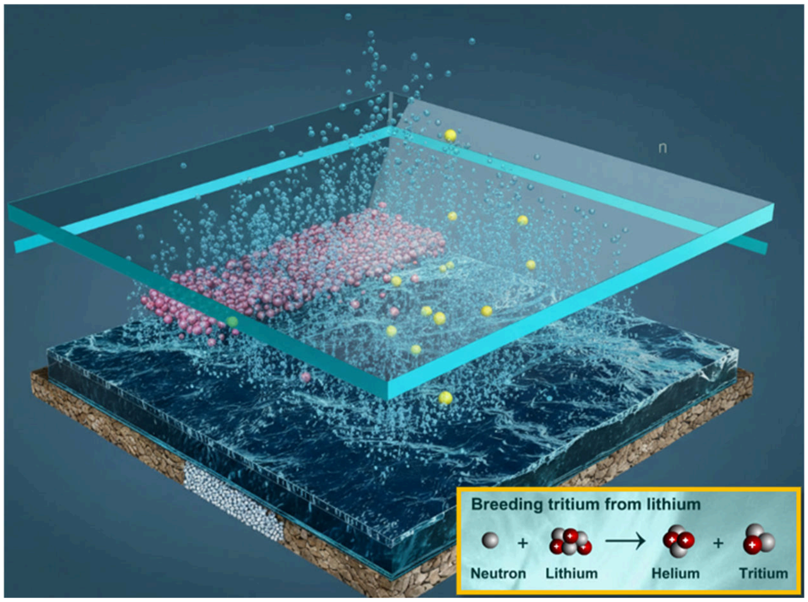
**Nuclear Corrosion Test Facilities, possible scope of work and challenges**

| Materials Corrosion Testing | Challenges |
|---|---|
| Standardized autoclaves testing and evaluation of materials structures. Different liquid media, temperatures, and flow rates. Influence of impurities on corrosion mechanisms.<br>6-12 months test campaigns at 300 ˚C - 650˚C. | Specific autoclaves and test rigs to match different media (water, lithium, lead, molten salts etc).<br>Handling of toxic and/or dangerous substances (beryllium, lithium).<br>In-situ monitoring systems. |

# 4. High Temperature Materials for Tritium Breeding Components

Tritium breeding is an absolute must for a commercial fusion power plant to achieve a self-sustaining source of fuel. Today there is no clear solution for a machine system to fulfil this task with different candidate design concepts being developed in parallel. The community needs to be brave and support acceleration of innovative designs as this system is very challenging.

Tritium breeding blankets are critical components, unique to each reactor design comprising structural materials, lithium-based tritium breeding material solutions, coolant media interfaces, and functional barriers. It is essential that the design prevents tritium permeation.




Fictive lifting a cover plate of Tritium Breeding Blanket section where neutrons interact with liquid lithium-lead producing tritium and helium. *Illustration by S. Wikman.*

The tritium breeding blankets are designed with a function to interact with neutrons generated by the plasma to generate new fuel (tritium), convert neutron energy to heat and to shield adjacent components from harmful irradiation.

Neutrons split lithium into helium and tritium and the generated gas is extracted and separated. Thus, achieving a fuel cycle loop.

Neutron multipliers (as lead and beryllium) can be used to promote the reactions.

A water-cooled lithium-lead test blanket system and a helium cooled ceramic pebble test blanket system are the two concepts being investigated via F4E. Different aspects must be considered for the manufacturing design followed by step wise optimization.

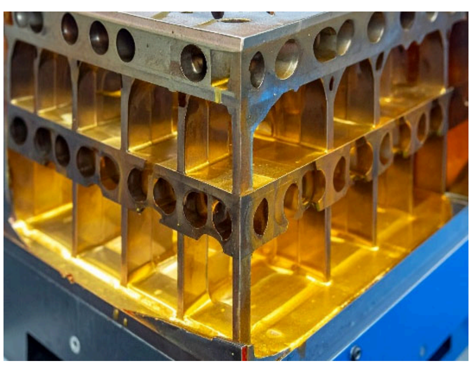


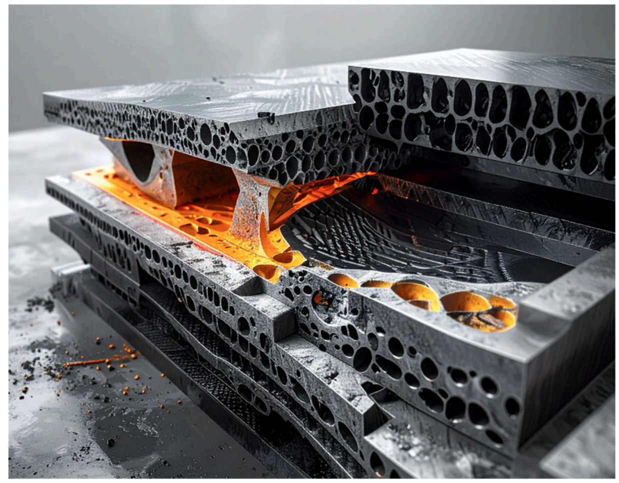
Illustration of a corner of conventionally made breeding blanket structure. *Illustration by S. Wikman.*

A complex design of tritium breeding blankets is unavoidable as it is important to maximize exposed lithium containing volumes to neutrons for tritium generation while considering structural strength, thermohydraulic parameters and corrosion resistance of the modules.

Most concepts until today are based on conventional manufacturing transforming plates and forgings by complex machining, deep drilling and via high number of joints to machine components. This may appear tedious, outdated, and difficult to justify commercially.

Additive manufacturing opens to a completely new way of tailor-made breeding blanket systems based on thermohydraulic optimized flow patterns.

Newly developed alloys can be introduced in previously not possible cost-efficient processes as raw material for AM is powders or wires. This raw material can be tailor made in small batches.



Fictive breeding blanket structures are made with full freedom by additive manufacturing.
*Illustration by S. Wikman.*

**Challenge areas to advance TRL levels**

| **Liquid Lithium** | **Challenges** |
|---|---|
| Lithium is key for tritium breeding and integrating lithium loops. Compatibility with interfaces during operation is essential. Low oxygen content is necessary as tritium has high affinity in oxides.<br><br>Lithium consists of two natural isotopes 7.6% Li-6 and 93.4% Li-7. For tritium breeding it is important to have as high value of Li-6 as possible. | Impurity control during manufacturing/installation and maintaining high purity during operation.<br><br>Map corrosion material loss rates and corrosion mechanisms (based on temperature and flow velocity).<br><br>Lithium is very reactive if it gets in contact with the ambient environment.<br><br>Li-6 isotope enrichment facility. |
| | |
| **Liquid Lead-Lithium (low TRL)** | **Challenges** |
| The intended use of Li-Pb is the eutectic mixture (15.7% Li and 84.3% Pb). The Li-Pb eutectic has low reactivity with oxygen and water and is a good shield-breeder-coolant combination. GenIV fission liquid lead reactors as Blykalla can provide valuable reference data and will be valuable collaboration partners as liquid lead fission reactor concepts have reached high TRL levels. | Introduction of corrosion barriers (coatings).<br><br>Influence of neutrons and transmutations.<br><br>Sensitivity to impurities.<br><br>Compatibility liquid/solid interfaces (corrosion). |
| | |
| **Liquid salt solutions (Low TRL)** | **Challenges:** |
| FLiBe is a candidate salt with high potential that is obtained by mixing lithium fluoride LiF and beryllium fluoride $BeF_2$. Alternative salts in literature are ClLiF and FLiPb, but with limited data. | Introduction of corrosion barriers (coatings).<br><br>Compatibility liquid/solid interfaces.<br><br>Investigate the effect of 14 MeV neutron interaction with salts and production of aggressive radicals.<br><br>Be is highly toxic and will be an issue with manufacturing supply chain (as lessons learned with beryllium First Wall manufacturing).<br><br>Tritium retention in fluorides and salt generated corrosion layers. |

| | |
|---|---|
| **Qualification Testing of Tritium Breeding** | **Challenges:** |
| DONES-IFMIF (see section on Test Facilities) | Presently no facility that can support this. |
| | |
| **Test Facilities for Corrosion Experiments** | **Challenges** |
| Autoclave systems for liquid metal and liquid salt mixtures operating at different temperatures (see section on Test Facilities). | Requires complex autoclaves and test rigs. |
| | |
| **Supply Chain** | **Challenges** |
| Industrial facilities, R&D labs, and expertise. | Expand the network and establish efficient supply routes. |
| | |
| **Compatibility with Structural Materials** | **Challenges** |
| ODS steels, RAFM, new emerging materials<br>Vanadium alloys, Eurofer97, SiCf/SiC.<br>(see section on Structural Materials) | Complex geometries (foreseen to be based on additive manufacturing) – different flow velocities and corrosion mechanisms to map. |
| | |
| **Solid Pebble Breeders (Helium Cooled)** | **Challenges** |
| Safer and less challenging to manage than liquids, but lower tritium breeding rates compared to liquid breeders. | LiOH (lithium hydroxide) formation<br>Irradiation damage and Li consumption – toxic and radioactive ceramic dust.<br>He coolant influence on corrosion and sensitivity to impurities. |
| | |
| **Tritium Retention** | **Challenges** |
| Tritium retention, hydrogen is well known to accumulate in oxide compounds.<br>Outgassing of tritium. | Facilities to map retention and outgassing of tritium.<br>Remote handling system as tritium is highly radioactive. |

# 5. Heat Sinks and Shielding

## 5.1 Shielding Materials

Neutron and gamma irradiation shielding materials are needed for protection in nuclear facilities. Boron carbide, B4C, is a well-known material manufactured in different variants as blocks, pellets or as customized shaped shielding. The Boron-10 isotope is a great neutron attenuator, but requires isotope separation to increase efficiency. Tungsten carbide, WC, and tungsten boride are two alternative materials discussed in the fusion community. Cobalt is the commonly use binder for WC, but Co can basically be considered forbidden for nuclear applications due to the Co-60 activation. Thus, low activation binders need to replace conventional binders. Zirconium hydrides, $ZrH_2$, and hafnium hydrides, $HfH_2$, are other options at very low TRL level. Complex shield geometries generate stress concentration points in the brittle materials due to thermal expansion and influence on properties due to neutron irradiation. Functional graded materials can prevent such issues.

**Challenge areas to advance TRL levels**

| **Materials topic** | **Challenges** |
|---|---|
| Boron carbide, $B_4C$ with customized geometries.<br>Tungsten carbide, WC development<br>Tungsten boride, WB development<br>Emerging alloys – new developments<br>Composites<br>Claddings with shielding function<br>Isotope separated claddings | $B_{10}$ isotope separation for commercial use and facilities for that process.<br>Microstructure properties development to mitigate embrittlement.<br>Complex geometry manufacturing of brittle shield materials.<br>High dpa irradiation of developed shield materials to map swelling, transmutations, and embrittlement.<br>Direct joining methods to heat sinks or structural materials. |

## 5.2 Copper Alloys as Heat transfer Material

Copper alloys are since long considered for heat sinks in fusion reactors. The commercial precipitation hardened CuCrZr grade is used in a high variety of applications. This grade functions well in general, but is sensitive to heat treatments and the necessary joining processes are deteriorating the material properties, sometimes leading to chaotic grain growth and loss of mechanical strength.

The dispersion strengthened Cu-alloy variant (ODS copper) can also be considered. ODS copper is manufactured via powder metallurgy where fine oxide particles are dispersed on Cu-powders followed by hot isostatic pressing to achieve a fully dense material.

It is also important to investigate alternative Cu-alloys, for example as prepared TDP study to manufacture graphene reinforced copper and evaluate the properties.

The sensitivity to erosion as coolant water interface is rapidly increasing >150 ˚C for Cu-alloys, especially under influence of neutron induced radiolysis and the erosion rates needs to be assessed for all new grades.

**Challenge areas to advance TRL levels**

| Copper-alloys, CuCrZr | Challenges |
|---|---|
| Commercial precipitation hardened CuCrZr grade with stable materials properties after repeated heating above 1000 ˚C (for example, to join surfaces of CuCrZr to stainless steel requires ≥1040 ˚C via Hot Isostatic Pressing).<br><br>Dispersion strengthened, ODS copper.<br><br>Alternative Cu-alloys. | Fluctuations in materials properties and chaotic grain growth is a common issue with precipitation hardened CuCrZr.<br><br>ODS copper needs development and testing for comparison with precipitation hardened CuCrZr.<br><br>Alternative Cu-alloys as graphene reinforced copper to be developed and tested.<br><br>Joining of Cu-alloys to low activation steels. |

## 5.3 Joining of Dissimilar Materials

With heat sink and shielding materials comes challenges in how to achieve good joints to other machine systems or structural materials.

**Challenge areas to advance TRL levels**

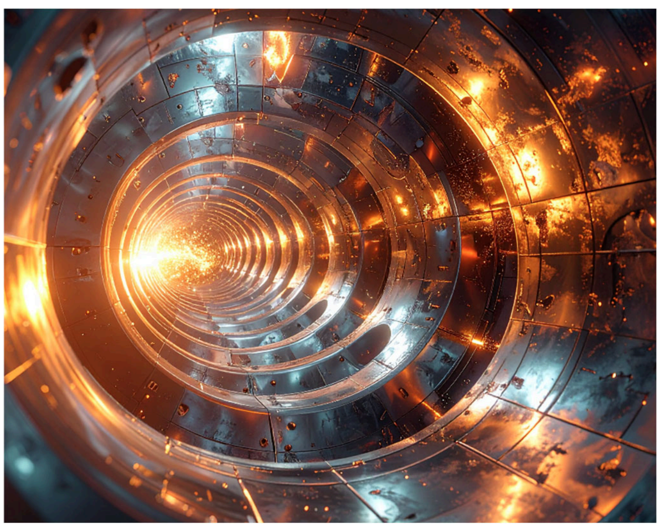
| Joining of Dissimilar Materials | Challenges |
|---|---|
| Electron Beam welding<br><br>Laser Welding<br><br>Friction Welding<br><br>Conventional welding using fillers (TIG, MIG etc)<br><br>Diffusion bonding (flat areas or complex structures)<br><br>Brazing (non-demanding, non-structural applications)<br><br>Additive Manufacturing<br><br>Gradient joint development | Fluctuations in materials properties.<br><br>Different thermal expansion coefficients.<br><br>Development and qualifications for codes & standards. |

# 6. Structural Materials

Structural materials are used in a variety of fusion machine systems such as vacuum vessels, blanket modules, support structures and ports etc. For commercial fusion powerplants the development of reduced-activation materials is in focus to facilitate operational safety, replacements, decommissioning and waste management. Transmutations due to high energy neutrons and He-bubble formation result in volumetric swelling, and this phenomenon requires certain design of structural materials for applications in the proximity of the plasma. Low activation steels and vanadium alloys are two candidate materials extensively studied. Emerging materials like SiC composites are also investigated for this purpose.

While many austenitic stainless steels are widely used as structural material in fusion test reactors, most austenitic stainless-steel grades are not sustainable for fusion power plants due to severe volumetric swelling caused by He-bubble formation (not an issue for the low doses accumulated in test reactors). For commercial power plants the austenitic steel structures must be placed further away from the plasma. Austenitic steels have high TRL levels and don't require in-depth development.

Reduced Activation Ferritic Martensitic (RAFM) is a group of materials designed for dimensional stability while minimizing transmutations of activated isotopes under influence of neutron irradiation. Typical RAFM steels are based on Fe with 7-9% Cr with smaller additions of W, Mn, V and Ta (for example Eurofer97 and F82H) to promote precipitates (carbides, nitrides) during heat treatments. Reduced Activation Bainitic Steels is another low alloy steel variant for nuclear applications, with 2-3% Cr content and equal amount of W and smaller additions of V and Ta. The benefits of bainite variants are higher toughness and thermal creep resistance.



Possible view towards a fusion plasma via diagnostics service channel through structural materials. *Image generated by S. Wikman.*

Oxide Dispersion Strengthened (ODS) alloys are manufactured via powder metallurgy to obtain tailored microstructures. For example, by mixing fine (nanometer or single micrometer) powders of yttrium-oxides with base alloy powders followed by Hot Isostatic the final product will have an oxide dispersion strengthened microstructure. The oxide particles allocated in the grain boundaries prevent thermal creep and increase tensile strength.

Liquid lead cooled reactors pose different challenges, as with Blykalla Gen IV reactor, where the selected structural material is FeCrAl. This material forms a stable protective oxide layer allowing long lifetime operation with molten lead.

SiC composites are also proposed for structural material applications.

**Challenge areas to advance TRL levels**

| Materials topic | Challenges |
|---|---|
| Oxide Dispersion Strengthened (ODS) steels<br>Reduced Activation Ferritic Martensitic (RAFM) steels<br>Reduced Activation Bainitic (RAB) steels<br>Vanadium alloys<br>SiCf/SiC<br>Emerging materials | Supply chain to manufacture batches.<br>Powder and wire for Additive Manufacturing to lower cost of mock-up development and qualification.<br>Effects of strong magnetic fields (accumulation of corrosion products).<br>He and H driven embrittlement.<br>Radiation effects |

# 7. Plasma Facing Materials

Plasma interactions with materials generate debris, surface "fuzz" and direct damage, that varies depending on selected materials and manufacturing processes. No material can sustain long-term exposure to fusion plasma, but the materials can be designed to prolong the commercial operational lifetime. The surface fuzz generation phenomenon, in the case of tungsten, occurs due to formation of helium rich fiber-like structures. This fiber structure continues to grow during plasma operation resulting in decreased thermal conductivity at the surface. The incoming particles from an active plasma will interact in a similar way with every type of surface material.

Surface cracks appear with time and due to thermal shocks. The crack initiation and crack growth mechanisms can be mitigated, and to some extent controlled, with clever materials design. Joining the surface materials to the next materials layer, often a heat sink, requires special attention due to the difference in thermal expansion.

Direct joining of tiles, for example tungsten tiles on CuCrZr heat sink gives a difference factor of 3.8 in thermal expansion with risk of delamination due to thermal fatigue with time. One approach to mitigate this issue is to manufacture gradient joints to allow gradual transition of materials with large differences in thermal expansion.

Until now the two main candidate plasma facing materials have been beryllium and tungsten. Beryllium with the drawback of being highly toxic and issues with formation of Be-debris. It is a gap when it comes to development of new plasma facing materials and alloys.

The plasma facing components are exposed to energetic particles generated by the plasma that relentlessly bombard the materials. *Images generated by S. Wikman.*

## 7.1 Tungsten (W) Base Materials

Tungsten is the main candidate today for plasma facing material due to its resilience to high temperatures, low tritium permeability and low neutron activation. The main issue for W is the brittleness, and the brittleness increases at a threshold called the Ductile to Brittle Transition Temperature (DBTT) that is varying based on manufacturing processes. The DBTT is where tungsten shifts from brittle (at lower temperature) to ductile (higher temperature). DBTT is also altered to higher values due to high temperature operational conditions and exposure to neutrons. Advances in additive manufacturing demonstrate potential for tailor-made commercial W-components.

Tungsten fiber reinforced tungsten is an interesting alternative as W-fibers are available on the market with ductile properties (DBTT of fibers can get very low <50°C). However, it is relatively untested and influence of neutrons on the materials properties needs to be assessed.

**Challenge areas to advance TRL levels**

| Tungsten Manufacturing Development | Challenges |
|---|---|
| Additive Manufacturing process development for commercial high density crack free W (with embedded 3D cooling structures).<br><br>Raw materials and use of chemical reduced CR powders. | Effects of neutrons on surface effects (W-fuzz), He formation, transmutations and swelling.<br><br>Recrystallization and DBTT mapping of each W-grade and effect on DBTT from neutrons and thermal shocks.<br><br>Access to W (raw material supply chain). |
| Tungsten fiber reinforced tungsten (W/W composites). | Commercial manufacturing process of larger scale components.<br><br>Influence of neutrons on the fibers. |

## 7.2 Tungsten Alloys

Tungsten alloys are commonly manufactured via powder metallurgy to obtain a ductile matrix material that is surrounding the W-particles. The most famous example is W-Co that is widely used as cutting tool by the manufacturing industry, however Cobalt cannot be considered for nuclear applications due to formation of active long-lived Co-isotopes. W-Ni-Fe and W-Cu are two other material combinations more widely studied where Ni also imposes a risk with too much long-lived Ni-59 isotopes. Regardless of selected alloying element the effect of thermal shocks and neutrons needs careful evaluation to map surface melting, evaporation and swelling.

Gradient tungsten-based materials are another route where a complex shaped W-structure can be produced via additive manufacturing that is infiltrated by another material (as Cu) or by generating different compositions from powder metallurgical mixing of W with other elemental particles.

By using dopants (adding small, controlled amount of a specific element), it is possible to influence materials' properties in desired directions. One such example with proven beneficial effects is Potassium (K) doping of Tungsten where the Potassium is finely dispersed along the Tungsten grain boundaries. This has a stabilizing effect against recrystallization and positive impact on ductile to brittle transition temperature (DBTT).

**Challenge areas to advance TRL levels**

| W-alloys | Challenges |
|---|---|
| Doping of W (about <0.1% of element addition). | Potassium doping mapping against DBTT and microstructure.<br><br>Investigate doping possibilities with other elements. |
| W- Gradient materials. | Manufacturing methodology and testing at operational conditions. |
| Full out alloying W with other elements.<br><br>W-Ni-Fe, W-Cu and more. | Influence of exposure to high temperature on the lower melting temperature material.<br><br>Influence of neutrons. |

## 7.3 Liquid Metal Armor

There are potential benefits of incorporating liquid metals in the plasma facing armor structure. The inner liquid part will not be subject to swelling, thermal cracking, and neutron damage. A liquid metal with good thermal properties can be used for heat transfer while providing shielding. Liquid metals also have very low tritium retention.

Lead and lithium are the two most considered materials for such applications. Lead provides shielding and heat transfer. Lithium functions as tritium breeding material have benefits if tritium separation is part of the solution. Tin (Sn) is another potential liquid metal that can potentially be used in internal tungsten channels. Bismuth (Bi) and Cadmium (Cd) are two other possible materials, but little is known and practically TRL 0 for such applications. Eutectics of the different metals can also be considered as LiPb, SnPb and SnLi and so on, but remains to be experimentally tested for compatibility and how the different materials stick on interface surfaces. Overview of what materials are available today and where are the gaps.

**Overview of what materials are available today and where are the gaps.**

| Liquid Metal Armor | Challenges |
|---|---|
| Sn, Pb, Li, Bi, CD, PbSn, LiPb, SnLi concepts.<br>Develop mock-ups with liquid metals for assessment (for example W structure with liquid Sn). | Map transmutation generated activated isotopes.<br>Corrosion rates.<br>Compatibility with structural materials.<br>May need development of protective coatings. |

## 7.4 Emerging Materials

A new chapter to be written with development of new low TRL materials concepts.

**Challenge areas to advance TRL levels**

| Materials topic | Challenges |
|---|---|
| Refractory materials, heat resistant coatings, high performance ceramics (nitrides, borides, carbides etc).<br>Coatings with isotope separation for efficient function.<br>SiC claddings. | Identify potential manufacturers.<br>Identify relevant R&D in different technical disciplines. |

## 7.5 High Temperature Composite Materials

Silicon carbide composite (SiC) as a material for nuclear applications is attractive for its high temperature performance, low activation and low neutron absorption. SiC fibers have high strength and with fibers embedded in a carbon matrix this material achieves a ductility in so called SiCf/SiC composites. The potential is there, but the influence of neutrons in combination with thermal shocks on material properties remains to be properly assessed.

In a similar case of carbon reinforced carbon (CFC), that was extensively tested for use as plasma facing component, the CFC material presented poor performance with rapid erosion and carbon dust creation due to neutron damage mechanisms. Another aspect is to map tritium retention as deterioration opens gaps to trap gases in composite matrix structures.

It is important to manufacture and test representative size SiC components under relevant operational conditions. SiC components also have a potential for use as structural material where thermal shocks generated by plasma operation is less of an issue.

**Challenge areas to advance TRL levels**

| SiC SiCf/SiC combinations | Challenges |
|---|---|
| SiCf/SiC<br><br>SiC | Low TRL for nuclear applications needs with demonstration high density samples.<br><br>Tritium retention needs mapping.<br><br>Dust generation from carbon matrix<br><br>Influence of neutrons (transmutations, He-swelling, damage mode)<br><br>Joining SiC to other materials |

# 8. Other specific functional materials

There are several other materials relevant for fusion that are targeted by different technical disciplines and not subject to this first round of materials road mapping exercise.

- **Radiation Hardened Materials**, are generally considered to cover components with electronic functions intended to sustain limited radiation damage, for example cabling, transistors and connectors.
- **Superconducting Materials**, relevant for the magnets with function to maintain the high magnetic fields to control the charged particles in the plasma.
- **Cryogenics Materials**, for magnetic confinement these materials are relevant for the functioning of the superconductors down to temperatures of 4K.
- **Numerical Modeling of Materials**, the tools needed to develop materials design and simulate performance.
- **Artificial Intelligence,** for materials design

# 9. Workshop Agenda for critical technology mapping - May 2026

To develop and keep a roadmap updated it is necessary to organize a series of workshops (possibly bi-annually). The workshops are part of a process to establish a roadmap for materials development aimed at supporting stakeholders with commercialization of fusion energy. This action involves establishing a vision and strategy by gathering input, defining, and prioritizing technological development actions. Companies, research labs, universities, and big science organizations are invited to contribute.

## Draft Workshop Agenda
## Advanced Fusion Materials
### Critical technology mapping for a fusion materials roadmap

| 5 May 2026 | 6 May 2026 | 7 May 2026 |
|---|---|---|
| 08:00 – 08:30, Reception Registration | 08:30 – 10:00 Session 5<br>Plenary Talks | Guided visits to ESS<br>08:30 – 12:30 |
| 08:30 – 10:00 Session 1<br>Welcome and Introduction<br>Plenary Talks | 10:00 – 10:30 Break | |
| 10:00 – 10:30 Break | 10:30 – 12:00 Session 6<br>Break Out Rooms |  |
| 10:30 – 12:00 Session 2<br>Break Out Rooms | | |
| 12:00 – 13:30 Lunch | 12:00 – 13:30 Lunch | |
| 13:30 – 15:00 Session 3<br>Break Out Rooms | 13:30 – 15:00 Session 7<br>Break Out Rooms | |
| 15:00 – 15:30 Break | 15:00 – 15:30 Break | |
| 15:30 – 17:00 Session 4<br>Break Out Rooms | 15:30 – 17:00 Session 8<br>Plenary - Conclusions | |
| | | |
| Dinner 19:00 – 21:30 | | |

Venue: The Loop, Rydbergs torg 4, 224 84 Lund, Sweden. Located opposite the European Spallation Source.

## 9.1 Vision - Outcome of The Workshop

Questions need to be addressed to build a vision to narrow down areas to facilitate funding to fill critical gaps.

- Key infrastructure needs – testing facilities availability and gaps (milestones to fill gap).
- Adoption of a commercial approach to manufacturing key materials (milestones to fill gap).
- Innovation driven design of new materials (milestones to fill gap).
- Bridge building and connect related programs in different fields and enable collaborations (milestones and action plans).
- Development actions to support breakthroughs.
- Inspire students and young engineers to work in the rapidly growing field of nuclear materials development.
- Identify other needs (databases, AI, and integration actions to use those tools).
- Maintain the network of expertise (private and public), expand it and support R&D communities.
- Supply chain (identify supply chain for critical needs and actions to be taken, milestones).

It is important to attract university students and young engineers to the rapidly growing field of Fusion Technologies.
*Image generated by S. Wikman.*