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# Considerations of Technology Readiness Levels for Fusion Technology Components

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International Atomic Energy Agency

# CONSIDERATIONS OF TECHNOLOGY READINESS LEVELS FOR FUSION TECHNOLOGY COMPONENTS

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# CONSIDERATIONS OF TECHNOLOGY READINESS LEVELS FOR FUSION TECHNOLOGY COMPONENTS

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2024

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## FOREWORD

Assessing the technology readiness of fusion reactors involves evaluating various technical and commercial factors such as the availability of materials and components, the maturity of key technologies, the ability to demonstrate a sustained fusion reaction, and the feasibility of scaling up to a commercial scale power plant. Additionally, the economic viability of fusion power needs to be considered, including the cost of developing and building a fusion power plant, the cost of producing fusion fuel and the cost of generating electricity. Overall, the technology readiness of fusion reactors can be assessed on a scale ranging from basic research to commercialization. Currently, most fusion research falls under the categories of early stage research and development, and demonstration projects. To reach commercialization, significant advancements are still to be made in areas such as the development of materials that can withstand the high temperatures and radiation levels inside a fusion reactor, and the optimization of fusion reaction conditions to achieve sustained and economically viable operation. Therefore, there is an identified need to define a consistent approach for assessing the technology readiness of fusion reactors in order to provide a standardized way to evaluate the technology, allowing stakeholders such as investors, regulators and potential customers to assess the level of risk involved in pursuing further development.

Given the state of fusion technology, with its many complex and novel systems, it is crucial to have an efficient and consistent method for evaluating the readiness of the various critical technologies and their components involved in developing fusion technology. This is where the use of technology readiness levels can greatly benefit large projects and the wider fusion community. To ensure that technologies are tested under conditions that accurately reflect the environment of a fusion power plant, dedicated test beds are necessary. A fusion specific technology readiness level framework, along with a clear process for evaluating technology readiness levels and guidance for users, is crucial for ensuring the effective and efficient development, deployment and commercialization of fusion energy.

Technology readiness levels provide a standardized and objective method for evaluating the maturity of fusion technologies, making it easier for all stakeholders to understand and use. By using technology readiness levels in fusion programme planning, everyone from government and research organizations to private sector developers, end users and the supply chain can benefit from a consistent and transparent evaluation process. This publication addresses the growing need for the use of technology readiness levels in fusion programmes, and it is expected that their use will continue to increase in the future.

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# CONTENTS

# 1. INTRODUCTION

## 1.1. BACKGROUND

Fusion reactors are not yet commercially viable and still in the research and development stage. Although significant progress has been made in the understanding of fusion science and the design of fusion facilities, many technical challenges remain to be addressed before fusion power can become a reality. These include achieving a sustained fusion reaction, scaling up to a commercial scale power plant, and developing efficient and economically viable methods for extracting energy from a fusion reaction. Therefore, fusion power deployment and commercialization still has to overcome several challenges. When a reality, fusion will be a source of low carbon energy and can contribute to decarbonization and diversification of energy generation in the long term to meet the mitigation of greenhouse gas emissions.

There are various approaches to fusion, including magnetic confinement (toroidal and spherical), inertial confinement, magnetized target fusion, and hybrid fusion. However, this publication aims to be technology neutral and not prioritize one approach over another. Instead, it focuses on providing a common framework and process for evaluating the readiness of technologies and their components involved in fusion energy development. By being technology neutral, the publication can be useful to the wider fusion community and provide a consistent method for evaluating the maturity of different fusion technologies.

Technology readiness levels (TRLs) are a widely used approach for assessing the maturity and readiness of a technology for commercialization. The use of TRLs for fusion reactors is important because it provides a standardized way of evaluating the technology and helps stakeholders such as investors, regulators, and potential customers to understand the level of risk involved in pursuing further development. In the context of fusion reactors, TRLs provide a useful tool for tracking progress and setting realistic expectations for the technology's development and commercialization timeline. Technology readiness levels help to identify technical and commercial challenges that need to be addressed and prioritize research and development efforts. By using TRLs to evaluate the maturity of different technologies and their components involved in fusion development, stakeholders can get a better understanding of the strengths and weaknesses of each technology, as well as the areas that require further development. This information can then be used to make informed decisions about the direction and focus of research and development efforts, ensuring that resources are allocated in the most effective and efficient manner.

Technology readiness levels provide a standardized and objective method for evaluating the maturity of fusion technologies, making it easier for all stakeholders to understand and use. By using TRLs in fusion programme planning, everyone from government and research organizations to private sector developers, end-users, and the supply chain can benefit from a consistent and transparent evaluation process.

## 1.2. OBJECTIVE

This publication is a compilation of the work carried out by selected experts in the field of fusion research and technology development to provide guidance on how to define and assess the TRLs for fusion technology and its components, focused on fusion technology systems, materials, software, manufacturing, and instrumentation. The objective of this publication is to address the growing need for the use of TRLs in fusion programmes, as it is expected that their use will continue to increase in the future.

### 1.3. SCOPE

The TRLs framework consists of nine levels ranging from basic principles and observations (TRL1) to fully robust technologies validated for application in industry (TRL9). These TRLs provide a clear understanding of the maturity of a technology or its specific component and are widely used by industry and government organizations.

The scope of this publication includes five streams of TRLs related to critical technologies in fusion development as follows:

- Systems;
- Materials;
- Software;
- Manufacturing;
- Instrumentation.

By evaluating the TRLs for each of these five streams, this publication provides a comprehensive picture of the maturity of different technologies and their components involved in fusion energy programmes and helps to identify areas for further development and improvement.

### 1.4. STRUCTURE

Section 1 introduces the need for TRLs. Section 2 describes the TRLs as currently used and applied in other relevant industries, while Section 3 discusses proposed TRLs for fusion technology focusing on materials, manufacturing technologies, instrumentation, software, and systems. Section 4 describes processes for assessing the TRLs; Section 5 provides a description about strategy and development plan; Section 6 introduces guidance for the users. Conclusion remarks are provided in Section 7. The two annexes provide illustrative examples and discuss the TRLs for fusion technology components such as tritium breeding blanket and toroidal field coil.

## 2. TECHNOLOGY READINESS LEVELS

Technology readiness levels were first developed by National Aeronautics and Space Administration (NASA) in 1974 and later formally defined [1]. They have been widely adopted by various agencies and industries as a systematic and objective way of measuring the maturity of a technology.

The use of TRLs in Technology Readiness Assessments (TRAs) has been encouraged by the USA General Accounting Office, which in 1999 concluded that failure to mature new technologies before incorporating them into a product can lead to cost and schedule overruns. The USA General Accounting Office emphasized that maturing new technology in the laboratory environment is the most important factor in the success of the eventual product [2]. In 2007, it recommended that the USA Department of Energy adopt a consistent approach for assessing technology readiness [3]. In response, the USA Department of Energy published a Technology Readiness Assessment Guide in 2009 to help with technology assessments and the development of Technology Maturation Plans for capital acquisition projects [4]. At about this same time, the Global Nuclear Energy Partnership programme produced a

Technology Development Plan using this approach [5]. This assessment considered five key issues requiring focused research and development:

1. Light water reactor (LWR) spent fuel processing;
2. Waste form development;
3. Fast reactor spent fuel processing;
4. Fuel fabrication;
5. Fuel performance.

The USA Department of Defense has adopted the TRL methodology as a best practice for evaluating the readiness of new technologies for operational use. The TRL is used to guide the development of new technologies and to assess their readiness for use in Major Defence Acquisition Programmes. The USA Department of Defense now requires a technology readiness assessment for critical technologies that are part of Major Defence Acquisition Programmes [6].

The use of TRLs has been adopted by several agencies in Europe, including the European Space Agency and the European Commission. The European Space Agency uses TRLs to evaluate the readiness of new technologies for their programme elements and follows the ISO (International Organization for Standardization) 16290:2013 standard for space systems [7]. The European Commission has explored the use of TRLs for nuclear reactor decommissioning under European Union Horizon 2020 [8], while the UK Nuclear Decommissioning Authority has produced a related TRL guide [9].

The NASA and European Space Agency use similar TRLs, defined in Table 1 for the aerospace industry, and the European Commission Horizon 2020 project provided similar definitions as listed in Table 2.

Three phases of technology development proposed by the United Kingdom are shown in Table 3, [3, 9].

TABLE 1. TECHNOLOGY READINESS LEVELS USED BY NASA AND EUROPEAN SPACE AGENCY, [7]

| Level | Definition |
|---|---|
| TRL 1 | Basic principles observed and reported |
| TRL 2 | Technology concept and/or application formulated |
| TRL 3 | Analytical and experimental critical function and/or characteristic proof-of-concept |
| TRL 4 | Component and/or breadboard functional verification in laboratory environment |
| TRL 5 | Component and/or breadboard (reduced scale) critical function verification in relevant environment |
| TRL 6 | System model (full scale) critical functions demonstration in relevant environment |
| TRL 7 | System model performances demonstration in operational environment |
| TRL 8 | Actual system completed and accepted for operational environment through test and demonstration ("mission qualified") |
| TRL 9 | Actual system "mission proven" through successful mission operations |

TABLE 2. TECHNOLOGY READINESS LEVELS USED BY EU HORIZON 2020, [8]

| Level | Definition |
|---|---|
| TRL 1 | Basic principles observed |
| TRL 2 | Technology concepts formulated |
| TRL 3 | Experimental proof of concept |
| TRL 4 | Technology validated in lab |
| TRL 5 | Technology validated in relevant environment (Industrially relevant environment in the case of key enabling technologies) |
| TRL 6 | Technology demonstrated in relevant environment (Industrially relevant environment in the case of key enabling technologies) |
| TRL 7 | System prototype demonstration in operational environment |
| TRL 8 | System complete and qualified |
| TRL 9 | Actual System Proven in Operational Environment (Competitive manufacturing in the case of key enabling technologies; or in space) |

TABLE 3. THREE PHASES OF NUCLEAR TECHNOLOGY DEVELOPMENT USED BY UK NUCLEAR DECOMMISSIONING AUTHORITY, [9]

| Phase | TRL | Stage | Description |
|---|---|---|---|
| **Research** | TRL1 | Basic Principles | Basic properties have been established |
| | TRL2 | Invention and Research | Practical application is invented or the investigation of phenomena, acquisition of new knowledge or correction and integration of previous knowledge. |
| | TRL3 | Proof of Concept | Demonstration in principle that the invention has the potential to work. |
| **Deployment** | TRL4 | Bench Scale | Starting to be developed in a laboratory or research facility. |
| | TRL5 | Pilot Scale | Undergoing testing at small to medium scale size to demonstrate specific aspects of the design |
| | TRL6 | Large Scale | Undergoing testing at or near full-scale size. The design will not have been finalised and the equipment will be in the process of modification. It may use a limited range of simulants and not achieve full throughput |
| | TRL7 | Inactive Commissioning | Technology is undergoing inactive commissioning. Works testing and factory trials on the final designed equipment using inactive simulants comparable to that expected during operations. Testing at or near full throughput will be expected |
| | TRL8 | Active Commissioning | Technology is undergoing active commissioning |
| **Operations** | TRL9 | Operations | Technology is being operationally used in an active facility |

Technology readiness levels encompass nine levels of achievement, or hurdles, that need to be passed to progress toward a final product. They are not a fixed and rigid framework, and the actual progression through the levels may vary depending on the technology, the application, and the development environment. The nine levels are explained as follows (Table 1):

TRL 1. *Basic principles observed and reported*. At TRL1, the basic principles of a technology are observed and documented, often through theoretical or computational studies. At this stage, the technology is in its earliest form, and there may be limited understanding of its potential applications and limitations. The focus is on exploring and verifying the underlying science and understanding the basic principles of the technology. The outputs of this stage are typically reports, papers, or studies that describe the observed principles and their potential applications.

TRL 2. *Technology concept and/or application formulated*. At TRL2, the technology concept and/or application is formulated, and invention begins. With a better understanding of the basic principles, potential applications of the technology can be imagined and described. However, at this stage, the applications are still speculative, and there may be limited analysis to support the assumptions. The focus is on developing a clear understanding of the potential applications and the feasibility of the technology, including any technical or economic challenges that may need to be overcome. Examples of outputs at this stage include conceptual designs, analytical models, and simulations that help to validate the assumptions and evaluate the feasibility of the technology.

TRL 3. *Analytical and experimental critical function and/or characteristic proof of concept*. At TRL3, active research and development is initiated, and the focus shifts to testing and validation of the technology. Analytical and experimental studies are conducted to physically validate the predictions made in earlier stages. The technology is tested and evaluated at a component level, with the aim of demonstrating the critical functions and characteristics of the technology. The focus is on proving the concept and ensuring that the technology works as expected. The outputs at this stage include laboratory prototypes and demonstrations of individual components or subsystems. The prototypes may not be representative of the final system, but they provide evidence that the technology is viable and has the potential to meet its intended purpose.

TRL 4. *Component and/or breadboard validation in laboratory environment*. At TRL4, the focus is on integrating the basic technological components to demonstrate that they will work together as a system. The technology is tested in a laboratory environment, often using a breadboard or similar low-fidelity setup. The aim is to demonstrate that the components can be integrated and that they can perform the basic functions of the system. At this stage, the laboratory prototypes are still relatively low fidelity compared to the final system, but they provide valuable information on the compatibility and performance of the components and allow for any necessary modifications to be made before proceeding to higher levels of technology readiness. Examples of outputs at this stage include low-fidelity prototypes and laboratory demonstrations that show how the components will work together to perform the intended functions of the system.

TRL 5. *Component and/or breadboard validation in relevant environment*. At TRL5, the technology is tested in a more relevant environment, with a higher level of fidelity. The basic technological components are integrated with more realistic supporting elements to create a more representative prototype. The goal at this stage is to demonstrate the technology's performance in a simulated environment that is as close as possible to the intended operational environment. The aim is to identify any remaining technical risks and limitations before proceeding to higher levels of technology readiness. Examples of outputs at this stage include high-fidelity laboratory prototypes that are tested in simulated operational environments to demonstrate the technology's performance and determine if it meets design specifications. These prototypes provide valuable information on the technology's viability and readiness for further development and eventual deployment.

TRL 6. *System/subsystem model or prototype demonstration in a relevant environment*. At TRL6, a more advanced and representative model or prototype of the system or subsystem is tested in a relevant environment. This level represents a significant milestone in the technology's demonstrated readiness, as the prototype system is much more advanced than the breadboard technology tested at TRL5. The focus at this stage is on demonstrating the technology's performance and capabilities in a realistic environment. Examples of outputs at this stage include laboratory testing of high-fidelity prototypes or testing of the prototypes in simulated operational environments that are as close as possible to the intended operational environment. The goal at this stage is to identify any remaining technical risks and limitations and to determine if the technology is ready for further development and eventual deployment.

TRL 7. *System prototype demonstration in an operational environment*. At TRL7, the technology is demonstrated in an operational environment. The prototype system tested at this stage is near or at the planned operational system and represents a significant step up from the previous stage. The focus at this stage is on demonstrating the technology's performance and capabilities in a real world operational environment. This could include testing the prototype on a surrogate platform, demonstrator, or test bed that closely simulates the intended operational environment. The goal at this stage is to further validate the technology's performance and to identify any remaining technical challenges that need to be addressed before the technology can be deployed in an operational setting. This stage represents a critical transition point in the technology development process, as it provides the evidence needed to support decisions regarding the implementation and deployment of the technology.

TRL 8. *Actual system completed and qualified through test and demonstration*. TRL8 represents the final stages of technology development and is considered to be the end of true system development. At this stage, the technology has been completed and is ready for commercialization, with all its components integrated and operating in its final form. The technology has been tested and demonstrated to be effective and reliable in meeting design specifications and operating under expected conditions. The focus of this stage is to validate the technology through test and demonstration and to ensure it is ready for commercialization and widespread use. Examples of technology at TRL 8 include developmental test and evaluation of the system in its intended final form and commercial products that have undergone rigorous testing and are now available on the market.

TRL 9. *Actual system proven through successful mission operations*. At TRL9, the technology is considered to be mature and has been proven to work successfully under real-world, operational conditions. This is the final stage of technology development, where the technology is deployed and used for its intended purpose, often on a large scale. Examples of this might include the use of a new technology in a commercial product, or the deployment of a new space mission using cutting edge technology. At this stage, it is expected that the technology will perform as intended and meet all design specifications, and that any necessary modifications have been made based on the results of earlier tests and demonstrations.

The technology readiness level pathway is a widely used framework for evaluating the maturity of a technology, from the initial stages of basic research and development to the point where it is ready for commercialization and widespread use. As technology moves along the TRL pathway, the level of technology development and system integration (i.e., fusion reactor) increases, as well as the fidelity of the simulation or testing environment. This process helps to assess the risks associated with developing and deploying a technology, and to identify areas that need further research and development. It is important to keep in mind that the TRL framework can be adapted and modified for different technologies, including fusion reactors.

To effectively use the TRL approach in fusion technology, it is important to define and adopt a clear and consistent terminology that is unique to fusion, specifically definition of terms such as “laboratory environment”, “relevant environment”, “operational environment”, “component” and “system”. This will help to ensure that all stakeholders involved in the development and use of fusion technology are speaking the same language and that there is clear communication regarding technology readiness. The use of TRLs can help to identify gaps in technology readiness, highlight at-risk technologies that require additional attention, and increase transparency in decision-making. Table 4 provides a summary of associated models, performance requirements, and environments for each of the nine TRLs. It is important when assessing the TRLs to check the type of modelling, its performance requirements, and the environment under which it is tested. For example, at TRL4, the model will be a mock-up that may not fully cover the technology and will be tested in a laboratory. These links are also presented in Table 4.

The TRL scale is just a guide to help assess the maturity of a technology and does not provide an absolute measure of its development. The time and resources required to move from one TRL to another can vary greatly depending on the specific technology, the resources available, and the goals and challenges faced in the development process. Additionally, some technologies may never reach a high TRL, while others may move through the scale more quickly or stall at a certain point. The TRL scale is a useful tool for technology development and evaluation, but it is important to use it in the context of other metrics and evaluations to get a complete picture of a technology's progress. In other words, technologies with low TRL can mature more quickly and technologies with high TRL can stagnate and never mature.

TABLE 4. MODELS, PERFORMANCE REQUIREMENTS AND ENVIRONMENTS PER TRL

| TRL | Associated models | Performance requirements | Required tests and environment representativeness | Comments |
|---|---|---|---|---|
| 1 | N/A | In elaboration | No | N/A |
| 2 | N/A | In elaboration | No | N/A |
| 3 | Mathematical (+experiments) | Partly defined | No | For monitoring progress (technology viability) |
| 4 | Mock-up (Breadboard/testbed) | Partly defined | Laboratory | For monitoring progress |
| 5 | Sub-scale engineering model | Fully defined | Relevant | Enables implementation phase (with higher risks) |
| 6 | Full scale engineering model | Fully defined | Relevant | Enables implementation phase (with lower risks) |
| 7 | Qualification model | Fully defined | Operational | Possible use of engineering qualification model or prototype model |
| 8 | Actual hardware | Fully defined | Operational | End of development |
| 9 | Actual hardware | Fully defined | Operational | Operationally proven |

Figure 1 presents various scenarios depicting the potential maturation of competing technologies. The underlying assumption is that the most advanced technology will likely achieve level 9 first, exemplified in scenario 1. However, this is not a guaranteed outcome, and alternative possibilities exist. For instance, scenario 2 envisions a less mature technology surpassing the more advanced ones, while scenario 3 shows a scenario where all technologies stagnate without any improvement. In the event that a more mature technology gets overtaken, scenario 4 suggests that a new technology might emerge and take the lead. Scenario 5 presents a situation where changes in technology render a once mature option obsolete, leading to the dominance of a competing technology. Conversely, scenario 6 illustrates a scenario where existing technologies can be adapted and enhanced to address challenges and catch up with new technologies. In essence, the competition among technologies can lead to a wide array of potential scenarios, each with distinct outcomes and implications. The future course of technology development remains dynamic and uncertain, making it essential to consider multiple possibilities and adapt strategies accordingly.

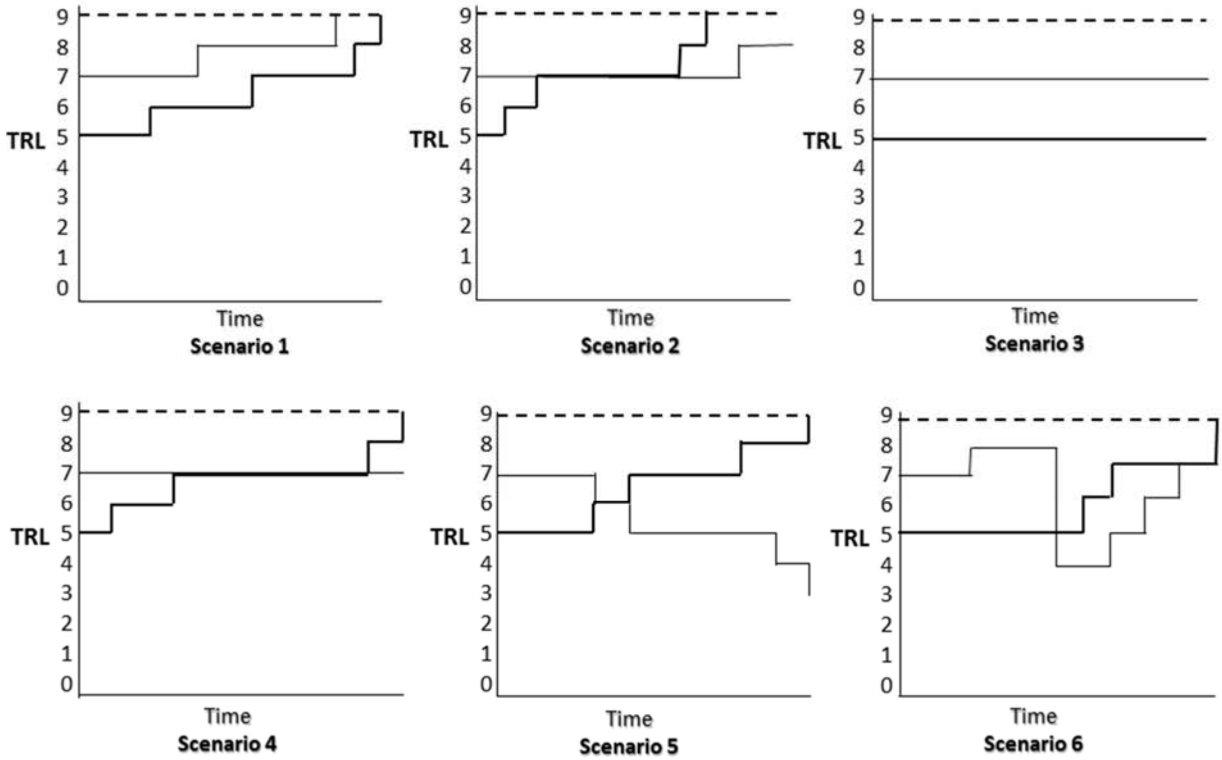


*FIG. 1. Example of six scenarios of two competing technologies maturing differently in time.*

Although the TRLs serve as a valuable gauge of individual technology maturity, they do not guarantee seamless integration among all technologies. Evaluating the integration and interfaces between different technologies requires separate assessments, as relying solely on TRLs of individual components may be inadequate. Furthermore, a technology that has reached maturity in one sector may not necessarily be ready for implementation in a different application or sector. This underscores the critical need for a more precise definition of TRLs to ensure optimal allocation of resources for technology development.

To effectively assess and advance new technologies, it is vital to consider both the integration and interfaces between different components. A well-defined TRL framework becomes instrumental in guiding this process. An illustrative example, demonstrated in Table 5, presents the target TRLs for a fusion project stage gate review. Additionally, the status column highlights the specific areas where development efforts need to be focused.

Therefore, a comprehensive approach that incorporates integration assessment, well-defined TRLs, and targeted development efforts is essential to drive successful technology advancements. By taking these factors into account, resources can be strategically allocated to pave the way for more efficient and effective technology development and integration.

TABLE 5. FIVE STREAMS OF FUSION SPECIFIC TRLs AND THEIR USE IN STAGE GATE / DESIGN REVIEWS

| TRL | Systems | Materials | Software | Manufacturing | Instrumentation |
|---|---|---|---|---|---|
| 1 | Basic principles | Evidence from literature | Mathematical formulation | Process concept proposed | Understand the physics |
| 2 | Technology concept | Agreed property targets, cost & timescales | Algorithm implementation documented | Validity of concept described | Concept designed |
| 3 | Proof of concept | Materials' capability based on lab scale samples. | Prototype architectural design of important functions is documented | Experimental proof of concept completed | Lab test to prove the concept works. |
| 4 | Validation in a laboratory environment | Design curves produced. | ALPHA version with most functionalities implemented with User Manual and Design File available | Process validated in lab | Lab demonstration of highest risk components |
| 5 | Partial system validation in a relevant environment | Methods for material processing and component manufacture | BETA version with complete software functionalities, documentation, test reports and application examples available | Basic capability demonstrated using production equipment | Requiring specialist support |
| 6 | Prototype demo in a relevant environment | Validated via component and/or sub-element testing. | Product release ready for operational use | Process optimised for capability and rate using production equipment | Applied to realistic location/environment with low level of specialist support. |
| 7 | Prototype demo in an operational environment | Evaluated in development rig tests | Early adopter version qualified for a particular purpose | Economic run lengths on production parts | Successful demonstration in test. |
| 8 | Test and demonstration | Full operational test | General product ready to be applied in a real application | Significant run lengths | Demonstrated productionised system |
| 9 | Successful mission operation | Production ready material | Live product with full documentation and track record available | Demonstrated over an extended period | Service proven |

## 3. FUSION SPECIFIC TECHNOLOGY READINESS LEVELS

The requirement for fusion specific TRLs arises from the distinct technological demands in the fusion sector, which are different from other industries. Additionally, there are significant differences between the technologies required for fusion and those required for fission, which highlight the need for a tailored TRL framework. The IAEA-TECDOC-1851 on Integrated Approach to Safety Classification of Mechanical Components for Fusion Applications highlights some of these differences [11]. For example, in the fusion applications, there is no reactivity control or emergency cooling requirements, and no core melt conditions to be addressed. Prevention of core meltdown is not a safety related function for fusion reactors. Most of the main parameters like the safety functions, consequences of failure, fault frequencies, contributing to the safety classification process in fission applications are different for the fusion applications. Yet, the fusion industry has mostly relied on existing codes, standards and industrial practices developed for fission. Fusion technology challenges are also different, if not more demanding. In fusion nuclear facilities, there are many kinds of accidents that can be postulated due the fact that a tokamak is a complex and dense infrastructure with many different energy source terms. In addition, the first confinement barrier, which is surrounded by those energy source terms, has a very complex boundary, and is subjected to a combination of extreme loads not seen in other industry sectors. In [10] the inadequacy of the existing TRLs for fusion is discussed, and an alternative methodology is proposed that allows a quasi numerical analysis by a combination of three quantities: unmitigated probability of failure, severity, and probability of failure detection. To help fusion technology achieve full industrialisation, it is prudent to consider internationally harmonised definitions for fusion specific TRLs and provide fusion specific definitions for all nine TRLs for system, materials, software, manufacturing, instrumentation, and most importantly fusion reactor TRLs.

The proposed addition of fusion reactor TRLs to the TRL matrix shown in Table 5 is an important recognition of the unique challenges associated with fusion technology development. The complex nature of fusion systems, with multiple technologies and components working together, means that system integration is a critical aspect of TRL assessment. Incorporating system integration into the TRLs will help to provide a more comprehensive view of the maturity of the technology and will facilitate better communication and coordination between different stakeholders involved in the development and deployment of fusion reactors. Fusion energy has been a focus of scientific research for several decades, and although significant progress has been made, many challenges remain to be overcome. Both tokamak and non-tokamak approaches to fusion energy face a range of technological challenges, including the achievement of high temperatures and vacuum conditions, the confinement and control of plasma, closed fuel cycle, and the efficient extraction of energy from the fusion reaction. It is hoped that the fusion specific TRLs proposed in this publication will help develop technologies to overcome these challenges. Some of the main challenges for magnetic confinement fusion are:

- *Plasma science*: confining and controlling the hot plasma is a major challenge in fusion technology. Plasma, which is a mixture of ions and free electrons, is highly energetic and difficult to contain. The intense heat of the plasma means that it needs to be confined in a magnetic field to prevent it from touching the walls of the reactor and cooling down;
- *Plasma exhaust*: intense heat generated by the fusion reaction creates a need for an effective exhaust system to manage the heat; this requires the development of materials that can withstand high temperatures and the associated thermal stresses, as well as advanced heat transfer and cooling systems;
- *Materials science*: fusion reactions produce high energy neutrons, which can cause significant damage to the materials used in the reactor; this means that new materials need to be developed that can withstand the high neutron dose and the attendant nuclear heating;
- *Fuel handling*: tritium, one of the fuels used in fusion reactions, is a radioactive isotope that needs to be bred and handled carefully; developing effective systems for breeding and handling tritium fuel is a critical challenge in the development of fusion technology;
- *Remote maintenance*: conditions inside a fusion reactor are demanding and potentially hazardous, making remote maintenance and repair an important consideration. Advanced

robotics and automation technologies will be needed to allow maintenance to be performed safely and efficiently;

— *Advanced manufacturing*: building a fusion reactor requires the production of complex components with precision and accuracy; this requires the development of advanced manufacturing techniques that can economically produce these components.

The TRL assessment is based on a matrix of five streams with nine scales each. This matrix aims to cover all possible new technology development with the fusion devices from its concepts to its operation and maintenance including dismantlement. Well detailed and defined streams and scales are essential to make a proper assessment of the maturity of technology. The following sections present this matrix with definitions oriented toward the fusion devices such as International Thermonuclear Experimental Reactor (ITER). These definitions are extracted and tailored from existing standards and guidelines related to systems engineering and TRL assessment [12−15]. First of all, some of the basic definitions of wording used usually in the assessment of TRL are given followed by the definitions of each stream and their related nine scales. These streams are the materials, manufacturing, instrumentation, software, and system. This splitting intends to ease the assessment with dedicated streams applicable in many technology developments.

### 3.1. GENERAL DEFINITIONS

The following definitions are useful while performing the assessment of a technology maturity. They are important to understand as they are commonly used wording in the TRL assessments:

*Breadboard (mock-up/testbed):* Physical model designed to test functionality and tailored to the demonstration needed

*Current or status TRL:* Readiness level assessed at the latest assessment (TRA)

*Critical function of an element:* Mandatory function which requires specific technology verification

*Critical function of technology:* Refers to a mandatory function that requires specific technology verification, as stated in the International Standard. This particular function becomes imperative when the element or its components are novel and cannot be evaluated based on previous implementations. It is also crucial when the element is employed in a new context, such as unexplored environmental conditions or a unique application that hasn't been previously demonstrated. In the context of the International Standard, the term critical function always refers to technology critical function, which should not be confused with safety critical function. The critical function of technology is a specific function of an element that needs to be verified to ensure that it works as intended and meets the necessary performance requirements. The verification process for critical functions of technology is essential to ensure that the element can perform its intended function without failure. This process involves testing and verifying the new technology to ensure that it works reliably and safely under various conditions. By verifying the critical function of technology, engineers and designers can ensure that the technology meets the necessary performance and safety requirements, and that it is suitable for use in its intended application.

*Critical technology or critical technology element:*

The significance of a technology element arises when the successful functioning of the system under development relies on this specific technology element to meet operational requirements within acceptable cost and schedule constraints. Additionally, the technology element or its application may be considered new, novel, or within an area that presents significant technological risks during detailed design or demonstration. For example:

- Plasma initiation, stabilisation, and control
- Superconducting materials
- High temperature and neutron radiation resistant materials
- Superconducting based magnets
- Tritium breeding
- Robotics (remote handling and maintenance)
- Advanced and high precision manufacturing

*Element (ISO 16290):* Item or object under consideration for the technology readiness assessment; an element can be a component, a piece of equipment, a subsystem or a system

*Feasibility of manufacturing:* During the design cycle, various characteristics are taken into account, with a focus on process capabilities, machine or facility flexibility, and the consistent ability to meet cost and quality requirements. The associated activities encompass a range of actions and collectively contribute to the design's ability to meet production requirements consistently, with the desired level of cost-effectiveness and quality. They may include:

- Designing for commonality and standardization, leading to fewer parts;
- Conducting a comprehensive technology assessment that considers commercial and industrial applications, as well as the supplier base;
- Designing for applications that can be used in multiple contexts or have dual uses;
- Incorporating modularity and plug-compatible interfaces/integration into the design;
- Designing for flexibility, adaptability, or utilizing robust design principles;
- Employing reliable processes and materials;
- Utilizing monolithic and determinant assembly techniques;
- Designing with manufacturing and assembly in mind;

— Striving to achieve high production yield.

*Laboratory environment:* Controlled environment needed for demonstrating the underlying principles and functional performance

*Level:* Refers to the equipment maturity that relates to the level of advancement and development of a particular piece of equipment. When equipment is already in use for a similar function in the same environment, it is considered to have a higher level of maturity compared to equipment that is still under development. These levels of maturity are assessed qualitatively and are represented on a nine-point scale, providing an indication of the equipment's overall maturity level.

*Model (ISO 16290):* Physical or abstract representation of relevant aspects of an element that is put forward as a basis for calculations, predictions, tests or further assessment.

*Operational environment:* Set of natural and induced conditions that constrain the element from its design definition to its operation.

*Pilot line environment:* Refers to a setting that encompasses essential elements of production realism. This includes the presence of appropriate equipment, skilled personnel, suitable facilities, materials, components, work instructions, processes, tooling, and factors such as temperature, cleanliness, and lighting. The purpose of the pilot line is to manufacture production configuration items, subsystems, or systems that meet design requirements during low rate production. It is important for the pilot line to employ full rate production processes to the greatest extent possible, ensuring a realistic and accurate representation of the eventual production environment.

*Producibility:* Refers to the degree of ease in manufacturing an item that satisfies engineering, quality, and affordability criteria. Several associated activities that collectively contribute to enhancing the producibility of the item, ensuring that it can be effectively manufactured while meeting the required engineering, quality, and affordability standards, may include:

— Designing with consideration for specific process capabilities and control parameters;
— Conducting material characterization analysis;
— Employing techniques such as Taguchi method and design of experiments to analyse and reduce variables;
— Developing critical materials and processes prior to finalizing product design;
— Utilizing modelling and simulation to assess trade-offs between product and process design;

— Designing and developing closed-loop process control mechanisms for crucial components.

*Production line:* Refers to an environment that encompasses all necessary capabilities for manufacturing production configuration items, subsystems, or systems that adhere to design requirements. It operates with manufacturing processes and procedures that are effectively controlled, meaning that factory acceptance tests have been satisfactorily completed. The production line is also capable of meeting the required production rate and quantities as specified. It ensures that the manufactured items are produced in accordance with design specifications, utilizing controlled and validated manufacturing processes, to achieve the desired production output within the specified timeframe.

*Production relevant environment:*

Refers to a setting that incorporates certain elements of shop floor production realism, including facilities, personnel, tooling, processes, and materials. During this phase, it is important to minimize reliance on laboratory resources. Demonstrating the capability to meet cost, schedule, and performance requirements of the engineering and manufacturing development phase is essential in a production relevant environment, primarily through the production of prototypes. This demonstration should instil confidence in the programme's ability to achieve these targets. Additionally, there should be a clear indication of the intended approach to fulfil the requirements in both production representative and pilot environments, ensuring that the demonstrated results can be replicated in these settings.

*Production representative environment:*

Refers to a setting designed to emulate production conditions as closely as possible, taking into account the maturity of the design. It incorporates production personnel, equipment, processes, and materials that will be present on the pilot line whenever feasible. High quality work instructions and tooling are utilized, with any anticipated changes limited to downstream design modifications that address performance or production rate concerns. There is no reliance on laboratory environments or personnel within this context, emphasizing the aim of aligning the environment with actual production conditions to ensure realistic outcomes.

*Prototype:* Refers to a physical or virtual model that serves the purpose of assessing the technical or manufacturing feasibility and utility of a specific technology, process, concept, end item, or system. It allows for the evaluation and exploration of the potential of the aforementioned aspects, providing valuable insights into their practicality and effectiveness. The prototype serves as a tangible representation that aids in understanding and testing the functionality, design, and overall viability of the technology or process under consideration.

*Readiness:* Refers to time; specifically, it means ready for operations at the present time

*Relevant environment:* Minimum subset of the operational environment that is required to demonstrate critical functions of the element performance in its operational environment.

*Simulated/operational environment:*

Environment is (1) either a real environment that can simulate all the operational requirements and specifications required of the final system or (2) a simulated environment that allows for testing of a virtual prototype. Used in either case to determine whether a developmental system meets the operational requirements and specifications of the final system.

*System of interest*: The system whose life cycle is under consideration.

*Target TRL:* Level / maturity requested by the project / operational requirement.

*Technology readiness assessment (TRA):*

TRA is a formal, systematic, metrics based process and accompanying report that assesses the maturity of technologies called critical technology elements to be used in systems.

*Trade-off:* Decision making actions that select from various requirements and alternative solutions based on net benefit to the stakeholders.

## 3.2. MATERIALS TECHNOLOGY READINESS LEVELS

This section describes the application of TRLs to the development of materials. Materials are defined as physical substance used to build the system/subsystem/component in order to fulfil one or more functions; for instance, structural integrity or/and functional purpose such as thermal/electric isolation or anticorrosion. Thus, this includes the structural and the functional materials. The tritium breeding materials are considered among the functional materials. The definitions as follows, are similar to the material readiness levels developed by the EUROfusion[1] [16] although the qualification process and the manufacturing somehow included in the original version was discarded in order to be assessed separately within the method stream and manufacturing stream, respectively. The use of these TRLs

[1] EUROfusion is a consortium of national fusion research institutes located in the European Union, the United Kingdom, Switzerland and Ukraine. It was established in 2014 to succeed the European Fusion Development Agreement as the umbrella organisation of Europe's fusion research laboratories.

will depend on the definition of validated for the relevant material. The appropriate codes and standards or criticality will shape the level of appropriate testing and need for physical validation. The definitions are:

*Materials TRL1: research about the material(s)*

The evidence that applied research about this/these material(s) are demonstrated from reports and/or publications. There is a basic information about the composition of the material/s.

*Materials TRL2: environmental/operating conditions and material requirements identified*

The conceptual studies of the application have been performed with the purpose to identify the full ranges of environmental/operating conditions and material requirements. The first trials at the laboratory scale (with the batches of no more than few kilogrammes) of the material are available. There are some results based on coupon scale samples for characterization.

*Materials TRL3: basic properties are known*

The first data are collected and analysed in order to confirm the possible application in operation conditions. For instance, the basic thermophysical and mechanical properties of the material/s have been identified over the required temperature range of operation. The irradiation effects, if applicable, in single material specimens are already investigated.

The purpose of the material/s starts to be studied collecting data for example about the compatibility with the coolant, the joining techniques demonstration, or the cyclic heat flux tests for prototyping. Constitutive models are developed to predict material behaviours and they are used to validate produced raw data.

*Materials TRL4: material behaviour demonstration*

After the studies, the demonstrations have been done on the feasibility to use the material/s for their intended purpose at the scale of the material product forms (plate, tube, sheet,...). Consequently, with data and modelling, the joining techniques have been demonstrated; data and modelling of coolant and other corrosive interactions exist; dedicated heat flux experiments demonstrate key mechanical behaviours under normal and off-normal conditions. Data and modelling are now collected at the scale of the subcomponent or component (i.e., subsystem). The behaviours of the subsystems are studied such as the irradiation effects. The design curves start to be produced.

*Materials TRL5: feasibility of manufacturing*

Larger scale (sufficient to build component or system) fabrication of the products forms are carried to study the reproducibility. Prototypes have been built and operated in a simulated integrated environment (e.g., non-neutron test facilities). The environment needs to be representative of the system that it is operating in, including all interfaces, lifecycle history.

The inspection methods (e.g., non-destructive test) starts to be developed to evaluate the structures integrity and/or the production maturity. It has to be noted that the manufacturability is to study the feasibility of manufacturing and not to develop all the detailed procedures of manufacturing (e.g., welding procedures and qualification), these are done within the manufacturing stream and possibly method stream.

*Materials TRL6: validated via component and/or sub-element testing*

The prototypes have been operated and tested in a relevant environment. The test results confirm the structural integrity or the functional purpose of the material/s. At this level, it is advised to have the technical reference that is the set of standards and codes (see method stream) drafted before moving to the next level.

*Materials TRL7: validated in operational environment*

The material has been used in a component tested in its operational environment. The database is well populated, and the material handbooks cover the design curves and the design rules adequate for all operation conditions. If applicable, it is good practice at this level to have started the certification / qualification of the material/component.

*Materials TRL8: full operational test*

The end-of-life failure mode and rates are understood at this level. The characteristics in operation have been fully demonstrated. The prototypes, if any, have been operated to end of life. The end-of-life characteristics are understood (failure modes and rates).

*Materials TRL9: material and component successfully used in operation*

The material has been used in operation, and it is important to collect the data during the operation in order to confirm the data availability about the behaviours demonstrated during the development of the material/s.

## 3.3. MANUFACTURING TECHNOLOGY READINESS LEVELS

Manufacturing is the process of converting raw materials, components, or parts into finished goods that meet a customer's expectations or specifications. For manufacturing TRL, there is a TRL10[2] for optimization of the production. The following definitions are based on [17] being a well established stream:

*Manufacturing TRL1: process concept proposed*

Fundamental research broadens scientific principles that could potentially lead to manufacturing applications. The primary emphasis is on conducting a comprehensive evaluation of potential manufacturing opportunities. This research remains unrestricted and open-ended, allowing for exploration without limitations.

*Manufacturing TRL2: validity of a concept described*

Explores manufacturing science and/or concepts within a practical context. It focuses on the application of these principles. However, the identification of materials and process approaches is confined to theoretical studies and analyses. The study is in its early stages, and initial manufacturing feasibility and challenges are beginning to surface.

*Manufacturing TRL3: experimental proof of concept completed*

To verify the findings of the paper studies, analytical or laboratory experiments have been undertaken. Experimental hardware or processes have been developed; however, they have not been fully integrated or made representative of the actual manufacturing conditions. An assessment has been carried out to characterize the materials and/or processes for their feasibility and availability in manufacturing. Nevertheless, additional evaluation and demonstration are needed to further validate and refine these aspects.

*Manufacturing TRL4: process validated in laboratory*

The necessary investments, including manufacturing technology development, have been identified. Robust processes have been established to guarantee manufacturability, producibility, and product quality, ensuring the capability to produce technology demonstrations. Manufacturing risks have been thoroughly assessed in preparation for building a prototype. Moreover, the drivers impacting manufacturing costs have been identified. Producibility assessments of various design

[2] TRL 10 is the readiness/maturity level applicable to a system/technology which has been proven through extended operations; typically it is demonstrated in all typical operating environments and its performance levels and failure rates are characterized.

concepts have been completed, and key performance parameters are well understood. The process has highlighted specific requirements concerning tooling, facilities, material handling, and the skills needed to successfully execute the manufacturing phase.

*Manufacturing TRL5: basic capability demonstrated using production equipment*

The manufacturing strategy has undergone refinement and now requires the integration of a comprehensive risk management plan. The identification of enabling and critical technologies and components has been successfully accomplished. Demonstrations have been conducted on prototype materials, tooling, test equipment, and personnel skills in a production-relevant environment, which has yielded positive results. However, it is important to note that several manufacturing processes and procedures are still in the development phase. Producibility assessments of key technologies and components are currently ongoing to ensure optimal efficiency and effectiveness. To aid in decision-making and cost estimation, a detailed end-to-end value stream map is being utilized as the foundation for building a cost model. This will provide valuable insights into the cost implications throughout the entire manufacturing process.

*Manufacturing TRL6: process optimised for capability and rate using production equipment*

The initial manufacturing approach has been formulated, and a significant portion of the manufacturing processes have been defined and assessed. However, certain engineering and design modifications are still underway. The preliminary design of critical components has been completed, and producibility assessments of key technologies have been concluded. Demonstrations of prototype materials, tooling, test equipment, and personnel skills have been successfully carried out on subsystems/systems in a production-relevant environment. In-depth cost analyses, including design trades, have been performed to establish cost targets. Moreover, long lead and essential supply chain elements have been identified and described. The Industrial Capabilities Assessment, which evaluates the readiness and capacity of industrial capabilities, has been fully completed. This comprehensive assessment provides valuable insights into the manufacturing landscape and its ability to meet project requirements.

*Manufacturing TRL7: capacity to produce systems/subsystems/components in a production representative environment*

Material specifications have received approval, and the necessary materials, including filler material where applicable, are available to meet the planned pilot line requirements. Manufacturing processes and procedures have been successfully demonstrated in an environment representative of actual production conditions. Concurrently, comprehensive producibility trade studies and risk assessments are in progress. The cost models have been updated to incorporate detailed designs and are being monitored against the set targets. Initiatives for reducing unit costs are actively being pursued. Additionally, the evaluation of the supply chain and the establishment of supplier quality assurance and control protocols have been defined. Long lead procurement plans have been put into place to ensure timely acquisition of critical components. Furthermore, the design and development of production tooling and test equipment have been undertaken at earlier TRLs to support efficient manufacturing processes.

*Manufacturing TRL8: pilot line capacity demonstrated*

The detailed manufacturing design has reached a highly advanced stage and is now stable enough to transition into low-rate continuous production. All required materials are readily available to support the planned low-rate production. The manufacturing and quality processes have been thoroughly tested and validated in a pilot line environment, demonstrating excellent control and readiness for low-rate production. Any known producibility risks have been effectively addressed, posing no significant barriers to low-rate production. The engineering cost model has been meticulously driven by detailed designs and duly validated. The supply chain has been established and remains stable, ensuring a steady flow of necessary components and resources. Given the comprehensive preparations and successful validation, the system is well-prepared for the manufacturing readiness review, which marks a significant milestone in the manufacturing process. The overall readiness and maturity of the manufacturing system instil confidence in its ability to progress smoothly into the low-rate production phase.

*Manufacturing TRL9: full capacity demonstrated over an extended period*

The key design features of the major system have been thoroughly tested and evaluated, demonstrating stability and reliability. Adequate materials are readily accessible to fulfil the planned rate production schedules. Established manufacturing processes and procedures adhere to stringent quality standards, achieving a level of control that meets design key characteristic tolerances within the low rate production environment, typically at a three-sigma level or other appropriate quality benchmarks. Continuous monitoring of production risks is ongoing to ensure timely identification and mitigation of any potential issues. The initial production costs for low rate production have successfully met the set goals, and the learning curve has been validated, allowing for possible improvements in efficiency and cost-effectiveness. Moreover, a comprehensive actual cost model has been developed, taking into account the full rate production environment and considering the impact of continuous improvement efforts. This comprehensive cost model aids in optimizing production costs and enhancing overall performance.

## 3.4. INSTRUMENTATION TECHNOLOGY READINESS LEVELS

This section describes the application of TRLs to the development of instrumentation. The instrumentation is integration of device(s) into the system that communicates, denotes, detects, indicates, measures, observes, records, or signals a quantity or phenomenon, or controls or manipulates another device. In fusion applications, instrumentation plays a critical role in diagnostics and control of plasma.

The maturity of these functions of instrumentation is assessed with this TRL stream:

*Instrumentation TRL1: understand the physics*

The instrument is based on one or several physics processes / phenomena to provide its function(s). All these physics processes / phenomena need to be well identified and described in the reports.

*Instrumentation TRL2: concept designed*

The interactions between these physics processes / phenomena and the interceptive character of the instrumentation with the operation and any other system/s is sufficiently understood for a development of a conceptual design.

*Instrumentation TRL3: laboratory test/s to prove the concept works*

On or several test rigs/benches have been built to establish that the concept works. The limitation needs to be well reported in order to understand if it can work in the operational environment.

*Instrumentation TRL4: laboratory demonstration/s of the most critical components*

First mock up or prototype or breadboard has been developed to demonstrate that the function of the instrumentation works as required. It is not necessarily fully integrated. At the minimum, the sensor/measurement system/s as well as the data acquisition/ recording system/s are working properly together with the control system/s.

*Instrumentation TRL5: support/adaptation requirements identified*

The integration of the instrumentation into its final physical environment have been studied to identify how it will be done and if it can meet the requirements. Concurrent engineering sessions with possible design/manufacturing re/iterations can occur between the instrumentation and the systems constituent of its environment to study the full integration.

*Instrumentation TRL6: applied to relevant environment with low level of support/adaptation*

The integrated prototype has been built for demonstration in a relevant environment. Interceptive behaviour and/or interaction with the operational modes/scenarios has to be investigated in relevant environment. As a result, the full integration in relevant environment is now understood and ready to be developed.

*Instrumentation TRL7: successful demonstration in test in operational environment*

The prototype and/or models (only for some specific loading cases such as irradiation) have been tested in an operational environment. Interceptive behaviour and/or interaction with the operational modes/scenarios has to be investigated in operational environment. The result needs to show compliance with all the requirements of the instrumentation.

*Instrumentation TRL8: demonstrated productionised system*

The instrumentation was produced in or with the systems constituent of its environment. The finalization of the production control needs to demonstrate that it is compatible with the sensitivity / accuracy of the requirements. The test result needs to show compliance with not only all the requirements of the instrumentation but also the other systems constituent of its environment.

*Instrumentation TRL9: service proven*

The instrumentation worked in its actual environment during operation. Its functions were performed as expected and possible optimization can take place considered the lessons learned.

### 3.5. SOFTWARE TECHNOLOGY READINESS LEVELS

The ISO TRL definition does not address the use of TRLs for software and there is no international uniform approach for using the TRLs for software development. It is proposed to use the standard ISO scale applied for software development by providing a clear definition of the expected software development state at each TRL.

Software TRL are to be applied to assess the maturity of technologies implemented in software which may be part of the fusion reactor, ground supporting systems or engineering tools. Due to their very different development and application characteristics, two main types of software need to be identified for the purpose of software TRL definition:

— *Software tool*: software element that runs in a stand alone mode, i.e. that performs a function without requiring a specific input/output simulator;
— *Building block software*: embedded software element that has an identifiable function within a more complex (software) system, and that can potentially be reused for a range of

applications. It necessarily interacts with other software and possibly also with hardware. It is executed as part of a larger software application. It includes intellectual property cores for microelectronics as a functional block of logic or data used to make a field-programmable gate array (FPGA) or for the application specific integrated circuits (ASICs).

For specific embedded software targeting a specific application and not conceived to be reused in another domain of application (e.g. specific equipment embedded software) the corresponding hardware TRL stream (instrumentation, system) is applicable, the specific software is part of the hardware TRL assessment.

### 3.5.1. Underlying principles of the software technology readiness level stream

Similarly to hardware TRLs, the software TRL stream is not intended for managing software development projects, as there are typically established software engineering and management standards for such projects. Instead, the software TRL stream serves as a valuable tool to assess the maturity of specific software technologies (such as building blocks or tools) within the context of their intended applications. The software TRL stream is structured as follows:

- **TRL 1 to 4**: These levels represent the initial stages of development, where functionality is progressively implemented, starting from mathematical formulations and advancing through prototyping and incremental enhancements. For software tools, TRL 4 corresponds to the alpha version, while for building blocks, it represents a pre-product prototype.
- **TRL 5 and 6**: These levels signify the transformation of a prototype into a product with frozen requirements. At this stage, a pre-qualification data package is available, instilling confidence in the product's performance in the final environment. For software tools, TRL 5 corresponds to the beta version, and TRL 6 corresponds to the first released version. For building blocks, TRL 6 indicates a released product verified within a simulated environment.
- **TRL 7**: This level entails software qualification for the intended application, verifying software performance in its designated environment. For software tools, this corresponds to full validation on a representative pilot case, while for building blocks, it involves successful qualification as part of the intended application.
- **TRL 8**: At this level, the software is considered ready for final product acceptance and operation. For software tools, it indicates readiness for full deployment in operation, and for building blocks, it signifies successful final acceptance of the product embedding software.
- **TRL 9**: The highest level corresponds to successful operations and achievement of desired performance in the intended application.

It is important to note that the criticality of software, as defined in relation to dependability and safety based on the consequences of failures, is not linked to the maturity described by the TRL. These aspects are independent of each other.

TABLE 6. DESCRIPTION OF SOFTWARE TRLs

| TRL | Description | Requirements | Verification | Viability |
|---|---|---|---|---|
| 1 | **Mathematical formulation** detailed description. Research results published. | Expression of an issue and of a concept of solution. | Proven mathematical formulation. | Feasibility to be implemented in software demonstrated. |
| 2 | **Algorithm** implementation documented. Practical application identified. | Concrete specification of a part of the issue. | Individual algorithms undergo rigorous testing, leading to their thorough characterization and successful demonstration of feasibility. | Feasibility to build important functions in a system architecture demonstrated. |
| 3 | **Prototype** architectural design of important functions is documented. | Requirements for some solutions to a range of issue. Main user cases implemented. | A selected portion of the complete functionality is developed and subjected to testing, enabling the demonstration of performance within a simulated laboratory environment. | Feasibility to build an operational system taking into account performance demonstrated. |
| 4 | **ALPHA version.** Most functionalities implemented; user manual and design file available. | The domain of applicability is precisely identified, and requirements for solutions to various issues are specified. All user cases are successfully implemented. | Verification and validation process is partially completed, or completed for only a subset of the functionalities, in a representative simulated laboratory environment. | Feasibility to complete missing functionalities and reach a product level quality demonstrated. |
| 5 | **BETA version.** Implementation of complete software functionalities. Documentation, test reports and application examples available. | Formal definition of the domain of (re)use and associated variability. All user cases and error handling specified. | Validated against the requirements of the complete domain of applicability including robustness, in an End-to-end representative laboratory environment including real target. | Feasibility to fix all the reported issues. User support organization in place. |
| 6 | **Product release.** Ready for use in an operational/production context, including user support. User friendliness validated**.** | Engineering and quality assurance documentation available. Configuration control and quality assurance processes fully deployed. All use cases and error handling implemented. | - Building block: validated against the requirements of the complete application domain in test environment.<br>- Tool: validated process is complete for the intended scope, including robustness in an end-to-end fully representative laboratory environment. | Feasibility to be applied in an operational project demonstrated. Availability of a data package to support future qualification. |

TABLE 6. DESCRIPTION OF SOFTWARE TRLs (Cont.)

| TRL | Description | Requirements | Verification | Viability |
|---|---|---|---|---|
| 7 | **Early adopter version.**<br>- For building block software: qualified for a particular purpose.<br>- For tool software: ready for market deployment. | Requirements traced to application requirements.<br>Requirement specifications validated by the users. | - Building block: integrated in the nuclear fusion application following the applicable software standards<br>- Tool: has been successfully validated in a pilot case representative of intended application. | Engineering support and maintenance organization in place, including helpdesk. |
| 8 | **General product.** Ready to be applied in a real nuclear fusion application. | Application requirements specification validated by the users.<br>Full documentation available including qualification file, manuals and anomalies reports. | - Building block: integrated in nuclear fusion applications and system qualification successfully completed.<br>- Tool: successfully applied in an operational project but not yet validated against the final environment. | Capability for real time data exploitation and post run analysis. |
| 9 | **Live product.** Applied in the execution of a real nuclear fusion application. Full documentation and track record of nuclear fusion applications available. | Building block: Maintained<br>Tool: full process implemented, maintenance, updates, etc. | - Building block: fully validated for the application and qualified for intended range of applicability.<br>- Tool: Successfully validated in one or several nuclear fusion applications. All anomalies encountered have been analysed and resolved. | Sustaining engineering, including maintenance and upgrades, in place. |

### 3.5.2. Examples

The software TRLs are described in Table 6. This subsection discusses some relevant and representative examples.

*3.5.2.1. Software building block*

A typical software building block, like an operating system, follows the TRLs definitions as follows:

**TRL 1:** mathematical formulation and theoretical foundations of the software building block are formulated, and the fundamental concepts and principles have been observed and documented in scientific literature or technical reports;

**TRL 2:** prototype of the algorithm itself exists, independent of any hardware or application context. A technology concept is developed, and there is an initial plan for building the software block with this particular algorithm;

**TRL 3:** feasibility of the software building block is demonstrated through analytical and/or experimental methods. An architecture is in place that showcases the algorithm's integration into an operating system;

**TRL 4:** operating system features a specified interface for application software users, and all expected functions are implemented, though not all are fully tested (e.g., priority inversion protection). The operating system is validated through simulations on the target processor's simulator, which operates on standard hardware;

**TRL 5:** the operating system's domain of use is defined, in terms of target processors (such as for example ERC32 processor that is radiation tolerant and thus applicable to space applications, or performance computing such as PowerPC, a reduced instruction set computer instruction set architecture), communication capabilities (such as 1553 drivers) or operational capabilities (such as maximum number of priorities, tasks, semaphores). The system is validated for all parameters and hardware environments relevant to its intended reuse. This validation is conducted on a hardware board with a representative target processor and hardware communication drivers;

**TRL 6:** formal qualification data package, adhering to the software standards applied at the expected criticality level, is available and approved by software product assurance. It serves as a qualification credit for potential projects. The process for delta qualifying the operating system in user projects is defined. Support structures, such as a helpdesk, are established. The operating system is considered a product and can be offered to users;

**TRL 7:** user selects the operating system for application software. Thus, specific parameters for the intended use are chosen, including the target processor, communication drivers, and maximum sizes and ranges. The operating system is successfully qualified with these chosen values in the intended environment, using the actual hardware of the project for validation;

**TRL 8:** software is integrated into final hardware that has been accepted and is ready for use;

**TRL 9:** operating system functions nominally and reliably in its intended operational environment.

*3.5.2.2. Software tool*

A typical software tool, such as a software compiler (or a hardware description language compiler in microelectronics) progresses through the following TRLs:

**TRL 1:** the algorithm for parsing source code to generate machine code or gates, in one or multiple passes, is in existence;

**TRL 2:** set of prototypes is developed, capable of reading a selection of the source code syntax and generating machine code using part of the instruction set;

**TRL 3:** the architecture of the compiler is defined, encompassing the complete source code syntax and semantics;

**TRL 4:** the alpha version of the compiler features a basic man–machine interface, generating non-optimized machine code, with relatively slow execution times. It is validated using typical examples of source code;

**TRL 5:** the beta version of the compiler improves machine code generation optimization, performance, and the ergonomics of the man–machine interface. A reference test suite of source code is established to validate the compiler, and the generated object code successfully runs on the hardware processor;

**TRL 6:** the compiler is transformed into a fully-fledged product with comprehensive documentation and acceptable performance. It generates complete and user-friendly error messages. Support services, product packaging, and delivery are efficiently organized;

**TRL 7:** the compiler is delivered to early adopters for extensive testing. User feedback is diligently considered to enhance the compiler's robustness;

**TRL 8 and TRL 9:** the compiler is deployed to the entire user community, reaching full-scale implementation and utilization.

## 3.6. SYSTEM TECHNOLOGY READINESS LEVELS

In system engineering, a system (or system of interest) is an integrated collection of elements, subsystems, or assemblies designed to achieve a defined objective [18]. These elements encompass various components, such as hardware, software, firmware, processes, people, information, techniques, facilities, services, and other supporting elements. A more general definition is provided in [19] that is a combination of interacting elements organized to achieve one or more stated purposes.

The TRLs applied to the development of a system are described as follows:

*System TRL1: basic principles observed and reported*

At this lowest level (initial level) of technology readiness, the basic principles are observed and reported, laying the foundation for applied research and development (R&D). The technology's fundamental properties are explored through scientific research, and the identified principles are documented in research papers or technical reports that underlie this technology with references to who, where, when.

*System TRL2: technology concept and/or application formulated*

Once the basic principles are observed, the invention process begins, and potential practical applications can be identified. However, these applications are speculative at this stage, lacking detailed analysis or proof. Analytical studies or basic experiments may be conducted, outlining the considered applications and providing analysis to support the concepts.

*System TRL3: analytical and/or experimental function and/or characteristic proof of concept*

Active R&D commences at this level, with analytical and laboratory studies aimed at proving the concept's functional and characteristic viability. The technology's separate elements are validated physically through tests, with results collected and compared to analytical predictions. Early trade-offs between competing technologies can be explored at this stage.

*System TRL4: component and/or breadboard function verification in a laboratory environment*

This level involves verifying the functionality of basic technological components integrated into a laboratory environment. The fidelity at this stage is relatively low compared to the final system. The integration is typically limited to ad hoc hardware in the laboratory, and it is crucial to demonstrate how the results differ from the expected system goals.

*System TRL5: component and/or breadboard function verification in a relevant environment*

The fidelity of breadboard technology significantly increases. The basic technological components are integrated with realistic supporting elements, enabling testing in a simulated environment. High fidelity laboratory integration of components occurs, and the test results demonstrate how the breadboard system integrates with other supporting elements in the simulated operational environment.

*System TRL6: prototype and/or model tested and demonstrated in a relevant environment*

A representative model or prototype system is tested in a relevant environment, showcasing a major leap in technology's demonstrated readiness. High fidelity laboratory or simulated operational testing of the prototype system is performed, demonstrating performance closely aligned with desired configurations, including weight, volume, and other constraints.

*System TRL7: prototype and/or model tested and demonstrated in operational environment*

The prototype system is tested and demonstrated in an operational environment, representing a significant advancement from TRL 6. The system prototype is close to, or at, the planned operational level. The testing outcomes are carefully tracked, documenting any encountered problems, plans, options, or actions taken to resolve issues before advancing to the next level.

*System TRL8: actual system of interest qualified through test and demonstration*

At this stage, the actual system of interest is qualified through tests and demonstrations. The technology has been proven to work in its final form under the expected conditions. Developmental tests and evaluations are conducted to determine if the system meets its design specifications. The results are to demonstrate that the system operates as expected within the specified range of environmental conditions.

*System TRL9: actual system of interest proven in operation*

Actual application of the technology in its final form and under mission/operation conditions, such as those encountered in operational test and evaluation. It is important to note that the hardware commissioning and the conditioning are generally not sufficient and not considered enough to reach this level of technology readiness.

## 3.7. FUSION DEVICE TECHNOLOGY READINESS LEVELS

This section presents a practical example of the TRLs applied to a whole system representing fusion devices [20]. This TRL stream can be viewed as an attempt to integrate all five streams described earlier in this publication. There are many experimental fusion devices at different levels of TRLs where different streams are integrated. Fusion device TRLs are defined in Table 7. The TRL9 here is for the fusion device that generates stable reliable electricity. Current and future fusion devices can be assessed to be at / or to be intended to achieve TRL4 (e.g. NIF, Laser Megajoule, Wendelstein 7-X, KSTAR[3]), TRL5 (e.g. EAST, WEST, JET, JT-60), TRL6–7 (e.g. ARC, ITER) up to TRL8 (e.g. DEMO) when operational only.

The examples of the TRLs for two fusion technology components are presented in Annex I.

TABLE 7. ILLUSTRATIVE EXAMPLE OF FUSION DEVICES TRLs

| TRL | Description | Requirements | Device |
|---|---|---|---|
| 1 | Concept/basic principles to achieve plasma. Magnetic confinement (toroidal/spherical) / inertial confinement/magnetised target fusion/hybrid fusion | | N/A |
| 2 | Application of concept / design | | N/A |
| 3 | Lab based small scale plasma | | |
| 4 | Plasma control / disruption avoidance achieved. Divertor physics. | | |

[3] NIF is the National Ignition Facility in the USA; Laser Mégajoule is a large laser-based inertial confinement fusion research device in France; Wendelstein 7-X is the world's largest stellarator fusion device; KSTAR is the Korea Superconducting Tokamak Advanced Research; EAST is Experimental Advanced Superconducting Tokamak in China; WEST, Tungsten Environment in Steady-state Tokamak, (formerly Tore Supra) is a French tokamak; JET is the Joint European Torus; JT-60 is short for Japan-Torus-60; ARC stands for the affordable, robust, compact reactor conceptual design developed in the USA; ITER is international nuclear fusion research and engineering megaproject aimed at creating energy through a fusion; DEMO is DEMOnstration Power Plant.

TABLE 7. ILLUSTRATIVE EXAMPLE OF FUSION DEVICES TRLs (Cont.)

| TRL | Description | Requirements | Device |
|---|---|---|---|
| 5 | Steady state achieved with full diagnostics and control systems. | | Sub scale reactor |
| 6 | Prolonged exposure to intense neutron radiation sustained.<br>Capable to achieve self-sufficiency.<br>Tritium processing. | | Full scale experimental |
| 7 | Steady state plasma under full load condition. | Capable to achieve availability > 50%<br>High neutron fluxes and tritium fuel generated.<br>Plasma fusion gain ($Q_{DT}$) = 5–10.<br>Fusion power 100–500 MW<br>Plasma duration 500–3000 sec. | Full scale experimental |
| 8 | Pilot plant generated net electricity and high temperature heat. | Plasma duration $10^6$–$10^7$ sec.<br>Plasma fusion gain ($Q_{DT}$) ≥20.<br>Fusion power > 500 MW | Full scale prototype |
| 9 | Fusion as reliable energy source. Contributing electricity to the grid as a commercial/industrialised product. | Plasma duration > $3\times10^7$ sec.<br>Plasma fusion gain[4] ($Q_{DT}$) ≥30.<br>Fusion power > 2000 MW | Full scale power plant |

## 4. PROCESS FOR ASSESSING THE TECHNOLOGY READINESS LEVELS

While performing the TRAs, it is important to know that it can be carried out by the same experts and engineers in charge of the development of this technology. In such a case, it is referred to as self assessment. On the other hand, the assessment can also be done by external experts and engineers, in such a case it is referred to as an independent assessment. The best practice is to start with self assessment and depending on the criticality of the technology on the project requirements to call for an independent assessment as needed.

Whatever the type of assessment it is, it is suggested to perform a periodic assessment to re-evaluate the TRL. An evaluation can lead to skipping a level or lower the current level because new elements arose during the development of technology. Additionally, if the project is broken down in reviews and gates such as design reviews and manufacturing readiness reviews, it is a good practice to carry out the assessment at each review/gate. In some projects, a given level needs to be achieved to pass to the review or gate, for instance, the TRL3 need to be reached at the conceptual design and TRL6 at the final design review. Obviously, it is preferable to start the identification of the critical technologies at early stage of the project as soon as conceptual design is completed. This will also help in technology selection and to perform the trade-off of the concepts.

This section provides some best practices on how to assess the TRLs but keeping in mind to adapt and to tailor the method and tools to one's system. Indeed, a method too complicated for some system/s

[4] Plasma fusion gain, or Q factor, represents a measure of the efficiency of a fusion reactor to generate power and is defined as the ratio of the power produced by the fusion reactions to the power input needed to maintain the plasma. If Q factor is larger than one, then the fusion reactor produced more power than it consumes. The experimental fusion facilities, all have the Q factor below one.

maybe cumbersome or one may miss an important point if the method is not detailed enough. Thus, the following is a description about different steps when performing the TRAs.

## 4.1. IDENTIFICATION OF CRITICAL TECHNOLOGIES

Initially, the first step of the TRAs is the identification of all critical technologies of the sub/system(s). By definition, a technology is a critical technology element if the system being developed depends on this technology element to meet operational requirements (within acceptable cost and schedule limits) and if the technology element or its application is either new or novel or in an area that poses major technological risk during detailed design or demonstration. Such technology elements are essential to the success of the system being developed and can often be the limiting factor in meeting operational requirements within cost and schedule constraints. The novelty or risk associated with the technology element makes it even more critical, as it may require special attention during the design and demonstration phases to ensure that it can perform as intended and meet the operational requirements. Proper management of critical technology elements is essential to the success of complex systems development efforts. Therefore, as part of the first step, the best practice is to start with the product breakdown structure of a system of interest together with its functional analysis. Each part/branch of the product tree provides a function, and it needs to be assessed if the implementation of this function is made using an existing technology or a new development is necessary and if this function is essential to meet the requirements of the system. If both conditions are fulfilled, then this new technology to be developed to realise this function is a critical technology.

This first step to identify the critical technologies needs to be done by a team of experts with competences covering the scope of the whole lifecycle of the technology from its design to its operation including its decommissioning. For this purpose, concurrent engineering sessions are often used to gather all the elements necessary for this identification. Given complexity and current state of fusion community, it is likely to have thousands of critical technology elements that will need to be assessed. It is also important to prioritize the critical technology elements based on their level of risk, potential impact, and feasibility of implementation, as this can help guide resource allocation and decision making throughout the development process. For example, the transportation, the storage, or the recycling of the product.

Additionally, it is a good practice to draft as part of this activity a technology matrix. This matrix lists all the technologies (critical or not) used in the system with those that are used as a baseline and other as a backup. This is especially true for the critical ones because for each one of them, a backup option needs to be provided with a maturity high enough to enable its use without further or limited development. This practice limits the technical risk of the project. Therefore, by organizing the critical technology elements in a matrix, stakeholders can quickly and easily see the status of each technology element and determine which ones require additional resources, attention, or risk mitigation measures. The technology matrix is a living document that is updated regularly throughout the development process to reflect changes in the status of critical technology elements as they progress through the development lifecycle.

## 4.2. PROCESS TO ASSIGN CURRENT TECHNOLOGY READINESS LEVELS

Following is a brief check list for TRAs:

— Identify the last validation, verification and/or test performed to demonstrate the technology;

— Check for the following points:
  - Model: which kind of model, if any, was used to run the validation;
  - Environment: in which kind of environment the validation was done;
  - Results: are all the target performances requirements achieved;
  - Compare with the TRLs description table and identify the achieved TRL.

Once the critical technologies are identified, the next step is to define one or several streams (system, materials, methods, manufacturing and/or instrumentation) for each one of them. This step is rather straightforward although some difficulties are faced for the system stream because the other streams often also integrate this aspect of integration at a given level. In such case, it is advisable to use the other stream except when it is solely the integration to the current system that is a challenge, meaning the adaptation of the technology to the system.

After the assignment of the stream, the current maturity level needs to be assessed for each critical technology. Similar to their identification, this needs to be done by a team of experts covering the whole lifecycle of the technology. The team is expected to review each level in assigning the correct maturity level. The definitions of the level provided in this publication are rather generic and it is recommended to tailor them if necessary, keeping it coherent over the overall project. The exit criteria[5] to move from one level to another are very system dependant (e.g. blanket module, divertors or vacuum vessel). If a level is satisfied partially, then it is the lower level that is the current level. There are many methods to assess the current level such as questionnaires (i.e. TRL calculator) to perform the assessment based on the list of questions and the processing of the answers that provide the current level. Yet again, it is system dependent.

While carrying out the assessment of the current level, it is important to track and record the date, the team of experts, the system stage (design, manufacturing, operation, ...), the milestones of the project (reviews and gates), the rationale justifying the current level and the purpose of the assessment (review of the development, reassessment of the criticality, …).

## 4.3. PROCESS TO DEFINE TARGET TECHNOLOGY READINESS LEVELS

The identification of the target level for each critical technology is an essential step that will shape the development plan of the technology to reach the desired level of maturity. The target level is the level that needs to be achieved to ensure a proper utilisation of the technology in the overall system in order to meet its intended use and function.

The operation programme is important to consider in particular in case of the TRLs 8–9. Since most of the devices listed in Table 7 are experimental, it is not necessary that all the technologies reach the TRLs 8–9 before the operation. Indeed, this final level can be achieved progressively through the hardware and/or plasma commissioning (or any other type of commissioning not necessarily with plasma) as well as during the conditioning of the system and its separate components prior to start the full operation, even in some cases during operation with dedicated experiments planned to test and

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[5] The TRL exit criteria are specific conditions or milestones that must be met before advancing a technology from one TRL to the next or before considering its readiness for implementation. The criteria help ensure that the technology has progressed sufficiently and has demonstrated the required capabilities and maturity for the intended application. These criteria help decision-makers assess the readiness of a technology to determine whether it is appropriate to move forward with the next phase of development or deployment. The specific criteria may vary across industries and organizations.

validate the technology. Typically, the operation environment is difficult to reproduce in a test bench, so it will be done qualifying the component and its related technology during the operation.

For some technology with relevance to safety, the component related to the technology may have a classification or a categorization, depending on their size and design, that precisely define its requirements. Such technologies have usually a high target level to ensure that the function is well met to satisfy any regulatory assessment (more details on regulatory supervision are provided in Section 6.5), for instance for licensing purposes. A typical example is the confinement barrier such as vacuum vessel and its welding technologies and most of all welding inspection technologies.

For some technologies, in particular system and instrumentation, the verification and validation plan are an important aspect in the evaluation of the target level. For example, technology can reach an intermediate level of maturity as a standalone technology but once integrated within its environment (with other technologies/components), it will go through tests to verify and validate its maturity at higher levels. These different steps are usually defined in the verification and validation plan. Thus, the system standpoint needs to be considered while setting the target level.

## 4.4. INTERACTIONS BETWEEN TECHNOLOGY READINESS LEVELS STREAMS

There could be several streams for a given technology. For example, the development of a new material would certainly necessitate a stream in manufacturing to study its limitation (minimum/maximum thickness of a plate made of this material).

For a given technology, the development plan in each stream can be done either in parallel or sequentially. The interfaces and the commonalities of the development plans need to be clearly identified to enable the exchange of data and for a smooth progress of the maturities in all streams.

Usually, when a critical technology is identified, its quality assurance and control during each step of its lifecycle are followed under scrutiny to make sure that the development is well carried out. This may lead to the gathering of data and even the development of dedicated processes that are by themselves critical technologies in the stream method.

## 4.5. TECHNOLOGY READINESS LEVELS OF A COMPLEX SYSTEM

Fusion projects involve complex systems. For example, there can be several different technologies embedded in several different components which form a system or a super system (system of systems). The TRL of a system that can take account of the interrelationships between technologies and components can be obtained by one of the two methods:

- The first method of obtaining the TRL of a system, which involves calculating the numerical product of TRLs, manufacturing readiness levels, integration readiness levels, and other readiness level streams with assigned weighting factors, is called the weighted average method. This method considers the interrelationships between technologies and components by assigning weights to different readiness level streams based on their importance to the overall system;
- The second method of obtaining the TRL of a system, which involves taking the minimum value of any of the TRL streams like the weakest link approach, is called the minimum score method. This method assumes that the system is only as ready as its least mature

component or technology, and therefore, the TRL of the system is determined by the component or technology with the lowest TRL.

Both methods have their advantages and disadvantages:

- The weighted average method is more comprehensive and considers the interrelationships between technologies and components, but it requires more detailed information and expertise to assign appropriate weights to different readiness level streams.
- The minimum score method is simpler and more conservative, but it may not accurately reflect the overall readiness of the system, particularly if some components or technologies are significantly more critical than others.
- Ultimately, the choice of which method to use depends on the specific context and goals of the assessment, as well as the availability of data and expertise.

# 5. STRATEGY AND DEVELOPMENT PLAN

## 5.1. DEVELOPMENT PLAN

The final step in the TRL assessment is to detail the development plan to bring the technology from its current level to the target level. The development plan details the activities that will be implemented in order to increase the maturity of a given technology for its stream or all its streams, basically how to raise TRL from the current level to the target level.

The first sections of the plan give the initial level, the current level, and the target level as well as the rationales explaining these levels. The record and history of the different evaluations is also provided.

This plan is anticipated to include but not limited to the deliverables expected with their milestones and scheduling, the acceptance tests with their procedures and criteria, the development of dedicated test bench or test facilities, the foreseen simulations with the representative simulated environment, the integration plan meaning the way the technology will be tested once integrated in its final or partial assembly. This plan needs to also cover the whole lifecycle of the technology including, for example, how it is planning to manufacture and operate it.

Similar to the assessment of the levels, the development plan is to be done on a periodic basis at each review/gate and major milestones of the project. This plan is to also give the schedule of these periodic assessments, in other words, how often the assessment will be performed and the expected level to be reached.

## 5.2. PROJECT PERSPECTIVES

The intellectual property and patent protection can play a critical role in the development of a technology. Developing a critical technology can require significant investment, and companies often seek to protect their investment through intellectual property rights such as patents[6] or trade secrets. In

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[6] Patent is a legal document that grants its holder the exclusive right to make, use, and sell an invention for a limited period of time, typically 20 years from the date of filing. Patents can provide a powerful tool for protecting a technology from competitors and can also generate licensing revenue for the patent holder.

many cases, the development of a technology will involve the creation of new intellectual property that can be patented. This may include inventions, processes, designs, or other forms of innovation that are novel and nonobvious. Companies may also seek to protect their technology through trade secret strategies, which involve keeping key aspects of the technology confidential and secret from competitors.

When developing a critical technology, it is important to have a clear intellectual property strategy in place to protect the technology and ensure that the investment in its development is safeguarded. This can involve filing patents, creating trade secrets, or a combination of both. It is also important to have a plan in place for how the intellectual property will be commercialized and monetized, whether through licensing, partnerships, or other means.

In the development plan for a critical technology, the intellectual property strategy needs to be clearly outlined, including a patent tree that illustrates how the technology will be protected through patents or trade secrets. This can help to ensure that the technology is properly protected and that the investment in its development is maximized.

It has to be understood that the efforts to increase the maturity of a technology are closely linked to the resources such as the cost involved in the development. The development of a technology to bring it to the higher levels is not a linear, hence the estimation of the efforts in particular the cost needs to be addressed in the development plan so that during the review/gate the risks associated to this development is well weighted.

Additionally, with well established TRL assessment process, the development plan also provides some technical parameters to define objective criteria for following the progress of the development. For example, if the technology is related to the welding of a plate of 4 cm thick then this thickness is a technical parameter to follow the progress of the welding technology or its inspection technique. There is even the possibility to draft a template of progress report that plots these parameters over time to analyse their evolutions. In the same way, these parameters can be used in a model (analytical or simulated) to evaluate the margins until fulfilment of the function.

### 5.3. BENEFIT FROM TECHNOLOGY READINESS LEVELS ACTIVITY

The TRL is an objective tool to report on the project maturity. It can provide many added values such as but not limited to:

- Useful for planning R&D activities at each design phase. The R&D needs are known by the teams, but the TRL exercise helps to put them together and for example plan and establish the priorities;
- Helpful to build a database to ease handling, reporting and identify synergies with other teams with similar developments;
- Ensures the risks associated with the development of critical technologies is duly mitigated before proceeding with a successive project phase (checked at gate reviews);
- Helps during the project implementation (even after design gate reviews) to identify areas which were overlooked in terms of criticality or level of maturity;
- Useful to record the implementation of development plans, serving as input to knowledge management databases.

For earlier stages of development (in particular during the design phase), the benefits are quite important and the level of commitment to implement the TRL needs to be higher to:

— Check the maturity of technologies for critical processes and define, if necessary, the R&D programmes to reach the desired maturity level for the execution;
— Identify the gaps that could lead to possible risks during execution and act in advance to mitigate them.

For ongoing later stage of the development (manufacturing and operation), the benefit is more limited:

— It is very similar to a risks assessment done in more systematic way. If something is found and required further actions to be implemented, the schedule and cost constraints could make its implementation difficult or impossible;
— It could allow to perform a mapping of actors that perform activities related to critical technologies for different developments.

# 6. GUIDANCE FOR USERS

This publication is developed for the whole fusion community; the TRLs can be utilised and provide general guidance for a range of different disciplines within the fusion programme/project teams. The joint understanding and the use of common language across the teams is a substantial benefit for the fusion specific TRLs.

This section discusses the indicative and non-exhaustive examples and guidance to different roles that would benefit from the application of TRL assessments, including key stakeholder/management, technology experts, system engineers, project managers and Regulatory bodies. Each discipline will likely use TRL assessments differently and integrate them with business systems and the decision making process.

## 6.1. TECHNOLOGY EXPERTS

The TRL assessments are typically led by experts in the field of the technology being developed, such as engineers or scientists, who have knowledge and experience in the specific technology area. These experts would use TRL assessments to evaluate the maturity of the technology and to identify any gaps or development needs that needs to be addressed in order to advance the technology to the next level. However, the TRL assessments are rarely used in isolation as they do not provide a complete picture of the development needs and risks associated with a critical technology. The TRL assessments are just one tool that can be used to evaluate the maturity of a technology, and they need to be used in conjunction with other assessments and analyses, such as market analyses, cost analyses, and risk assessments.

The technological community, including external stakeholders such as project managers, Regulatory bodies, and investors, may use TRL assessments to demonstrate the current state of technological readiness to these stakeholders. The TRL assessments can provide a common language and framework for discussing the maturity of a technology, which can be helpful in communicating with nontechnical stakeholders. The identification of the TRL for the critical technologies within the system can provide the technology experts with a wider viewpoint of critical issues and where technological developments are most needed.

The type of expert filling the main role of the technology expert may change during the lifecycle of development of the critical technology under the review, it is not always to be seen as a static role. Laboratory scientists would take a main role for TRL1−3 where the readiness of the technology is based primarily on fundamental and laboratory based experiments. Technical engineers will take the main role for TRL4−6 where the system is progressing on many levels and being integrated into a wider component or system of interest. Lead/system level engineers will take the main role for TRL7−9 where the functionality of the critical technology within the operation of the system of interest or wider plant/reactor is of interest to the TRL progression. During any TRA, often led by these expert groups, it is critical that the lifecycle of the critical technology and the system of interest will functionally perform in are taken into a consideration. The application of concurrent engineering in the assessments is of significant benefit during the TRL review process. Thus, the expert group needs to consist of a wide enough structure of knowledge to accommodate this concurrent engineering approach.

It is important that the TRL assessments are based on the evidenced observations rather than opinions. The TRL can drive the developmental plan to reduce technical risk; this can include gathering evidence for hypothesis or opinions. Often assumptions are necessary to evaluate a critical technology but as TRLs are contextually specific any assumptions have to be clearly recorded as part of the assessment and re-reviewed upon each TRL review of the critical technology. Verification of assumptions need to form part of the development plan.

## 6.2. SYSTEMS ENGINEERS

Systems engineering is an interdisciplinary field that focuses on the engineering management of designing, integrating, and managing complex systems over their life cycles. Systems engineers play a key role in the development of critical technologies and the management of their readiness levels. They typically work in collaboration with other engineers and stakeholders to identify the product breakdown structure and develop the systems needed to meet the project objectives. This involves defining the requirements, identifying the critical technologies, and developing the system architecture to ensure that the technology components can work together to meet the project objectives.

Once the critical technologies have been identified, systems engineers would typically play a supporting role in concurrent engineering processes and support the management of TRLs. This can involve working with other engineers and stakeholders to ensure that the development of the critical technologies is aligned with the overall project goals and that the readiness levels of the technologies are properly tracked and managed. Systems engineers may also be involved in risk management processes, including the identification of potential risks associated with the critical technologies and the development of mitigation strategies to address those risks. This can involve working with other stakeholders to ensure that the project risks are properly assessed and managed throughout the project lifecycle. Critical technologies are likely to change/evolve during the project/programme development. The requirements and interfaces, thus the TRL definitions, of the critical technology element, may change during the lifecycle of the project. The TRL needs to be periodically reviewed and each time the definition and requirements set on the technology reviewed as well.

Overall, systems engineers play a critical role in the development of critical technologies and the management of their readiness levels. Through their interdisciplinary expertise and collaborative approach, systems engineers help to ensure that the development of critical technologies is properly integrated into the larger project objectives and that the project risks are properly assessed and managed.

## 6.3. KEY STAKEHOLDERS AND DECISION MAKERS

The key stakeholders and decision makers would typically be users of TRLs as a mechanism to interrogate the status of the technological development of critical technologies and the wider system of interest. The TRLs can provide a high level view of the maturity of a technology, which can be used by stakeholders and decision makers to make informed decisions about the development of the technology. By using TRLs, stakeholders and management can gain a better understanding of the progress that has been made in the development of critical technologies and the level of maturity that has been achieved. This can help to identify any gaps or development needs that have to be addressed in order to advance the technology to the next level.

The use of TRLs can also aid in the interrogation of probable cost and time required for the development of critical technologies. By understanding the current level of maturity of a technology, stakeholders and decision makers can make more accurate estimates of the resources that will be required to further develop the technology. The use of TRLs can help stakeholders and management to understand the risks associated with the development of critical technologies and the wider programme. By identifying the current level of maturity of a technology, stakeholders and decision makers can better assess the likelihood of success and the potential impact of failure on the programme. Management needs to be insistent upon a common set of TRL definitions being used across the project/programme if they are to be reviewed in conjunction. Key stakeholders/management are expected to be aware of the applicability of TRLs, especially that they do not represent risk, operate on an ordinal scale, and are not guaranteed to be applicable (especially true at lower TRL1–6).

## 6.4. PROJECT MANAGERS

The project managers would typically lead the integration of TRL within the project lifecycle assessments and technical management systems for the whole engineering lifecycle of an engineered product. Project managers are responsible for the overall planning, execution, and monitoring of the project. This includes ensuring that the project is delivered on time, within budget, and to the required quality standards. As part of this responsibility, project managers are expected to ensure that the development of critical technologies is properly integrated into the project objectives and that the readiness levels of the technologies are properly tracked and managed throughout the project lifecycle. To achieve this, project managers need to work closely with systems engineers and other stakeholders to ensure that the development of critical technologies is aligned with the project goals and that the readiness levels of the technologies are properly assessed and managed. This can involve developing project plans and schedules that incorporate the development of critical technologies, establishing project metrics that track the maturity of the technologies, and implementing risk management processes to identify and mitigate potential risks associated with the development of the technologies. Project managers need to also ensure that the use of TRLs is properly integrated into the technical management systems for the whole engineering lifecycle of the engineered product. This can involve developing and implementing TRL assessment processes that are aligned with the project objectives, establishing clear criteria for the assessment of readiness levels, and ensuring that the TRL assessments are properly documented and communicated to stakeholders. Overall, project managers play a critical role in the integration of TRL within the project lifecycle assessments and technical management systems for the whole engineering lifecycle of an engineered product. Through their leadership and coordination, project managers help to ensure that the development of critical technologies is properly aligned with the project objectives and that the readiness levels of the technologies are properly tracked and managed throughout the project lifecycle.

Table 8 illustrates a process where development of a project from feasibility through preliminary and detailed definitions to operational phase are tied to critical technology elements reaching set TRLs to demonstrate sufficient maturity and reduction in risk. The amount of effort, time, or cost required to progress between TRL stages will depend on a range of factors, including the complexity of the technology, the availability of resources, the level of risk, and the project objectives. Therefore, project managers need to set appropriate gates for the project, based on the specific objectives and requirements of the project, rather than assuming a fixed percentage of effort, time, or cost needed to progress between TRL stages. This may involve developing a detailed project plan that considers the specific technical challenges, risks, and uncertainties associated with the project, as well as the resources and constraints that are available.

TABLE 8. USE OF TRLs AT DIFFERENT PHASES OF PROJECT DEVELOPMENT

| Development phase | Potential use of TRL assessment | ≈TRL |
|---|---|---|
| Feasibility phase. First studies. | – Consolidate technology development plan<br>– Re-orient the design for improving technology readiness and implementation decision schedule | TRL1<br>TRL2 |
| Feasibility phase. Preliminary requirements<br>(ended by preliminary requirements review[7]) | – Assess progress in technology development plan implementation<br>– Consolidate technology development plan<br>– Select criteria for competing objectives | TRL3<br>TRL4 |
| Preliminary phase – system requirements and conceptual design<br>(ended by a conceptual design review[8] or system requirements review[9]) | – Assess readiness to move to implementation phase → TRL5 (higher risks) or TRL 6 (lower risks) or >TRL6<br>– Select criteria for competing objectives | TRL5<br>TRL6 |
| Preliminary phase - preliminary design<br>(ended by a preliminary design review[10]) | – Assessment of equipment supplier proposals<br>– **Decision to place contracts → TRL6 or higher**<br>– Confirm readiness to move to implementation phase | |
| Industrial implementation of<br>final design (ended by a critical or final design review[11]) | – TRL can be of less use. | |
| Qualification (ended by a qualification review[12]) and manufacturing.<br>commissioning. | – The maturity of technology can be managed in a critical item list<br>– However, a TRL assessment can be done. | TRL7<br>TRL8 |
| Operational phase | | TRL9 |

[7] Preliminary requirement review is a formal review process that involves stakeholders from across the organization, including technical experts, project sponsors, and end users, to provide feedback and identify gaps or areas for improvement in the preliminary requirements.

[8] Conceptual design review focuses on validating the conceptual design of the system, including its technical feasibility, performance, and cost effectiveness.

[9] System requirements review focuses on validating the system requirements, ensuring that they are complete, accurate, and consistent with the project objectives and constraints.

[10] Preliminary design review is a formal review of the system design and provides an opportunity for stakeholders to evaluate the design, assess its feasibility, and identify any issues or concerns.

[11] Final design review is to evaluate the final design of the system and ensure that it meets all of the project requirements and specifications.

[12] Qualification review is performed to evaluate the results of the qualification testing and to ensure that the system is fully qualified and demonstrate that the system meets all of the relevant performance, safety, and regulatory requirements and is ready for deployment.

When considering the project lifecycle of the systems of interest, project managers need to be cognisant of the different critical technology elements and ensure that the system overall TRL is graded appropriately, typically at the lowest TRL of the critical technology elements or the lowest of the different streams when considering the five streams, the system, materials, manufacturing, method, and instrumentation. Each of these streams can have a different TRL, and the overall TRL of the system will depend on the lowest TRL of any of these streams.

### 6.5. REGULATORY BODIES

The regulatory bodies would typically use TRLs in the requirement setting and may recommend or mandate that demonstrated proof of the system or critical technology element has reached a sufficient TRL to allow acceptable (often safe) operation. Regulatory bodies are responsible for ensuring that the engineered product or system meets regulatory and safety requirements. To achieve this, Regulatory bodies may conduct independent TRL assessments or reviews to verify that the critical technologies have reached an appropriate level of maturity to meet the requirements for safe and acceptable operation. This review team needs to ensure that there is substantiated evidence with no caveats used to validate the proposed TRL.

Regulatory bodies may also use TRLs to assess the overall technical maturity of the engineered product or system and to identify any risks associated with the use of critical technologies. This information can be used to inform decision making regarding the approval or certification of the product or system. A TRL assessment from a Regulatory body is expected to be a logical review process of acceptable risk and performance of the system or critical technology. A Regulatory body may accept a lower TRL then requested if there is acceptable justification.

Regulatory bodies need to have a good understanding of TRLs, that a high or low TRL does not inherently stipulate a good or bad system or critical technology element, or that one is closer to being applicable; this is especially true for lower TRLs 1–6. To ensure consistency and clarity in TRL definitions, the Regulatory body is expected to establish a standard TRL set and definition that is used by all parties involved in the programme or project. This includes the associated suppliers and reviewers, who may come from different industries or disciplines. This publication may be useful for the fusion community in developing a common TRL set and definition that is specific to the field. It can serve as a reference for establishing TRL criteria and guidelines that are relevant and appropriate for fusion technologies and applications. By using a common TRL set and definition, the fusion community can enhance collaboration and alignment across different organizations and stakeholders, accelerate technology development and deployment, and ultimately achieve the goals more efficiently and effectively.

The use of TRLs can help to provide an objective and standardized approach to assessing the technical readiness of critical technologies and can help to ensure that the product or system meets regulatory and safety requirements.

## 7. DISCUSSION AND CONCLUSION

Fusion energy technology is still in the experimental stages and has not yet reached full industrialization. Despite the progress made in fusion R&D, both tokamak and non-tokamak approaches face significant technological challenges that need to be overcome to achieve commercialization.

However, the advances in several areas have opened new opportunities for fusion technology. The advanced manufacturing and modular construction approaches offer great potential to build smaller and more flexible fusion devices that can be optimized for specific applications. In addition, the developments in artificial intelligence driven instrumentation and data analysis have made it possible to monitor and control fusion reactions with greater precision and efficiency.

Organizations engaged in fusion energy research use different techniques and tools to assess the maturity of fusion technologies and provide insight into the risks associated with cost, schedule, and performance. These techniques and tools are essential for making informed decisions about funding, development, and commercialization of fusion energy technologies.

One commonly used technique for assessing technology maturity is the TRL system that provides a standard framework for assessing the maturity of a technology based on its level of development and demonstrated capabilities.

While the TRL system was originally developed to assess the readiness of a single technology, it is not always sufficient for assessing the readiness of complex systems such as those used in fusion projects. Fusion systems typically involve the integration of several different technologies into multiple components, which has to work together to achieve the desired level of performance and reliability.

There is no fusion reactor TRL that encompasses all aspects of fusion technology and system development. This publication, therefore, propose a simplified matrix of five streams of TRLs that are combined to give an overall readiness of a complex fusion system. The five streams are materials, manufacturing technologies, instrumentation, software and system. Such a matrix could be used to combine TRLs for individual technologies and their components, such as magnets, vacuum systems, and plasma diagnostics, along with TRLs for subsystems and overall system integration. The resulting matrix could provide a more holistic view of the readiness of a fusion system and help identify areas where further development or testing may be needed. However, it is important to note that any such matrix or framework would need to be tailored to the specific needs and requirements of the fusion system being assessed. Additionally, such assessments need to be conducted by experienced and qualified personnel and need to consider a wide range of factors beyond just technical readiness, including cost, schedule, safety and performance requirements.

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## ANNEX I EXAMPLE TECHNOLOGY READINESS LEVELS FOR BREEDING BLANKET IN FUSION SYSTEMS

In the Japanese DEMOnstration Power Plant (DEMO)[13] breeding blanket, a water cooled ceramic breeding system, was employed in order to utilize existing established technologies as much as possible to reduce the risk. However, since the fusion reactor and its in-vessel structures are first-of-a-kind systems that will not be under full operational conditions until the fusion DEMO reactor is in operation, many technical challenges have been identified. To proceed with the development of the in-vessel components within these constraints, it is important to make best efforts to identify technology readiness levels that are essential for the realization of the in-vessel components.

In this example, an attempt is made to identify the TRL exit criteria (see footnote 5 in the main text for definition) for the breeding blanket system based on current understanding of the related technologies for the Japanese water cooled ceramic breeding type breeding blanket. Four streams for the breeding blanket system TRL assessment can be considered as follows:

1. Structural materials TRL for evaluation of technology maturity of the Japanese breeding blanket structural material F82H[14];
2. Functional materials TRL for evaluation of technology maturity of tritium breeders and neutron multipliers, including raw material production technology maturity;
3. Manufacturing technologies TRL for assessing the breeding blanket manufacturing technologies maturity;
4. System TRL to evaluate the overall technology maturity.

The TRL assessment for instrumentation is not considered here. The TRL for the breeding blanket is deduced from the following scheme:

*Structural materials TRL ≥ functional material ≥ manufacturing technologies TRL ≥ overall breeding blanket system TRL*

The procedure for identifying TRLs is taken from the US Department of Energy guide [DOE G413.3–4A TRL Guide (2015)]. This procedure first defines the work breakdown structure (WBS), then defines the critical technology elements, which are the technologies that are essential and indispensable for the realization of the system, and then defines the TRL achievement criteria for those critical technology elements. The WBS is defined referring to the US Department of Energy and NASA WBS guideline [DOE WBS handbook (2012), NASA WBS Handbook 2019 NASA/SP–3404].

Not all the technologies necessary for the development of a Japanese DEMO breeding blanket system are covered here; only the major ones. This discussion focuses on the TRL for the development of the sub-modules of the blanket module, the main elements of the Japanese water cooled ceramic breeding

[13] DEMO is a proposed demonstration fusion power plant that will be designed to prove the feasibility of commercial scale fusion power plant. One important component of the DEMO reactor is the breeding blanket responsible for producing and maintaining the tritium fuel needed in the fusion reaction.

[14] F82H is a type of ferritic/martensitic steel that is designed to withstand the harsh conditions of a fusion reactor, including high temperatures, high neutron fluences, and high thermal stresses.

blanket system, as shown in Fig. I–1. Technologies related to the first wall, key structures, back plates, limiters, in-service eligibility, etc. are not included.

Therefore, this section describes the TRL assessment only as an example and it is not to be considered as authorised strategy for fusion development in Japan.

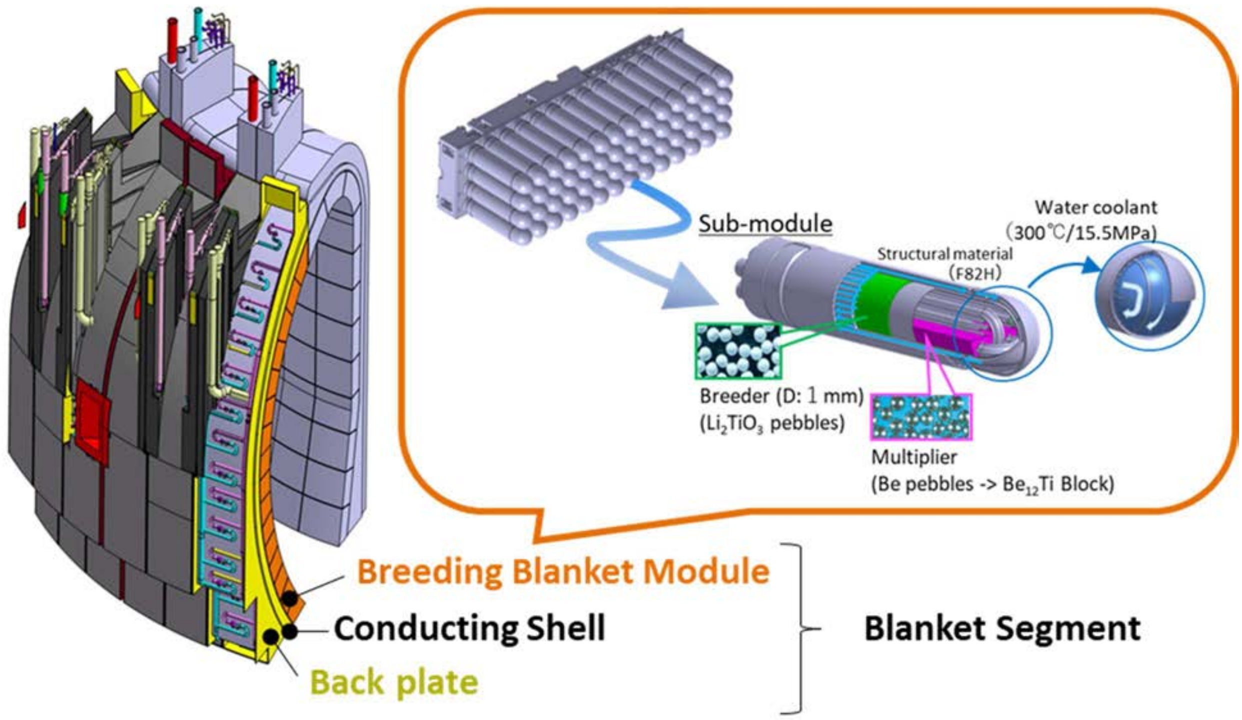



*FIG. I–1. Japanese DEMO breeding blanket design.*

The technical outcomes to be achieved in order to meet the TRLs are defined as exit criteria. For each of the exit criteria, it is expected that design documents and reports will be presented to provide the basis for achievement. By detailing these exit criteria and scoring the level of achievement against each exit criterion, it is possible to identify the TRL. The following sections describe TRLs and exit criteria for structural material, functional material, manufacturing technology and the breeding blanket system.

## I–1. STRUCTURAL MATERIAL TECHNOLOGY READINESS LEVEL AND ITS EXIT CRITERIA

Structural materials TRL is defined for evaluation of the material technology maturity. The exit criteria are defined for technology levels of the Japanese breeding blanket structural material F82H.

According to Table I–1, the breeding blanket structural material's TRL is estimated to be at TRL5.

TABLE I–1. STRUCTURAL MATERIAL TRLs AND THEIR EXIT CRITERIA

| TRL | Definition | Exit criteria |
|---|---|---|
| 1 | Material concept | Basic design idea and concept (Evidence from literature)<br>Evaluation on basic properties |
| 2 | Agreed target use | Initial screening irradiation test on basic properties<br>Database on basic properties |
| 3 | Materials' capability based on lab scale samples.<br>Reference material. | Candidate material specification has been consolidated.<br>Material property handbook (non-irradiation).<br>Irradiation database on basic properties.<br>Applicability of weld/joint technologies has been demonstrated. |
| 4 | Radiated and un-irradiated design curves produced.<br>Codification/handbook.<br>Variability in properties. | Qualification strategy of material has been established.<br>Irradiation database on weld/joint has been provided.<br>Laboratory scale structure material fabrication. |
| 5 | Methods for material processing and component manufacturing | Irradiation database of relevant environnements (neutron irradiation, ion irradiation, etc.).<br>Irradiation tests of sub-scale components (structures with welds and joints) to demonstrate the feasibility of joining technologies in appropriate environments.<br>Standardization of structural materials is carried out.<br>Applicable recycling technologies are identified.<br>Material specification has been fixed. |
| 6 | Validated via full scale component and/or sub-element testing. | Full scale component tests in relevant environments (high magnetic fields, fission reactors, etc.).<br>MPH and procurement (quality control) strategies have been established.<br>The final production form of structural materials at DEMO scale has been demonstrated.<br>Recycling technology has been demonstrated at lab scale.<br>Material quality control requirements have been established. |
| 7 | Evaluated in development rig tests through full operational tests | Testing of materials and subcomponents in a fusion neutron irradiation environment up to the dose expected in the initial operation of DEMO Phase 1 (test blanket module FPO-2 operation, FPO-3 and beyond).<br>Procurement of raw materials (high purity Fe) and production of final product forms at DEMO scale.<br>Demonstration of waste treatment and recycling technologies at test blanket module. |
| 8 | Material production ready | Verification of predetermined material degradation predictions by post-operation material tests (evaluation of damage accumulation).<br>Establish a database of fusion neutron irradiation doses up to the dose expected in the second stage of DEMO reactor operation.<br>Demonstration of waste treatment and recycling technologies. |
| 9 | Structural material used in operational fusion reactors | Structural material is in operational use in the Breeding Blanket of nuclear fusion reactors.<br>Fusion neutron irradiation database up to the target dose for the final DEMO reactor operation (and for the initial power plant operation) has been established.<br>Waste management and recycling technologies have been established. |

## I–2. FUNCTIONAL MATERIAL TECHNOLOGY READINESS LEVEL AND ITS EXIT CRITERIA

Functional materials TRL exit criteria are defined for TRL evaluation of tritium breeders and neutron multipliers, including raw material procurement technologies. According to Table I–2, the breeding blanket functional material's TRL is estimated to be at TRL5.

TABLE I–2. FUNCTIONAL MATERIAL TRLs AND THEIR EXIT CRITERIA

| TRL | Definition | Exit criteria |
|---|---|---|
| 1 | Material concept | Basic design idea and concept were provided (evidence from literature).<br>Evaluation on basic properties has been conducted |
| 2 | Agreed target use | Initial screening irradiation test (non-fusion) on basic properties has been done.<br>Database on basic properties has been provided. |
| 3 | Materials' capability based on lab scale samples. Reference material. | Candidate material specifications were organized.<br>Handbook of material properties (non-irradiation) Irradiation database on basic properties was provided.<br>Demonstrated applicability of manufacturing technologies (including procurement of raw materials such as Be and $^{6}Li$).<br>Basic manufacturing technologies for functional materials have been identified and demonstrated in lab scale. |
| 4 | Radiated and unirradiated design curves produced. Codification/handbook. Variability in properties. | A certification strategy for functional materials has been established.<br>An irradiation database has been established.<br>Basic production technologies for functional materials have been demonstrated. Prototype scale production technologies have been identified and demonstrated on a lab scale.<br>Recycling technology has been established and demonstrated in lab scale.<br>Laboratory scale functional material fabrication |
| 5 | Methods for material processing and component manufacture | Provides an irradiation database in an environment (nautron irradiation) relevant to the end product.<br>Demonstrate its feasibility by irradiation tests on sub-scale product form.<br>Demonstrate the production of the final form of functional materials and demonstrate the procurement of raw materials (Be and $^{6}Li$).<br>Identifying recycling technologies for functional materials used in the environment and demonstrating them on a lab scale (cold).<br>Material specifications have been established. |
| 6 | Validated via full-scale component and/or sub-element testing. | Full scale component tests under high magnetic field and fission neutron environments have been conducted to verify feasibility.<br>MPH and procurement (quality control) strategies have been established.<br>Production of functional materials in their final form using DEMO scale technology has been demonstrated.<br>Waste treatment and recycling technologies have been established.<br>Material quality control requirements have been established. |

TABLE I–2. FUNCTIONAL MATERIAL TRLs AND THEIR EXIT CRITERIA (Cont.)

| TRL | Definition | Exit criteria |
|---|---|---|
| 7 | Evaluated in development rig tests through full operational tests | Completed tests under fusion neutron irradiation environment up to the expected dose in DEMO Phase 1<br>Actual use in test blanket module FPO-2, (to be continued after FPO-3 if possible)<br>Full-scale operation from procurement of raw materials (Be and Li) to production of final products.<br>Demonstration of waste treatment and recycling technologies in test blanket module PIE. |
| 8 | Material poduction ready and acceptance of material components done | The predetermined degradation predictions have been verified through post-operation material tests (evaluation of damage accumulation).<br>A database of fusion neutron irradiation up to the dose assumed in the initial operation of DEMO stage 2 has been established.<br>Waste treatment and recycling technologies have been demonstrated. |
| 9 | Functional material used in operational fusion reactors | Functional material is in operational use in the Breeding Blanket of nuclear fusion reactors<br>Fusion neutron irradiation database up to the target dose for the final DEMO reactor operation (and for the initial power plant operation) has been established.<br>Material quality control requirements have been established.<br>Waste management and recycling technologies have been established. |

## I–3. MANUFACTURING TECHNOLOGY READINESS LEVEL AND ITS EXIT CRITERIA

The TRLs and exit criteria for the manufacturing technologies of proliferation blankets are discussed. The criteria for the manufacturing technologies required in actual production of the whole segments are not provided, but only the blanket module (submodule) manufacturing, not blanket segments with the conductor shell and back plate (Fig. I–1). According to Table I–3, the breeding blanket manufacturing TRL is estimated to be at TRL5.

TABLE I–3. MANUFACTURING TECHNOLOGY TRLs AND ITS EXIT CRITERIA

| TRL | Def | Exit criteria |
|---|---|---|
| 1 | Process concept | Manufacturing principles reported |
| 2 | Validity of concept described | Manufacturing technologies proposed |
| 3 | Experimental proof of concept completed | Applicable blanket manufacturing specification has been identified. |
| 4 | Process validated in lab | Blanket manufacturing specification has been consolidated. |
| 5 | Basic capability demonstrated using production equipment.<br>Code/regulation compliance. | Blanket manufacturing specification for all positions (including sector structure) has been demonstrated through sub-scale components manufacturing.<br>Blanket fabrication technology (specification) has been finalized. |
| 6 | Process optimized for capability and rate using production equipment | Preparation of the production facility of raw material (Be, $^{6}Li$) in DEMO scale technology has been completed. Blanket DEMO relevant manufacturing specification (for all blanket positions and sector) has been demonstrated, including fabrication of breeding material into the final form (block, pebble, etc.). |

TABLE I–3. MANUFACTURING TECHNOLOGY TRLs AND ITS EXIT CRITERIA (Cont.)

| TRL | Def | Exit criteria |
|---|---|---|
| 7 | Economic run lengths on production parts | Procurement of a full set of DEMO blankets has been done.<br>Quality control of production technology has been established. |
| 8 | Significant run lengths | Blankets are successfully manufactured at low production rate.<br>Decommissioning and recycle processes have been demonstrated. |
| 9 | Demonstrated over an extended period | All blankets are successfully manufactured at nominal production rate over an extended period.<br>Decommissioning and recycle processes are available. |

## I–4. SYSTEM TECHNOLOGY READINESS LEVEL AND ITS EXIT CRITERIA

The system TRLs for full integration are used to evaluate the overall technology maturity. The TRLs for full integration of the breeding blanket system are typically evaluated based on a number of factors, including:

- Maturity of the individual components of the breeding blanket system, such as the breeder and coolant materials, the structural materials, and the diagnostic and control systems;
- Level of testing and validation that has been conducted on the individual components, as well as on the integrated system as a whole;
- Level of integration of the individual components into a functional system, including the design and optimization of the system and the identification and resolution of any issues or challenges;
- Level of RAMI[15] that has been achieved for the system as a whole.

According to Table I–4, the breeding blanket TRL is estimated to be at TRL4.

TABLE I–4. SYSTEM TECHNOLOGY TRLs AND ITS EXIT CRITERIA

| TRL | Definition | Exit criteria |
|---|---|---|
| 1 | Basic principles | The basic principle technology has been observed and reported |
| 2 | Technology concept | The technology concept application has been formulated |
| 3 | Proof of concept | Equipment and process analysis and proof of concept demonstrated in a simulated environment.<br>High risk immature technologies identified.<br>Prototyping has been completed. |
| 4 | Validation in a laboratory environment | Lab-scale tests (breeding blanket element tests) of similar equipment systems have been completed in simulated environments (e.g., non-fusion irradiation environment: thermal loading conditions).<br>The system performance specifications and constraints have been defined and the basic breeding blanket specifications have been finalized.<br>The ITER-PFPO-2 test blanket module final design has been approved. |

[15] RAMI (Reliability, Availability, Maintainability, and Inspectability) is a critical aspect of the design and operation of a fusion power plant, including DEMO. The fully integrated breeding blanket system is a key component of the DEMO reactor, and its RAMI performance is essential for the overall success and feasibility of the fusion power plant.

TABLE I–4. SYSTEM TECHNOLOGY TRLs AND ITS EXIT CRITERIA (Cont.)

| TRL | Definition | Exit criteria |
|---|---|---|
| 5 | Sub-scale system validation in a relevant environment | Bench-scale equipment testing (breeding blanket sub-module mock-ups) has been demonstrated in relevant environments (non-irradiated environments).<br>High risk component technology development for breeding blanket systems has been completed and low risk breeding blanket system components (designs) have been identified.<br>A RAMI strategy has been established.<br>The final design of the ITER-FPO-1 TBM has been approved. |
| 6 | Full scale prototype demo in a relevant environment | Testing of engineering-scale prototype devices (full module breeding blanket) have been demonstrated in relevant environments (e.g., test blanket module tests in ITER-PFPO2, mock-up tests in a non-fusion neutron irradiation environment) and include testing of safety functions.<br>Integration of system components to be verified.<br>System functionality integration to be verified.<br>The RAMI strategy to be demonstrated.<br>The final design of the ITER-FPO-2 TBM has been approved. |
| 7 | Prototype demo in an operational environment (qualified) | The actual equipment (full-module breeding blanket) have been successfully operated under the relevant operational environment (test blanket module tests at the ITER FPO have been successfully completed).<br>The threshold capability of the breeding blanket system have been demonstrated at the operational level using the operational interface.<br>The final design be virtually completed, and the manufacturing design have been established.<br>A fully integrated prototype (one segment) has been successfully demonstrated in a simulated operational environment. |
| 8 | Test and demonstration | The actual equipment has been successfully operated in a limited operational environment (DEMO hot commissioning phase - low dose operation in pulsed mode).<br>The interoperability of the breeding blanket system (of all sections) has been demonstrated in the operational environment (including the post operational environment for maintenance). |
| 9 | Proven in operation | The fully integrated breeding blanket system has demonstrated RAMI in DEMO operation over the target lifetime.<br>The integrated performance has been fully characterized and is consistent with the requirements as a power plant.<br>Breeding blanket system has achieved the initial target operational capability demonstration and meets the mission objectives. |

## I–5. SUMMARY

In order to appropriately identify the TRL of a system, it is important to first define the critical technology elements of that system, which are the technical elements against which the TRLs need to be assessed. The WBS has to be carefully prepared to cover all the technical elements of the system under consideration. The identification of TRLs may otherwise become meaningless.

Significant changes in design or the introduction of new technologies can be considered a development risk when working towards achieving the exit criteria of a given TRL. This is because such changes can often lead to significant increases in the difficulty of development and can potentially impact the overall feasibility and viability of the technology being developed.

In the context of the fully integrated breeding blanket system for a fusion power plant, changes in design or the introduction of new technologies could have a significant impact on the performance and RAMI of the system. For example, if a new material with better radiation resistance and higher thermal conductivity were to be identified, this could lead to significant changes in the design and optimization of the breeding blanket system. Similarly, if a new control system were to be developed that improved the accuracy and reliability of diagnostics and monitoring, this could also impact the overall design and performance of the system. In such cases, these changes would need to be carefully evaluated to determine the potential impacts on the overall feasibility and viability of the fully integrated breeding blanket system. This may involve additional testing and validation efforts, as well as modifications to the overall development plan and timeline. As a result, changes in design or the introduction of new technologies can be considered a significant development risk and has to be carefully evaluated and managed to ensure that the overall development goals are achieved.

In summary, the evaluation of new and old technologies and the trade-offs involved need to be sorted out. Specifically, the criticality of the technology to mission success, the development risks that may occur if the technology is selected, and the development tests that will be required has to be evaluated, and the possibility of risk avoidance through trade-offs with other factors has to be considered before the decision to adopt the new design or technology. Those risks cannot be measured by TRLs. However, the TRL is an input for the project risks assessment. In particular, TRL6 or higher need to be reached for all components before starting the full development phases of a sub-system or system; accepting instead TRL5 for some of the components induces higher project risks to which appropriated measured need to be taken.

## ANNEX II EXAMPLE TECHNOLOGY READINESS LEVELS FOR TOROIDAL FIELD COIL IN FUSION SYSTEMS

### II–1. TOROIDAL FIELD COIL

In this Annex, the TRL of toroidal field coil is presented as one of the examples of TRL estimation of fusion reactor components under the following assumptions:

- Same design as ITER except its dimensions are applicable to toroidal field coil for future fusion reactor, such as DEMO [II–1].
- Tolerances are similar or relaxed from those of ITER toroidal field coil, but this example does not apply to the ITER project.

To explain this example, the major parameters of the ITER toroidal field coil and its manufacturing procedure are briefly described. The technical challenges and their solutions are then mentioned to support the estimation of TRL of technology for toroidal field coil.

### II–2. TOROIDAL FIELD COIL MAIN PARAMETERS

The ITER magnet system consists of 18 toroidal field coils using Nb3Sn cable-in-conduit superconductor, 6 poloidal field coils, central solenoid and 18 correction coils, as shown in Fig. II–1, [II–2].

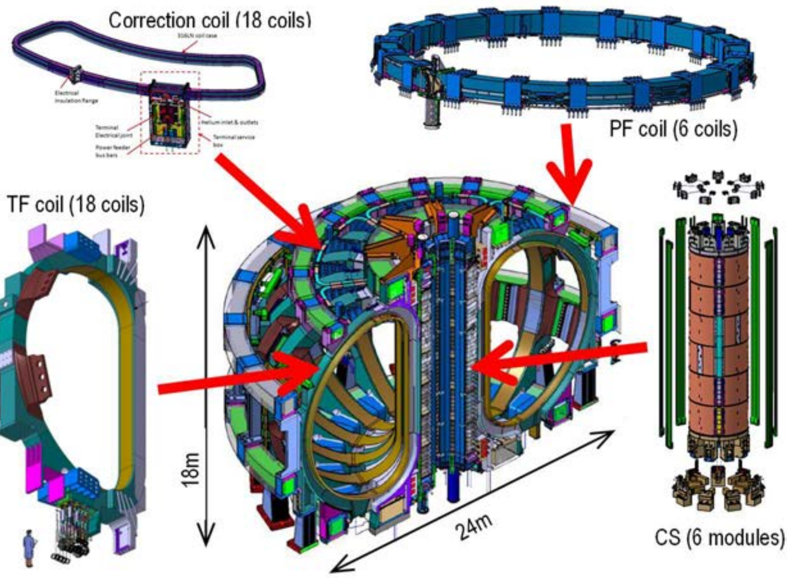



*FIG. II–1. ITER magnet system.*

The National Institute for Quantum Science and Technology, serving as the Japan Domestic Agency in the ITER project in Japan, is responsible for the procurement of 9 toroidal field coils [II–3] and their coil cases [II–4], as well as 10 additional coil cases to house the 10 toroidal field coils being fabricated in the European Union [II–5]. Each toroidal field coil is composed of 9 m wide, 14 m high and 110 ton winding pack with a coil cases, which supports huge electromagnetic forces in the order of several hundred mega Newtons, as shown in Fig. II–2.

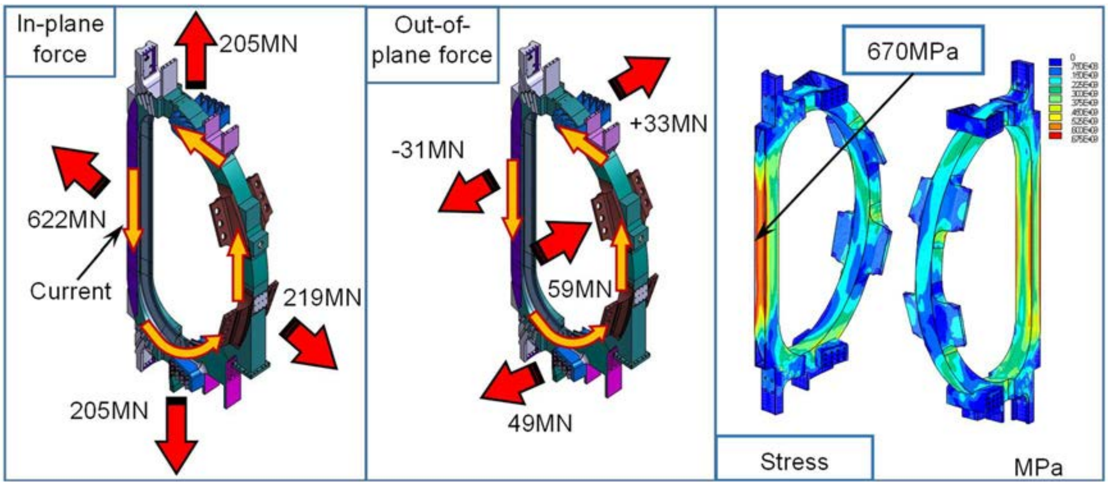



*FIG. II–2. Forces to be subjected to ITER toroidal field coil.*

The winding pack consists of 5 internal regular and 2 side double-pancakes, as shown in Fig. II–4. Each double-pancake has a radial plate. A radial plate has a groove and toroidal field conductor with turn insulation is inserted into this groove. The toroidal field conductor is fixed by laser welding cover plates to teeth of the radial plate. The coil case consists of main components, so called as sub-assemblies of AU, BU, AP and BP, as shown in Fig. II–3. Nominal current and magnetic field are 68 kA and 11.8 T, respectively.

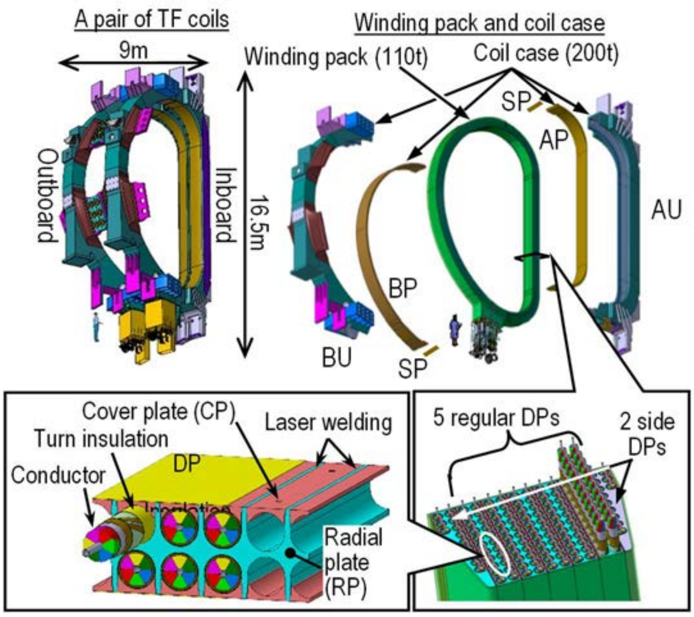



*FIG. II–3. ITER toroidal field coil.*

Main parameters of toroidal field coil are provided in Table II–1. References [II–3], [II–4], [II–6], [II–27] provide other details about the systems.

TABLE II–1. MAIN PARAMETERS OF THE ITER TOROIDAL FIELD COIL

| Parameter | Value |
|---|---|
| Conductor outer diameter | 43.7 mm |
| Cable diameter | 39.7 mm |
| Conduit material | SS316LN |
| Number of coils | 18 |
| Number of DPs per coil | 7 (5rDPs + 2sDPs) |
| Conductor length in DP | 760 m / rDP, 415 m / sDP |
| Nominal current | 68 kA |
| Nominal field | 11.8 T |

## II–3. TOROIDAL FIELD FABRICATION PROCESS

Fabrication process of toroidal field coil in Japan includes:

a) Fabrication of double-pancakes
b) Fabrication of radial plate and cover plates in parallel with double-pancakes fabrication;
c) Fabrication of winding pack using completed double-pancakes;
d) Fabrication of coil cases in parallel with a) and c);
e) Assembly of winding pack and coil cases, as illustrated in Fig. II–4.

The major technical issues related to each fabrication process are indicated as the number with heading character 'T', in the explanation of each fabrication process in order to understand relation between the fabrication process and technical issue. This is explained in Section II–2.3.

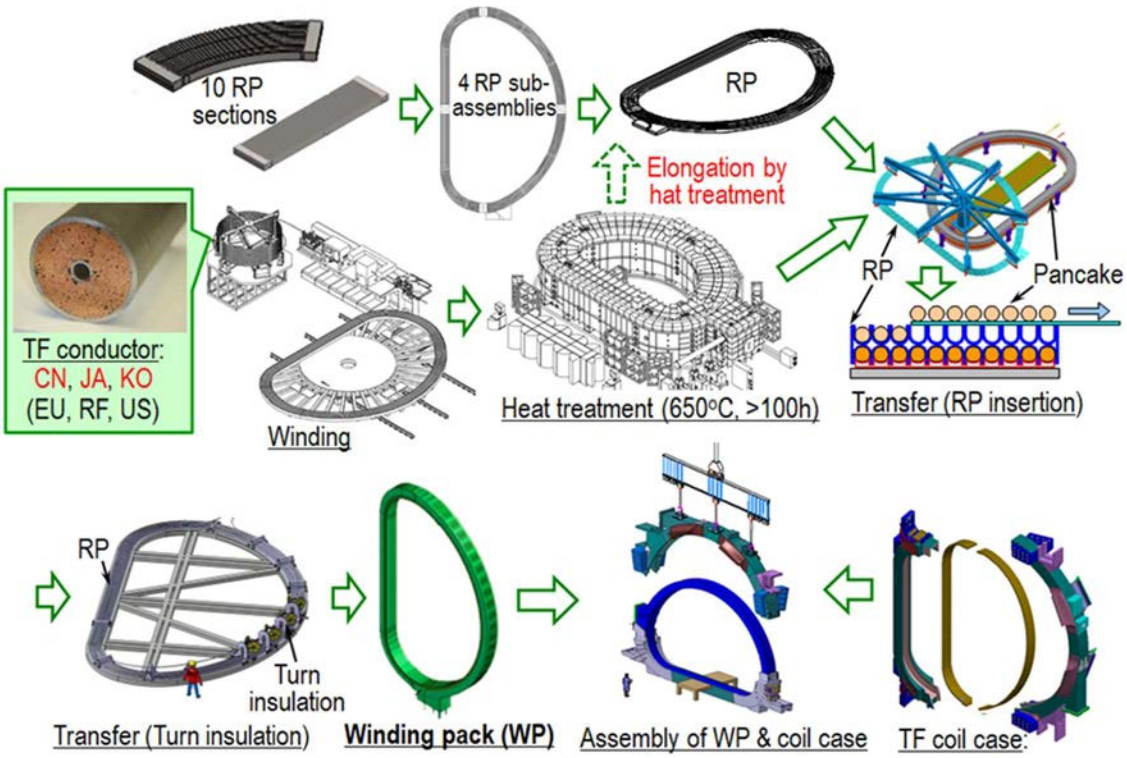



*FIG. II–4. Toroidal field coil manufacturing procedure.*

### II–3.1. Double-pancake fabrication process

Double-pancake fabrication process is as follows:

i. Conductor is wound into a D-shaped double-pancake winding (Fig. II–5): T1;
ii. Helium inlet is made on the conductor between upper and lower pancakes, and electrical joints are attached at both ends of the conductor;
iii. Conductor is heat treated at 650°C for more than 100 hours to generate $Nb_3Sn$ superconductor (Fig. II–6): T1;
iv. Radial plate is inserted between the pancakes by expanding the distance between the pancakes and the conductor is once inserted in the groove of the radial plate (Fig. II–7). This operation is hereafter called a transfer;
v. Conductor is lifted from radial plate groove, wrapped with a 2 mm multilayer glass polyimide turn insulation, and re-inserted into the grooves on both surfaces of the radial plate without degrading the conductor performance and/or damaging the turn insulation (Fig. II–8): T1;
vi. Cover plate is welded to the radial plate teeth to fix the conductor in place (Fig. II–9): T2;
vii. Double-pancake is wrapped in multilayer glass polyimide insulation with a minimum thickness of 1 mm (Fig. II–10);
viii. Double-pancake insulation is vacuum pressure impregnated together with the turn insulation (Fig. II–11): T3.

Details about manufacturing of double-pancakes are found in [II–3], [II–13]–[ II–18].


*FIG. II–5. Winding toroidal field conductor.*

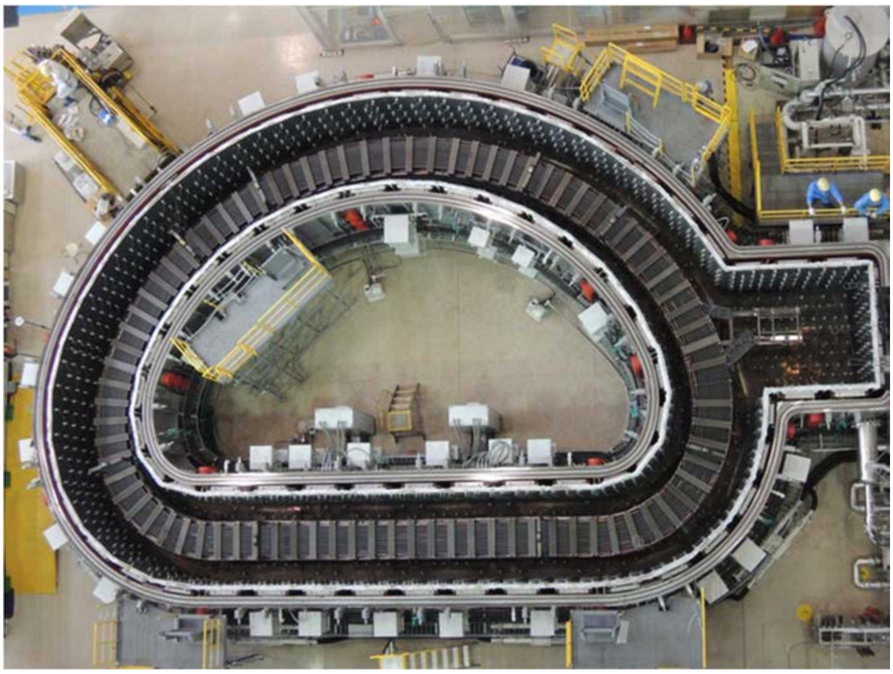


*FIG. II–6. Heat treated wound toroidal field conductor.*

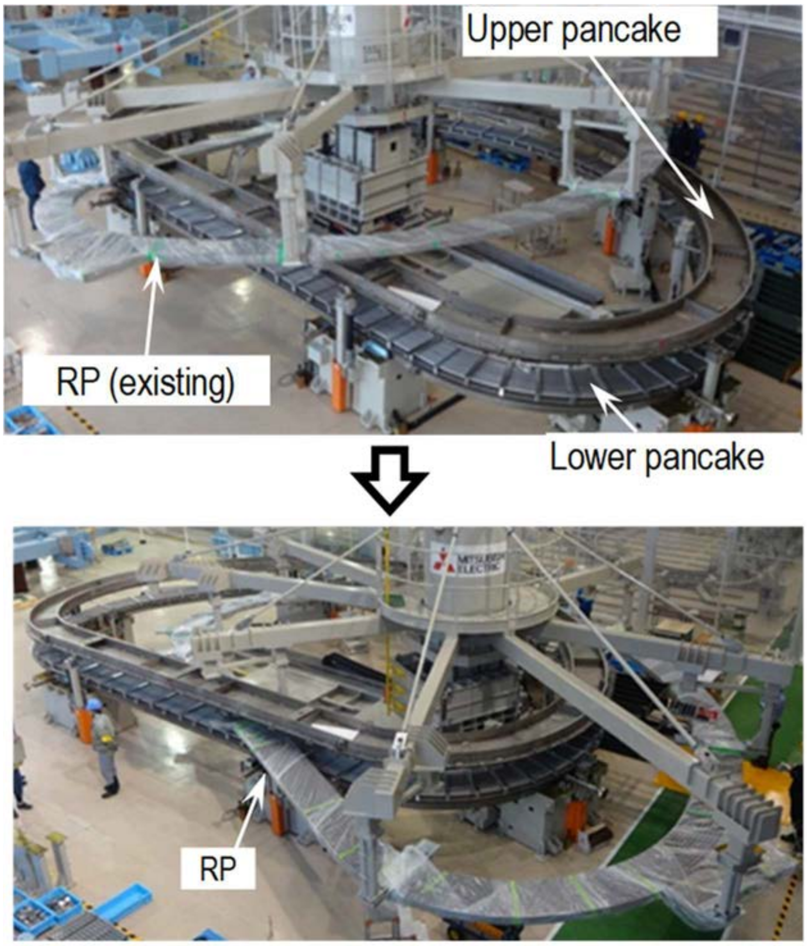



*FIG. II–7. Transfer (RP: radial plate).*

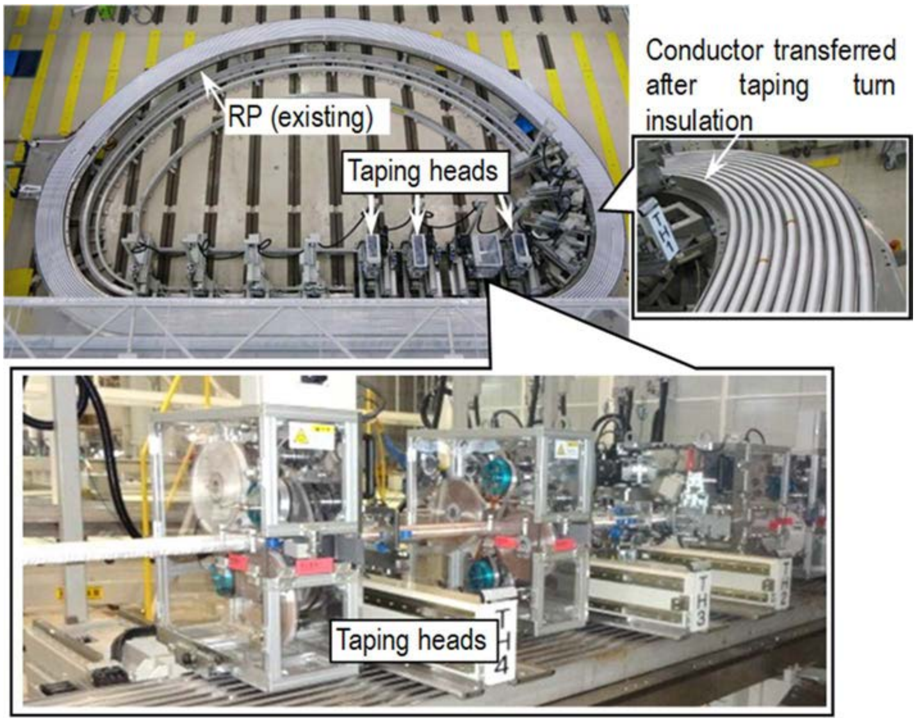



*FIG. II–8. Toroidal field conductor turn insulation and re-insertion.*

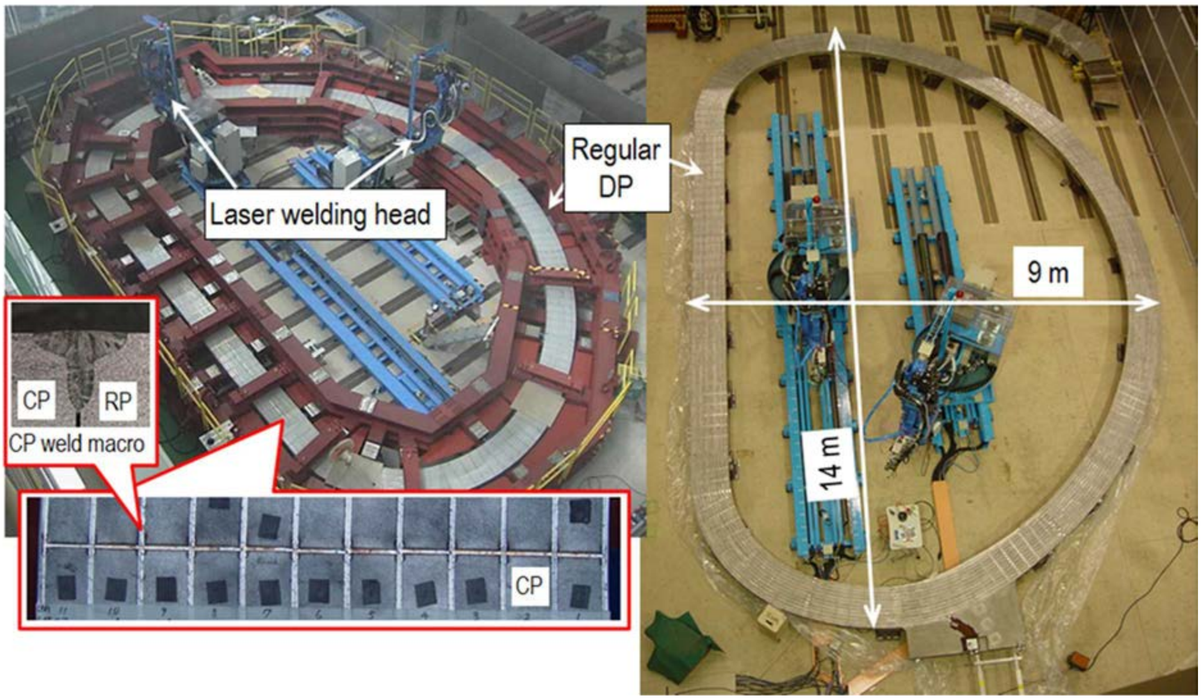



*FIG. II–9. Cover plates welding (DP: double-pancakes; CP: cover plates).*

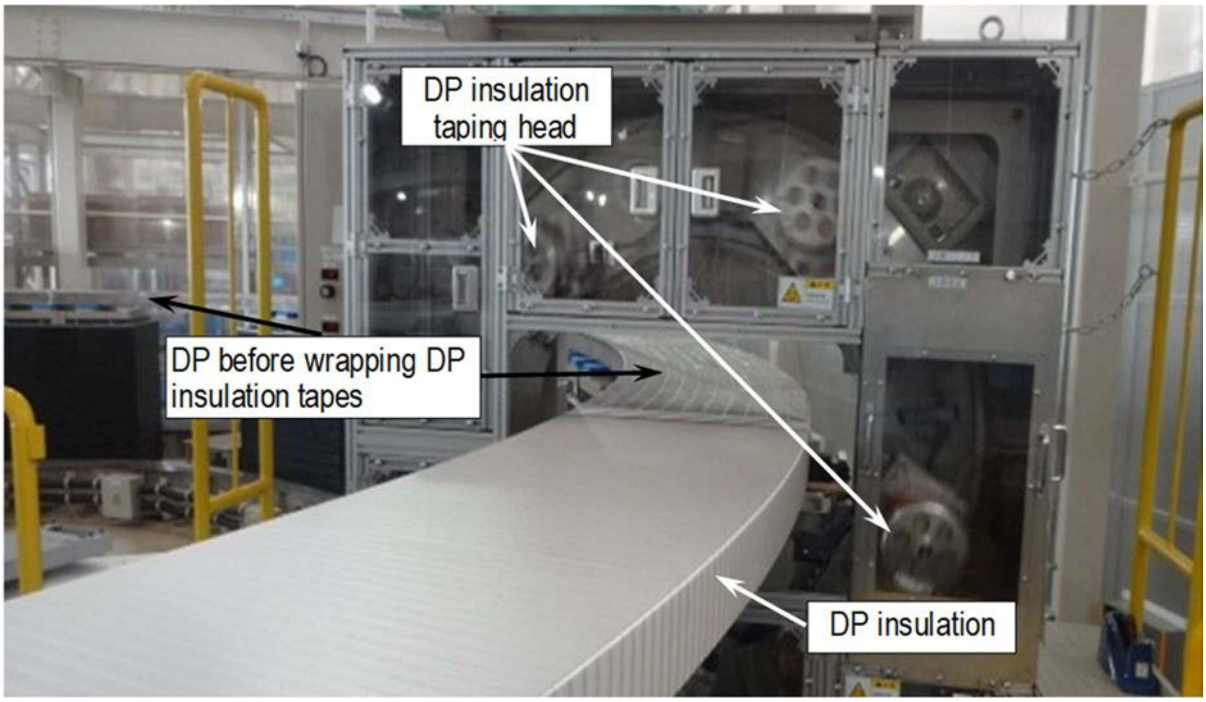



*FIG. II‒10. Double-pancakes insulation.*


*FIG. II‒11. Double-pancakes impregnation.*

### II-3.2. Fabrication process for radial plate and cover plates

The fabrication process for radial plate and cover plates is as follows:

i. Machining 10 radial plate segments in parallel as shown in Fig. II‒12;

ii. Joining rectangular joints at ends of radial plate segments by laser welding and then TIG (tungsten inert gas)[16] welding to make four radial plate sub-assemblies;
iii. Welded rectangular joints are machined in order to make the groove and then, four radial plate sub-assemblies are completed as may be seen in Fig. II–13;
iv. Radial plate sub-assemblies are assembled by laser and TIG welding and then, radial plate is completed as shown in Fig. II–14;
v. In parallel radial plate fabrication, cover plates are fabricated with the following three methods:
    a. Hot rolling and then, cold drawn to fabricate straight cover plate (Fig. II–15);
    b. Bending the above straight cover plate by three points bender to fabricate curved cover plate with single curvature (Fig. II–16);
    c. Machining short cover plate having difference curvatures;
vi. Fitting test of radial plate and cover plates.

Details about manufacturing radial plate and cover plates are found in [II–9]–[II–11].

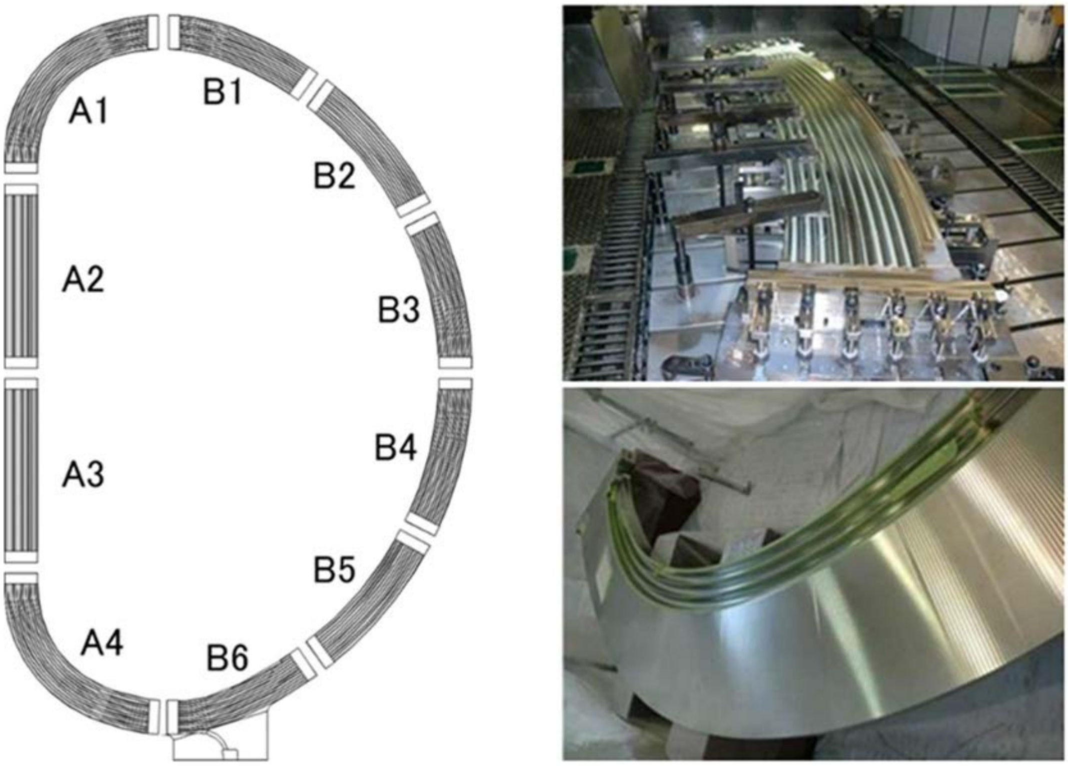



*FIG. II–12. Radial plate segment.*

[16] Often used for high-precision welding of thin materials such as aluminum, stainless steel, and titanium, TIG welding, also known as gas tungsten arc welding (GTAW), is a welding process that uses a non-consumable tungsten electrode to produce a weld.

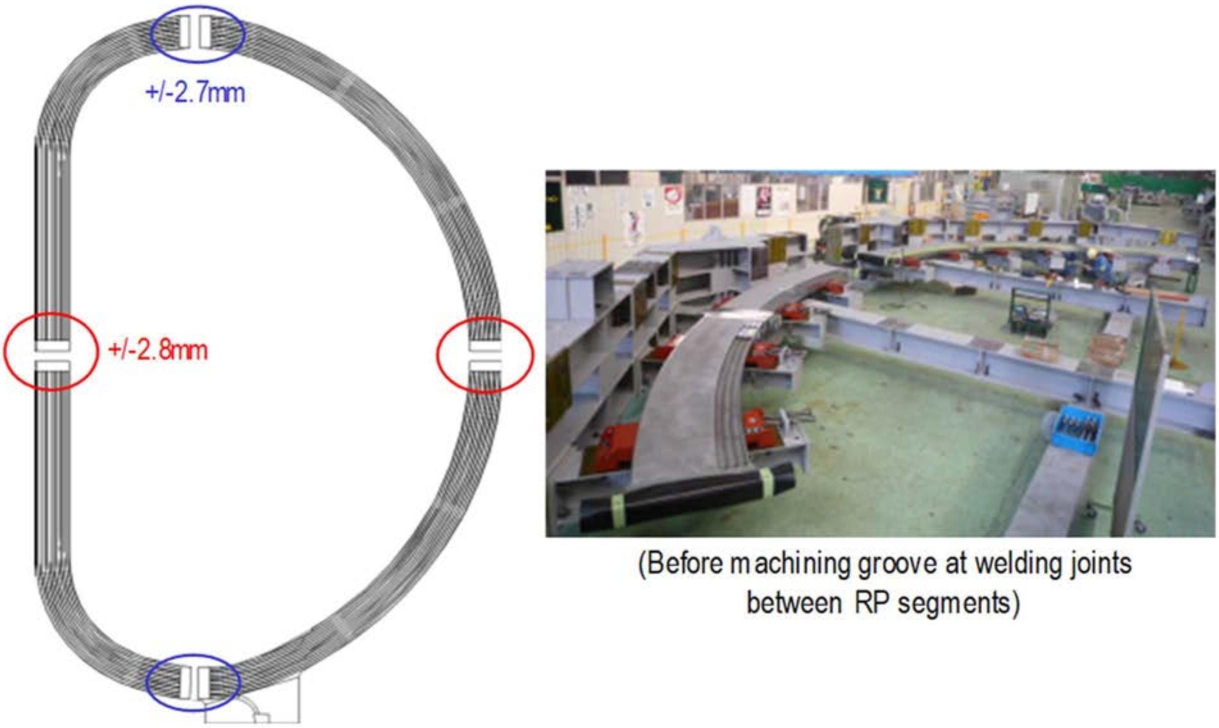



*FIG. II–13. Radial plate sub-assembly (RP: radial plate).*

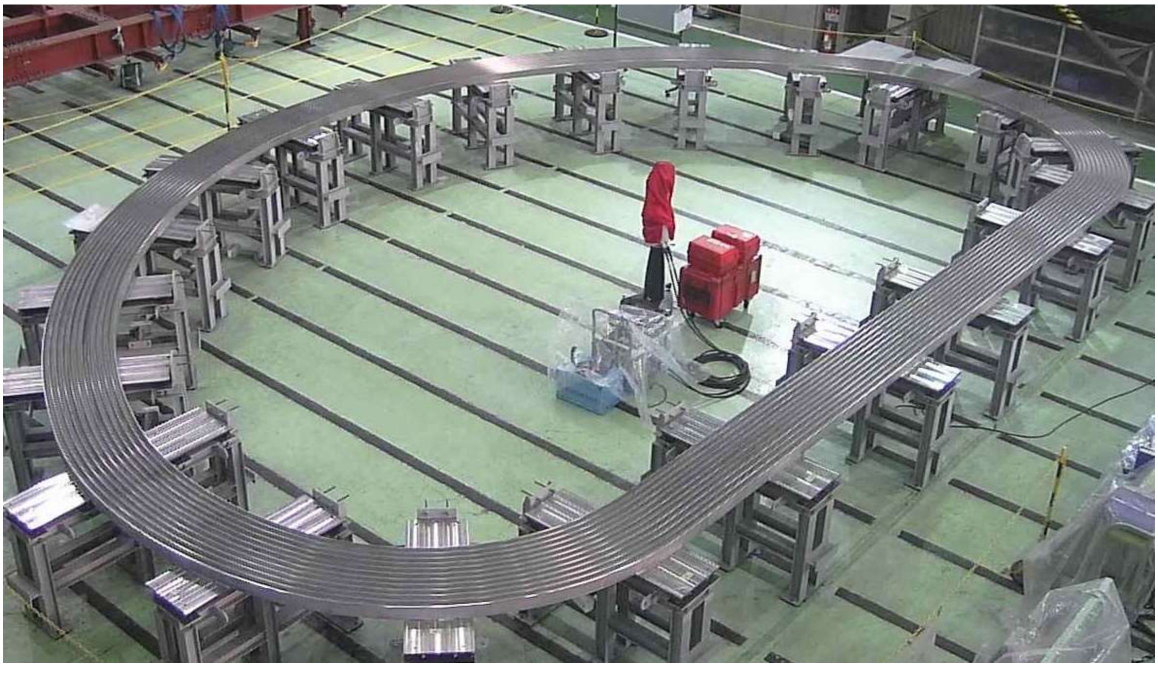


*FIG. II–14. Completed radial plate.*

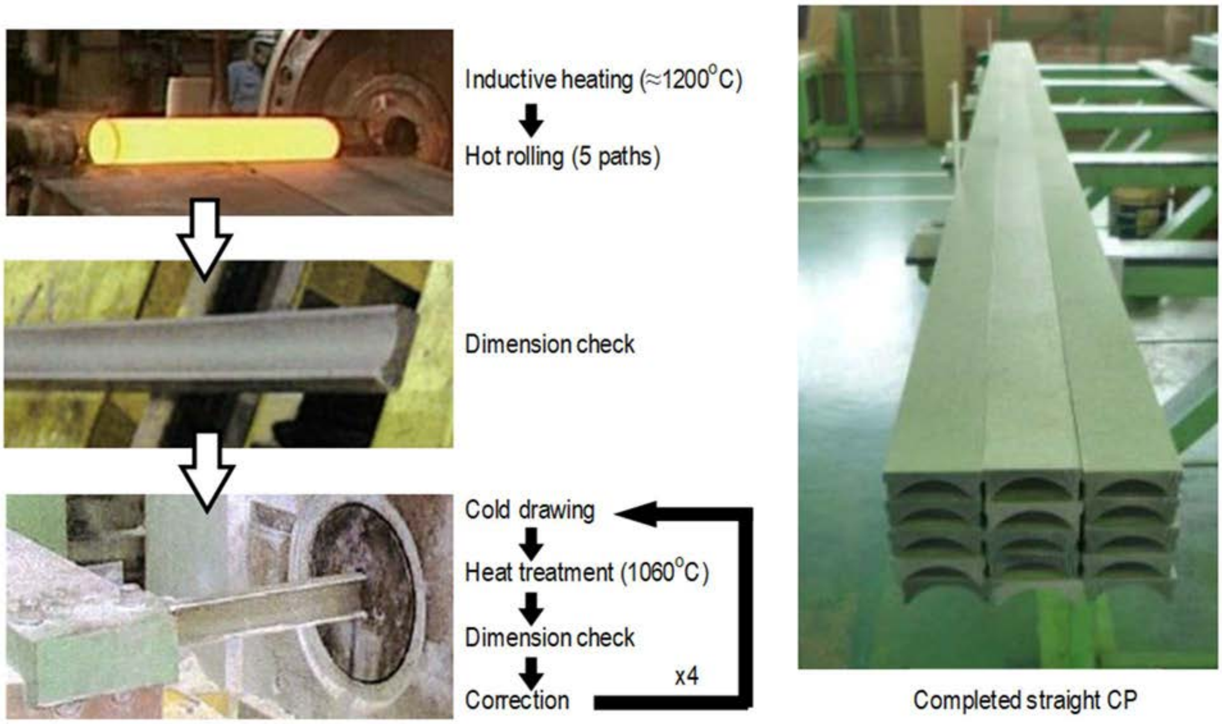



*FIG. II–15. Fabrication of straight cover plate (CP: cover plate).*

*FIG. II–16. Fabrication of curved cover plate with single curvature.*

### II–3.3. Fabrication process for winding pack

Winding pack fabrication process is as follows:

i. Stacking of 7 completed double-pancakes (Fig. II–17);
ii. Wrapping stacked 7 double-pancakes by polyimide and glass tapes (Figs. II–18 and II–19);
iii. Winding pack insulation is vacuum pressure impregnated together (Fig. II–20);
iv. Assembly of cooling pipes and attachment of high voltage instrumentation wires (high voltage wires);

v. Final testing of the winding pack, including a cold test at 80 K for the first three winding packs. Figure II–21 shows completed winding pack, which is placed in a vacuum chamber for cold test.

Further details about manufacturing the winding pack are found in [II–17], [II–20]–[II–22].

*FIG. II–17. Double-pancakes stacking.*

*FIG. II–18. Winding pack ground insulation wrapping.*


*FIG. II–19. Winding pack after wrapping the ground insulation.*

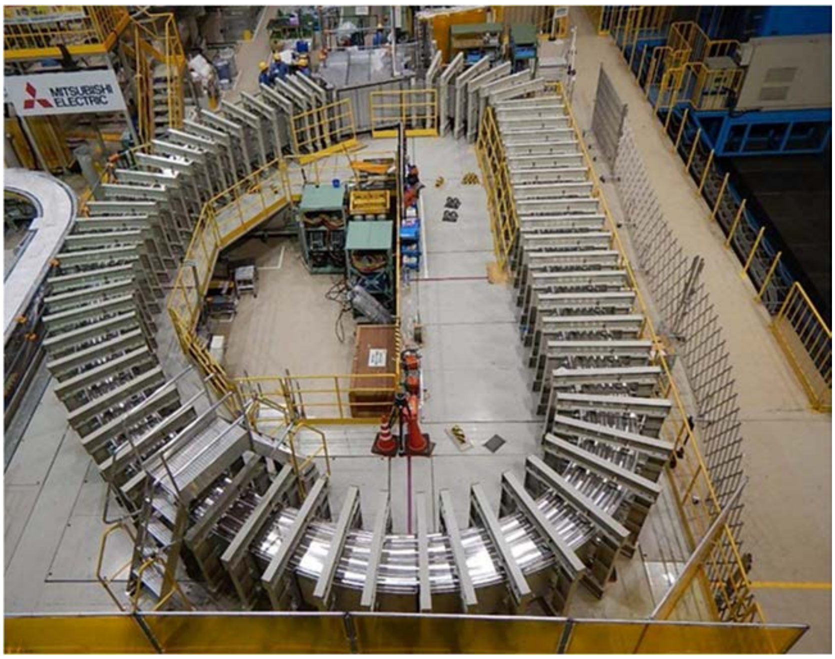



*FIG. II–20. Winding pack before impregnation (winding pack is in mould).*

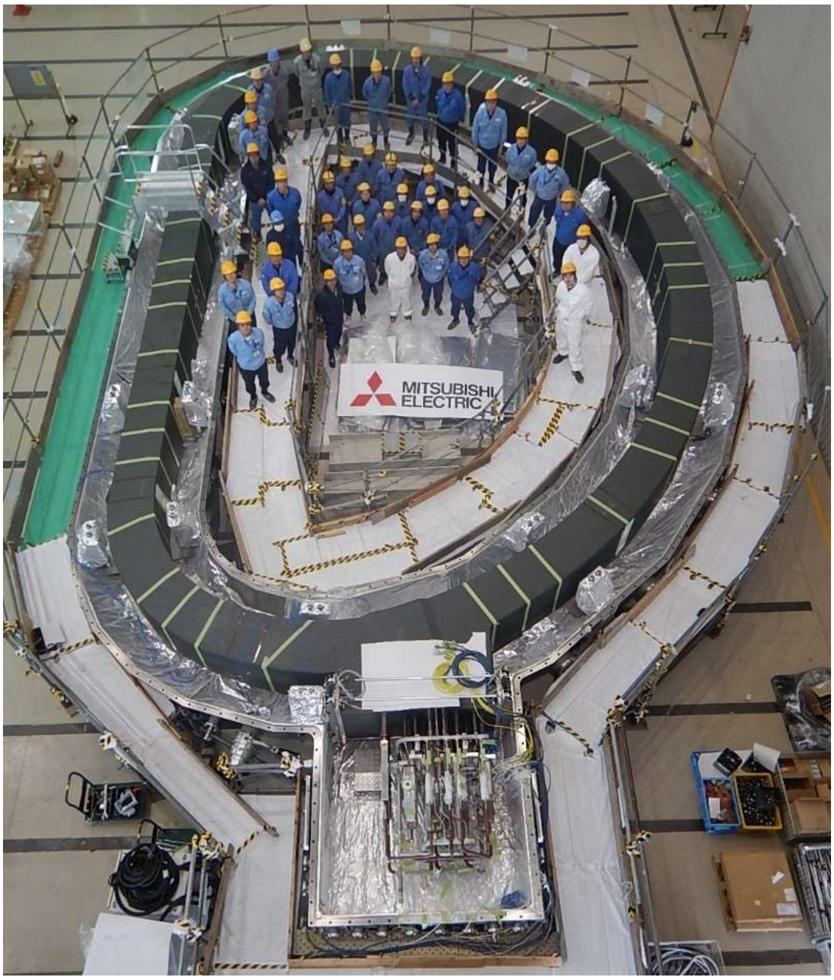



*FIG. II‒21. Completed winding in vacuum vessel for cold test.*

**II‒3.4. Fabrication process for coil cases**

Fabrication process for coil cases is shown in Fig. II‒22. The process consists of the following:

i. Material (SS316LN ITER grade) fabrication by forging and hot rolling;
ii. Machining plates for basic segment;
iii. Welding these plates to make basic segment;
iv. Machining basic segments and then, completion of basic segments (Fig. II‒23);
v. Welding among the basic segments to make sub-assemblies of AU, BU (Fig. II‒24), AP and BP.
vi. Cooling pipe attachment. Cooling pipes are embedded into grooves machined on the inner surface of coil cases. Patty was generally used to fix the cooling pipes and conduct heat from the coil cases to the cooling pipes (Fig. II‒25). However, special pipes hipped Cu tube is welded to AP to enable higher cooling performance and avoid deterioration cooling performance as result of cracking of the putty.
vii. Fitting test of welding bevel between AU-AP, BU-BP and AU-BU (Figs. II‒26, II‒27 and II‒28).

Further details about fabricating the coil cases are found in [II‒4], [II‒19], and [II‒21].

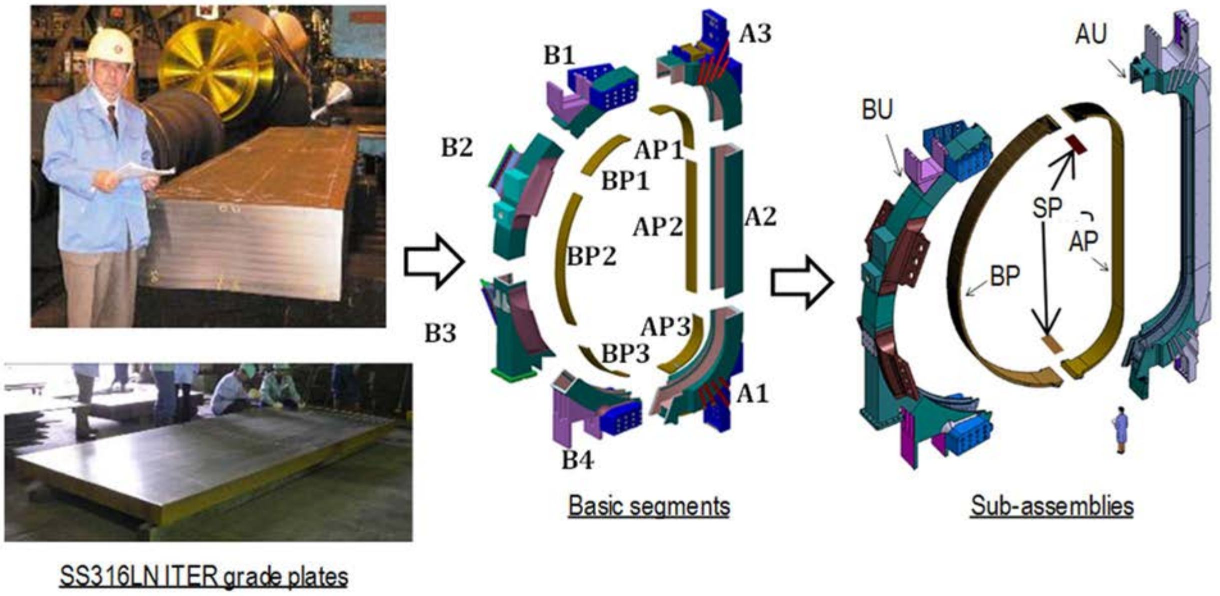



*FIG. II‒22. Fabrication process for coil cases.*

*FIG. II‒23. Basic segments (A3 and A3).*

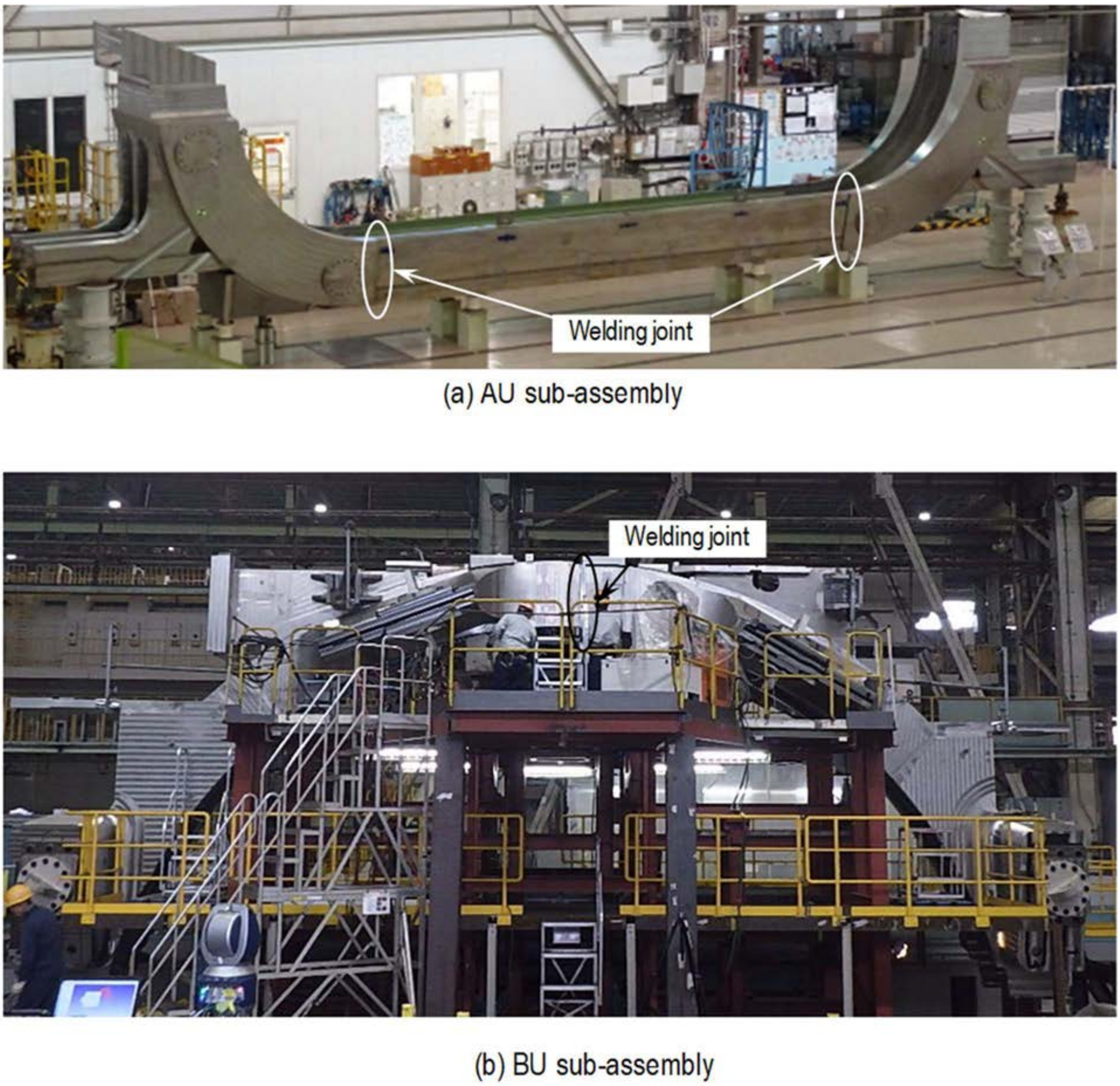



*FIG. II–24. Welding of sub-assemblies.*

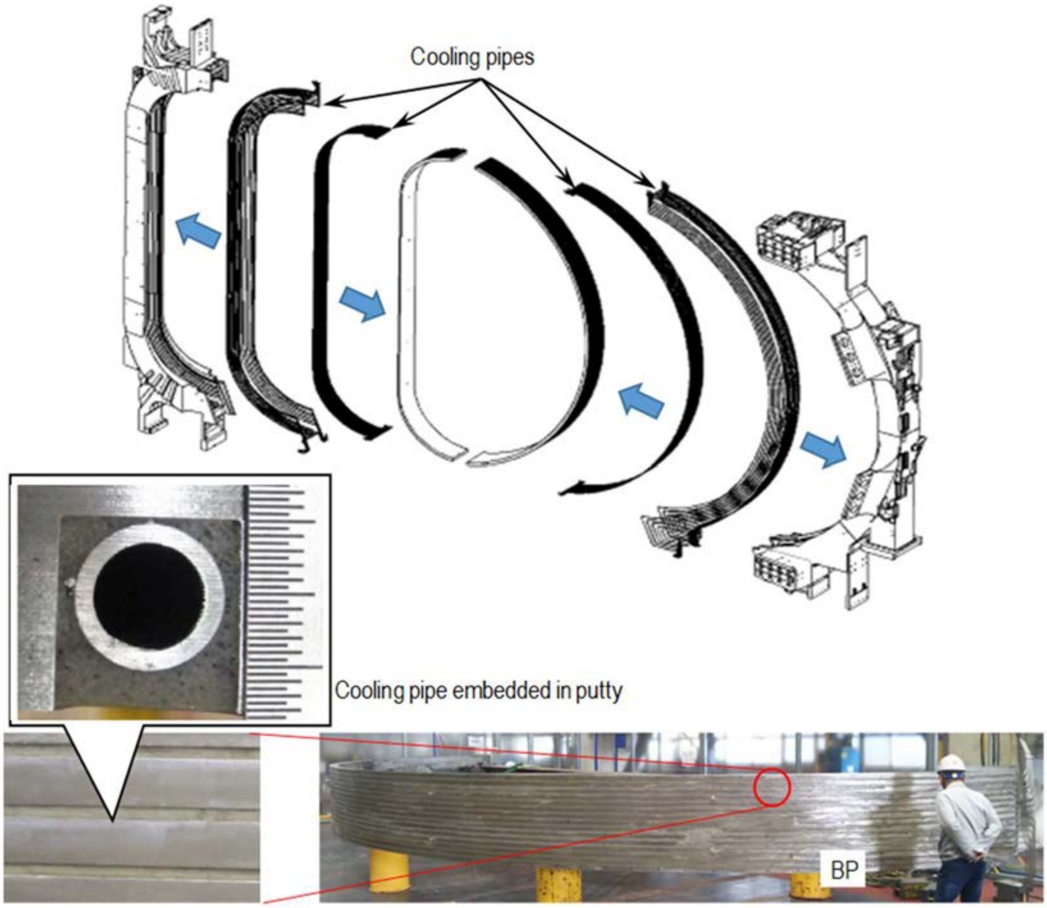



*FIG. II–25. Cooling pipe.*

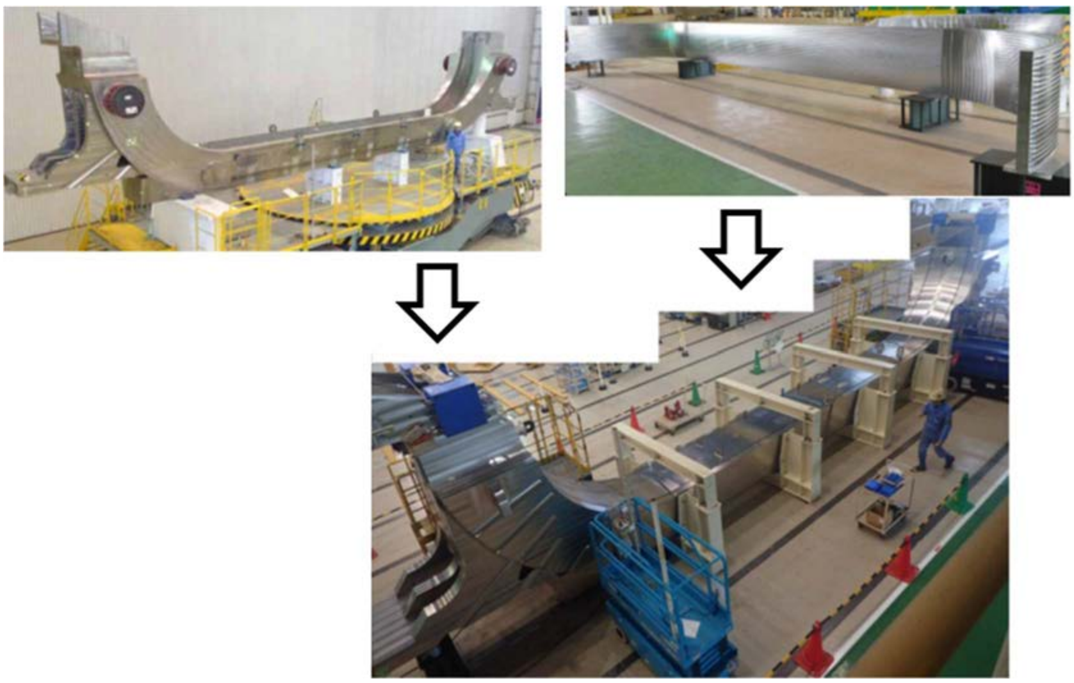


*FIG. II–26. Fitting test for AU and AP.*

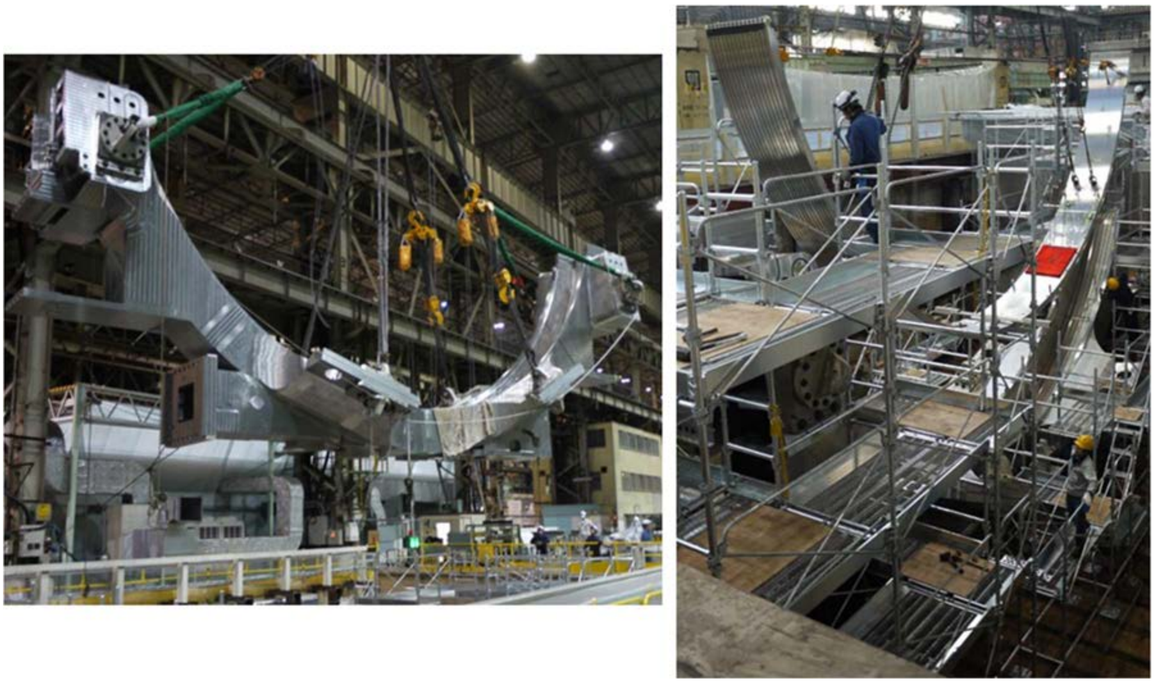


*FIG. II‒27. Fitting test for BU and BP.*

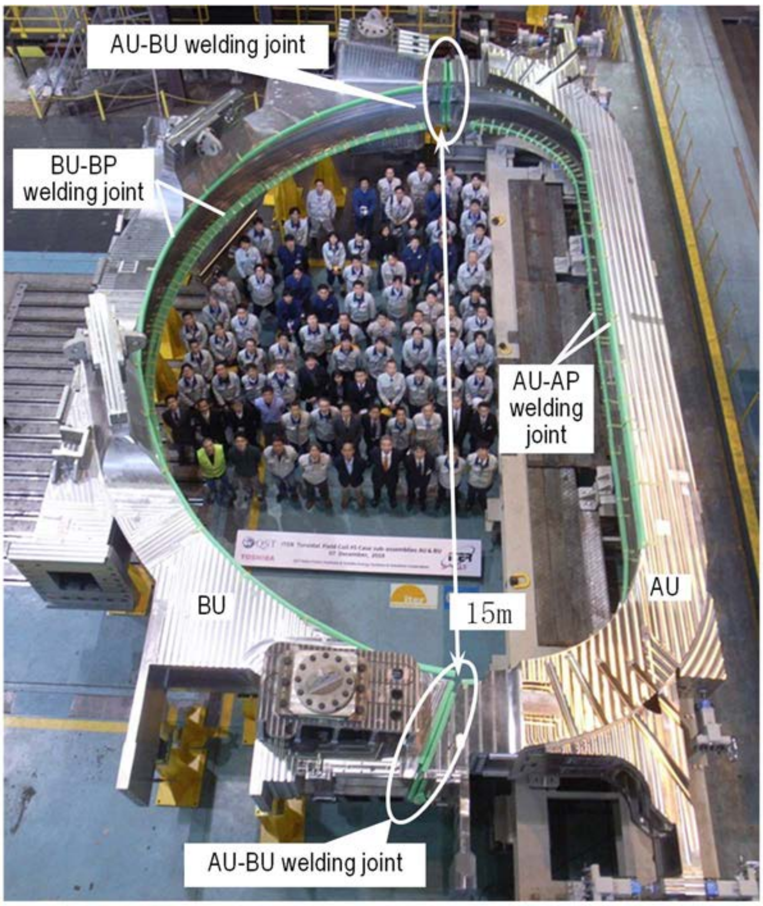



*FIG. II‒28. Fitting test for AU and BU.*

### II–3.5. Assembly of winding pack and coil cases

The assembly process for winding pack and coil cases is shown in Fig. II–29. The process consists of the following:

i. Winding pack is inserted into AU (Fig. II–30);
ii. BU is placed over the winding pack and AU;
iii. AU and BU are butt-welded (Fig. II–31);
iv. Cover plates, AP and BP, are inserted to inner side of the AU and BU (Fig. II–32);
v. AP and BP are welded to AU and BU, respectively. SPs are welded between AP and BP (Fig. II–33). These welding is called poloidal weld hereafter;
vi. Gap between the WP and CC is filled with resin with filler [28]. (Fig. II–34);
vii. Interfaces are final machined (Fig. II–35).

Further details about the assembly are found in [II–21], [II–23]–[II–27].

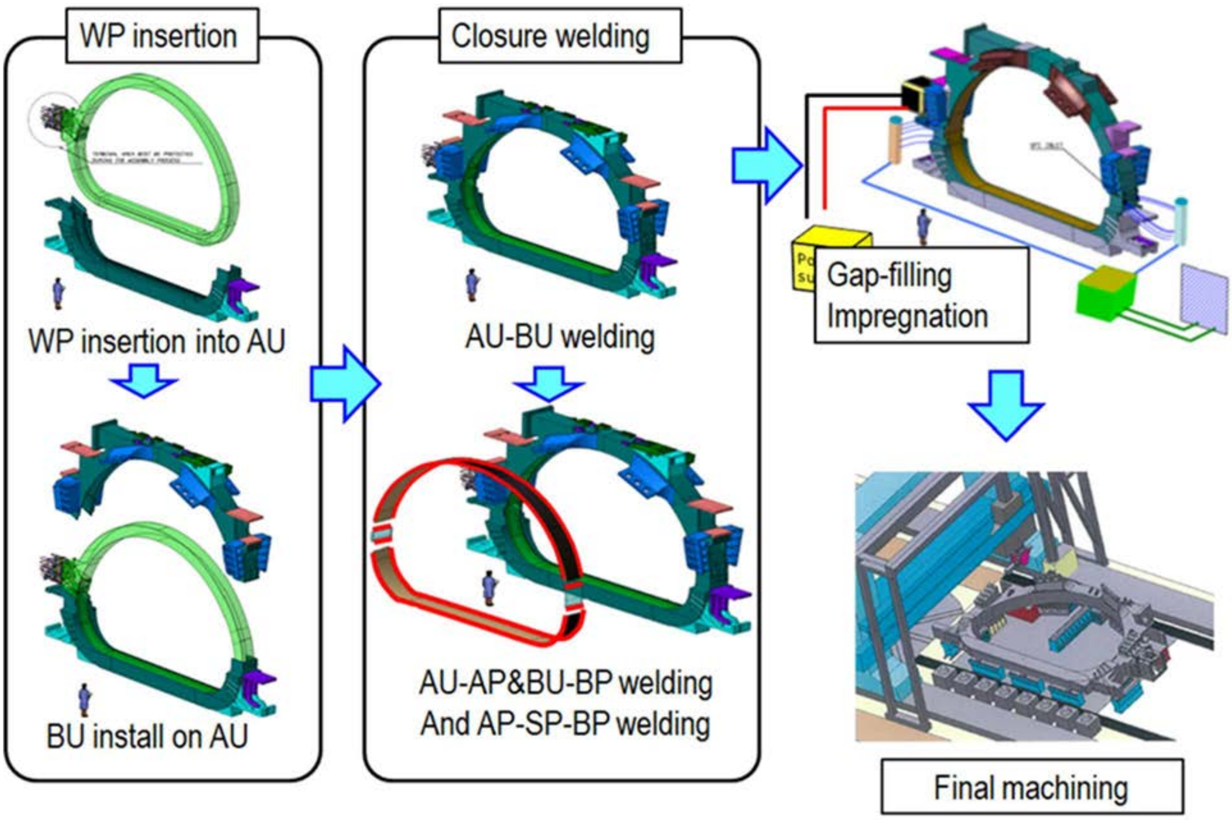



*FIG. II–29. Assembly of winding pack and coil cases (WP: winding pack).*


*FIG. II–30. Winding pack insertion.*

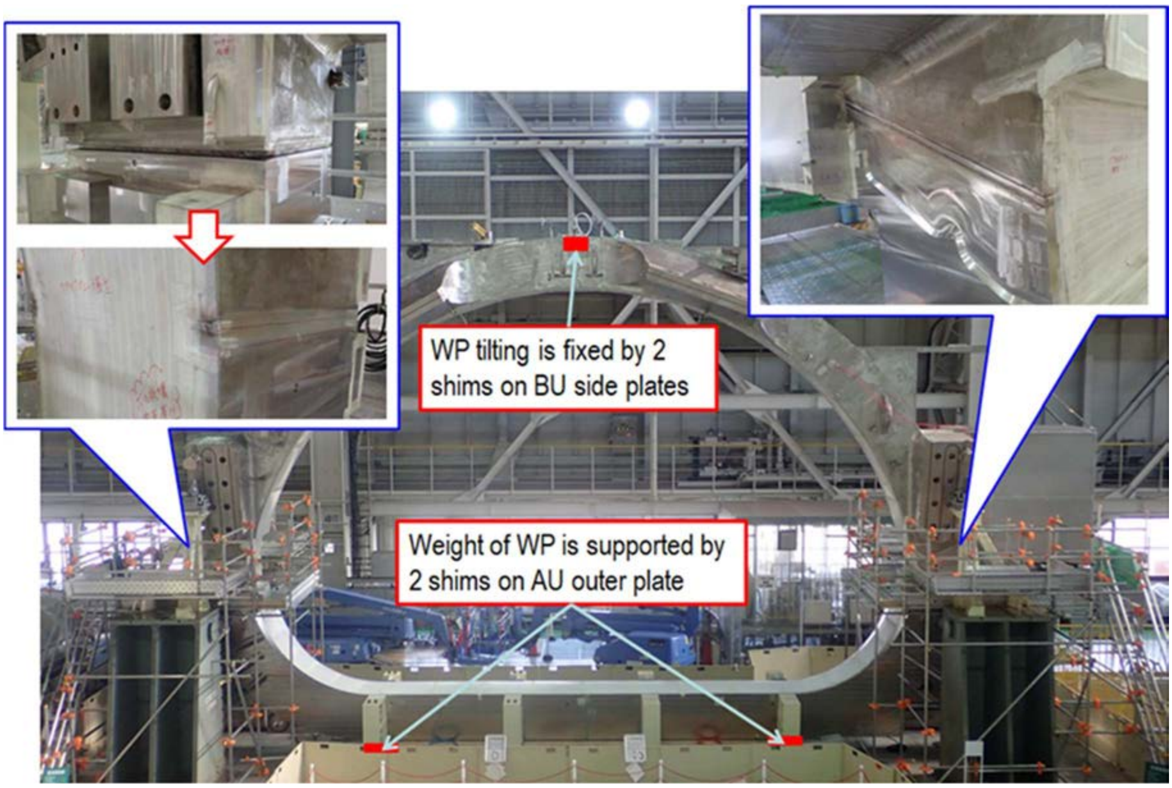



*FIG. II–31. AU-BU welding.*

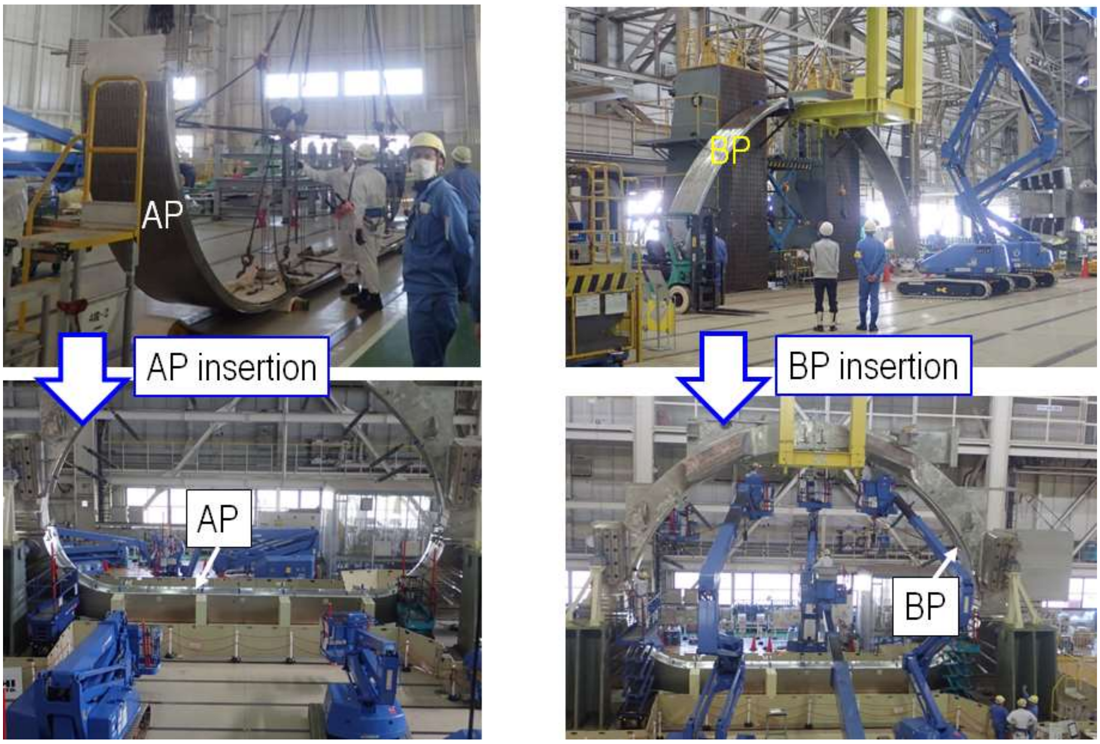



*FIG. II–32. AP and BP insertion.*

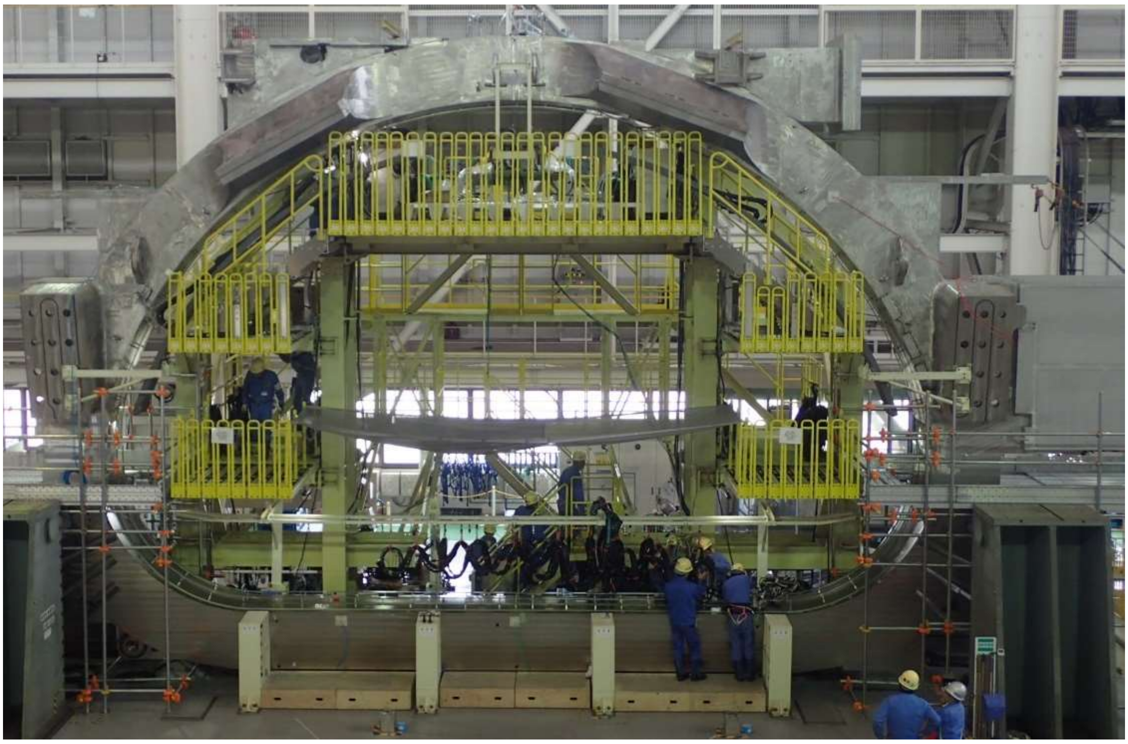


*FIG. II–33. Poloidal welding.*

FIG. II–34. Gap filling.

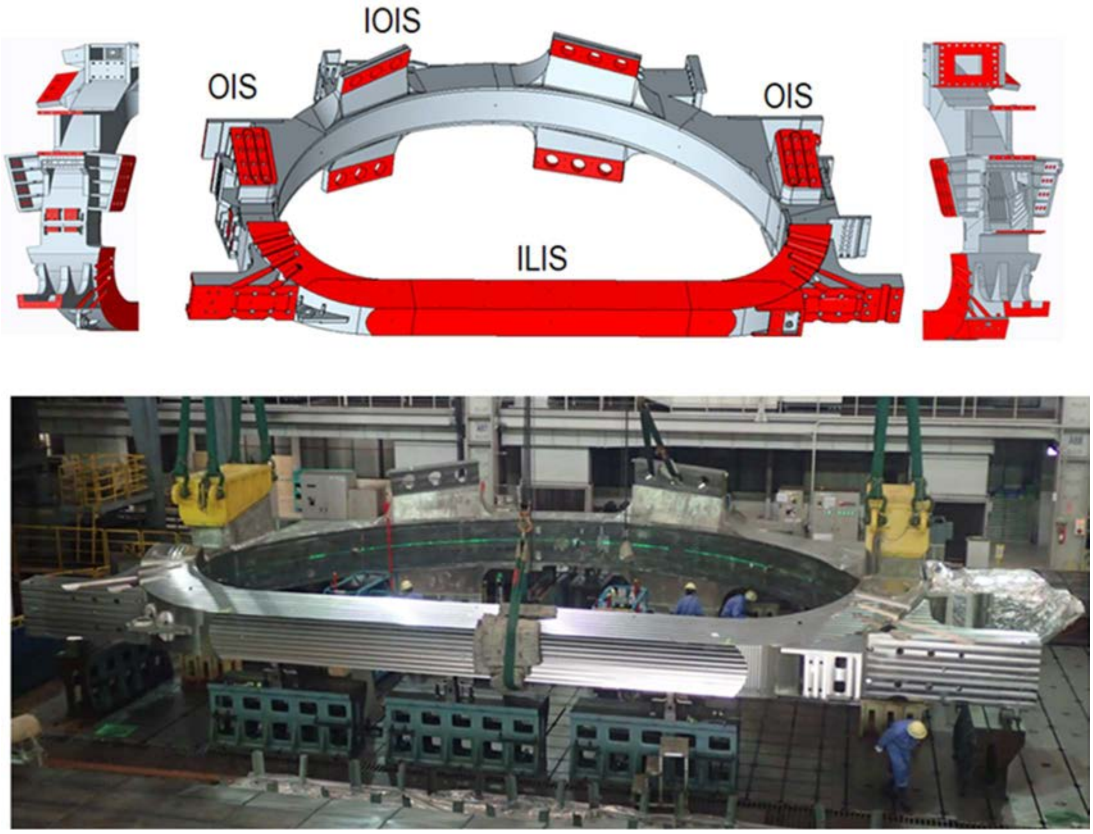



FIG. II–35. Final machining.

II–4. TECHNICAL CHALLENGES AND KEY TECHNOLOGIES IN TOROIDAL FIELD COIL FABRICATION

As described in Section I–2.2, the major technical issues related to fabrication process are indicated as the number with heading character ‘T.’ The following is description of the issues:

T1: *Insertion of toroidal field conductor with turn insulation into radial plate groove*

All toroidal field conductors with turn insulation, which have been wound into D shape and heat treated, need to be inserted into the groove of all radial plates. On the other hand, if the length between the toroidal field conductor and radial plate groove has relatively large difference, it is impossible to insert the toroidal field conductor into the radial plate groove, as illustrated in Fig. II–36.

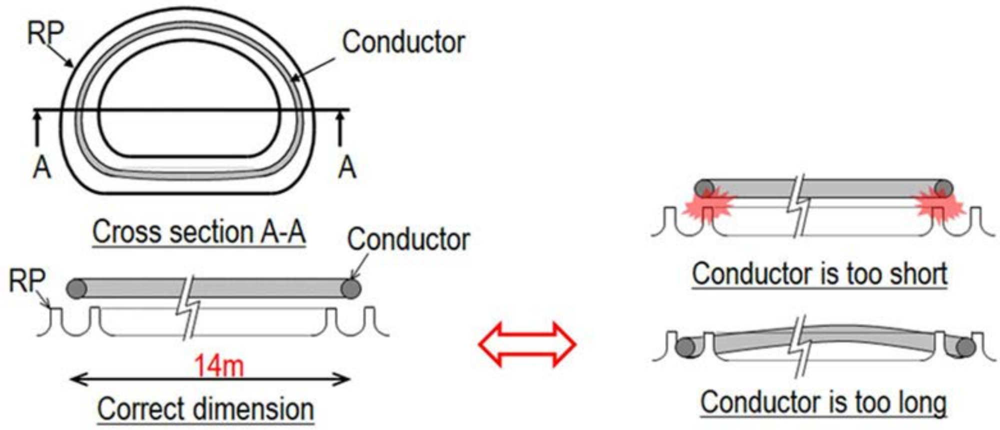



*FIG. II–36. Schematics of the insertion of toroidal field conductor into radial plate groove.*

Tolerances between the radial plate groove teeth and the turn insulation is about ±3 mm at the top and bottom of the winding and about ±2 mm at the outboard. These tolerances are quite minimal compared to the overall toroidal field winding height of 14 m and width of 9 m. Although error in the curvature of the winding can be corrected by slightly bending the conductor, error in conductor length cannot be corrected. If the conductor is too long or too short, the shape after winding would not allow the conductor to be inserted into the radial plate groove, as mentioned above. The elongation or shrinkage of the conductor because of heat treatment was measured to be 0.03–0.07%. The winding dimension prior to heat treatment is therefore determined by taking this change into account. However, the error exists in this prediction. In addition, the length of the radial plate groove has an error. Thus, the allowable error in measuring the length of the conductor during winding is expected very tight. The achievable error should be defined, and proper manufacturing procedure of radial plate and winding should be established.

Further details can be found in [II–6], [II–13] and [II–14].

T2: *Tolerance of severe deformation as a result of cover plates welding*

Although the total length of all welds for each regular double-pancake measures approximately 1.5 km, the required flatness of the completed double-pancake is 2 mm. A radial plate may acquire distortion during its fabrication. Out-of-plane distortion as a result of the radial plate fabrication process should be minimized to satisfy the tight tolerance. Tolerances due to cover plates welding are also minimized by using minimize welding power and optimize welding sequences. In addition, due to asymmetry of side double-pancake, relaxation of the tolerance to side double-pancake needs to be accepted and new acceptable tolerances has to be defined [II–6], [II–9].

T3: *Double-pancake and winding pack impregnation*

Since the toroidal field coil is much larger than the existing coils before toroidal field coil development, it was expected that the impregnation period may take much longer than those experienced. In addition, the resin has to be able to endure irradiation by a fast neutron fluence of $1\times10^{22}$ n/m$^2$. Cyanate ester resin[17] [I–29] is one of the best candidates to meet these specifications. However, there was a little experience in impregnating a large magnet with cyanate ester resin at that time. Additionally, the huge mass of the double-pancake and winding pack makes it difficult to control the temperature during gelling and curing. Therefore, impregnation and curing techniques for the double-pancake and winding pack remained as a major technical challenge. In addition, in double-pancake impregnation, the turn insulation is impregnated by the resin through holes on cover plate, which is under double-pancake insulation layer, and gas remained in turn insulation is evacuated from these holes. Therefore, impregnation of turn insulation with resin was thought to be difficult and it was our concern that void might remain in turn insulation.

T4: *Joint resistance*

It is important to achieve sufficiently low joint resistance, such as 3 nΩ, for inter double-pancake joints of toroidal field coil termination. Soundness of the joint fabrication process during toroidal field coil manufacture is confirmed by full size joint sample test [II–12], in addition to the severe process control established through ITER EDA model coils[18] project [II–30]. However, it is more effective if real toroidal field joints can be inspected directly. 100% inspection of toroidal field joints will be able to reduce the risk of high Joule heating at joints. However, joint resistance measurement on the toroidal field coil was not practical from viewpoint of schedule and cost because a large cryostat to cool down the whole of toroidal field coil to 4K was necessary in terms of huge mass and size of toroidal field coil. In addition, even if the joint resistance could be revealed as not acceptable after the joint resistance measurement test on toroidal field coil, it is very difficult to repair the joint at that stage since double pancakes stacking and joint soldering are already done. In the worst case, toroidal field coil is scrapped.

T5: *High voltage instrumentation wire*

High voltage instrumentation wires are attached on toroidal field conductor or inlet and outlet of cooling pipes and extracted through ground insulation layer. Since extraction of high voltage wire is the weakest point against Paschen high voltage test[19], very careful work is required.

---

[17] Cyanate ester resin is a type of thermosetting polymer that is used in a variety of high-performance applications, such as aerospace, electronics, and automotive industries. It is made by reacting a cyanic acid derivative with an epoxy resin or an unsaturated polyester resin.

[18] The early demonstration and assessment (EDA) phase of ITER involved the development of several prototype coils to test and validate the manufacturing techniques and performance of the magnet system. The EDA model coils consisted of six toroidal field coils, two poloidal field coils, and one central solenoid coil.

[19] The Paschen high voltage test, also known as the Paschen curve test or Paschen breakdown test, is a method of determining the breakdown voltage of a gas at a specific pressure and gap distance. It is named after the German physicist Friedrich Paschen, who first described the phenomenon in 1889.

T6: *Minimization of welding distortion*

In AU and BU, achieving tight tolerances of approximately 1 mm is crucial. To compensate for welding deformation, an additional thickness of material is used, which is later machined after welding. However, the machining process for the assembled AU and BU is time-consuming, and there are only a limited number of machines capable of performing this task. Consequently, precise control of welding deformation becomes essential to minimize the need for excessive extra material thickness. Similarly, during the closure welding process for the assembly of the winding pack and coil cases, a similar technique need to be employed to manage welding deformation effectively.

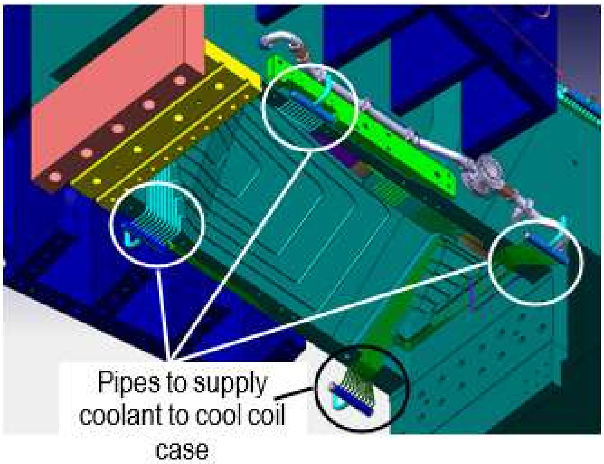
T7: *Accurate positioning of current centre line*

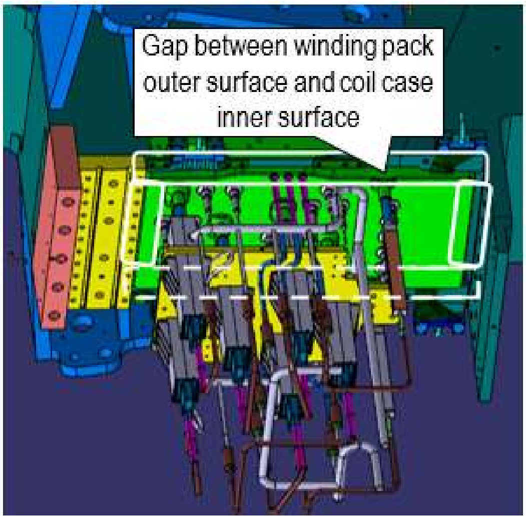
In the toroidal field coil, accurate positioning of the current centre line, which is defined as barycentre of the toroidal field conductors, is required to achieve stable plasma. In particular, the current centre line needs to be placed within 1.3 mm from the nominal position along the inboard straight section. In addition, out-of-plane deformation of current centre line is required to be within ±3 mm. In addition, the straight section of a winding pack is deformed by gravity by ~1 mm [II–23]. While accurate positioning of a huge winding pack is challenging, deformation of winding pack makes it more challenging to position the current centre line within the tolerances. The method to overcome these difficulties needs to be developed. On the other hand, a sufficient gap has to exist between the winding pack and coil cases in order to enable filling with high viscosity resin [II–28]. The target minimum gap was originally 4 mm [II–21]. Distortion of side plates of AU and BU due to closure welding between the AU and AP, and BU and BP reduce this gap [II–21]. The distortion of the BU by AU-BU welding reduces gap at the outboard as discussed in [II–21]. After welding of the coil cases, these requirements have to be satisfied simultaneously. The required tolerance is in the order of mm and very demanding considering the overall dimensions of toroidal field coil of 16 m×9 m.

T8: *Gap-filling between welding distortion and coil cases*

The total volume of gap filling resin to be injected is approximately 1.5 $m^3$ in toroidal field coil. Such big volume should be filled by high viscosity resin with filler. In addition, viscosity of this resin increases much within 24h, especially when normal mixing method is used. Therefore, gap filling needs to be implemented within properly short duration before increase of viscosity of the resin or without influence of increase of the viscosity.

There is a big opening at welding distortion terminal region in the coil cases as shown in Fig. II–37 (a). Since a gap between the welding distortion and coil cases is filled under vacuum pressure and gap filling resin is pressurized before curing, the gap between the welding distortion and coil cases at this opening (Fig. II–37 (b)) needs to be leak-tight. However, welding distortion peninsula is pulled into coil cases when evacuating inside the coil cases and extruded from the coil cases when pressurizing inside the coil cases. This load is relatively large, about 15 tons, in case of toroidal field coil because of large area of the opening. Such large force may originate relative movement between the welding distortion and coil cases, resulting in making sealing between the welding distortion and coil cases difficult. If a serious leak happened from here during gap filling of a real toroidal field coil, gap filling is failed. In this case, toroidal field coil might have to be scraped or long delay might be expected. Therefore, a risk of leak there should be avoided as much as possible. Proper method for sealing there needs to be developed.




*(a)* *(b)*

*FIG. II–37. Gap between winding pack and coil case at terminal region: (a) opening of coil case at terminal region, (b) terminal region when winding distortion is inserted in coil case.*

T9: *Final machining*

Since toroidal field coils are framework of ITER, they have a lot of interfaces with other components and their gravity supports. Tolerances to these interfaces are tight on most of these interfaces. For example, the tightest tolerance is ±0.2 mm profile on 8 m long and 0.8 m wide surfaces at the side plate of the AU straight section. When the closure weld deformation and requirement to current centre line are considered, these tight tolerances are also challenging. In addition, since only upper side of toroidal field coil on a gantry machine can be finally machined, the positioning of toroidal field coil at turn-over directly affects the tolerance of toroidal field coil interfaces. If the required tolerances are tight, positioning of the better accuracy than the tolerances are required. This was also challenging because of the tight tolerances.

T10: *Other key technology*

Welding of full austenite stainless steel (SS316LN ITER grade) except high power welding, such as laser beam welding and electrical beam welding, is not challenging but the key technology. In case of toroidal field coil, weld on the thin jacket of toroidal field conductor need to be done for He inlet and joint fabrication [II–11, II–12]. In these welds, the temperature of cable in the toroidal field conductor should be lower than some threshold, such as 200°C. These techniques are also important.

## II–5 RESOLUTION OF MAJOR TECHNICAL CHALLENGES IN TOROIDAL FIELD COIL FABRICATION

T1: *Insertion of toroidal field conductor with turn insulation into radial plate groove*

To succeed in insertion of all 63 toroidal field conductors with turn insulation into radial plate groove for 9 toroidal field coils, the target tolerances in each manufacturing process, which is source of error in conductor length, are optimized as follows [II–13, II–14]:

i. Tolerance in winding is ±0.01%;
ii. Prediction of heat-treated conductor elongation or shrinkage is ±0.02% including a scatter of ±0.01% among each turn;
iii. Dimension measurement of conductor is ±0.01%, which seems conservative;
iv. Manufacturing of radial plate is ±0.01%.

Dedicated winding machine was then developed [II–13, II–14]. The conductor length was precisely measured optically and then, the accuracy was significantly improved from the conventional measurement by an encoder. In addition, the optimized radial plate manufacturing procedure was established [II–10]. Radial plate is fabricated by connecting four sub-assemblies by laser beam welding and then TIG welding in order to minimize welding shrinkage. In addition, extra thickness was remained at both ends of the radial plate sub-assemblies, to enable adjustment of the radial plate groove length to the length of wound and heat-treated toroidal field conductor. The technique of high power (30 kW) laser beam welding of SS316LN has been developed [II–10] through toroidal field coil project and hot cracking could be avoided in toroidal field coils and radial plate manufacturing. As result of these measures, all 63 double-pancakes' winding have been inserted into groove of radial plates in Japan [II–27, II–5].

This technique can be used in DEMO.

The toroidal field coil's fabrication is at TRL7, i.e., the capacity to produce in a production representative environment, but not yet TRL8, i.e., the pilot line capacity demonstrated, since the production is limited to the toroidal field coils for one fusion reactor unit (ITER), i.e., kind of prototypes manufacturing.

T2: *Tolerance of severe deformation as a result of cover plates welding*

To evaluate out-of-plane distortion and in-plane shrinkage of the toroidal field coils double-pancakes by cover plates welding, analysis using inherent strain [I–31] was performed. In this method, welding deformation is evaluated using an elastic model for assuming normally anisotropic residual strains around the welding bead. Although an accurate evaluation of inherent strain is a key part of this method, an analytical method for precisely estimating such strain has not been established yet for large structures such as double-pancakes. The inherent strain was therefore estimated by comparing the test results of an 1 m radial plate mock-up [II– 6] with the calculated out-of-plane distortion and in-plane shrinkage in a circumferential direction. The inherent strain was updated through larger scale mock-ups and then, optimized cover plates welding sequence was developed.

From these efforts, 3 mm of the target flatness was achieved except one side double-pancakes, whose flatness was 3.3 mm (a little large than the target) [II–32]. The major source of the distortion is relatively long sinuous out-of-plane deformation along radial plate circumference direction [II–16]. Such distortion can be corrected by compressing double-pancakes during double-pancakes stacking [II–16]. In fact, method to improve flatness of completed double-pancake was developed and the target tolerance of 2 mm flatness of the double-pancake has been achieved [II–17].

This or similar technique can be used in DEMO.

The cover plate welding technology is at TRL7, i.e., capacity to produce in a production representative environment, but not yet TRL8, i.e., pilot line capacity demonstrated, since the production is limited to the toroidal field coils for one fusion reactor unit (ITER), i.e., kind of prototypes manufacturing.

T3: *Double-pancake and winding pack impregnation*

After double-pancake insulation, double-pancake is impregnated with cyanate ester and epoxy blended resin. Since the potlife of this resin is sufficiently long [II–7], it was allowed to spend a few days for double-pancake impregnation. This is one of the key factors to succeed in double-pancake impregnation. During double-pancake impregnation, double-pancake is inclined by 10 degrees to avoid trapping of gas in the insulation layer and capacitance is measured to confirm turn insulation is fully impregnated. Indeed, it was confirmed that the capacitance is saturated during impregnation.

Qualification tests were conducted using two prototype double-pancakes: a regular double-pancake and a side double-pancake. The regular double-pancake underwent a thermal cycle test at 80 K, as well as electrical and leak tests, all of which it passed successfully. Moreover, a destructive test was carried out to ensure that no significant voids remained in the turn insulation. Figure I–38 illustrates a cross-section of the cut proto side double-pancake. The void ratio was found to be less than 1%, meeting the specified requirement.

For winding pack impregnation, the same technique was applied and successfully impregnated [II–21].

This technique can be used in DEMO.

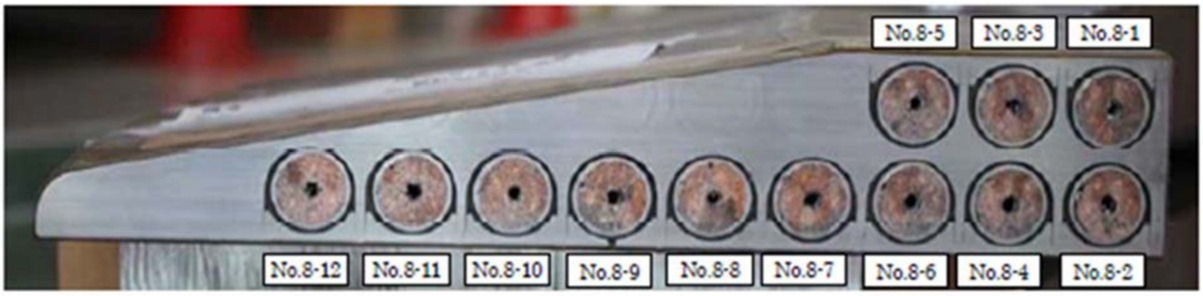



*FIG. II–38. Cross sectional view of cut proto side double-pancake.*

Successful tests and checks using proto double-pancakes have been done: 1) thermal cycle to 80 K and electrical and leak tests on one proto regular double-pancakes, which are partial but not complete operational environment tests and 2) verification on the impregnation voids on only one proto side double-pancakes. These tests and checks using elementary full scale double-pancakes prototypes correspond to TRL6 when considering the whole toroidal field coil component required performances under full operational environment (e.g. under low temperature and radiation environment within the tokamak).

T4: *Joint resistance*

As stated in [II–12], it was confirmed that developed joint satisfied the required joint resistance. During manufacturing of joint, process control, such as control of impurity in Ar gas flowed in the toroidal field conductor during heat treatment, was implemented to keep the required quality. In addition, as described in [II‒18] and [II‒22], the new inspection method of joint resistance at room temperature was developed. In this method, penetration length of small current is very precisely measured at room temperature and confirm if the joint resistance can be not bad. This allowed to avoid a risk of scrap of toroidal field coil as a result of bad joint resistance and this technique can be used in DEMO.

The [manufacturing] technology to ensure reliable low resistance for inter double pancake joints of toroidal field coil termination is still at mid TRL level (i.e. TRL6). Indeed, although tests on a full size joint sample and a severe process control have been done, 100% of actual inter double pancake joints would need to be inspected to reduce the risk of high Joule heating at joints, which is not done since it requires a long and costly process. Moreover, it is very difficult to repair an out-of-specification joint when identified during the joint resistance measurement test at toroidal field coil level, which induces a potential scraping of the defective toroidal field coil.

T5: *High voltage instrumentation wire*

To avoid Paschen discharge around high voltage wire extraction, it is necessary to avoid appearance of void around high voltage wire, where the resin can drop by gravity before gelling. The high viscosity resin with high filler content was used to fill this space, as shown in Fig. I‒39 (a), [II‒25, II‒27]. Single layer glass tape is then wound, this resin is cured, and visually confirmed that no void exits around high voltage wire. After that main ground insulation was applied. At beginning, high voltage wires are attached after all cooling pipes are assembled with applying the above method. It was however time consuming to attach the high voltage wires because each set of high voltage wires is connected each cooling pipes one by one from limitation of accessibility to the cooling pipes. Therefore, high voltage wires are connected to all cooling pipes simultaneously before assembly of the cooling pipes [II‒27]. In addition, the ground insulation around the high voltage wire extraction is impregnated in vertical position to secure full impregnation around the extraction, as shown in Fig. II‒39 (b), [II‒27]. No Paschen discharge was observed at high voltage wire extraction applying both methods mentioned above so far. Accordingly, it can be concluded that the technique for high voltage wire extraction has been developed and rationalized.

This technique can be used in DEMO.

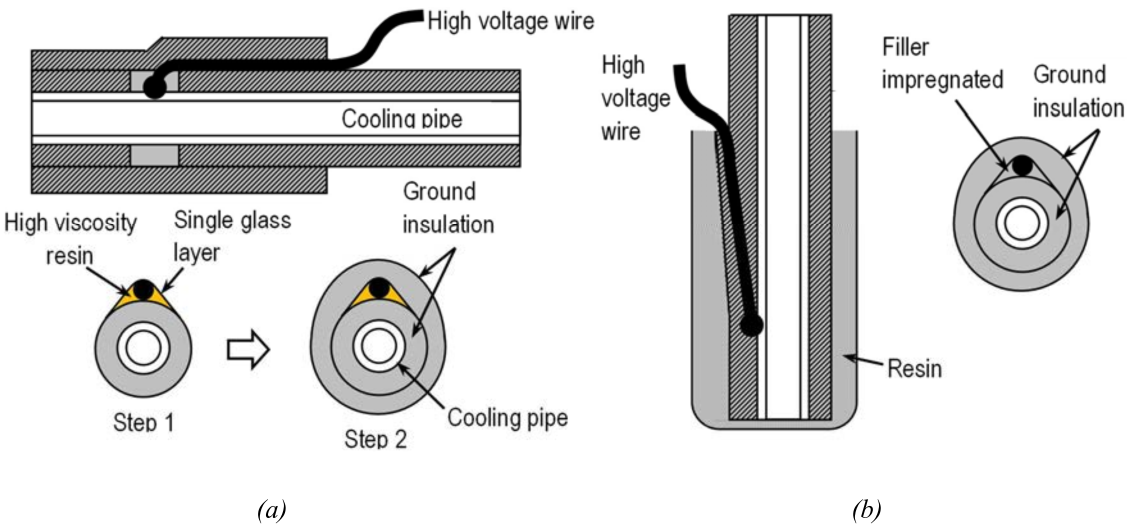



*FIG. II‒39. Techniques for high voltage wire extraction: (a) original technique, (b) rationalized technique.*

The high voltage wire technology is at TRL7, i.e., capacity to produce in a production representative environment, but not yet TRL8, i.e., pilot line capacity demonstrated, since the production is limited to the toroidal field coils for one fusion reactor unit (ITER), i.e. kind of prototypes manufacturing.

T6: *Minimization of welding distortion*

The balanced welding technology was applied in welding of coil cases and toroidal field coils closure welding to control welding distortion and ± few mm tolerance of welding distortion was achieved [II–19]. In addition, a new technique was developed to control welding distortion more precisely by combination of the balanced welding and evaluating welding distortion by optically measuring fiducial points on coil cases and toroidal field coils using a laser tracker. The welding distortion is controlled by optimizing welding sequence and/or by welding with constraints correcting welding distortion when it becomes larger, according to the optical measurements during the welding.

Figure II–40 shows an example of how to minimize the welding deformation. The horizontal axis in Fig. II–40 is the length of the outer plate inner surface from top side. As it can be seen, the deviation in radial direction, δR (m), is within ±1.2 mm. A similar or better precise tolerance was achieved in welding distortion in out-of-symmetric-plane direction. Therefore, the validity of the developed technique can be confirmed. Based on these findings, it is possible to reduce the thickness of the extra material that needs to be removed during the final machining process. As a result, the fabrication of coil cases can be expedited, leading to faster production times.

This technique is used for all welding of assembly of sub-assemblies and assembly of winding pack and coil cases. Welding distortion could then be very precisely controlled.

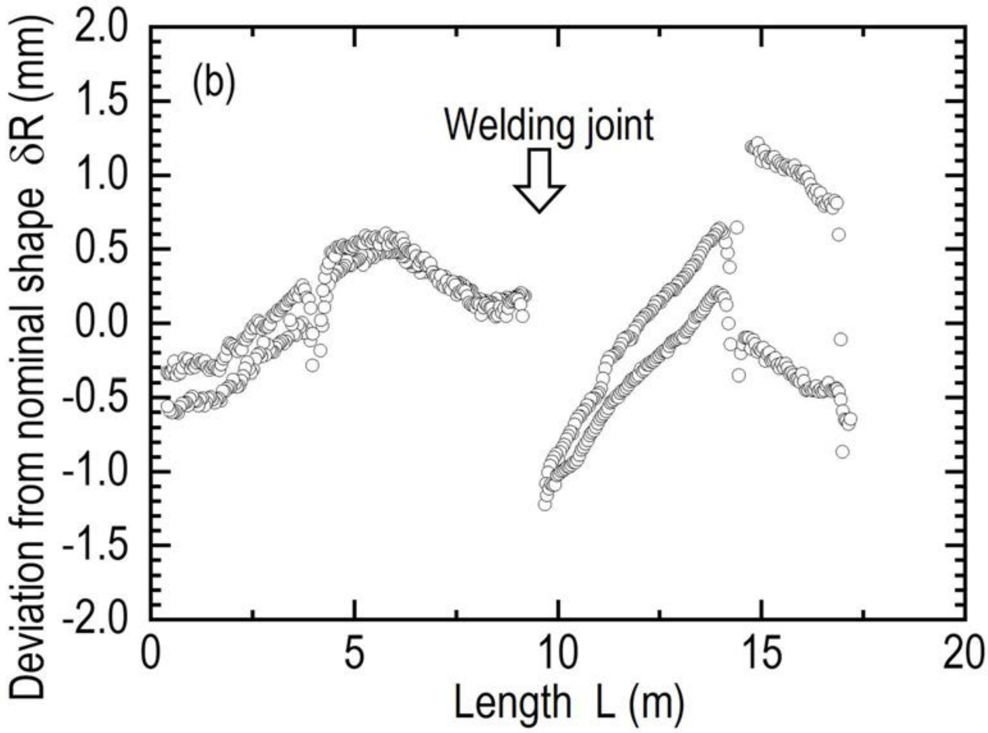



*FIG. II–40. Deviation of profile by welding deformation.*

The welding deformation control technology is at TRL7, i.e., capacity to produce in a production representative environment, but not yet TRL8, i.e., pilot line capacity demonstrated, since the production is limited to the toroidal field coils for one fusion reactor unit (ITER), i.e., kind of prototypes manufacturing.

T7: *Accurate positioning of current centre line*

The position of winding pack in vertical direction is decided to put two custom shims and glass sheets on inner surface of the outer plate of the AU. The thicknesses of the glass sheets were optimized once winding pack was temporary inserted and its vertical position was measured precisely by a laser tracker. The winding pack position in radial direction is adjusted by measuring its position optically during its lowering. By this method, very accurate positioning of winding pack, such as a few hundred µm, was achieved [II–21]. After closing the weld between AU and BU, flexible shims, whose thickness can be adjusted, is inserted in the gap between winding pack and BU to optimize winding pack position in BU. These shims allow slippage between winding pack and BU inner surfaces in order to avoid winding pack deformation by coil case deformation by poloidal weld [II–21].

The compensation for the deformation of the winding pack is achieved by pushing the inner surface of the pack using screwing bolts into BP at the outboard, as illustrated in Fig. II–41 [II–21]. Fiducial points, denoted as open circles from A to H, are strategically positioned to measure the deformation caused by the closing weld. Additionally, gap filling holes are indicated as open squares in the figure. To estimate the displacement of the winding pack even after the closure weld, gap filling holes are utilized. These holes are instrumental in measuring the displacement of markers attached to the winding pack, which helps correct the pack’s deformation due to gravity. The location of these holes is also depicted in Fig. II–41. It is important to note that measuring the winding pack's deformation was not initially planned, and there are limitations in drilling holes on the coil case from both a stress point of view and the coil case's geometry. Consequently, these holes were drilled at different positions from the current centerline to accommodate the measurement requirements.

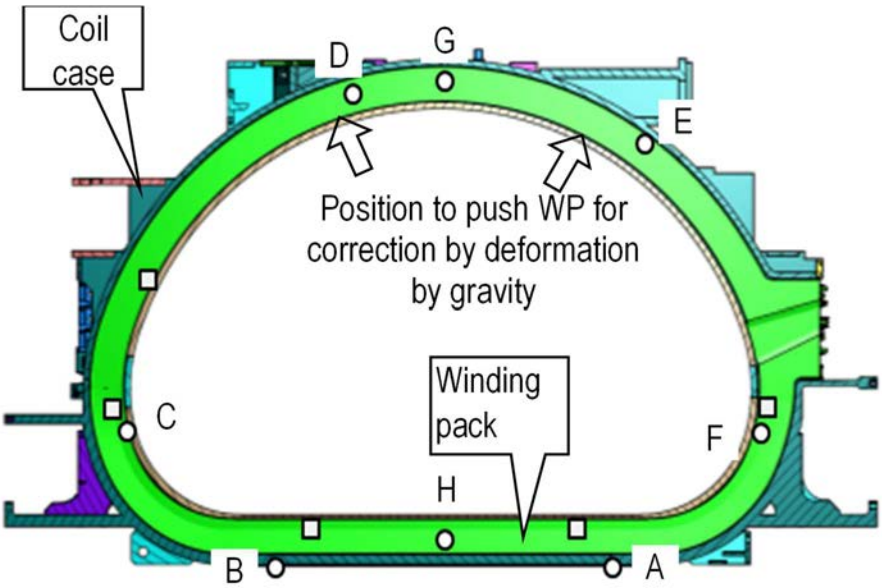



*FIG. II–41. Pushing winding pack for correction of its deformation by gravity.*

When winding pack is deformed by correction of its deformation by gravity, relative position among current centre line and the marker on the winding pack is changed. In order to estimate displacement of current centre line position of the deformed winding pack, analysis, in which displacement of the winding pack markers are assumed as measured, was performed. The displacement of current centre line is therefore evaluated from this analysis result. Thus, current centre line position is estimated after closure weld and correction of winding pack shape deformed by gravity.

Examples of the deviation of current centre line are shown in Fig. II–42; horizontal axis, θ [deg], denotes angle from magnetic center. The deviation at the straight section is defined by a distance from the nominal position, δr (m), and the others are out-of-plane deviation. The current centre line position is controlled very precisely.

The above technique can be applied in DEMO.

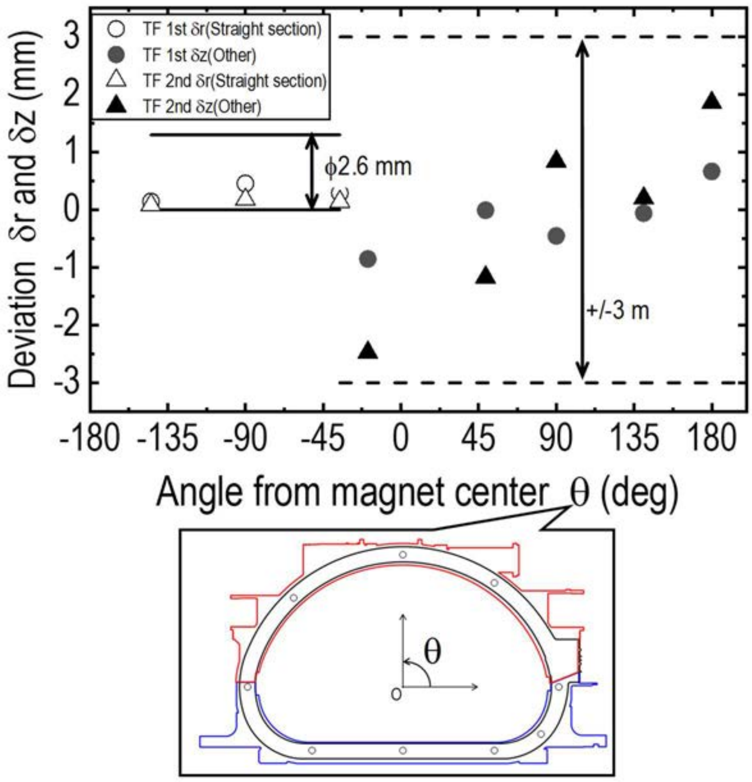



*FIG. II–42. Examples of current centre line positioning.*

The current centre line positioning technology is at TRL7, i.e., capacity to produce in a production representative environment, but not yet TRL8, i.e., pilot line capacity demonstrated, since the production is limited to the toroidal field coils for one fusion reactor unit (ITER), i.e. kind of prototypes manufacturing.

T8: *Gap filling between a winding pack and coil cases*

Sufficient gap has to exist between a winding pack and coil cases in order to enable gap filling with high viscosity resin. The target minimum gap was originally 4 mm, as described previously. It was however figured out that a gap between the winding pack and coil cases can be reduced to 3 mm locally although 4 mm gap is kept at almost all region by confirming impregnability at the minimum gap of 2 mm. More details about this test are reported in [II–26].

Distortion of side plates of AU and BU due to closure welding between AU and AP, and BU and BP reduces this gap. In addition, distortion of BU by AU-BU welding reduces gap at the outboard as discussed in [II–21]. Moreover, it was figured out in the first toroidal field coils poloidal weld that the distortion of the side plates becomes larger than that of a mock-up.

After closure welding of the coil cases, the requirement for the gap needs to be satisfied. Therefore, properly large welding distortion was assumed in the assessment of the gap before closure welding and when deciding winding pack (current center line) position.

Figure II–43 shows an example of the evaluated gap between winding pack and coil cases after closured welding in the second toroidal field coil [II–27]. The real welding distortion of the side plates, which is larger than that of the mock-up, is taken into account in the assessment of the winding pack and coil cases gap in Fig. II–43. It was confirmed that 4 mm minimum gap can be kept at the most region and a little smaller than 4 mm gap appears locally.

The same method to control gap between a winding pack and coil cases is applicable to DEMO.

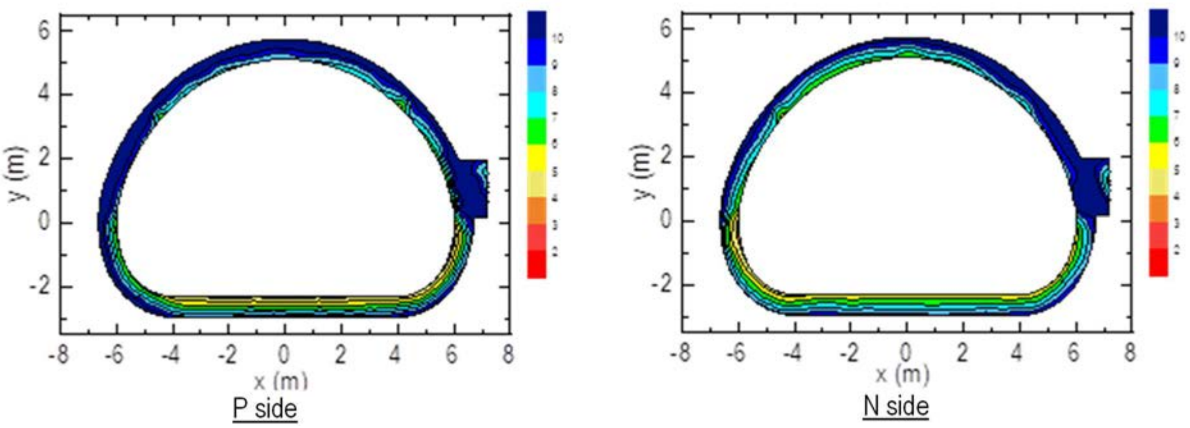



*FIG. II–43. Evaluated gap between winding pack and coil case.*

This gap control technology is at TRL7, i.e., capacity to produce in a production representative environment, but not yet TRL8, i.e., pilot line capacity demonstrated, since the production is limited to the toroidal field coils for one fusion reactor unit (ITER), i.e. kind of prototypes manufacturing.

T9: *Final machining*

Prior to the final machining process, all machined surfaces were optically measured to assess the remaining thickness of the extra material. Based on the results of these assessments, the machining program was optimized to minimize the need for measurements by the gantry machine itself. This optimization effort significantly contributes to reducing the overall machining duration.

Following the completion of the final machining on the interfaces of toroidal field coils, a dimension inspection was carried out. Figure II–44 illustrates the dimension inspection results for the major machined interfaces as an example, along with the final machined surfaces. The inspection confirms that highly accurate machining was achieved on these major interfaces, with the inner leg inter-coil structure surfaces meeting the challenging tight tolerance of ±0.2 mm. For all other machined interfaces, except for a few, the tolerances were satisfied, and any deviations were minor. As a result, it can be concluded that the final machining was successfully completed. In DEMO, similar accurate final machining is applicable.

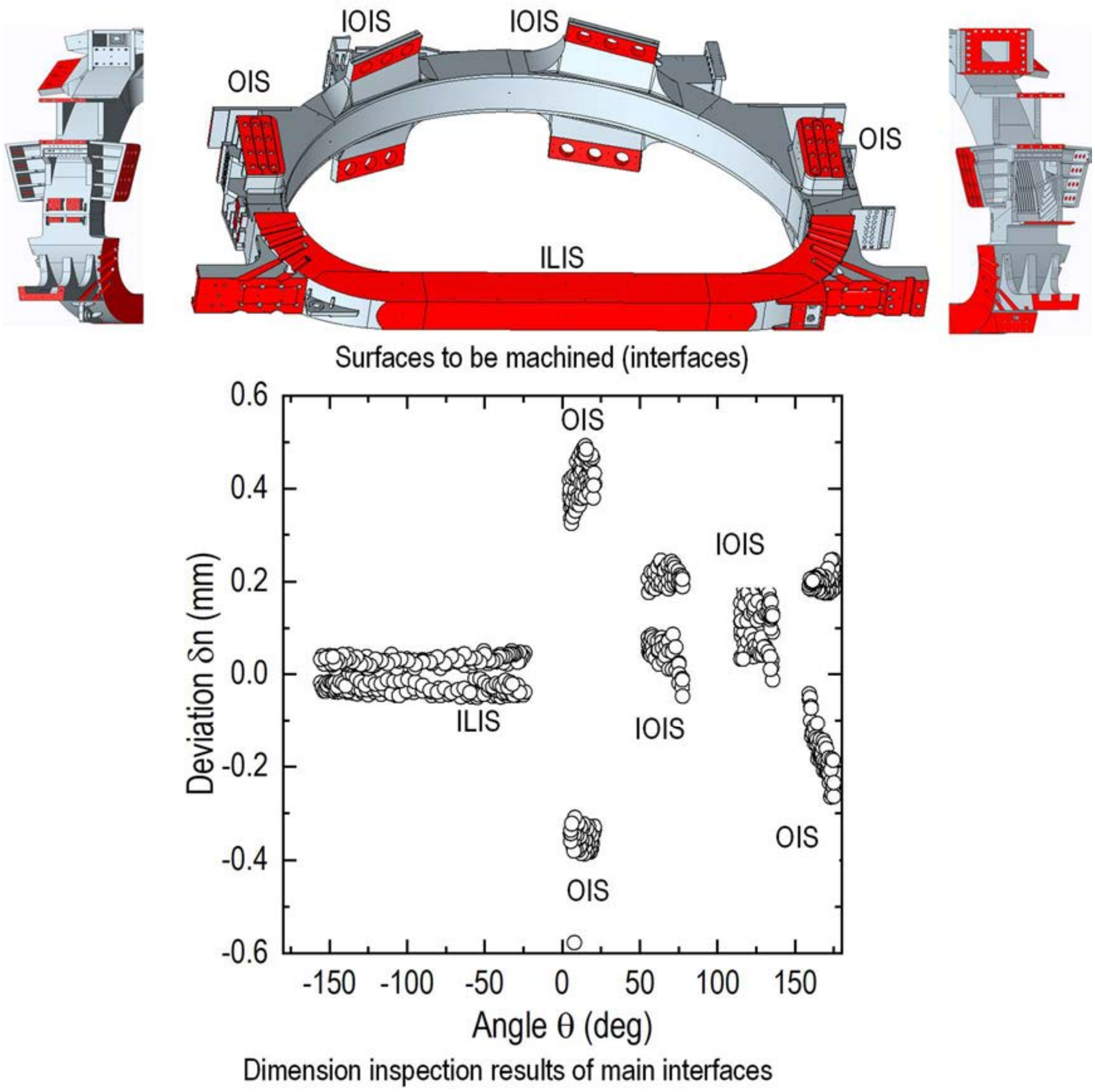



*FIG. II–44. Final machined interfaces and dimension inspection results of the major interfaces [ILIS: inner leg inter-coil structure; IOIS, OIS: outer inter-coil structures].*

Although a very accurate machining was achieved on the major interfaces (e.g. ILIS surfaces) with respect to the tight tolerance of ±0.2 mm, a few interfaces show some deviations (up to ±0.4 mm) even though considered minor.

This final machining technology is at TRL7, i.e. capacity to produce in a production representative environment, but manufacturing not yet sufficiently stable to enter in low rate production, i.e. kind of prototypes manufacturing.

T10: *Other key technology*

Welding technologies was well developed in toroidal field coils. In DEMO, it is expected that welding would be critical technology.

However, the welding technology is at TRL7, i.e., capacity to produce in a production representative environment, but not yet the TRL8, i.e., pilot line capacity demonstrated, since the production is limited to the toroidal field coils for one fusion reactor unit (ITER), i.e. kind of prototypes manufacturing. Moreover, it is expected that welding would be a critical technology for DEMO.

## II–6. TECHNOLOGY READINESS LEVEL FOR COMPLETE TOROIDAL FIELD COIL

The TRL is estimated for each double-pancake, radial plate, coil case fabrications and assembly of winding pack and coil case as provided in Table II–2 (column Manufacturing). In this table, related technologies are also listed.

Concerning current TRL of materials, it can be assessed as TRL6 since they are validated at prototype level in a relevant environment, though not in a full operational environment. The test results confirm the structural integrity and the functional purpose of the materials in that relevant environment. Instrumentation current TRL can be assessed as TRL7 since the prototype and/or models have been tested is some operational environments (e.g. temperature, irradiation). Interaction with the operational modes/scenarios has to still be investigated in operational environment.

TRL of the completed toroidal field coil system is assessed as TRL6 in coherence with materials, manufacturing and instrumentation TRLs and because it has to be qualified under operational environment.

TABLE II–2. TECHNOLOGY READINESS LEVELS FOR TOROIDAL FIELD COIL

| Process | Applied technology | Material | Manufacturing | Instrumentation | System |
|---|---|---|---|---|---|
| Double-pancake fabrication | · Optical measurement<br>· Accurate bending<br>· TIG welding (thin SS316LN plate)<br>· Heat treatment (650 °C)<br>· Laser beam welding (low power)<br>· ***Impregnation (TRL6)*** | 6 | 6 | 7 | - |
| Radial plate fabrication | · SS316LN machining<br>· Laser beam welding (high power)<br>· Hot/cold drawing (cover plates)<br>· Precise bending (cover plates)<br>· Pressing | 6 | 7 | 7 | - |

TABLE II–2. TECHNOLOGY READINESS LEVELS FOR TOROIDAL FIELD COIL (Cont.)

| Process | Applied technology | Material | Manufacturing | Instrumentation | System |
|---|---|---|---|---|---|
| Coil case fabrication | · Thick SS316LN plate (forging)<br>· Accurate welding distortion control<br>· Precise machining<br>· Laser beam welding (low power) | 6 | 7 | 7 | - |
| Assembly of winding pack and coil case | · Optical measurement<br>· Accurate welding distortion control<br>· Impregnation with resin with filler<br>· Precise machining<br>· ***Joint resistance test (TRL6)*** | 6 | 6 | 7 | - |
| Completed toroidal field coil | · Operation at 4 K<br>· Radiation of insulation | 6 | 6 | 7 | 6 |

Figure II–45 shows status of the assembly of toroidal field coil with vacuum vessel in the ITER site as of Nov. 2021. The TRL of the completed toroidal field coil will be higher as proceeding the assembly and commissioning.

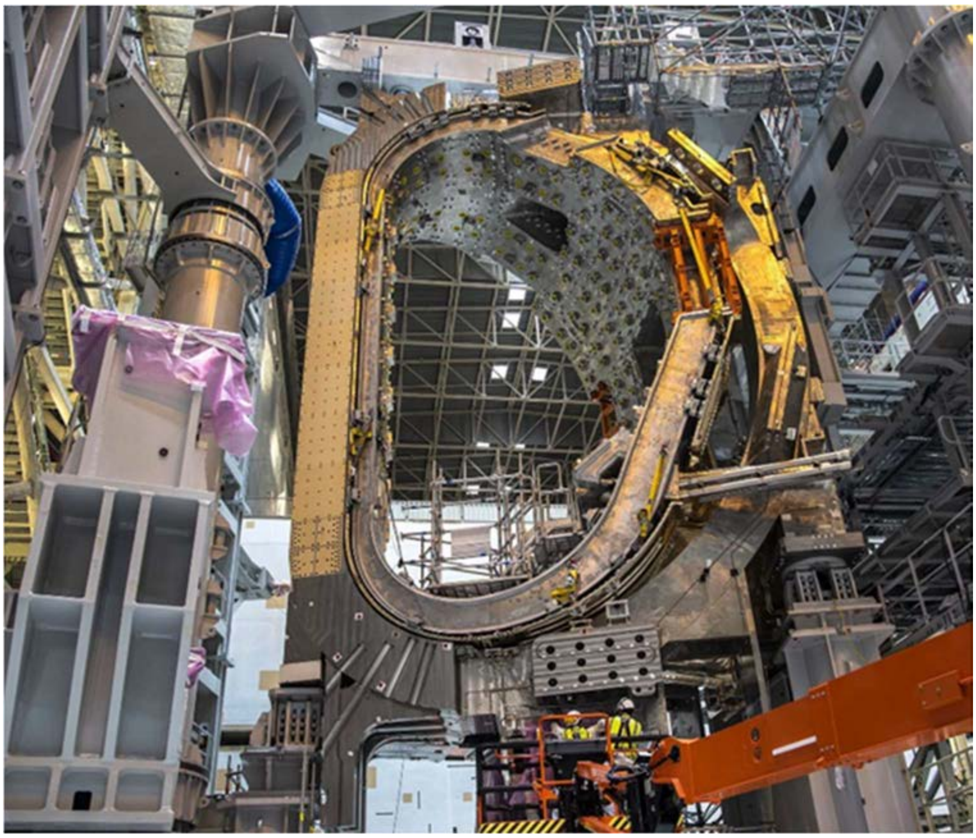


*FIG. II–45. Assembly of toroidal field coil with vacuum vessel in the ITER site.*

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## ABBREVATIONS

| | |
|---|---|
| ASICs | Application Specific Integrated Circuits |
| FPGA | Field-Programmable Gate Array |
| ISO | International Organization for Standardization |
| ITER | International Thermonuclear Experimental Reactor |
| NASA | National Aeronautics and Space Administration |
| $Q_{DT}$ | Plasma fusion gain |
| TRAs | Technology Readiness Assessments |
| TRLs | Technology Readiness Levels |

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## MEETINGS

Consultancy Meeting on Technological Readiness Level Assessment for Fusion Energy Systems, 25–26 April 2021, IAEA Headquarters, Vienna

Consultancy Meeting on Technological Readiness Level Assessment for Fusion Energy Systems, 5–6 September 2022, IAEA Headquarters, Vienna

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