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EVALUATION OF THE EU-DEMO FUSION REACTOR DIVERTOR MANIPULATOR CONCEPTS

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Miika Uusi-Illikainen: Diverttorin kuljetin konseptien arviointi EU-DEMO fuusioreaktoriin

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Euroopassa on kehitteillä tapoja fuusioenergian käyttöönottamiseksi energiantuotannossa. Vuonna 2014 aloitettu kehitysprojekti nimeltä EU-DEMO on osa tätä suunnitelmaa. EU-DEMO-kehitysprojektin tavoitteena on demonstroida fuusiovoiman kaupallinen toteuttamiskelpoisuus. EU-DEMO-kehitysprojekti on tällä hetkellä ideointivaiheen loppuvaiheessa. Tällöin kaikki reaktorin eri osa-alueisiin liittyvät esitetyt konseptit arvioidaan. Näistä konsepteista valitaan muutama lupaavin jatkokehitystä varten. Reaktorin huolto on yksi näistä osa-alueista. Huollon kesto vaikuttaa merkittävästi fuusiovoimalan kannattavuuteen. Diverttori on yksi tärkeimmistä huollon kohteista. Diverttorin tehtävänä on poistaa lämpöä ja epäpuhtauksia tyhjiökammiosta. Reaktorin ollessa toiminnassa siihen kohdistuu voimakas lämpö- ja neutronikuorma. Neutronikuorma heikentää diverttorin materiaaleja, ja lämpökuorma aiheuttaa jännityksiä diverttorin rakenteisiin. Tästä syystä diverttori täytyy vaihtaa noin kahden käyttövuoden jälkeen. Diverttori on jaettu pienempiin osiin nimeltä kasetti, jotta diverttorin vaihto olisi helpompaa. Diverttorin kasetteja kuljetetaan reaktorin tyhjiökammion ja kasettien kuljetuskontin välillä kuljettimella. Tässä opinnäytetyössä arvioidaan ja verrataan kolmea esitettyä diverttorin kuljetin konseptia. Tuloksen on tarkoitus avustaa lupaavimpien konseptien löytämisessä. Konseptien arviointikriteerit pohjautuvat EU-DEMO-projektin suunnittelukriteereihin. Tärkeimmät reaktorin sisällä tehtävien huoltotöiden kriteerit ovat tyhjiökammiossa tehtävän työn, huollon keston, tilankäytön ja teknisten riskien minimointi. Opinnäytetyön tutkimuskysymykset ovat: millaisia konsepteja on esitetty, ja kuinka hyvin työhön valitut konseptit täyttävät EU-DEMO projektin suunnittelun kriteerit. Kehitysehdotuksia on myös esitetty arvioitaville konsepteille. Opinnäytetyössä on arvioitu kolmea kuljetin konseptia: yksinkertaisesti tuettu palkki -, ulokepalkki - ja kuljetusalusta -lähestymistapa. Tulokseksi saatiin, että ulokepalkki -konseptissa huollon kesto on lyhin ja kuljetin on lyhimmän ajan tyhjiökammiossa. Yksinkertaisesti tuettu palkki -konseptissa huollon kesto on pisin, ja kuljetin on pisimmän aikaa tyhjiökammiossa. Ulokepalkki -konseptissa kuljetin tarvitsee korotetun kuljetuskontin ja ylimääräistä tilaa diverttorin huoltotunnelissa varoetäisyyksiä varten. Muuten sen tilan tarve on minimaalinen. Yksinkertaisesti tuettu palkki - ja kuljetusalusta -konsepteissa kuljetin tarvitsee tilaa kasetin alapuolelta. Näissä konsepteissa liikkeet ovat hyvin tuettuja, joten varoetäisyydet voidaan pitää pieninä. Yksinkertaisesti tuettu palkki -konseptissa tekniset riskit ovat pienet, koska kuljettimen liikkeet ovat hyvin tuettuja, teknologia on hyvin käytännössä testattua ja käyttäjävirheen riskit ovat pienet. Ulokepalkki -konseptissa tekniset riskit ovat arvioiduista konsepteista suurimmat, koska käyttäjävirheen riskit ovat suuret vähemmän tuettujen liikkeiden aikana. Kuljetusalusta -konseptissa tekniset riskit ovat toisiin arvioituihin konsepteihin nähden keskimääräiset, koska kuljettimen liikkeet ovat hyvin tuettuja, mutta liikesuunnan vaihdot lisäävät riskejä. Yksinkertaisesti tuettu palkki -konseptiin esitettiin kehitysehdotuksia täydentämään kuljettimen vielä suunnittelemattomat osa-alueet. Ulokepalkki -konseptiin esitettiin kehitysehdotus teknisten riskien pienentämiseksi. Kuljetusalusta -konseptiin esitettiin kehitysehdotuksia yksinkertaistamaan huollon vaiheita. Lähdetiedon vähyys ja tämän tutkimuksen laajuus rajoittivat työn tulosten hyödyllisyyttä, mutta työn päämäärä saavutettiin. Tätä opinnäytetyötä voidaan käyttää konseptien valintaprosessien tukena.

Avainsanat: DEMO, diverttori, etähuolto, huolto, arviointi, konsepti, cantilever approach, simply supported beam approach, mobile platform approach

ABSTRACT

Miika Uusi-Illikainen: Evaluation of the EU-DEMO fusion reactor divertor manipulator concepts
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As part of the European plan to realize feasible fusion power, the development of a fusion power reactor, the so-called European DEMOnstration fusion power reactor (EU-DEMO), has been started in 2014. The purpose of the EU-DEMO project is to demonstrate commercial feasibility of fusion power plants. The development of the EU-DEMO reactor is now in the end of the pre-conceptual design phase where proposed concepts for all areas of reactor are narrowed down to the few promising concepts for further development. One sector is reactor maintenance, the duration of which affects greatly the power plant viability. One maintained part is a divertor that extracts heat and impurities from the plasma. Intense heat and neutronic loads in the vacuum vessel during reactor operation stresses and weakens the divertor materials so that they have to be replaced after two years of operation. The divertor is divided into the cassettes in order to make replacement process easier. Cassettes are transported in between the vacuum vessel and the transport cask with a manipulator. In this study, three proposed cassette manipulator concepts are evaluated in order to support concept selection process. The evaluation criteria of the concepts are based on the EU-DEMO development drivers. The development drivers are a minimization of in-vessel operation, maintenance duration, space requirements and of technical risks. The research questions are, how the divertor manipulator follows the development drivers for the fusion power plant maintenance and what kind of divertor manipulator concepts are presented. Possible concept improvements are also proposed. The evaluated concepts are a simply supported beam, a cantilever and a mobile platform approach Based on the results, the manipulator in the cantilever approach requires the least amount in-vessel and overall operations. The simply supported beam approach require the largest amount of the in-vessel and overall operations. In the cantilever approach, the manipulator requires additional space from the transport cask, additional clearances in the divertor maintenance port. Otherwise, it requires minimal additional space around the cassette. In the simply supported beam and mobile platform approaches, the manipulator requires additional space under the cassette. Movements are well supported and guided, so clearances in the maintenance port can be minimal. Technical risks in the simply supported beam approach are low due to the good support, the use of proven technologies and the low risk of human error. In the cantilever approach, the technical risks are relatively high due to the higher possibility of human error during non-guided movements. In the mobile platform approach, the technical risks are moderate. The movements are well supported and guided, but the rotation between linear and toroidal directions may introduce additional technical risks. In the simply supported beam approach, improvements were found to compensate for the missing parts of the design. In the cantilever approach, only a minor improvement was found to mitigate the technical risks. In the mobile platform approach, possible improvements were found to decrease the complexity of the design. The amount of source material and the scope of the study limited the usefulness of the results, but the goals of the study are satisfied. This study can be used as one of many evaluations in order to find the most promising concepts.

Keywords: DEMO, divertor, remote handling, maintenance, evaluation, concept, cantilever approach, simply supported beam approach, mobile platform approach.

FOREWORD

This bachelor's thesis is part of the master's program in mechanical engineering. The study is conducted independently without contacting authors of the concepts in question. The study evaluates the presented divertor manipulator concepts based on the EU-DEMO maintenance development drivers with the aim of assisting in the concept selection process.

I would like to thank the examiner of the work, Jouko Laitinen, for the patience and guidance during this study. I would also like to thank my wife for proofreading and giving me motivation during this time and also my family and friends for proofreading.

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GLOSSARY

ITER = International Thermonuclear Experimental Reactor

EU-DEMO = European DEMOnstration fusion power reactor

R&D = Research and development

TF = Toroidal field

PF = Poloidal field

IVC = In-vessel component

PFC = Plasma facing component

RHE = Remote handling equipment

D-T = Deuterium and tritium

EFDA = European Fusion Development Agreement

dpa = Displacement per atom

DOF = Degrees of freedom

S*O = Severity times occurrence

RAMI = Reliability, Availability, Maintainability and Inspectability Analysis

FMECA = Failure Modes, Effects and Criticality Analysis

1. INTRODUCTION

Nuclear power is a relatively new way of producing energy and it has many advantages compared to fossil fuels. It is clean and a reliable source of energy with a great energy producing potential. Nuclear energy can be obtained in two ways: The first way is fission where energy is released by splitting large nuclei into smaller ones. The second method is fusion where energy is released by combining two small nuclei into a larger one. The fusion power is safer, and it produces significantly less radioactive waste than fission power. Fusion is therefore the more promising method of energy production. The problem is that fusion technology is not yet mature enough for energy production purposes. (Song et al. 2014. pp. 1-2)

As part of an international plan to realize feasible fusion power, the development of an International Thermonuclear Experimental Reactor (ITER) has been started in the year 2005 (ITER 2019a). Key goals of the ITER project are to demonstrate the technical feasibility of fusion reactors and to serve as a test platform for key functional fusion reactor components. The experience from the ITER project will be used for future fusion reactor designs. The European EUROfusion organization is coordinating the research and design (R&D) of the reactor called European DEMOnstration fusion power reactor (EU-DEMO). The EU-DEMO reactor project is one of the many projects utilizing the experience from the ITER research. The EU-DEMO is supposed to be the last experimental reactor before the building of commercial reactors in Europa. The development of the EU-DEMO has been started in 2014. (Donné et al. 2018, p. 3) The development of the EU-DEMO is going to be in the pre-conceptual phase until 2020 (Donné et al. 2018, p. 21).

One part of the EU-DEMO design process is the development of a feasible maintenance system for the fusion reactor part called divertor (see chapter 3). One part of the divertor maintenance systems is the manipulator that transports divertor parts called divertor cassettes into the reactor core called vacuum vessel (see chapters 3 and 4). The development of the manipulator is in the end of the pre-conceptual phase which means that there are several preliminary manipulator concepts proposed (Donné et al. 2018, p. 21). After the pre-conceptual phase, only two to three concepts will be developed further. At the moment, those two to three concepts must be selected (Donné et al. 2018, p. 32). In this thesis three proposed concepts are evaluated and compared in order to support the selection of the most promising.

1.1 Structure of the thesis and research questions

In this thesis, three divertor manipulator concepts are evaluated. There are more than three proposed concepts, but due to the scope of the study, the number of concepts has been restricted to three. The concepts are selected based on their level of development. Three concepts with adequate and approximately the same level of development are selected. The research questions of this thesis are:

- What kind of divertor manipulator concepts have been proposed?
- How do divertor manipulator concepts follow the development drivers for fusion power plant maintenance? These development drivers are the minimization of
    - in-vessel operation,
    - maintenance duration,
    - space requirements,
    - critical failures and failure criticality.
- How can the presented concepts be improved?

The main focus of the thesis is to evaluate the three presented concepts by using development drivers. The concept improvement research has less focus in this thesis.

In order to understand the situation during the EU-DEMO divertor maintenance, the fundamentals of the tokamak type reactor are introduced in chapter 2. In chapter 2.1 the EU-DEMO development principles and goals are introduced. That chapter explains why these particular evaluation criteria have been chosen. In chapter 2.2, the timeline of the EU-DEMO project is introduced in order to explain why this evaluation is relevant.

Understanding the divertor and the environment during operation and maintenance, are crucial parts of the evaluation. In chapter 3, the function of the divertor and of all the main parts of the divertor are presented. In the beginning of chapter 4, reasons are shown why frequent maintenance for the divertor is needed. Maintenance frequency and maintenance duration operations are also presented. In chapter 4.1, the main divertor maintenance steps are introduced. The vacuum vessel environment during the power plant operation and maintenance are presented in chapter 4.2. The divertor manipulator concepts are presented in chapter 4.3. Chapter 4.4 explains the maintenance drivers and how they are implemented into the evaluation process. In chapter 5, the evaluation process of the divertor manipulator concepts are presented with results. In chapter 5.5, improvement proposals for the concepts are presented. In chapter 6, all results are concluded, and study success and usefulness are evaluated.

2. FUNDAMENTALS OF THE TOKAMAK TYPE REACTOR AND THE EU-DEMO PROJECT

The successful usage of fusion power requires the fusion process to produce more energy than it consumes. In the fusion reactors, the potential fuel is a combination of two hydrogen isotopes, deuterium and tritium (D-T). They are used because they are widely accessible on earth, they ignite in relatively low temperature, and they have the highest energy production potential compared to other fusion fuels. (Max Planck Institute for Plasma Physics 2019a; Schneider. 2001) The plasma ignition requires a sufficient plasma density, temperature and confinement time. The confinement time is the period the thermal energy of the plasma stays inside of the plasma. In fusion reactors with D-T reaction, the requirements are:

- plasma temperature of at least 100 million degrees,
- energy confinement time of around two seconds and
- plasma density of around 10^{14} particles per cubic centimeter. For comparison purposes, the earth's air mantel density is 250,000 times higher. (Max Planck Institute for Plasma Physics 2019b)

In order to achieve such a high temperature and such a long confinement time, the plasma is confined in a vacuum to avoid contact with other materials. No material can withstand such a high temperature without melting. The contact in between the plasma and the wall material would also cool thin plasma drastically. In the Tokamak type fusion reactor, the plasma is confined using magnetic fields. Magnetic fields keep the plasma away from the vacuum vessel walls. (Max Planck Institute for Plasma Physics 2019c)

The plasma confinement with magnetic fields is based on the physical property of the charged particles that allows charged particles to be forced to move with magnetic fields in one direction. The plasma consists of charged particles. Charged particles have a tendency to orbit helically around magnetic field lines (figure 1). In a straight magnetic field, like in figure 1, charged particles move into one direction. Therefore, the fusion particles would eventually leave the confinement within such a magnetic field. (Max Planck Institute for Plasma Physics 2019c)

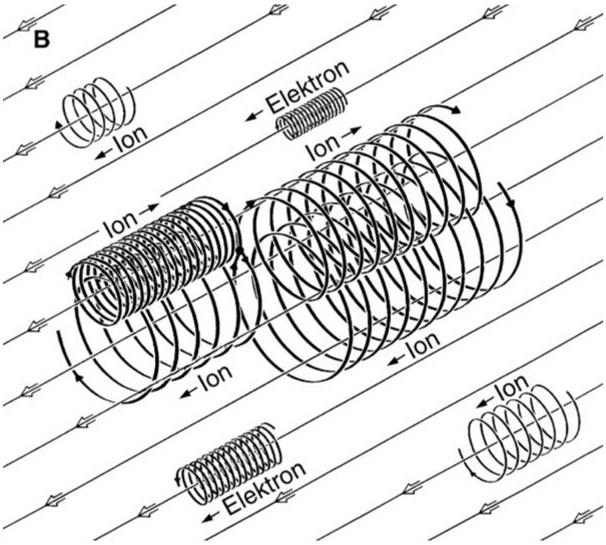

Figure 1. *Charged particles moving helical path around the magnet lines. (Max Planck Institute for Plasma Physics 2019c)*

In the Tokamak type reactor, this problem is solved by producing a circular magnetic field where the charged particles can indefinitely move in one direction without colliding with the vacuum vessel walls. The circular magnetic field is created using several toroidal field (TF) coils (figure 2). However, TF coils alone are not sufficient to keep the plasma confined. Charged particles would still move towards the vacuum vessel walls. The solution for this problem is the magnetic field line twisting with transformer and vertical field coils (figure 2). This configuration forces the charged particles into the torus shaped form. (figure 2) (Max Planck Institute for Plasma Physics 2019c; Song et al. 2014. pp. 3-4)

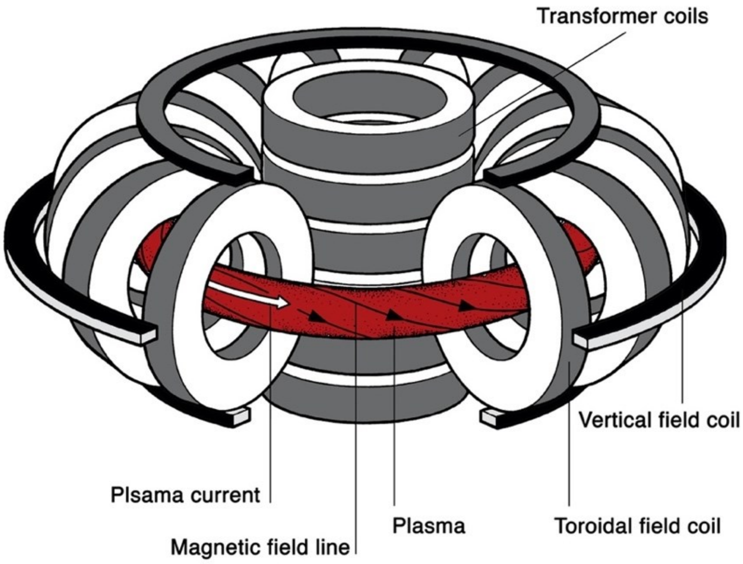

Figure 2. *Magnet system in the Tokamak type fusion reactor. (Max Planck Institute for Plasma Physics 2019c)*

Plasma also has to be heated. The first means of plasma heating are transformer coils. Alongside the confinement, transformer coils produce a large amount of heat in plasma by accelerating charged particles. This heating method is called current heating. (Max Planck Institute for Plasma Physics 2019d) Heating plasma with transformer coils has one technical disadvantage: It causes instabilities in the plasma. Therefore, the Tokamak type reactors are not able to generate a continuous flow of plasma. (Song et al. 2014. pp. 4) Current heating alone is not sufficient to heat up plasma to over 100 million degrees. Other means to heat up the plasma are the high-frequency heating principle and the neutral particle heating. High-frequency heating is produced by beaming electromagnetic waves with the harmonic frequency of the plasma into the plasma. The charged particles in the plasma resonate with the beamed electromagnetic waves and absorb energy from the waves. The neutral particle heating is produced by injecting neutral particles with high kinetic energy into the plasma. Neutral particles transfer their energy into the charged particles by means of collision. (Max Planck Institute for Plasma Physics 2019d)

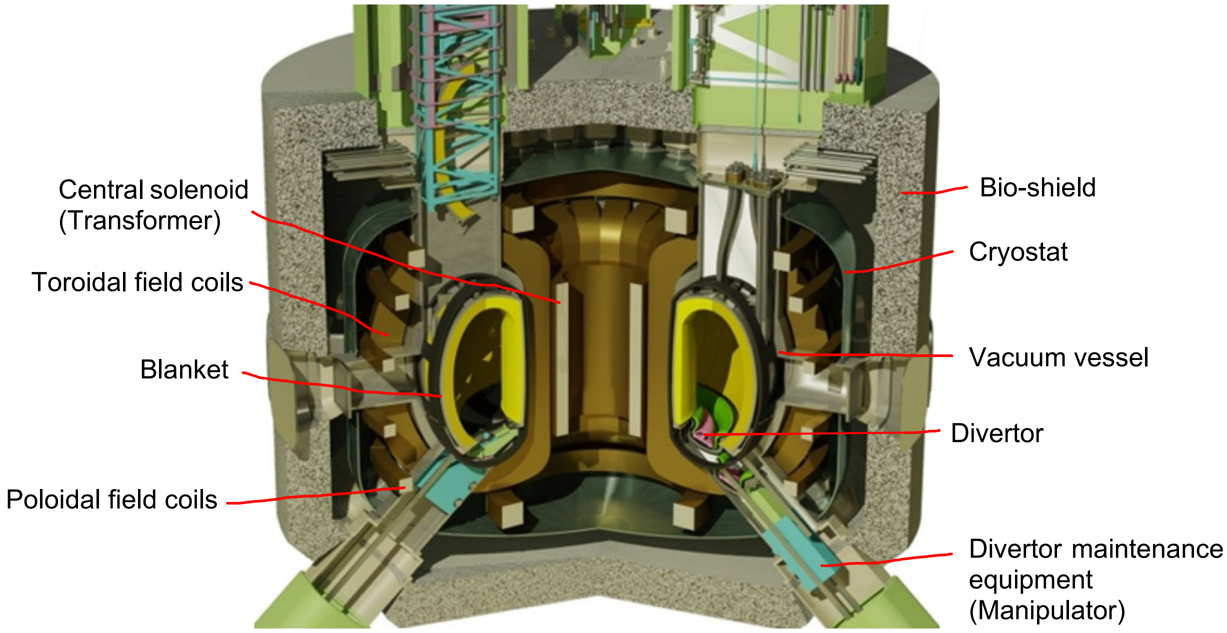

Figure 3. *Overview of the Tokamak type reactor. (Crofts et al. 2016, p. 1396)*

Plasma requires a near vacuum environment to burn because even a small amount of air could extinguish burning plasma. For that reason, the plasma is inside the vacuum vessel (figure 3). The vacuum vessel does not only keep air away from the plasma but also stops the plasma from escaping the vessel. Vacuum vessel in fusion reactors has to be capable of holding down to a 10^{-8}millibar absolute pressure. (Max Planck Institute for Plasma Physics 2019e) The vacuum vessel itself cannot withstand thermal and neutronic loads caused by burning plasma. The vacuum vessel is covered from inside with blankets and with a divertor (figure 3). (Song et al. 2014. p. 7) The Blankets and the divertor protect the vacuum vessel and other reactor core parts from heat- and radiative fluxes. The divertor removes impurities from the plasma and works as a passageway to pump vacuum into the vacuum vessel. For this reason, the divertor receives the highest amount of heat and radiative fluxes. The EU-DEMO blankets also have a second function; The blankets produce tritium out of the escaping neutrons and the lithium. This process is called tritium breeding. (Donné et al. 2018, pp. 8-9, 28)

The magnets are located outside the vacuum vessel close to the vessel walls (figure 3). In some Tokamak type reactors, including ITER and EU-DEMO, the magnets are superconducting in order to achieve extremely low resistance. Magnets with lower resistance consume less power. Superconductive magnets have one downside: They must be cooled down to 4 Kelvin in order to work. Due to superconductivity, the magnets are surrounded by a vessel called cryostat (figure 3). The main functions of the cryostat are to create a vacuum environment, to reduce the heat transfer in between the magnets and the environment, and to interconnect the magnet system and the vacuum vessel with the cryoplant, the power supplies and the data processing system. (Song et al. 2014. Pp. 5-6, 11)

2.1 EU-DEMO development principles and goals

European fusion research institutions have founded the consortium European Fusion Development Agreement (EFDA) that coordinates the European fusion research. EFDA has published the paper *Fusion Roadmap: Fusion Electricity – A roadmap to the realization of fusion energy* (Romanelli et al. 2012). In this paper, the European fusion research and the development (R&D) strategy is published. It functions as a guide to R&D prioritizing for most of the European fusion projects. The key principles of the EU-DEMO R&D are the emphasis on system thinking, the requirements driven development, which takes design feasibility and risks in consideration, the strong use of ITER experiences and industrial resources, and the emphasis on studying and evaluating the multiple parallel design options and technologies during R&D. Already proven and easily licensable technologies and design options are also favored. These principles aim to mitigate the development risks. (Federici et al. 2018, pp. 729-730)

In the paper *Fusion Roadmap,* the EU-DEMO project goals are also presented. The EU-DEMO project goals are:

- to make reactor that produce hundreds of megawatts of electricity to the grid,
- to develop a functioning closed fuel-cycle,
- to minimize the amount of activated waste,
- to function as a component test facility for future fusion power plants and
- to achieve a reasonable power plant availability. (Federici et al. 2018, pp. 729-730)

The closed fuel-cycle reactor produces sufficient amount of tritium for its own deuterium-tritium burning process. Tritium is produced through a breeding process where escaping high energy neutrons from plasma react with lithium atoms, splitting lithium into helium and tritium atoms. (Romanelli et al. 2012, pp. 23-24; Antunes. 2017)

2.2 Timeline of the EU-DEMO project

According to the current plan of the EUROfusion organization, the EU-DEMO project was started in 2014 and the power plant should start its operation around the year 2050. This schedule (figure 4) relies strongly on the schedule of the ITER project due to the strong reliance on the ITER experience. The EU-DEMO project plan consists of four main stages:

- pre-conceptual design stage,
- concept design stage,
- engineering design and site selection stage, and
- procurement and construction stage. (figure 4)

After these four stages the commissioning and operation of the power plant will start. (Donné et al. 2018, p. 21)

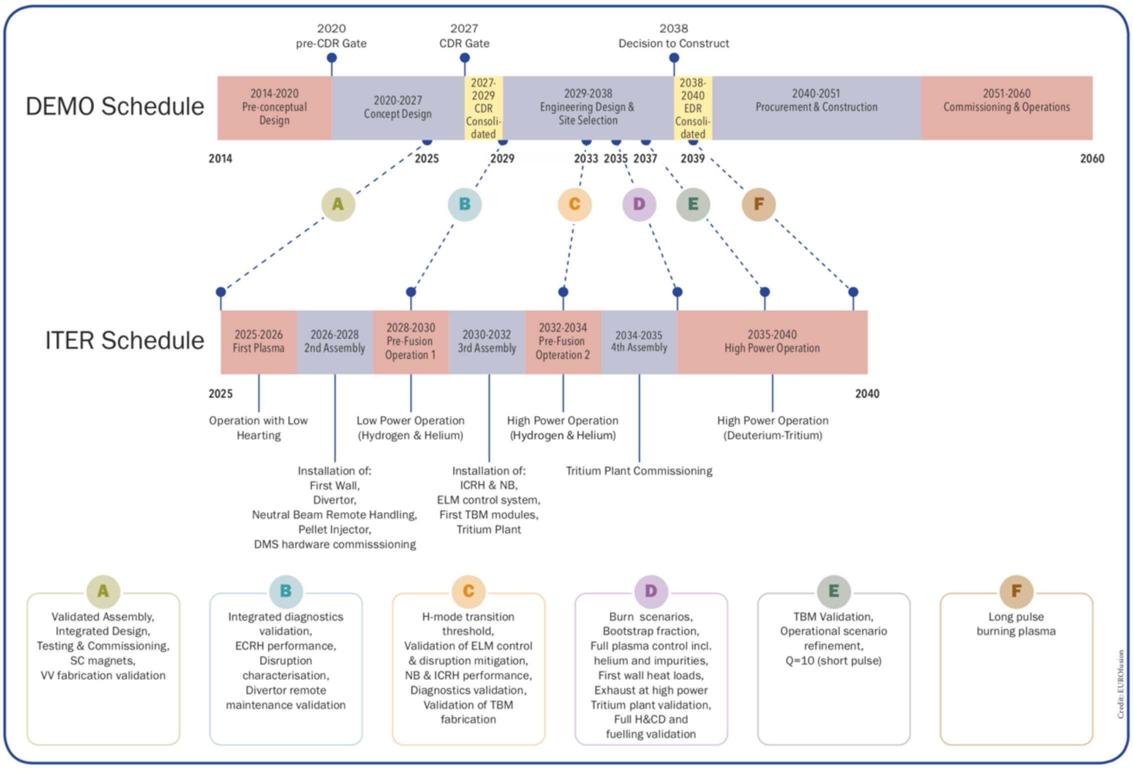

Figure 4. *The EU-DEMO and ITER schedules and ITER experience exploitation plan. (Donné et al. 2018, p. 21)*

The pre-conceptual design stage started in 2014 and it is planned to last until 2020. During this stage, many different designs are developed and assessed. During the pre-conceptual design stage, there is lesser emphasis on the exploitation of the ITER experience. At the end of the stage, the count of designs is reduced to the few most promising designs. This process is called gate review. The EU-DEMO gate review process focuses on design feasibility, on risks, on key design decisions and integration progress, and on status characteristics. (Donné et al. 2018, pp. 41-42) This thesis concentrates on supporting this gate review process for divertor manipulator by evaluating three proposed manipulator designs.

The concept design stage will start after the pre-conceptual stage and it is planned to last until 2030. During the concept design stage, selected designs from the pre-conceptual stage will be further investigated and compared to each other. The remote maintenance strategy will be confirmed by testing concepts with test-rig. During the concept design stage, the requirements of the initial designs and the analysis are finalized in order to avoid later concept changing costs. During this stage, the exploitation of the ITER experiences will start. (Donné et al. 2018, pp. 41-42)

The engineering design and site selection stage will start after the concept design stage. It is planned to last until 2040. During this stage, the final demonstrations regarding the designs and technologies will be carried out by creating prototypes and by testing. All the technologies used in the EU-DEMO will be validated and the quality and part manufacturing costs will be confirmed during this stage. Licensing of the technologies will also be discussed, and safety analysis will be executed. The power plant life cycle will also be planned. The exploitation of the ITER experience will continue during this stage. (Donné et al. 2018, pp. 43)

After the engineering design and site selection stage, the construction of the EU-DEMO power plant will start. According to plans, the construction will be ready around the 2050s. After the construction, the EU-DEMO power plant will be commissioned and operated. (Donné et al. 2018, p. 43)

3. INTRODUCTION TO THE DIVERTOR

According to the European Research Roadmap to the Realization of Fusion Energy, the divertor is a magnetic field configuration with which impurities are diverted to a target chamber. In fusion literature, this target chamber is often called a divertor. (Donné et al. 2018, p. 67) In this thesis, the target chamber is also called divertor.

Fusion reaction produces heat, high speed neutrons and impurities like helium ash. Heat causes extreme thermal loads and neutrons neutronic loads to the in-vessel components (IVC) and to the vacuum vessel. Impurities contaminate the plasma and can cause the plasma to extinguish. The divertor shields components behind the divertor from thermal and neutronic loads and extracts impurities and heat from the plasma. (ITER 2019b; Song et al. 2014. pp. 122-124)

3.1 Divertor components

The currently planned EU-DEMO divertor is segmented into 48 individual cassettes (figure 5) that are toroidally positioned (Marzullo et al. 2019, p. 2). The segmentation of the divertor reduces the size and weight of the individual parts. The reduced part size and weight allows divertor maintenance through divertor maintenance ports by using a manipulator system. (Song et al. 2014. p. 10) The divertor cassette subcomponents are a cassette body, a shielding liner, cooling pipes and a cassette-to-vacuum vessel fixation system (Marzullo et al. 2019).

The cassette body (figure 5) works as a supporting structure for the cassette. All other subcomponents are attached to the cassette body. The cassette body is designed to withstand thermal and neutronic loads from plasma, magnetic loads from magnets and pressure loads from the hydraulic system inside the cassette. In the middle part of the cassette body is a vacuum pumping hole (figure 6). (Frosi et al. 2019) The cassette materials alone are not capable of withstanding the heat load, so the cassette body is cooled with flowing water inside of the cassette body. Hot cooling water coming from the cassette is used for energy production. The heat load is affecting the plasma facing components (PFC) the most. Therefore, the PFCs are cooled with extra cooling pipes outside the cassette body. (figure 5). (You et al. 2017, pp. 367-369)

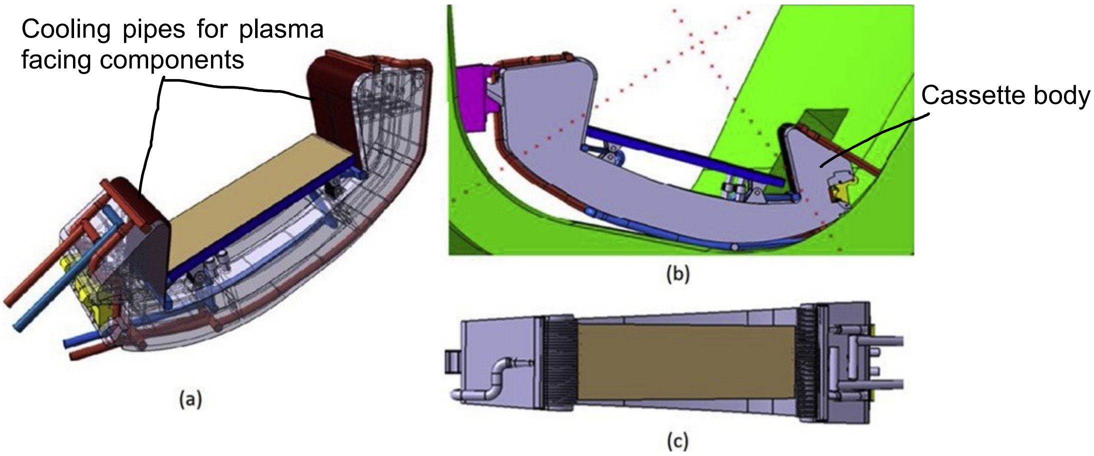

Figure 5. *Divertor cassette (Marzullo et al. 2019, p. 2).*

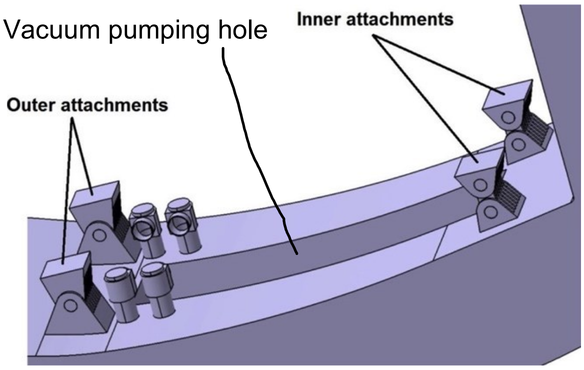

Figure 6. *Divertor shielding liner attachments (Marzullo et al. 2019, p. 3)*

During the vacuum pumping, heat and impurities are pumped through the vacuum pumping hole. Heat and radiation irradiate the vacuum pumping hole and vacuum vessel. In order to protect the vacuum vessel and the vacuum pumping hole, a cooled shielding liner is placed in front of the vacuum pumping hole (figure 7). One shielding liner concept can be seen in figure 7. (Marzullo et al. 2019, p. 3)

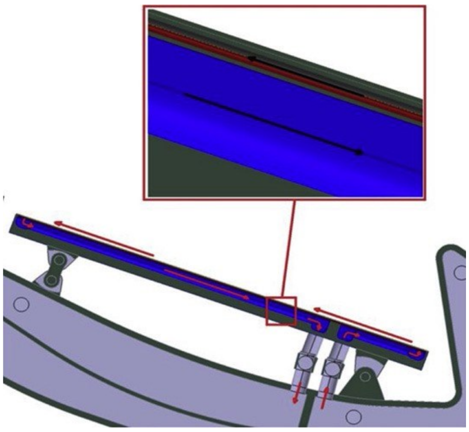

Figure 7. *Divertor shielding liner (Marzullo et al. 2019, p. 3)*

The divertor cassette has to be fixed into the vacuum vessel firmly and accurately but, at the same time the fixation has to be flexible. Thermal expansions and electromagnetic forces from the usage of the magnets deform the cassette. The flexibility of the fixation system mitigates secondary stresses caused by thermal expansion. In addition, flexible fixation ensures the needed electrical connection in between the vacuum vessel and the cassette. The fixation system has to be compatible with remote handling equipment (RHE). The fixation system is called cassette-to-vacuum vessel fixation system. One of the fixation concepts is presented in figure 8. (Marzullo et al. 2019, p. 3)

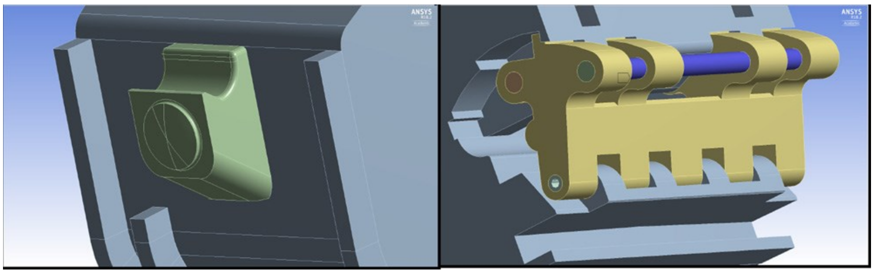

Figure 8. *One cassette-to-vacuum vessel fixation system concept (Frosi et al. 2019, p. 120)*

4. DIVERTOR MAINTENANCE

During the operation, the divertor is exposed to extreme neutronic, electromagnetic and heat loads. These loads slowly degrade the divertor materials and can eventually break the divertor (see chapter 4.2). In order to avoid malfunctions, the divertor requires frequent maintenance. (Crofts & Harman 2014, p. 2383) It is estimated that the divertor must be replaced after 2 years of operation and the replacement of the divertor alone takes maximum four months. The replacement time is based on the assumption that the power plan availability has to be at least 75%. The planned combined replacement of the divertor and of the blanket modules takes estimated six months and it will be executed after 4 years of operation. The planned maintenance cycle can be seen in figure 9. (Crofts & Harman 2014, p. 2387)

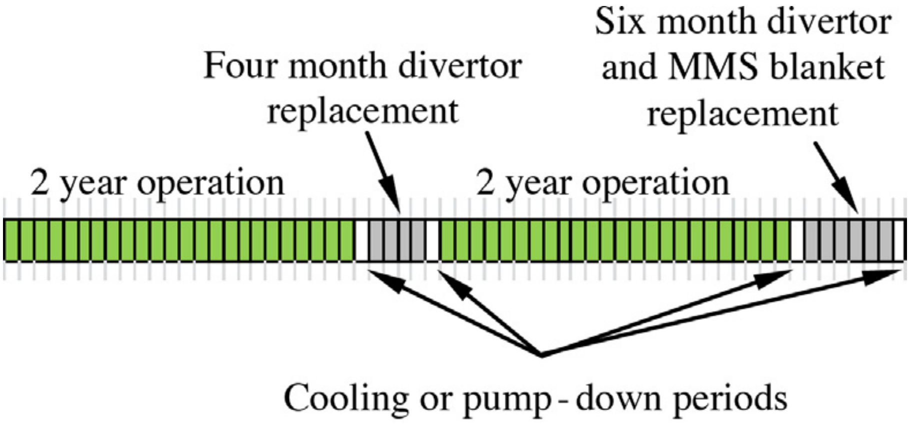

Figure 9. *Planned maintenance cycle where 75% power plant availability is reached for EU-DEMO. (Crofts & Harman 2014, p. 2387)*

Before the maintenance operation can start, the vacuum vessel has to cool down for one month and the cooling water must be drained from the divertor cassettes. After the maintenance operation, the vacuum is pumped into the vacuum vessel, the divertor pipes are filled up with coolant and the vacuum vessel is conditioned for operation. This process requires one month. These operations are the white areas in figure 9. (Crofts & Harman 2014, p. 2387) Even the cooled vacuum vessel environment is not suitable for humans during the maintenance operation (see chapter 4.2). Therefore, all maintenance operations will be executed with RHE. (Crofts et al. 2016, p. 1393)

4.1 Main steps of the divertor cassette maintenance

After the cooling down period, begins the maintenance operations that consists of few major steps. The remote maintenance operations start with the maintenance port preparation. Then, only the divertor or the divertor and the blankets are replaced. And finally, the port is sealed, and transport casks leave the reactor area. The divertor cassette replacement is executed through the divertor maintenance ports. Three cassettes are replaced through one maintenance port. *(Crofts & Harman 2014)*

The maintenance port preparation and removal of all three cassettes is executed so:

- The transporter cask attaches to the divertor maintenance port (Crofts et al. 2016, pp. 1392).
- The divertor cooling pipe cutter cuts the divertor cassette cooling pipes inside the vacuum vessel (Keogh et al. 2018, pp. 461-466).
- The divertor cassette manipulator goes into the vacuum vessel, detaches the cassette from the vacuum vessel supports and transports the cassette to the transporter cask.

- This is done to all three cassettes. (Mozzillo et al. 2017; Cafora et al. 2015; Li et al. 2019)

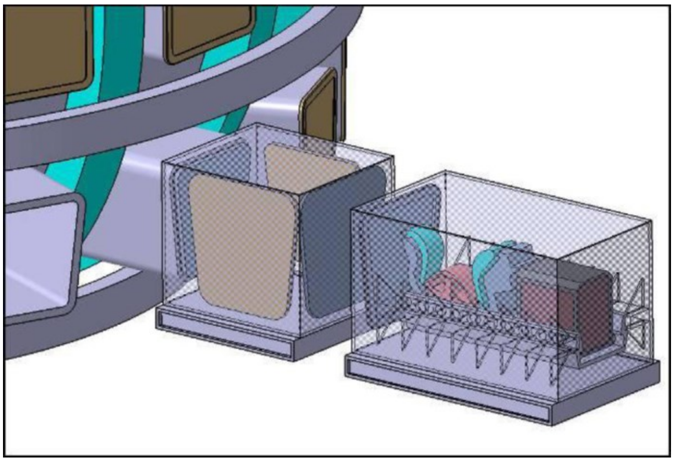

Figure 10. *One transport cask system maintenance port attachment concept. (Thomas et al. 2013, p. 2125)*

- The transporter cask detaches from the divertor maintenance port and transports the divertor cassettes to the hot cell (figures 10 and 11). The hot cell is used for cooling down and maintenance of the cassette (Thomas et al. 2013, p. 2125).

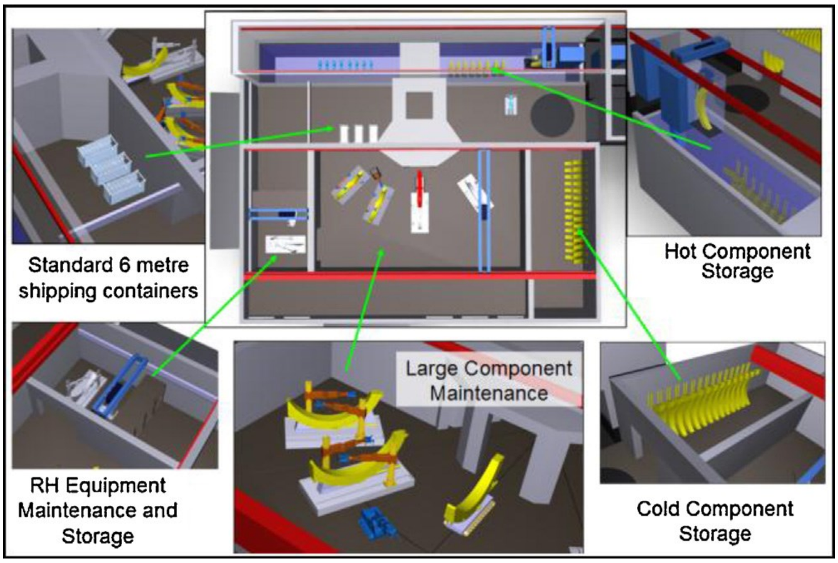

Figure 11. *Hot cell facilities concept. (Thomas et al. 2013, p. 2126)*

After the removal operations, the new divertor cassettes are installed. The blanket modules are replaced in between the divertor removal and installation. The blanket module replacement requires access to the blankets from the divertor maintenance port. Therefore, the blanket replacement is only possible when the divertor cassettes are removed. *(Crofts & Harman 2014, p.* 2387*)* The installation of the divertor cassettes is executed so:

- The transporter cask transports new cassettes from the hot cell and the cask attaches to the divertor maintenance port (Thomas et al. 2013, p. 2125).
- The divertor cassette manipulator installs cassettes onto the vacuum vessel supports (Mozzillo et al. 2017; Carfora et al. 2015; Li et al. 2019).
- The divertor cooling pipe welding tool welds cassette cooling pipes and pipes located inside the vacuum vessel together (Keogh et al. 2018, pp. 461-466).
- The maintenance port is sealed, and the transporter cask detaches from the divertor maintenance port.
- The transporter cask leaves the reactor area. (Crofts et al. 2016, pp. 1392)

The full remote maintenance equipment system consists of multiple parallel working transport cask systems. In order to achieve the EU-DEMO power plant availability requirements, estimated four parallel working transport cask systems are required. *(Crofts & Harman 2014, p.* 2386-2387*)*

4.2 Vacuum vessel environment and divertor maintenance

The environment in a fusion reactor is severe for IVCs during the power plant operation. Extreme heat load combined with escaping high-energy neutrons and fusion fuels reacting with IVC materials cause displacements, sputtering and activation inside the IVC materials. (Spilker 2019) In addition, superconducting magnets and plasma currents induce temporal electromagnetic forces to the IVCs. (Song et al. 2014. pp. 102-103) After the reactor shut down, the environment in the vacuum vessel is still hazardous for a long time. That affects greatly the way the divertor maintenance is conducted. (Bachmann et al. 2018, pp. 88-89)

4.2.1 Vacuum vessel environment and divertor during power plant operation

High-energy neutrons have the potential to knock atoms from their lattice positions. This causes vacancies and voids in the materials, degrading the material. The neutrons can get absorbed by the atoms and turn into other materials through a transmutation process. These other elements disturb the IVC material lattice structure, thus the degrading material. The degradation of the material is measured in displacement per atom (dpa). Neutrons can also get captured by the component materials and excite the materials. Excitation turns materials radioactive. (Spilker 2019)

Escaping fuel atoms collide with the PFC materials and cause sputtering. This causes erosion in PFC materials. Eroded material particles have the potential to cool plasma and even extinguish plasma. (Glukhikh et al. 2018, p. 211-212; Spilker 2019) The intensity of erosion depends on materials used and on component temperatures. The erosion process is stronger at higher temperatures. Erosion does not occur evenly in the first wall material. Less erosion resistant atoms sputter away first. This process is called preferential sputtering and it leads to erosion-resistant atom rich material, usually tungsten rich material, that does not meet the operational requirements for PFC. (Spilker 2019)

In the EU-DEMO, the estimated average neutron wall load is around 1 MW/m^2 during 2 h of burn-time for one pulse. For the EU-DEMO, the total cumulative limiting fluence is 7 MWa/m^2 (61 320 MWh/m^2) which restricts the reactor usage to up to 30 000 pulses (around 60 000 MWh/m^2). Limiting fluence of 7 MWa/m^2 corresponds with the dpa amount of 70 dpa for EUROFER steel that most IVCs are made of. (Federici et al. 2019, pp. 33-34)

Heat from the plasma conducts and radiates to the PFCs. One of the main functions of the PFCs is to extract that heat for the energy production purpose. The heat load intensity varies considerably in between operation phases and the locations of the PFCs. For example, the PFCs of the divertor have a relatively small surface area but the divertor extracts the highest amount of heat. (Song et al. 2014. pp. 102-103) The strike point regions of the divertor PFCs are expected to receive the heat load of 10-20 MW/m^2. The estimated heat load induced to the blankets is around 5 MW/m^2. (Song et al. 2014. pp. 102-103; Bachmann et al. 2018, pp. 87-95) Under the heat load, the surface of the PFCs could reach up to 1000 ℃. PFCs should also withstand this temperature without eroding too fast. (Song et al. 2014. pp. 102-103) The PFC materials are not able to withstand this amount of heat and neutron loads for the full fusion power plant operation duration. Therefore, it is necessary to replace the PFCs frequently. (Song et al. 2014. pp. 102-103; Bachmann et al. 2018, pp. 87-95)

The extreme in-vessel environment degrades any material but with good material selection the degradation can be minimized. A high melting point, a high thermal conductivity and a strong erosion-resistance are important material properties for IVCs. The plasma cooling down effect caused by eroded material atoms must also be minimal. (Spilker 2019)

The divertor extracts impurities like helium and sputtered materials from the plasma in order to prevent plasma from extinguishing (Glukhikh et al. 2018, p. 218-219). The divertor alone cannot extract all of the impurities. Some of the impurities are loosely trapped inside the in-vessel component materials. The process called baking is included regular maintenance of a fusion reactor in order to extract impurities. During the baking, the IVCs are heated with hot water going though reactor cooling pipes to 200-350 ℃ for 100 hours. The baking allows impurities, such as oxygen and fusion fuels to escape. (Pitts et al. 2010; Song et al. 2014. pp. 102-103)

IVCs are under significant inertial loads. The components are so heavy that their own deadweight causes significant stresses to the components. The cooling water causes during operation additional inertial loads to the PFCs due to high pressure (3.5 MPa). (Song et al. 2014. pp. 102-103; Frosi et al 2019. p. 121)

Superconducting magnets and plasma current cause additional stresses to the IVCs. During the disruption of plasma and quenching of the magnets, changing magnetic flux induces current into the component structures. Induced current and magnetic fields interact with each other and cause electromagnetic loads to the components. In addition, halo current occurs when the plasma is temporarily moving near the PFCs. Halo current causes additional electromagnetic forces. (Song et al. 2014. pp. 102-103)

4.2.2 Vacuum vessel environment and divertor during maintenance

During reactor operation, some of the neutrons get captured by first wall materials and cooling water causes material excitation. Excitation makes materials radioactive. Excited materials emit alpha, beta and gamma radiation. 8 weeks after the reactor shutdown, the gamma radiation level in the vacuum vessel is 1000 Sv/h (Figure 13). Behind the port closure plate (Figure 12), the gamma radiation is expected to be several hundred of $\mu Sv/h$ after 12 days after shutdown. The man-access limit for gamma radiation is 500 $\mu Sv/h$ for exceptional access and 100 $\mu Sv/h$ for occasional access. The amount of gamma radiation near the vacuum vessel is fatal to people. Therefore, the reactor is accessed only with RHE. (Bachmann et al. 2018, pp. 88-89)

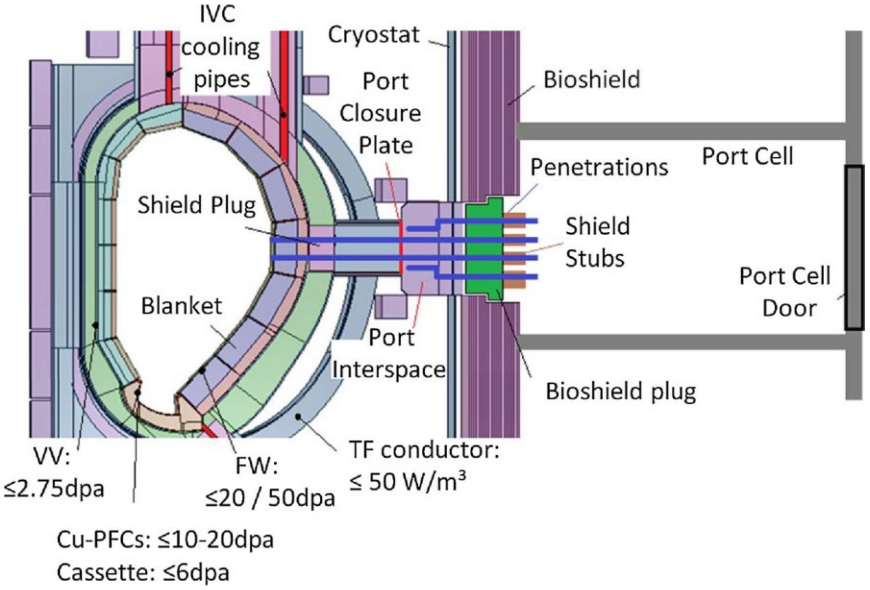

Figure 12. *Shielding structures in DEMO and selected neutron irradiation limits. (Bachmann et al. 2018, pp. 89)*

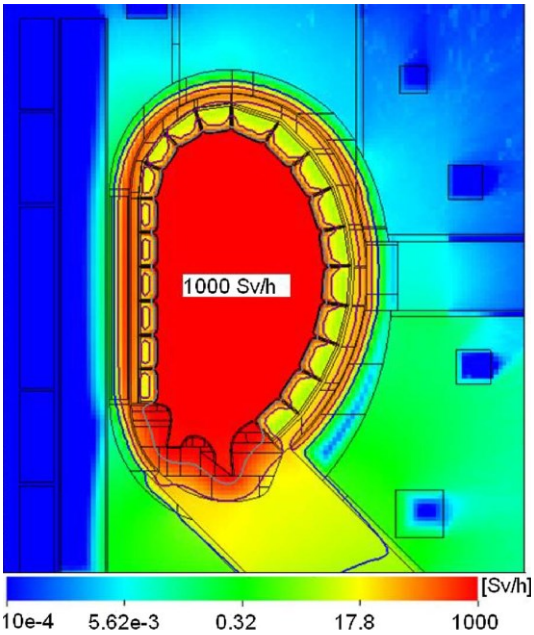

Figure 13. *Gamma radiation level (shut-down dose rate) 8 weeks after plant shutdown. (Bachmann et al. 2018, p. 89)*

Around one month after the shutdown, the divertor replacement is conducted. Therefore, in the beginning of the maintenance operation, the remote maintenance equipment is affected by over 1000 Sv/h gamma radiation. This corresponds to an absorption rate in silicon of around 900 Gy/h. As a comparison: The silicon absorption rate was 530 Gy/h in the containment vessel of the Fukushima reactor in early 2017. The RHE for the damaged Fukushima reactor are developed with a lifetime of 10 000 Sv. They would last only for 10 h inside the EU-DEMO vacuum vessel during maintenance. Special RHE is needed for the EU-DEMO with a required lifespan of an around 900 h vacuum vessel operation. (Bachmann et al. 2018, pp. 89-90)

For the maintenance, the component surface temperature requirement is 100 ℃ or lower which cannot be achieved only by waiting one month. Therefore, all the reactor components that are not being removed are ventilated with the ventilation rate of 10 kg/s. (Crofts et al. 2016, pp. 1395-1396)

4.3 Proposed remote maintenance concepts

The divertor manipulator design process is in the end of the pre-conceptual design phase. There are several proposed manipulator concepts (Li 2017, pp. 24-28; Mozzillo et al. 2017; Carfora et al. 2015; Li et al. 2019). Three manipulator concepts are selected in this study for evaluation. These three concepts are selected based on their different approach to the problem, similar level of development and similar main reactor design. The selected concepts are the simply supported beam, the cantilever and the mobile platform approach.

Almost all the reactor parts have multiple parallel concepts and, therefore, some assumptions are required. For this thesis, single reactor design is assumed to support the comparison of the manipulator concepts. The assumptions are:

- the reactor has a single-null divertor, which means that there is one divertor on the bottom of the vacuum vessel (Donné et al. 2018, p. 28),
- there are three divertor cassettes for each divertor maintenance port, in total 16 ports and 48 cassettes in the vacuum vessel (Carfora et al. 2015, p. 1437),
- the divertor maintenance ports are inclined to avoid collision with the TF coils (Carfora et al. 2016) and
- the divertor is maintained with dedicated maintenance equipment (Crofts et al. 2016, p. 1393).

4.3.1 Simply supported beam approach

The simply supported beam approach is designed for the older divertor cassette version. The approach still can be used in evaluation because the older version of the cassette is heavier and bigger than the new version. The manipulator should be able to handle also the new version of the cassette with minor changes. In this concept the lower port inclination of 45° is assumed (figure 14). (Mozzillo et al. 2017, p. 69; Marzullo et al. 2019, p. 2) The main argument for using the simply supported beam approach is the use of well-tested technologies. In this case, the truck tipping and the funicular railway mechanisms in the nuclear fusion field. The main systems in this concept are the carriage, the winch, the carriage actuator and the rail systems. (Mozzillo et al. 2017)

The carriage system (figures 14-16) consists of a carriage platform, a cassette support structure, wheels, a rotational hinge and a carriage services area. The main functions of the carriage system are to support the cassette, to allow linear movement and to lift the cassette. The carriage system rolls on top of linear rails and is moved by a winch system. The winch system is attached to the carriage services area (figure 16). The carriage actuator system is fully supported by the carriage system and the rotational hinge allows cassette tilting. (Mozzillo et al. 2017)

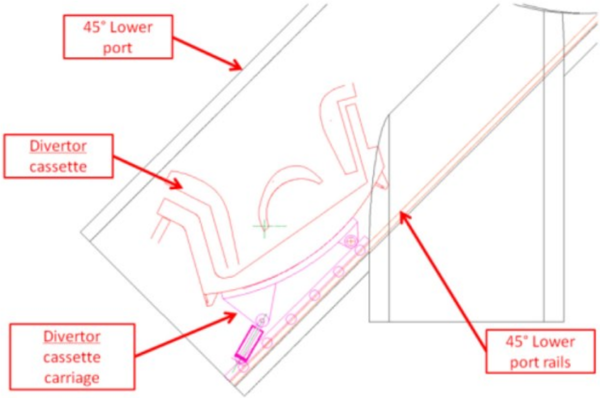

Figure 14. *The divertor cassette carriage system in the simply supported beam approach (Mozzillo et al. 2017, p. 68).*

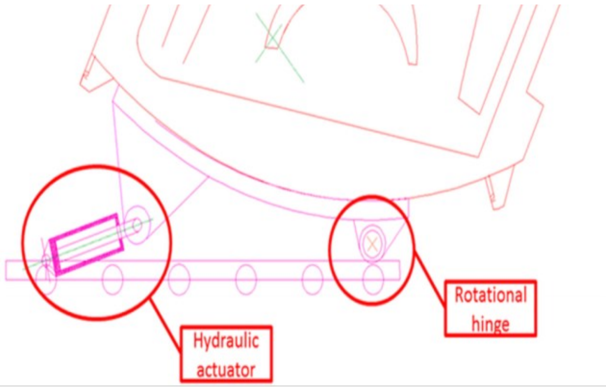

Figure 15. *The tilting system of the simply supported beam approach (Mozzillo et al. 2017, p. 69).*

The winch system (figure 16) consists of a winch, a steel wire and pulleys. The main functions of the winch systems are the carriage system linear transportation and the carriage supporting during in-vessel operations. The winch is located next to the maintenance port and the pulleys near the vacuum vessel in the maintenance port. The steel wire is routed through pulleys from the winch to the carriage system. (Mozzillo et al. 2017)

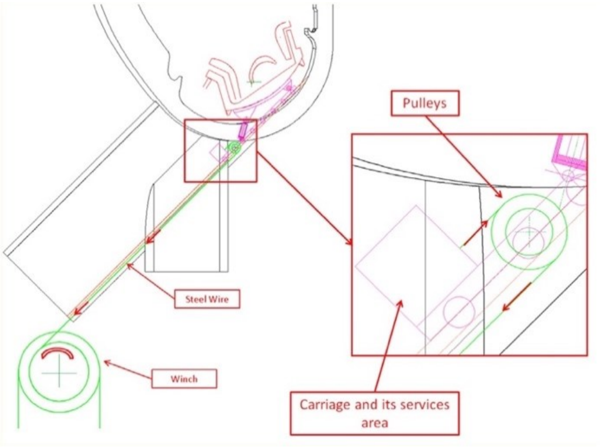

Figure 16. *The winch system of the simple supported beam approach (Mozzillo et al. 2017, p. 68).*

The carriage actuator system (figure 17) consists of tilting and toroidal pushing actuators, of a hydraulic system and of actuator joints. The main functions of the carriage actuator system are to tilt the cassette, to move the cassette toroidally and to support the cassette during the maintenance operation. The cassette tilting actuator is connected between the carriage platform and the cassette support. During the cassette installation, the tilting actuator tilts the cassette into level with the toroidal rails, thus allowing toroidal movement for the cassette. During the cassette removal, the actuator tilts the cassette down, thus allowing linear movement. The toroidal pushing actuators push and pull the cassette toroidally on top of the toroidal rails. (Mozzillo et al. 2017)

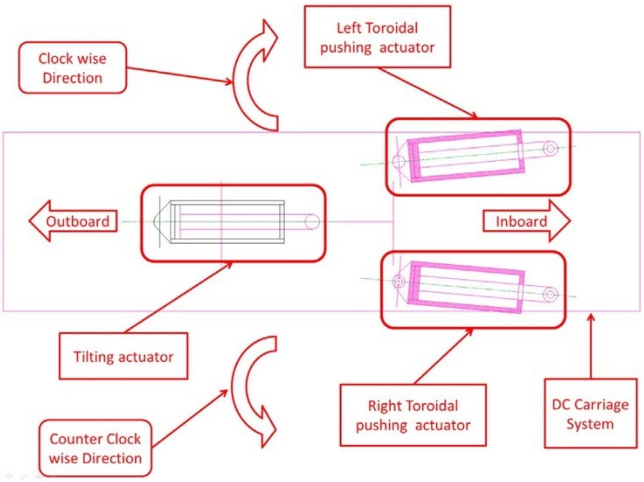

Figure 17. *Top view of the divertor cassette carriage (Mozzillo et al. 2017, p. 71).*

The rail system (figures 14 and 18) consists of linear, dummy and toroidal rails and of toroidal sliding supports. The main functions of the rail system are to support the carriage and the cassette and to allow linear and toroidal movements. The linear rails are fixed in the transport cask, in the divertor maintenance port and in the vacuum vessel. They allow the carriage movement and support the carriage during the movements. The toroidal rails with toroidal sliding supports allow the toroidal movement of the cassette and they support the cassette. The toroidal rails are equipped with rollers to mitigate friction. Before the cassette can be moved toroidally, dummy rails are installed to the toroidal rails. The dummy rails fill the gap that is made for divertor maintenance port in toroidal rails. Toroidal sliding supports are attached to the cassette (figure 18). (Mozzillo et al. 2017)

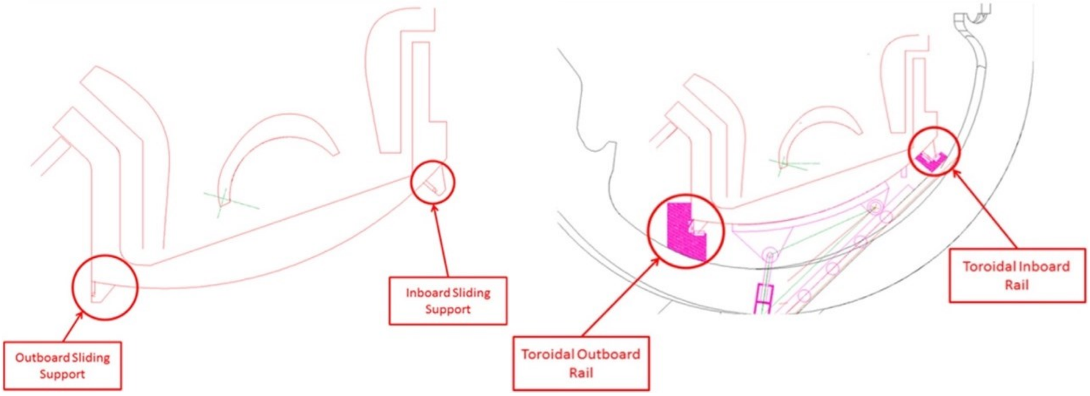

Figure 18. *Toroidal rails and sliding supports for the divertor cassette (Mozzillo et al. 2017, p. 71).*

In this concept, the right positioning of the cassette is ensured with mechanical stops. All movements are executed until the mechanical stop. With this method it is easier to move the cassette to the right position without the risk of collision. In the simply supported beam approach the divertor cassette-to-vacuum fixation system is not yet designed. The system could need an additional maintenance steps in order to get the cassette in its final position and to detach the cassette. Removing the cassette from the vacuum vessel is executed with the inverse process. (Mozzillo et al. 2017)

4.3.2 Cantilever approach

The cantilever approach is designed for the same version of the divertor cassette as in the simply supported beam approach (see chapter 4.3.1). In the cantilever approach, the divertor maintenance port inclination of 45° is assumed. The main idea of the cantilever approach is the need of only one tool during the divertor cassette installation. In this concept, a telescopic boom (figure 19) moves an end-effector system (figure 20). The end-effector moves the cassette inside the vacuum vessel. The rail system supports and guides the telescopic boom system from the transport cask and divertor maintenance port. (Carfora et al. 2015)

The telescopic boom system (figure 19) consists of the telescopic boom base system, of the telescopic boom, of the telescopic boom lifting actuators, of the end-effector attachment, of the hydraulic system and of the wheels. The main functions of the telescopic boom system are to move and to support the end-effector. The telescopic boom base system with the lifting actuators, the wheels and the hydraulic system moves and supports the telescopic boom. During the telescopic boom operation, the locking system locks the mover in place. The telescopic boom moves the end effector through the maintenance port. The telescopic boom has three sections. Two sections are extended with hydraulic telescopic pistons and the third one is attached to the telescopic boom base. (Carfora et al. 2015)

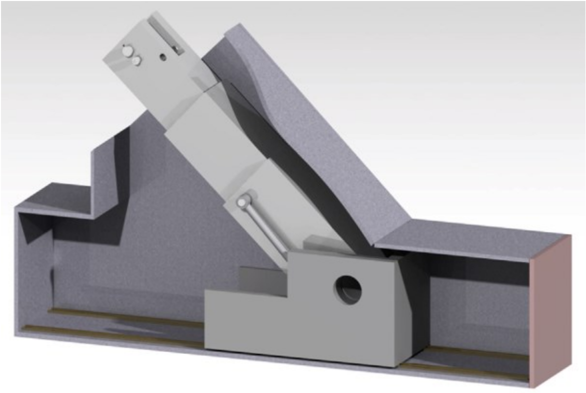

Figure 19. *Telescopic boom in the transportation cask (Carfora et al. 2015, p. 1439).*

The rail system consists of the transport cask rails and the maintenance port rails. The transport cask rails support the telescopic boom base and allow it to move linearly. The maintenance port rails support and guide the telescopic boom that could otherwise move and oscillate during the end-effector operation.

The end-effector system consists of end-effector lifting actuators, rotational joints, a hook plate, toroidal pushing actuators and a hydraulic system. The main functions of the end-effector system are to move the cassette, to support the cassette and to place/detach the cassette on/from the cassette fixation inside the vacuum vessel. The end-effector lifting actuators lift the cassette inside the vacuum vessel. The rotational joints with toroidal pushing actuators move the cassette toroidally inside the vacuum vessel. The hook plate attaches to the cassette, restricting the degrees of freedom of the cassette. Hook plate slides upwards on the divertor profile and locks itself to the cassette with a hook-like and a spherical part (figure 20). The hooking plate is attached to the end of the end-effector. The end-effector provides 4 to 5 degrees of freedom (DOF) for cassette movements. The end-effector system is connected to the mover with joint and lifting actuators. (Carfora et al. 2015)

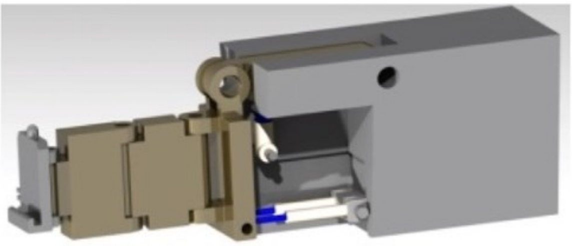

Figure 20. *One end effector concept for the cantilever approach (Carfora et al. 2015, p. 1439).*

Figure 21 shows the cassette removing sequence. It is planned that the central cassette will be removed first, then the cassette on the left side and last the cassette on the right side. The end-effector is capable of removing and installing all divertor cassettes. (Carfora et al. 2015)

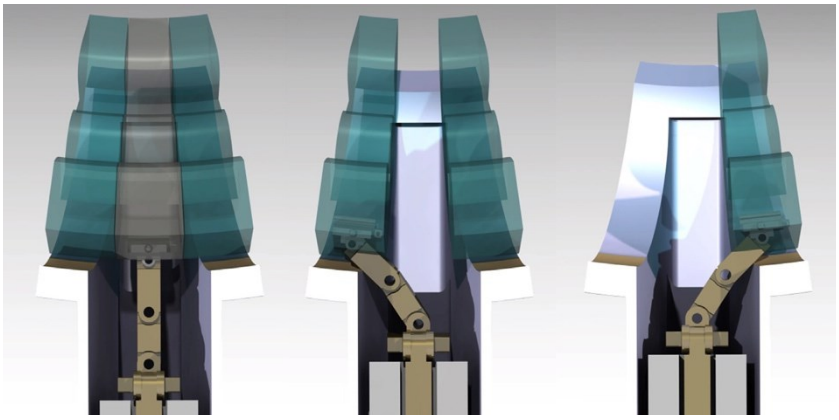

Figure 21. *Maintenance sequence of the divertor cassettes (Carfora et al. 2015, p. 1440).*

4.3.3 Mobile platform approach

The mobile platform approach concept is designed for the new version of the divertor cassette and with the divertor maintenance port inclination of 25°. The main idea of the mobile platform approach is to combine the welding, the cutting and the cassette mover into one system. RHE recoverability is also one of the main design drivers. This concept consists of a carriage, a mobile platform, a rail and track systems (figures 22-25). (Li et al. 2019)

The mobile platform system (figure 22) consists of cylinders, of a lock frustum, of scissors, of a scissor connector, of a mobile platform structure and of wheel units. The main functions of the system are to support the cassette, to lift the cassette and to allow the carriage to move the mobile platform. Cylinders with a spherical top place the divertor cassettes on the cassette fixation system and lift cassette out from it. They are capable of moving the cassette accurately. The lock frustum is used for locking the cassette during linear and toroidal movements. The wheel-unit allows mobile platform movement and linear-to-toroidal rotation. The scissors are used for pushing and pulling the mobile platform toroidally. The scissors are connected during toroidal movement to the track system with the scissor connector. (Li et al. 2019)

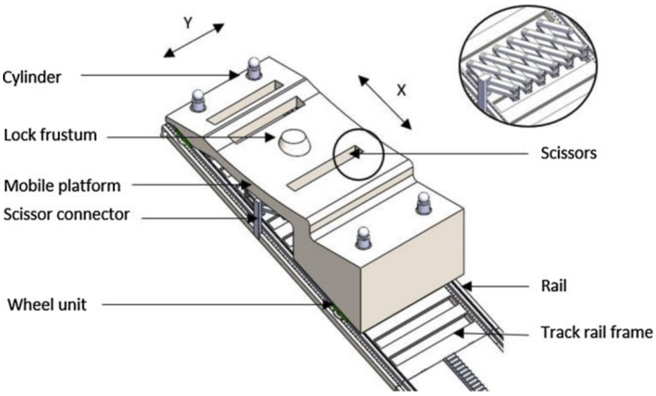

Figure 22. *Mobile platform (Li et al. 2019, p. 2).*

In figure 23, the wheel-unit is presented more accurately. It consists of a rotatable rail and a V-shaped wheel. The rotatable rail is connected to the track with a bearing and the V-shaped wheel is connected to the mobile platform with a bearing. The wheel unit is rotated with a motor installed inside the mobile platform. The mobile platform has four wheel-units. (Li et al. 2019)

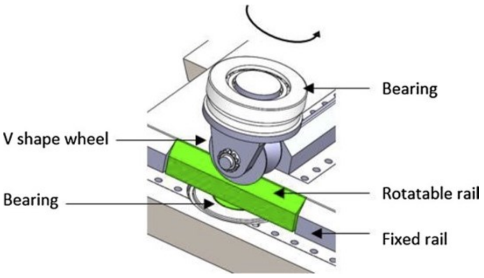

Figure 23. *Wheel-unit of the mobile platform (Li et al. 2019, p. 3).*

The track system (figure 24) consists of a track structure, of a vacuum vessel attachment, of fixed rails, of wheel units, of a scissor connector attachment and of a clamp attachment. The main functions of the system are supporting the mobile platform, allowing linear and toroidal movements and linear-to-toroidal rotation. The track is removable so that rails will not be affected by neutron flux and heat during the reactor operation. The clamp attachments allow the carriage system to transport the track system. (Li et al. 2019)

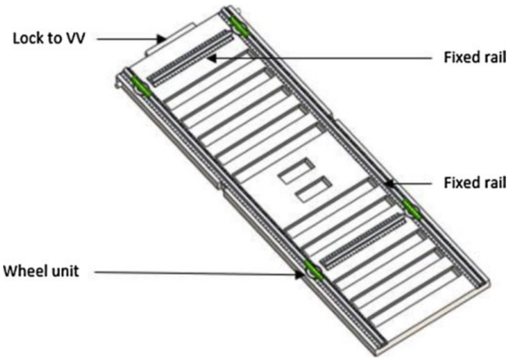

Figure 24. *Track rail frame (Li et al. 2019, p. 3).*

The carriage system (figure 25) consists of a robot with 6 DOF, of a rack and a pinion system, of linear guides, of a clamp and of a carriage structure. The main functions of the system are to move the mobile platform and the track and to execute other maintenance tasks. The rack and pinion system moves the carriage linearly. The linear motion guides guide the carriage system. The 6 DOF robot manipulates the mobile platform and the track with a clamp. Other maintenance tasks for the robot can be welding, cutting and recovery operations. The carriage moves linearly along the linear motion guides. (Li et al. 2019)

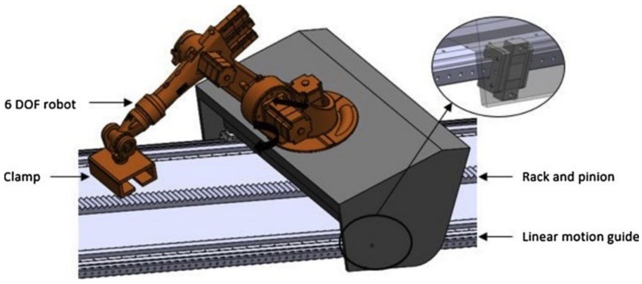

Figure 25. *Carriage (Li et al. 2019, p. 3).*

In figure 26, the divertor cassette removal process is presented. The process starts with the track installation (in figure 26 pictures a and b) and then the mobile platform is transported into the vacuum vessel (in figure 26 pictures c and d). For the cassettes on the sides: The mobile platform is connected to the toroidal rail by rotating the rail structure and the scissors push the platform toroidally (in figure 26 pictures e and f). Then the mobile platform cylinder connects to the cassette and lifts the cassette (in figure 26 picture h). In the end, the carriage moves the mobile platform with the cassette into the transport cask (in figure 26 picture h). After cassette removals, the new cassettes are installed, and the track rail frame is removed (in figure 26 picture i). The cassette installation is the reverse process of the removal process.

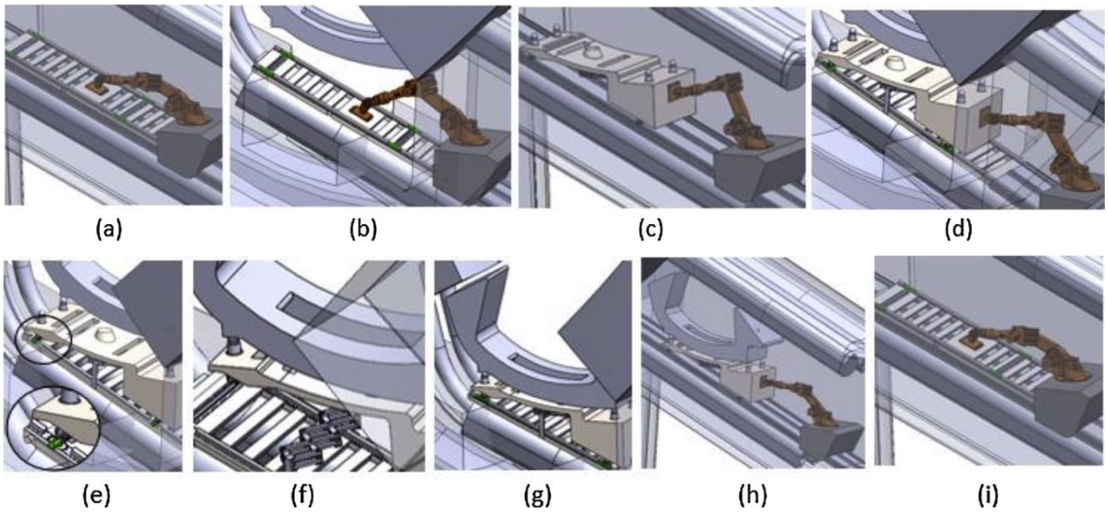

Figure 26. *The divertor cassette removal process (Li et al. 2019, p. 2).*

For this concept, accurate calculations for actuators, interfaces and sensors are needed. In this concept, the inclination of the maintenance port is less than in the other two concepts. (Li et al. 2019) This may cause collision problems with the TF coils.

4.4 Maintenance development requirements

In the paper *Overview of progress on the European DEMO remote maintenance strategy* the strategy drivers of the divertor maintenance are introduced. The maintenance strategy is driven by the need of in-vessel operation, maintenance duration and divertor maintenance port size minimization. As a part of the maintenance duration minimization, the technical risks are also included in the maintenance strategy drivers. (Crofts et al. 2016, p. 1393-1394) The concepts in this thesis are evaluated based on these strategy drivers. In this thesis, technical risks are separated from the maintenance duration estimate in order to simplify the maintenance duration calculations.

Due to high temperatures and high radiation levels in the vacuum vessel, operations in the vacuum vessel should be minimized. Radiation and high temperatures activate and induce stresses to the maintenance equipment materials and may break them when the operations take too long time in the vacuum vessel. Harsh environment and small clearances in between the cassette and the maintenance port walls significantly limit the visual and physical feedback during the maintenance operation. Lack of feedback increases the risk of unrecoverable failure during in-vessel operations. To minimize in-vessel operations, the segmentation of the divertor cassettes has already been planned. The segmentation allows the divertor maintenance through divertor maintenance ports instead from the vacuum vessel. (Crofts et al. 2016, p. 1393-1394) In this thesis, the in-vessel operation amount for the concepts is evaluated with two factors. The first factor is a number of steps that the maintenance equipment executes in the vacuum vessel during the replacement of three divertor cassettes. In the concept publications, no estimation of the maintenance duration was provided. The number of steps correlates moderately with the time that the maintenance equipment spends in the vacuum vessel during maintenance. The second factor is the number of maintenance equipment parts inside the vacuum vessel during maintenance operations. These two factors are combined by multiplying the number of steps with an average number of maintenance equipment parts in the vacuum vessel during the maintenance steps. The result of this calculation is used for concept evaluation.

TF coils and poloidal field (PF) coils are using most of the space around the vacuum vessel. The coils limit the divertor maintenance port size to a minimum. In the EU-DEMO, the divertor maintenance port is inclined in order to avoid overlapping with the TF coils. The size limitation of the maintenance port also limits the size of the RHE. The critical dimensions are maintenance port width and height. The maintenance equipment size limitation may decrease the load capacity and stiffness of the RHE. (Crofts et al. 2016, p. 1393-1394) In this thesis, the space usage evaluation for the maintenance equipment is separated to three factors. The first factor is extra space manipulator needs around the divertor cassette while operating inside the maintenance port. The second factor is required clearance between the maintenance port walls and the divertor cassette during the cassette transport. The third factor is required space in the transport cask and in the vacuum vessel.

The EU-DEMO power plant must demonstrate commercial viability which can only be achieved by high power plant availability. Availability is the percentage of time a reactor is able to operate during the lifetime of the reactor. The maintenance duration is one of the main factors that affects the reactor availability. Therefore, the maintenance duration must be minimized. (Crofts et al. 2016, p. 1393-1394) The maintenance duration is estimated and compared the same way as the in-vessel operation duration estimation. For maintenance duration, not only in-vessel operations are included but also full maintenance operation. In this thesis, the estimated time needed for welding, cutting and cassette transport outside the reactor are not included, as these are not manipulator tasks. It is also assumed that one transportation cask can transport three divertor cassettes regardless of the manipulator concept. The concepts are evaluated with two factors. The first factor is the number of steps required during the replacement of the three cassettes. It is assumed that a high number of steps relates with the longer maintenance duration. The second factor is the estimated speed of the manipulator during the maintenance. There is no data available regarding the speed of the manipulators. It is assumed that less supported manipulator movements tend cause bending and oscillations to the loaded RHE parts. Bending and oscillations make it more difficult to move the cassette. Therefore, it is assumed that less supported movements are slower than well supported movements. These two factors are used in the maintenance duration estimations. Due to a lack of accurate information, this study is only a rough comparison of the three presented manipulator concepts. Absolute maintenance durations are not estimated.

The divertor maintenance consists of many steps (see chapter 4.1). With the variety of steps, the complexity of the maintenance equipment increases. Technical risks tend to be higher and harder to mitigate for complex systems. The complexity increases the amount of potential malfunctioning parts. Failures cause maintenance delays that decrease the power plant availability. Top level technical risk assessment has shown that moving heavy IVCs with a high degree of accuracy causes one of the most critical risks during the maintenance. Technical risks assessments must be conducted in order to mitigate risks. For the DEMO reactor, the *Reliability, Availability, Maintainability and Inspectability analysis* (RAMI) has been already developed. The RAMI is a top-level analysis based on *Failure Modes, Effects and Criticality Analysis (FMECA*). (Crofts et al. 2016, p. 1393-1394) In this thesis, the technical risks are evaluated with FMECA without taking radiation and heat from the vacuum vessel to account. They are taken separately into account when the in-vessel operation amount is assessed. The evaluation is executed with a low accuracy due to the lack of source material and the limited scope of this study.

5. EVALUATION OF THE DIVERTOR MANIPULATOR CONCEPTS

The source material for the divertor maintenance concepts does not consist of calculations regarding maintenance duration estimations, part reliabilities or the actual size of the equipment. Therefore, the evaluation is based on personal estimates.

5.1 In-Vessel operation minimization

In all concepts, the maintenance operation is divided into similar sized steps in order to quantify the amount of in-vessel operation. The steps are divided into linear and toroidal movement steps only in case the steps are executed separately. The parts that are inside the vacuum vessel or in the maintenance port very close to the vacuum vessel during the maintenance steps are included as in-vessel parts. The manipulator parts are also included even though they are only partially inside the vacuum vessel during the step.

In the cantilever approach, the manipulator moves the cassette linearly and toroidally only with one step because no separate direction changing operation is required. During the installation of the cassette there are three steps during which the manipulator

1. transports the cassette to the vacuum vessel attachments,
2. attaches the cassette to the vacuum vessel attachments and
3. leaves from the vacuum vessel.

And during the removal of the one cassette, the manipulator

1. moves inside the vacuum vessel,
2. detaches the cassette from the vacuum vessel attachments and
3. transports the cassette out from the vacuum vessel.

During all these steps, only the end-effector is inside the vacuum vessel. (Carfora et al. 2015) The telescopic boom is supported by rails in the divertor maintenance port and rails can be used for removal of the blanket modules, if needed.

In the simply supported beam approach, toroidal and linear movements are separate steps because separate direction changing operation is required. It is also important to note that the vacuum vessel attachment of the divertor cassette and the detachment of the divertor cassette steps have not yet been developed for this concept. During the installation of the one cassette, the manipulator

1. transports the cassette into the vacuum vessel,
2. installs the dummy rail (not designed),
3. moves the cassette toroidally (this applies to two cassettes on the sides),
4. attaches the cassette to the vacuum vessel attachments,
5. moves toroidally back to the port
   (this applies to two cassettes on the sides),
6. removes the dummy rail and
7. leaves from the vacuum vessel.

And during the removal of the one cassette, the manipulator

1. moves inside the vacuum vessel,
2. installs the dummy rail,

3. moves toroidally to the cassette (this applies to two cassettes on the sides),
4. detaches the cassette from the vacuum vessel attachments,
5. moves the cassette toroidally (this applies to two cassettes on the sides),
6. removes the dummy rail and
7. transports the cassette out from the vacuum vessel.

During all these steps, the cassette carriage, the rails and the pulleys are in or near the vacuum vessel. In addition, toroidal dummy rails are not designed and, therefore, the exact number of steps required cannot be determined. (Mozzillo et al. 2017) The use of the dummy rails increases the amount of in-vessel operation. The manipulator in this concept is not suitable for blanket module handling but there are rails already in place for separate blanket module maintenance equipment.

In the mobile platform approach, toroidal and linear movements are also separated for the same reason as in the simply supported beam approach. In this concept, the maintenance starts with the preparations. During the preparation, the manipulator

1. transports the track into the vacuum vessel for the mobile platform,
2. attaches the track on bottom of the vacuum vessel and
3. leaves the vacuum vessel.

After the preparation, the manipulator installs the cassettes. During the installation and removal of the cassettes the manipulator conducts almost all the same steps as in the simply supported beam approach. Only the dummy rail is not included in this concept. After the removal of the cassettes, the manipulator

1. moves into the vacuum vessel,
2. detaches the track from the bottom of the vacuum vessel and
3. transports the track out of the vacuum vessel.

The preparation and the after-removal steps are done only once during the replacement of the three cassettes. During these steps, the carriage and the track are in the vacuum vessel. During installation and removal, the carriage, the track and the mobile platform are in the vacuum vessel. (Li et al. 2019) This concept also has the rails already installed for blanket module replacement and the carriage with the robot can be used for the blanket replacement.

The total number of steps executed in the vacuum vessel for each concept are counted and collected into the table 1. On the right side of table 1, the number of steps is multiplied with the average number of maintenance equipment parts during the maintenance.

Concept	Total in-vessel steps	Total in-vessel steps × average number of in-vessel parts
Cantilever approach	18	18
Simply supported beam approach	38	133
Mobile platform approach	32	90

Table 1. *In-vessel operation duration estimation and comparison table for concepts.*

The number in the right column in table 1 correlates with the amount of in-vessel operations. A higher number means more vacuum vessel operations– therefore, the smallest number is the most favorable.

5.2 Space requirements of equipment

The evaluation is done by evaluating how much additional space the manipulator and the divertor cassette together require compared only to the divertor cassette. An optimal design would require no additional space from the maintenance port or the vacuum vessel. The manipulator can require additional space from the maintenance port and from the vacuum vessel in two different ways: Manipulator parts can locate around the cassette during the operation or RHE movements require clearance in between the cassette and the surrounding walls. The clearance is required so that the cassette can be moved without any collisions inside the maintenance port. The third place where the manipulator can require excess space is the transport cask.

The manipulator in the cantilever approach moves mostly behind the divertor cassette during the maintenance. It requires minimal additional space from the divertor maintenance port or the vacuum vessel. Only the rail system requires additional space from the maintenance port. However, without the rails, the manipulator would require additional space for the clearances from the maintenance port. The weight of the cassette would affect the movement accuracy by bending the telescopic boom. Without proper visual feedback, these deformations cause uncertainties to the cassette position information. By slowing down the movement, clearances can be mitigated, but this also would increase the maintenance duration. The manipulator in the cantilever approach requires plenty of space from the top of the transport cask (figure 19). The telescopic boom requires also lengthwise additional space from the transport cask. During the cask transportation, it can be impractical to move such a high and long transport cask.

The manipulator in the simply supported beam approach moves the divertor cassette on top of the cassette carriage. The cassette carriage and the rails underneath the carriage require additional space from the divertor maintenance port. The rail system functions as a mechanical guide for the cassette carriage, therefore minimal clearance is required. The rails also require space from the vacuum vessel, but this does not affect the vacuum vessel size. Toroidal rails allow also smaller clearances in between the cassette and the cassette attachments during toroidal movements. The transport cask in the simply supported beam approach can be attached to the divertor maintenance port horizontally. The manipulator requires a minimal excess vertical space from the transport cask. The manipulator also requires minimal transport cask width and length, as the cassette carriage is located under the cassette in the transport cask. The winch and rail systems require small additional space from the divertor maintenance port and the vacuum vessel.

In the mobile platform approach, the mobile platform is underneath and the carriage behind the cassette. The manipulator requires approximately the same amount of additional space from the divertor maintenance port as the manipulator in the simply supported beam approach due to similarities of the mobile platform and the cassette carriage. The mobile platform is also guided by rails, so it requires minimal clearances. In the mobile platform approach, the carriage moves behind the cassette. Therefore, it requires some additional space lengthwise from the transporter cask.

5.3 Maintenance duration minimization

It is estimated that the cassettes and the blanket modules replacement through one divertor maintenance port takes around 1000 hours and that changing the cassettes alone takes around 700 hours. The cassettes are replaced during every maintenance operation and the blanket modules are replaced every second time. The cassette replacement consists of port preparation, cooling pipe cutting and welding, cassette transportation and port sealing operations. (Crofts & Harman 2014, p. 2386) Based on the maintenance durations presented by Crofts & Harman (2014), the estimated duration of the cassette transportation is around 400 hours from 1700 hours that is required for maintenance operations during 4 full power years. Therefore, the divertor transportation duration is around 20-25% of the time required for the maintenance through one divertor maintenance port without cooldown and pump-down periods. The maintenance duration is qualitatively discussed in this chapter. The concepts are compared step by step, from preparations to finalizing steps.

Preparations are required in two concepts. In the simply supported beam approach, the cassette carriage is attached to the winch-pulley system. In the mobile platform approach the carriage transports the track into the vacuum vessel. The manipulator in the cantilever approach does not require preparations. Transporting the track requires probably more time than attaching the carriage to the winch-pulley system. Therefore, the preparation duration in the mobile platform approach is estimated to be the longest compared to other concepts.

After the preparations, the manipulator **moves linearly into the vacuum vessel**. In the mobile platform and the simply supported beam approach the manipulator moves on rails. There is no notable difference in between these concepts during this step. In the cantilever approach, the telescopic boom moves without support from the transport cask to the maintenance port. At the maintenance port, the telescopic boom docks to the maintenance port rails. Docking operation and less supported movements require additional time. Therefore, the manipulator movements in the cantilever approach requires more time than the manipulator movements in the other concepts.

After linear movement, the manipulator **moves toroidally**. In the cantilever approach, the end-effector moves the cassette toroidally. The end-effector can start moving the cassette toroidally instantly after the telescopic boom stops moving. In the mobile platform and the simply supported beam approach, rails are used to transport the cassette toroidally. In these concepts, the cassettes need to be positioned for toroidal movement. In the mobile platform approach additional time is required to position the platform for platform wheel rotations. In the simply supported beam approach the cassette is positioned on the same level with the toroidal rails which requires additional time.

The divertor cassettes are detached from the vacuum vessel before the manipulator enters the vacuum vessel. The manipulator only **lifts the cassette** from the cassette supports. This process requires slower movements due to small clearances between the cassette and the blanket modules. For the simply supported beam approach this function is not designed. In the cantilever approach, the end-effector is supported by the telescopic boom coming through the maintenance port. The distance between the cassette attachment and the nearest supporting structure is rather long. The significant weight of the cassette causes bending and oscillations in the end-effector. Therefore, in the cantilever approach the manipulator must move slowly in order to mitigate the oscillations. In the mobile platform approach lifting cylinders are well supported from below, so movements can be executed faster than in the cantilever approach.

After lifting the cassette, the manipulator **transports the cassette from the vacuum vessel to the transport cask**. In all concepts, the manipulator moves back to the transport cask the same path it moved into the vacuum vessel. During this step, the weight of the cassette affects the speed of the manipulator movement the same way as in the cassette lifting step. In the cantilever approach, undocking the telescopic boom from the maintenance port requires more time than docking due to added weight. In other concepts, the manipulator moves along the rails. Therefore, the cassette slows the movements less in these concepts than in the cantilever approach.

In the transport cask, the manipulator **places the cassette** on a supporting structure. This part of the maintenance has not yet been developed. Therefore, it is assumed that the duration of the step is the same in every concept. After all, three cassettes are removed from the vacuum vessel, the new cassettes are installed. In the beginning of the installation, the manipulator **picks up the cassette** from the transport cask. This step is not presented in the source material, so it is assumed that the duration of this step is the same regardless of the concept.

Transporting the cassettes into the vacuum vessel is the reverse process to the cassette removal. Therefore, the manipulator speeds are the same but in inverse directions for all steps. At the end of the maintenance, the manipulators in the mobile platform approach and in the simply supported beam approach require additional steps. The manipulator in the simply supported beam approach is detached from the winch system. The manipulator in the mobile platform approach picks up the track from the vacuum vessel after the maintenance.

All steps are listed below for all concepts. The manipulators execute most steps more than once during the replacement of the three cassettes. All separate steps are presented, and the amount of repetitions are indicated with a number in brackets at the end of the step description. In the cantilever approach these steps are:

1. The telescopic boom moves the end-effector into the vacuum vessel. (3)
2. The end-effector lifts the cassette from the cassette vacuum vessel attachment. (3)
3. The telescopic boom transports the cassette out from the vacuum vessel. (3)
4. The manipulator places the cassette in the transport cask. (3)
5. The end-effector picks up the new cassette. (3)
6. The telescopic boom moves the end-effector with the cassette into the vacuum vessel. (3)
7. The end-effector places the cassette onto the cassette vacuum vessel attachment. (3)
8. The telescopic boom pulls the end-effector out from the vacuum vessel. (3)

In the simply supported beam approach these steps are:

1. The manipulator installs the dummy rail. (3)
2. The toroidal pushing actuator moves toroidally. (2)
3. The cassette carriage takes the cassette from the cassette vacuum vessel attachment. (3)
4. The toroidal pushing actuator moves the cassette into the maintenance port. (2)
5. The manipulator detaches the dummy rail. (3)
6. The carriage with the cassette moves into the transport cask. (3)
7. The carriage places the cassette into the transport cask. (3)
8. The new cassette is placed on top of the carriage. (3)
9. The cassette carriage moves the cassette into the vacuum vessel. (3)
10. The manipulator installs the dummy rail. (3)
11. The toroidal pushing actuator moves the cassette toroidally. (2)
12. The cassette carriage places the cassette on the cassette vacuum vessel attachment. (3)
13. The toroidal pushing actuator moves back toroidally. (2)
14. The manipulator detaches the dummy rail. (3)
15. The cassette carriage moves into the transport cask. (3)
16. The cassette carriage detaches from the winch system. (1)

In the mobile platform approach these steps are:

1. The robot picks up the track from the transport cask. (1)
2. The carriage transports the track into the vacuum vessel. (1)
3. The robot attaches the track on bottom of the vacuum vessel. (1)l
4. The carriage goes back to the transport cask (1)
5. The robot attaches to the mobile platform. (3)
6. The carriage moves the mobile platform into the vacuum vessel. (3)
7. The rotatable rails rotate, and the scissors push the mobile platform toroidally. (2)
8. The mobile platform lifts the cassette from the cassette vacuum vessel attachment. (3)
9. The scissors pull the platform back onto the track and the rotatable rails rotate. (2)
10. The carriage moves the platform with the cassette into the transport cask. (3)
11. The carriage places the cassette into the transport cask. (3)
12. The robot attaches to the new mobile platform with the cassette. (3)
13. The carriage moves the cassette into the vacuum vessel. (3)
14. The rotatable rails rotate, and the scissors push the mobile platform toroidally. (2)
15. The mobile platform places the cassette on the cassette vacuum vessel attachment. (3)
16. The scissors pull the platform back onto the track and the rotatable rails rotate. (2)
17. The carriage moves the platform into the transport cask. (3)
18. The carriage moves into the vacuum vessel. (1)
19. The robot detaches the track from the vacuum vessel. (1)
20. The carriage transports the track into the transport cask. (1)

The total number of steps varies significantly between the concepts. The high number of separate steps indicates the long maintenance duration. The total number of the maintenance steps is calculated for each manipulator concept. The steps include preparations, removal and installation of the cassettes and after-installation steps. In the cantilever approach, there are in total 24 separate steps. In the simply supported beam approach, there are in total 46 separate steps. And in the mobile platform approach, there are in total 42 separate steps.

5.4 Minimization of technical risks

The technical risks evaluation in this study consists of two different areas: The maintenance operation safety and the power plant availability. The safety discussion consists only of the effects of the maintenance operation failures on the power plant worker safety. In this chapter, the power plant availability discussion focuses on the maintenance equipment reliability and on the effects of the maintenance operation failures on the power plant availability. The maintenance equipment reliability evaluation consists of

- the amount of in-vessel operation (see chapters 4.4 and 5.1),
- the total maintenance operation step count (see chapters 4.4 and 5.3) and
- the technologies used.

The maintenance operation failures and their effects are evaluated employing the partial FMEA analysis. The FMEA analysis is used to determine the major technical risks more objectively. In this thesis, failure detection and the preventative method parts are left out from the FMEA analysis due to the lack of data and the limited scope of the study. The effects of the vacuum vessel radiation and heat are not included in the FMEA analysis because they have already been included in the discussion in chapters 4.4 and 5.1.

The results in chapters 5.1 and 5.3 indicate that the cantilever approach is potentially more reliable than other concept due to the lowest in-vessel operation amount and the overall maintenance steps. The second most potential concept is the mobile platform approach with its second lowest in-vessel operation amount and overall maintenance steps. The simply supported beam approach appears to be the least reliable, based on these factors. The technologies used, have also impact on the reliability of the concept. The technologies that are proven in practice tend to be more reliable (Federici et al. 2018, pp. 729-730). It is hard to give absolute truths about how proven technologies are but assuming that newer technologies are less proven, can give a good reliability estimation. Based on this assumption, the manipulator in the simply supported beam approach is the most reliable concept. It uses a long existing funicular railway technology with simple hydraulics and tipping technology. The manipulators in the cantilever and the mobile platform approaches use more complex robotics that require more advanced controlling systems.

In the FMEA analysis, all the parts of the manipulator are grouped into systems. Then all functions are listed for each system with all potential failure modes. After the failure modes, the potential effects of the failures are listed. The potential effects concentrate on a potential maintenance operation delay caused by failures. Therefore, the required failure correction actions are listed in potential effects lists. Then the potential causes of the failure modes are determined. Potential causes are malfunctioning parts or human errors that cause that particular failure mode. After the potential causes have been determined, the severity and occurrence rating tables (tables 2 and 3) are defined.

The occurrence scale is determined in such a way that the highest rating of 10 means that the failure occurs one or more times during one maintenance operation (through one maintenance port). The lowest rating of 1 is determined to represent the situation where the failure occurs once during a power plant lifetime or less frequently. In between the rating of 1 and 10, there are corresponding gradations. The provided data allows only a limited occurrence analysis. In order to mitigate the subjectivity in estimations, the count of function repetitions during the power plant lifetime are calculated and this amount is multiplied with the estimated failure probability. The failure probabilities are based on educated estimations without actual data. In general, functions with human interference have the highest failure probabilities and functions with less or guided movements have the lowest failure probabilities. The fusion power plant lifetime for the calculations is assumed to be 40 years. This assumption is based on fission power plant lifetime without further knowledge about fusion power plant lifetime.

The severity rating indicates the time required to correct failure in the worst scenario. The lowest rating of 1 is for under one-hour delays. The highest rating of 10 is for delays of over 3 months or more. The provided data also limits the severity accuracy but it is adequate for this study. It is assumed that there are always spare maintenance equipment and cassettes available due to the maintenance duration importance for the power plant availability.

Occurrence:	Description:
1	0-1 times during power plant lifetime
2	1-10 times during power plant lifetime
3	10-20 times during power plant lifetime
4	20-40 times during power plant lifetime 1-2 times during one reactor maintenance operation
5	40-80 times during power plant lifetime 2-4 times during one reactor maintenance operation
6	80-140 times during power plant lifetime 4-7 times during one reactor maintenance operation
7	140-200 times during power plant lifetime 7-10 times during one reactor maintenance operation
8	200-260 times during power plant lifetime 10-13 times during one reactor maintenance operation
9	260-320 times during power plant lifetime 13-16 times during one reactor maintenance operation
10	Over 320 times during power plant lifetime Over 16 times during one reactor maintenance operation More than 1 time during one section maintenance operation

Table 2. *Occurrence table for the FMEA analysis.*

Severity:	Description:
1	Under 1-hour delay
2	1-3 hours delay
3	3-6 hours delay
4	6-24 hours delay
5	1-4 days delay
6	4-7 days delay
7	1-2 weeks delay
8	2-4 weeks delay
9	1-3 months delay
10	Over 3 months delay

Table 3. *Severity table of the FMEA analysis*

Full results from the FMEA analysis can be found in the appendixes B to D. Major technical risks are determined by multiplying the severity with the occurrence (S*O) and selecting the failures with the greatest S*O number. For this study, only three to four failures per concept are selected and discussed. The discussion includes result reliability, risks and the risk mitigation possibility assessments.

Major technical risks in the cantilever approach according to the FMEA analysis are present when the telescopic boom and the end-effector are moved. The telescopic boom is supported only by the telescopic boom base during movements in the transport cask. In the transport cask the manipulator allows the telescopic boom to move into the wrong direction and to oscillate. This can cause a collision of the manipulator or of the cassette with their surrounding parts. Collisions can cause severe damage to the transport cask or to the maintenance port. Repairing the maintenance port can take long because it is fixed to the vacuum vessel and it can be accessed only by remote controlled equipment. In the worst-case, radiation sealing in between the transport cask and the maintenance port can break and allow radioactive dust to leak outside the vacuum vessel. Leakage mitigation operations take usually long time. The manipulator allows only small human error due to the DOFs and small clearances. Advanced controlling and location measurement systems can be used to mitigate the probability of error. When the telescopic boom is docked into the maintenance port, the telescopic boom is better supported. Therefore, the risk of error is lower during in-vessel operation. A high S*O number correlates with the technical risks. With further concept development, the risks can be mitigated. The end-effector is also supported only by the end of the telescopic boom and the end-effector has no movement limiters. Collision in the vacuum vessel is even more severe than in the transport cask because recovery operation in the vacuum vessel and vacuum vessel repair are more challenging.

Major technical risks in the simply supported beam approach, according to the FMEA analysis, are present when the cassette is tilted and the carriage is winched. The carriage moves well guided on the rails. In addition, movements can be limited at the end of the rails by mechanical stoppers. There is a good amount of tolerance for human error and a relatively high S*O number does not correlate well with actual risks. The tilting actuator tilts the cassette inside the vacuum vessel, and it has only one degree of freedom. The mechanical stops can also be used to position the cassette in order to minimize risks. The relatively high S*O number does not correlate well with the risk regarding the function. The FMEA analysis does not take into account that dummy rails that are required to move the cassettes toroidally because the dummy rails have not been developed for this concept. The dummy rail installation may introduce unexpected technical risks to the concept with otherwise low technical risks.

According to the FMEA analysis, the major technical risks in the mobile platform approach are present when the mobile platform is moved linearly and toroidally and when the wheel units rotate. The carriage moves the mobile platform on the rails using the 6DOF robot. Even though the robot has many DOFs, the mobile platform has only one degree of freedom. Mechanical stops can be included in the rail system to prevent collisions. The risk is not significant, and a high S*O number does not correlate well with the risks associated with the linear movement function. For toroidal movement, the same reasoning about rails applies. However, the scissors may increase technical risks. The scissors are attached to the track with a vertical connector bar and the forces that are affecting the connector bar are horizontal. The connector bar withstands the least amount of force on the direction where the main forces affect. Therefore, a higher S*O number corresponds better with risks associated with the toroidal movement function. Rail rotation is executed by a rotation motor inside the mobile platform. The wheel units in between the mobile platform and the track allow the rotation. During the rotation, the carriage system supports the mobile platform. Successful rotation requires the mobile platform to be accurately positioned so that the wheel units are aligned on top of each other. If the wheel units are not aligned, more force is required to rotate the rails because then the whole mobile platform also moves during the rotation. This may increase technical risks. The rails have to be well aligned in order to move the mobile platform safely in between the rotating rails and the fixed rails. Toroidal rails are inside the vacuum vessel during the power plant operation and, therefore, may bend and weaken due to heat and radiation loads. Bending may also cause problems when the rotational rails are aligned with the toroidal rails. The high S*O number correlates well with the risks associated with this function.

The maintenance operation is done remotely because of the safety reasons. It allows humans to stay away from the radioactive and hot part of the reactor. Based on the FMEA analysis, the greatest safety concern during the maintenance operation is a radioactive dust leakage that might occur when the seal in between the transport cask and the vacuum vessel breaks. The probability of such a failure is low because it requires the manipulator or the cassette to fall down during the operation. Based on all FMEA analyses, this type of failure has a very low probability. In addition, humans do not work in the rooms where the transport casks move, due to radiation risks. Therefore, leakage does not pose a threat to power plant workers. Due to low risks, safety during the maintenance operation is not the main concern.

5.5 Concept improvement proposals

The development of the concepts is in the beginning and none of the concepts have been finalized yet. In this chapter, possible improvements are proposed, based on the results of the study. Proposals are based on two questions: Is there a way to decrease the amount of in-vessel operation or maintenance steps and is it possible to alter the concepts so that technical risks decrease? In this study, proposals have not been evaluated properly and must be evaluated before their employment in a concept.

In the cantilever approach, the in-vessel operations and the maintenance steps are minimal and, therefore, no improvements are proposed for that. Technical risks are higher due to a high number DOF when moving the cassette. The end-effector could have supporting rails in the maintenance port and the vacuum vessel during in-vessel operation. This would limit the DOF for the end-effector and, therefore, mitigate technical risks.

In the simply supported beam approach, the toroidal cassette positioning system is not developed. If the carriage could lift the cassette and drive on toroidal rails, it could be used for cassette positioning. To make the translation seamless in between the linear and toroidal movements, the pulley could additionally rotate sideways. This would remove the need of cable detachment in between the movements. In order to move the carriage toroidally, toroidal pushing actuators could be used to push and pull the carriage. This proposal also increases the in-vessel operation during the toroidal movements, but the cassette can be placed with the manipulator. All other maintenance steps appear to be vital for this concept and technical risks are low in this concept, so no more improvements are proposed.

The mobile platform approach has a high number of in-vessel operation steps. In order to decrease the in-vessel operations, the robot could instead of scissors be used to move the mobile platform toroidally. This would decrease the number of parts inside the vacuum vessel during maintenance operation. Eliminating the need of scissors also decreases technical risks (see chapter 5.4). In order to decrease in-vessel and overall operations, the need of a removable track must be examined. If it is possible to replace the track with fixed rails, less operations would be needed. One downside would be that the rails would be inside the vacuum vessel during power plant operation. The wheel units in the track system can be designed adjustable in order to mitigate possible alignment problems in between rotatable and fixed rails.

6. CONCLUSIONS

This study focuses on the evaluation of three EU-DEMO fusion power plant divertor manipulator concepts. The EU-DEMO is the last step before the commercial use of fusion power plants that have the potential to revolutionize the energy production industry. The development of effective maintenance is a crucial part of the EU-DEMO’s success. The development of the EU-DEMO is currently in between pre-conceptual and conceptual design phases where it is important to narrow down the number of parallel designs for the EU-DEMO power plant. There are many proposed concepts for the manipulator, but three potential concepts were included in this evaluation: the cantilever approach, the simply supported beam approach and the mobile platform approach. The evaluation was based on the maintenance design drivers of the EU-DEMO. The aim of this study is to offer support on the decision making over the most promising divertor manipulator concepts for further development.

The first research question was: What kind of divertor manipulator concepts have been proposed? Several divertor manipulator concepts were found. All the concepts were planned for maintenance through maintenance port. Main differences between the concepts were the means of transport inside the maintenance port and vacuum vessel, and the shape of maintenance port required for the maintenance. Three of the concepts were analyzed more accurate: The cantilever approach, simply supported beam approach and mobile platform approach. The manipulator in the cantilever approach moves the cassette with the combination of the telescopic boom and the end-effector. The cassette is positioned in the vacuum vessel by the end-effector. The second concept is the simply supported beam approach where the cassette is moved on top of the carriage. The carriage is moved linearly by the winch system and the cassette is moved toroidally on top of the rails by using hydraulic actuators. The cassette positioning system and the dummy rail are not designed in this concept. The third concept is the mobile platform approach where the cassette is moved on top of the mobile platform. The platform is moved on rails linearly by the carriage with the robot and toroidally by the scissor system. The cassette is positioned in the vacuum vessel by the hydraulic actuator system on the mobile platform.

The second research question was: How do divertor manipulator concepts follow the development drivers for fusion power plant maintenance? The manipulator in the cantilever approach has the minimal amount of in-vessel and overall operations. The manipulator requires significant amount of additional space in the transport cask for movement and some space for clearances in the divertor maintenance port. The manipulator moves behind the cassette in the maintenance port and requires minimal additional space around the cassette. The technical risks are relatively high due to a higher possibility of human error during non-guided movements. The manipulator in the simply supported approach has a highest amount of in-vessel and overall operations due to need of dummy rails. The manipulator requires additional space under the cassette from the maintenance port. Movements are well supported and guided, so that clearances in the maintenance port can be minimal. The technical risks of the concept are low due to good support, employment of proven technologies and a low risk of human error. The manipulator in the mobile platform approach has a moderate amount of in-vessel and overall operation. The manipulator requires additional space under the cassette from the maintenance port for the mobile platform and the rails. Movements are well supported and guided, so clearances in the maintenance port can be minimal. The technical risks of the concept are moderate. The movements are well supported and guided but rotation between linear and toroidal directions may introduce additional technical risk.

The third research question was: How can the presented concepts be improved? For the cantilever approach, only a minor improvement was found to mitigate the technical risk. The end-effector could have supporting rails in the maintenance port and the vacuum vessel during in-vessel operation. For the simply supported beam approach, improvements were found to fulfill the missing parts of design. The missing positioning could be executed with the carriage, if it can be also moved toroidally. To make the translation seamless in between the linear and toroidal movements, the pulley could additionally rotate sideways. For the mobile platform approach, a couple of possible improvements were found to decrease the complexity of the design, thus technical risks. The robot could instead of scissors be used to move the mobile platform toroidally, in order to decrease the complexity of the design. The need of a removable track must be examined for the same reason. Also, the wheel units in the track system can be designed adjustable, in order to mitigate possible alignment problems in between rotatable and fixed rails.

The amount of data found from sources were insufficient for an accurate evaluation. Therefore, the evaluation was more qualitative and objective calculations were less used. The count of design drivers combined with the scope of this study also limited the amount of research regarding an individual design driver. The amount of evaluation was, nevertheless, sufficient to fulfill the goal of this study as it was possible to obtain reasonable results. Two concepts were designed for an older cassette design, but the concepts were also suitable for the newer cassette design. This study can be used as one of many evaluations in order to find the most promising concepts for further development. Additionally, the improvement proposals can be taken into consideration as ideas during further development.

After this study, broader evaluations of the designs including more accurate data are required in order to evaluate the technical feasibility of the concepts more accurately. The effects of radiation and heat must be studied for all parts of the manipulator that operate inside the vacuum vessel. Forces affecting the manipulator must be determined and also the effects of forces must be studied for each part of the manipulator designs.

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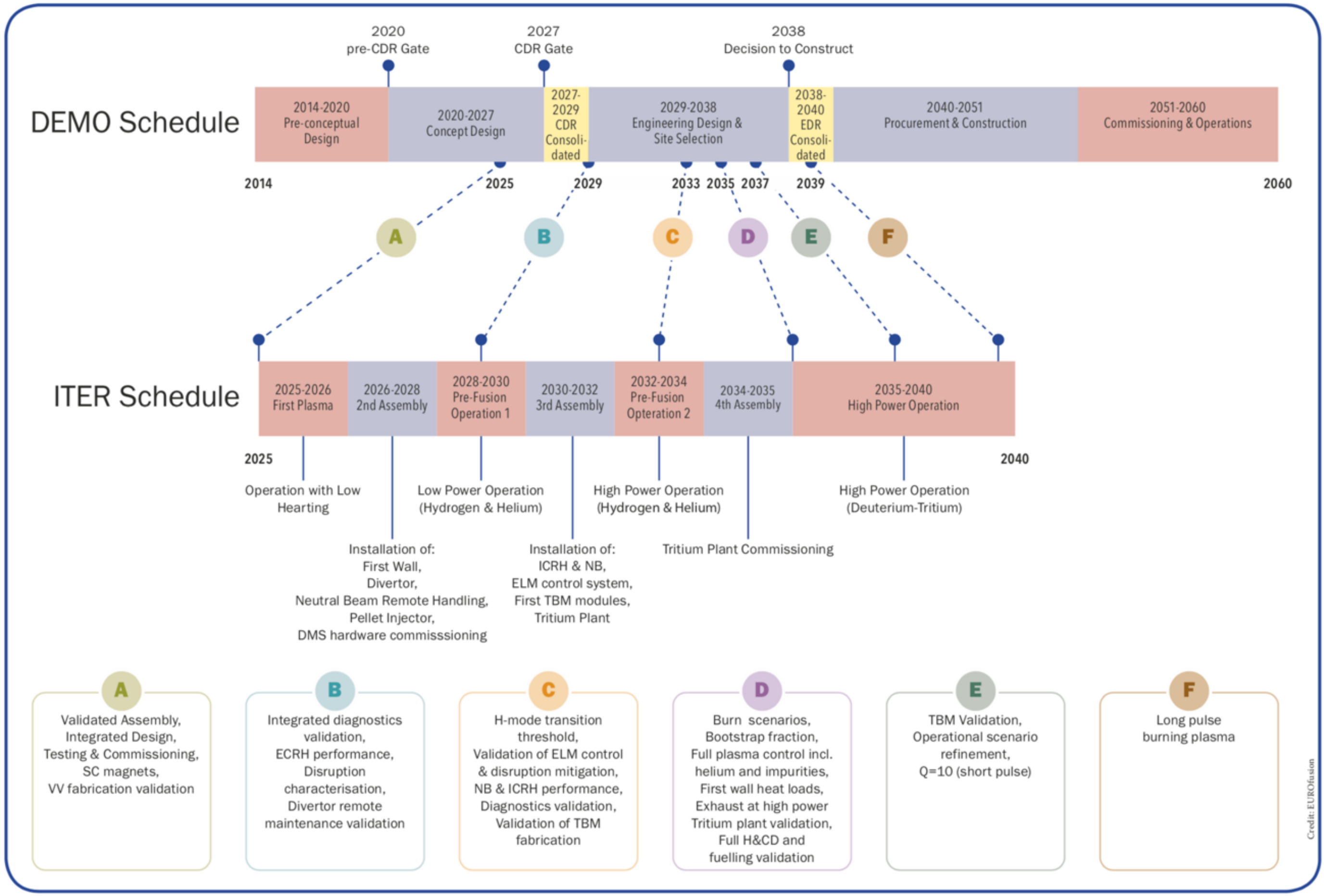
APPENDIX A:


2020
pre-CDR Gate
2027
CDR Gate
2038
Decision to Construct
DEMO Schedule
2014-2020
Pre-conceptual Design
2020-2027
Concept Design
2027-2029
CDR Consolidated
2029-2038
Engineering Design & Site Selection
2038-2040
EDR Consolidated
2040-2051
Procurement & Construction
2051-2060
Commissioning & Operations
2014
2025
2029
2033
2035
2037
2039
2060
A
B
C
D
E
F
ITER Schedule
2025-2026
First Plasma
2026-2028
2nd Assembly
2028-2030
Pre-Fusion Operation 1
2030-2032
3rd Assembly
2032-2034
Pre-Fusion Opertation 2
2034-2035
4th Assembly
2035-2040
High Power Operation
2025
2040
Operation with Low Hearting
Low Power Operation (Hydrogen & Helium)
High Power Operation (Hydrogen & Helium)
High Power Operation (Deuterium-Tritium)
Installation of:
First Wall,
Divertor,
Neutral Beam Remote Handling,
Pellet Injector,
DMS hardware commisssioning
Installation of:
ICRH & NB,
ELM control system,
First TBM modules,
Tritium Plant
Tritium Plant Commissioning
A
Validated Assembly, Integrated Design, Testing & Commissioning, SC magnets, VV fabrication validation
B
Integrated diagnostics validation, ECRH performance, Disruption characterisation, Divertor remote maintenance validation
C
H-mode transition threshold, Validation of ELM control & disruption mitigation, NB & ICRH performance, Diagnostics validation, Validation of TBM fabrication
D
Burn scenarios, Bootstrap fraction, Full plasma control incl. helium and impurities, First wall heat loads, Exhaust at high power Tritium plant validation, Full H&CD and fuelling validation
E
TBM Validation, Operational scenario refinement, Q=10 (short pulse)
F
Long pulse burning plasma
Credit: EUROfusion

APPENDIX B

System	System function	Potential Failure Mode	Potential Effects of the Failure Mode (Actions required to correct issue)	Severity (delay)	Potential Causes of the Failure Mode	Occurrence	S*O
Telescopic boom system	Move end-effector between transport cask and vacuum vessel	Telescopic boom gets stuck	1. Program reset, or movement correction required 2. Recovery operation required 3. Maintenance equipment replacement required	5	1. Telescopic boom hydraulic system or motor malfunctions 2. Telescopic boom lifting actuators malfunctions 3. Telescopic boom maintenance port wheels break 4. Telescopic boom base wheels break 5. User makes mistake	4	20
		Telescopic boom moves end-effector too fast	1. If no collision occurs: a. Movement correction required b. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	8	1. Movement controller malfunctions 2. User makes mistake	3	24

		Telescopic boom moves end-effector slower	1. Program reset, or movement correction required 2. Maintenance equipment replacement required 3. If also location information lost then extra location measurement required	2	1. Telescopic boom hydraulic system malfunctions 2. Movement controller malfunctions 3. Motor malfunctions or overheats 4. Telescopic boom lifting actuator malfunctions 5. Telescopic boom base or maintenance port wheels friction gets too high 6. User makes mistake 7. Movement controller malfunctions	4	8
		Telescopic boom moves end-effector to wrong direction	1. If no collision occurs: a. Movement correction required b. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	8	1. Telescopic boom hydraulic system malfunctions 2. Movement controller malfunctions 3. Motor malfunctions 4. Telescopic boom lifting actuator malfunctions 5. User makes mistake 6. Movement controller malfunctions	4	32
		Telescopic boom is unable to dock to maintenance port rails	1. Movement correction required 2. Extra location measurement required 3. Maintenance equipment repair or replacement required	4	1. Telescopic boom maintenance port wheel breaks 2. User makes mistake 3. Movement controller malfunctions 4. Location information gets lost	5	20

		Telescopic boom oscillates	1. Movement correction required 2. Extra location measurement required 3. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	7	1. User makes mistake 2. Movement controller malfunctions	4	28
	Support end-effector	End-effector gets loose from telescopic boom	Collision occurs almost certainly between cassette and surrounding parts 1. Recovery operation required 2. Cassette, maintenance equipment, vacuum vessel, maintenance port or another parts replacement required 3. Leakage mitigation for radioactive dust required, if transport cask seal breaks	8	1. End-effector attachment breaks	1	8
		Support lets end-effector move to wrong direction	1. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	7	1. Telescopic boom bends 2. Telescopic boom base breaks malfunction 3. Telescopic boom actuators malfunctions	3	21

End-effector system	Move cassette inside vacuum vessel	End-effector is not able to move cassette	1. Program reset, or movement correction required 2. Recovery operation required 3. Maintenance equipment replacement required	4	1. End-effector lifting actuator malfunctions 2. End-effector rotational joint gets stuck 3. Movement controller malfunctions 4. End-effector toroidal pushing actuator malfunctions 5. Hydraulic system breaks 6. User makes mistake	4	16
		Cassette moves to wrong direction	1. If no collision occurs: a. Movement correction required b. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	8	1. Movement controller malfunctions 2. User makes mistake 3. End-effector actuator hydraulic system breaks	4	32
		End-effector moves cassette slower	1. Program reset, or movement correction required 2. Maintenance equipment replacement required 3. Extra location measurement required, if also location information lost	2	1. User makes mistake 2. Movement controller malfunctions 3. End-effector hydraulic system malfunctions 4. End-effector rotational joints friction gets too high	4	8

		End-effector moves cassette too fast	1. If no collision occurs: a. Movement correction required b. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	8	1. Movement controller malfunctions 2. User makes mistake	3	24
	Support cassette	Cassette gets loose from end-effector	Collision occurs almost certainly between cassette and surrounding parts 1. Recovery operation required 2. Cassette, maintenance equipment, vacuum vessel, maintenance port or another part replacement required 3. Leakage mitigation for radioactive dust required, if transport cask seal breaks	10	1. Hook plate breaks 2. Hook plate attachment breaks 3. End-effector joints breaks	1	10
		End-effector lets cassette move to wrong direction	1. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	8	1. End-effector bends 2. Hydraulic actuator malfunctions 3. User makes mistake 4. Movement controller malfunctions	2	16

Rail system	Support telescopic boom system from transport cask	Rails does not fit with telescopic boom base wheels	1. Recovery operation required 2. Replacement of transport cask required	4	1. Rail attachment breaks 2. Rails bend	1	4
		Telescopic boom base falls down from the rails	1. Recovery operation required 2. Maintenance equipment, transport cask and/or cassette replacement required 3. Vacuum vessel and/or maintenance port repair required 4. Leakage mitigation for radioactive dust required, if transport cask seal breaks	10	1. Rail attachment breaks 2. Rails break	1	10
	Support telescopic boom system from maintenance port	Rails do not fit with telescopic boom maintenance port wheels	1. If no collision occurs: a. Recovery operation required b. Maintenance equipment replacement required 2. If collision occurs: a. Recovery operation required a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	5	1. Rail attachment breaks 2. Rails bend	1	5

		Telescopic boom falls down from the rails	1. Recovery operation required 2. Maintenance equipment, transport cask and/or cassette replacement required 3. Vacuum vessel and/or maintenance port repair required 4. Leakage mitigation for radioactive dust required, if transport cask seal breaks	10	1. Rail attachment breaks 2. Rails break	1	10
	Allow linear movement for telescopic boom base	Rails slow down telescopic boom base	1. Movement correction required 2. Rail or transport cask replacement required	2	1. Rails get dirty 2. Rails bend 3. Rails break	1	2
		Telescopic boom base gets stuck	1. Recovery operation required 2. Rail or transport cask replacement required	5	1. Rails get dirty 2. Rails bend 3. Rails break	1	5
	Allow linear movement for telescopic boom in maintenance port	Rails slow the telescopic boom down	1. Movement correction required 2. Rail replacement required	2	1. Rails get dirty 2. Rails bend 3. Rails break	1	2
		Telescopic boom gets stuck	1. Recovery operation required 2. Rail replacement required	5	1. Rails get dirty 2. Rails bend 3. Rails break	1	5

APPENDIX C

System	System function	Potential Failure Mode	Potential Effects of the Failure Mode (Actions required to correct the issue)	Severity (delay)	Potential Causes of the Failure Mode	Occurrence	S*O
Carriage system	To move mobile platform linearly	Carriage system gets stuck	1. Movement correction required 2. Program reset required 3. Recovery operation required 4. Carriage system replacement required	4	1. Robot malfunctions 2. Linear motion guides get stuck 3. Motor malfunctions 4. Rack and pinion system gets stuck	2	8
		Carriage system moves slower	1. Movement correction required 2. Program reset required 3. Carriage system replacement required 4. If also the location information is lost, then extra location measurement is required	3	1. Motor malfunctions 2. Linear motion guide friction gets too high 3. User makes a mistake 4. Controller system malfunctions	4	12
		Carriage system moves mobile platform in wrong direction	1. If no collision occurs: a. Movement correction required b. Carriage system replacement required c. Extra location measurement required 2. If collision occurs: a. Maintenance equipment and/or cassette replacement required b. Transport cask replacement and/or maintenance port repair required c. Recovery operation required	6	1. User makes a mistake 2. Robot malfunctions 3. Motor malfunctions 4. Mobile platform gets loose from clamp	4	24

		Clamp cannot attach/detach to the mobile platform	1. Program reset required 2. Movement correction required 3. Clamp/mobile platform replacement required	3	1. Clamp bends or breaks 2. User makes a mistake 3. Movement controller malfunctions	4	12
	Support mobile platform system	Carriage system allows mobile platform to move wrong direction	1. If no collision occurs: a. Movement correction required b. Maintenance equipment replacement may be required 2. If collision occurs: a. Maintenance equipment and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	6	1. Carriage structure bends 2. Robot malfunctions 3. Clamp bends 4. User makes a mistake	2	12
		Carriage system lets mobile platform loose	collision occurs almost certainly between cassette/mobile platform and surrounding parts 1. Recovery operation required 2. Replacement/repair of cassette, maintenance equipment, vacuum vessel, maintenance port or other parts required 3. Leakage mitigation for radioactive dust required, if transport cask seal breaks	9	1. Carriage structure breaks 2. Robot breaks 3. Mobile platform gets loose from clamp 4. Pinion or rack teeth breaks 5. Motor fails 6. Linear motion guides fail 7. User makes a mistake	1	9

Mobile platform system	Support cassette	Mobile platform system allows cassette to move to wrong direction	1. Mobile platform replacement required 2. If collision occurs: a. Maintenance equipment and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	6	1. Mobile platform structure bends 2. Lifting cylinder hydraulic system loses pressure 3. Lock frustum bends 4. Wheel unit dislocates 5. Clamp attachment bends 6. Scissor connector bends 7. User makes a mistake	1	6
		Mobile platform system lets cassette loose	collision occurs certainly between cassette and surrounding parts 1. Recovery operation required 2. Replacement/repair of cassette, maintenance equipment, vacuum vessel, maintenance port or other parts required 3. Leakage mitigation for radioactive dust required, if transport cask seal breaks	10	1. Mobile platform structure breaks 2. Lifting cylinders break 3. Most of the wheel units fail 4. Clamp attachment breaks	1	10
	Lift cassette	Lifting cylinder moves slower	1. Program reset, or movement correction required 2. Mobile platform replacement required 3. If also location information lost, then extra location measurement required	2	1. Lifting cylinder hydraulic system malfunctions 2. Lifting cylinder friction gets too high 3. User makes a mistake 4. Movement controller malfunctions	3	6
		Lifting cylinders are not able to lift the cassette	1. Program reset, or movement correction required 2. Mobile platform replacement required	4	1. User makes a mistake 2. Movement controller malfunctions 3. Lifting cylinder hydraulic system loses pressure 4. Lifting cylinder gets stuck	3	12

		Lifting cylinders lift unevenly	1. If no collision occurs: a. Movement correction required b. Mobile platform replacement required 2. If collision occurs: a. Maintenance equipment and/or cassette replacement required b. Vacuum vessel repair required c. Recovery operation required	5	1. User makes a mistake 2. Movement controller malfunctions 3. Hydraulic system pushes lifting cylinders unevenly 4. Some of the lifting cylinders gets stuck	3	15
	Allow carriage system to move mobile platform linear	Mobile platform gets stuck	1. Program reset, or movement correction required 2. Recovery operation required 3. Mobile platform replacement required	4	1. Movement controller malfunctions 2. Wheel unit gets stuck	2	8
		Mobile platform moves slower	1. Program reset, or movement correction required 2. Mobile platform replacement required 3. If also location information lost, then extra location measurement required	2	1. Movement controller malfunctions 2. Wheel unit friction gets too high	2	4
		Clamp cannot attach to the mobile platform	1. Mobile platform replacement required	3	1. Clamp attachment bends or breaks	3	9
	Execute rotation between linear and toroidal directions	Mobile platform rotates slower	1. Program reset, or movement correction required 2. Mobile platform replacement required 3. If also location information lost, then extra location measurement required	2	1. User makes a mistake 2. Movement controller malfunctions 3. Wheel unit friction gets too high	4	8

		Mobile platform cannot rotate	1. Program reset, or movement correction required 2. Recovery operation required 3. Mobile platform replacement required	4	1. User makes a mistake 2. Movement controller malfunctions 3. Wheel unit gets stuck	5	20
		Mobile platform rotates inaccurately	1. Program reset, or movement correction required 2. Mobile platform replacement required 3. If also location information lost, then extra location measurement required	2	1. User makes a mistake 2. Movement controller malfunctions	5	10
	Move cassette to toroidal direction	Mobile platform gets stuck	1. Program reset, or movement correction required 2. Recovery operation required 3. Mobile platform replacement required	5	1. User makes a mistake 2. Movement controller malfunctions 3. Wheel unit gets stuck 4. Scissors get stuck 5. Scissors attachment process fails	3	15
		Mobile platform moves to wrong direction	1. If no collision occurs: a. Movement correction required b. Mobile platform replacement required c. Extra location measurement required 2. If collision occurs: a. Maintenance equipment and/or cassette replacement required b. Vacuum vessel repair required c. Recovery operation required	5	1. User makes a mistake 2. Movement controller malfunctions	3	15
		Mobile platform moves slower	1. Movement correction required 2. Program reset required 3. Mobile platform replacement required 4. If also location information lost, then extra location measurement required	3	1. User makes a mistake 2. Movement controller malfunctions 3. Wheel unit friction gets too high 4. Scissors friction gets too high	3	9

Rail system	Allow linear and toroidal movement of the mobile platform	Mobile platform gets stuck	1. Recovery operation required 2. Rail or transport cask replacement required	4	1. Rails bend or break 2. Rail attachment breaks	1	4
		Mobile platform moves slower	1. Movement correction required 2. Rail replacement required	3	1. Rails bend or get dirty 2. Rail attachment bends	1	3
	Allow change between linear and toroidal directions	Rails rotate slower	1. Movement correction required 2. Rail replacement required	2	1. Rails bend or get dirty 2. Rail attachment bends	1	2
		Rails cannot rotate	1. Recovery operation required 2. Rail replacement required	4	1. Rails bend or break 2. Rail attachment breaks	2	8
	Support mobile platform system	Mobile platform moves to wrong direction	1. Rail replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	5	1. Rails bend or break 2. Rail attachment breaks	1	5
		Mobile platform drops down from the rails	1. Recovery operation required 2. Maintenance equipment, transport cask and/or cassette replacement required 3. Vacuum vessel and/or maintenance port repair required 4. Leakage mitigation for radioactive dust required, if transport cask seal breaks	9	1. Rails bend or break	1	9

Track system	Support rails	Rails detach from track system	1. Recovery operation required 2. Maintenance equipment, transport cask and/or cassette replacement required 3. Vacuum vessel and/or maintenance port repair required 4. Leakage mitigation for radioactive dust required, if transport cask seal breaks	9	1. Track structure breaks 2. Rail attachment breaks 3. Wheel unit breaks	1	9
		Track system lets rails bend	1. Track replacement required 2. Recovery operation required	4	1. Track structure bends	1	4
	Allow rotation between linear and toroidal directions	Rotation movement executes slower	1. Movement correction required 2. Track replacement required	2	1. Wheel unit friction gets too high 2. Wheel unit breaks 3. Track structure bends	2	4
		Rotation movement gets stuck	1. Recovery operation required 2. Track replacement required	4	1. Wheel unit breaks 2. Track structure bends	2	8
	Allow clamp to move track	Clamp cannot attach to the track	1. Track replacement required	2	1. Clamp attachment bends or breaks	1	2
	Allow scissors to attach/detach	Scissors cannot attach/detach to/from the track	1. Track replacement required	2	1. Scissor attachment bends or breaks	2	4

APPENDIX D

System	System function	Potential Failure Mode	Potential Effects of the Failure Mode (Actions required to correct issue)	Severity (delay)	Potential Causes of the Failure Mode	Occurrence	S*O
Carriage System	Support cassette	Carriage allows cassette to move to wrong direction	1. If no collision occurs a. Carriage system replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	6	1. Carriage platform structure bends 2. Cassette support structure bends 3. Carriage wheels bend 4. Rotational hinge bends	1	6
		Carriage lets cassette fall	Collision occurs almost certainly between cassette and surrounding parts 1. Recovery operation required 2. Cassette, maintenance equipment, vacuum vessel, maintenance port or another part replacement required 3. Leakage mitigation for radioactive dust required, if transport cask seal breaks	10	1. Carriage platform structure breaks 2. Cassette support structure breaks 3. Carriage wheels break 4. Rotational hinge breaks 5. Carriage services area lets steel wire loose	1	10
	Allow winch system to move carriage linearly	Winch system cannot attach to the carriage	1. Carriage system replacement required 2. Movement correction required 3. Program reset required	3	1. Carriage services area attachment for steel wire breaks 2. Carriage services area breaks	2	6

			4. Extra location measurement required				
		Carriage moves slower	1. Program reset, or movement correction required 2. Carriage system replacement required 3. If also location information lost then extra location measurement required	2	1. Carriage wheel friction gets too high	2	4
		Carriage gets stuck	1. Maintenance equipment replacement required 2. Movement correction required 3. Recovery operation required	4	1. Carriage wheel gets stuck	2	8
	Allow cassette tilting	Tilting actuator cannot tilt cassette	1. Carriage system replacement required 2. Movement correction required 3. Recovery operation required	4	1. Rotational hinge gets stuck 2. Tilting actuator attachments gets stuck	2	8
		Cassette tilting movement gets slower	1. Program reset, or movement correction required 2. Carriage system replacement required 3. If also location information lost then extra location measurement required	2	1. Rotational hinge friction gets too high	2	4

Carriage actuator system	Tilt Cassette support	Cassette tilts too much	1. If no collision occurs: a. Movement correction required b. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment replacement and/or cassette required b. Vacuum vessel repair required c. Recovery operation required	5	1. Tilting actuator limiter malfunctions 2. Hydraulic system malfunctions 3. User makes mistake	4	20
		Tilting actuator cannot tilt cassette	1. Maintenance equipment replacement required 2. Movement correction required 3. Recovery operation required	4	1. Actuator hydraulic system malfunctions 2. Tilting actuator gets stuck 3. Carriage actuator joints gets stuck 4. User makes mistake 5. Movement controller malfunctions	4	16
		Cassette tilting movement gets slower	1. Program reset, or movement correction required 2. Carriage system replacement required 3. If also location information lost then extra location measurement required	2	1. Actuator hydraulic system malfunctions 2. Tilting actuator friction gets too high 3. Carriage actuator joint friction gets too high 4. User makes mistake 5. Movement controller malfunctions	4	8

		Cassette tilts to wrong direction	1. If no collision occurs: a. Movement correction required b. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment replacement and/or cassette required b. Vacuum vessel repair required c. Recovery operation required	5	1. User makes mistake 2. Hydraulic system pressure too low 3. Movement controller malfunctions 4. Tilting actuator malfunctions	4	20
	Push/pull cassette toroidally	Cassette gets stuck	1. Maintenance equipment replacement required 2. Movement correction required 3. Recovery operation required	4	1. Actuator hydraulic system malfunctions 2. Toroidal pushing actuator gets stuck 3. Carriage actuator joints gets stuck 4. User makes mistake 5. Movement controller malfunctions	4	16
		Cassette moves slower	1. Program reset, or movement correction required 2. Carriage system replacement required 3. If also location information lost then extra location measurement required	2	1. Actuator hydraulic system malfunctions 2. Toroidal pushing actuator friction gets too high 3. Carriage actuator joint friction gets too high 4. User makes mistake 5. Movement controller malfunctions	4	8

		Cassette moves wrong direction	1. Movement correction required 2. Maintenance equipment replacement required	1	1. User makes mistake 2. Movement controller malfunctions 3. Toroidal pushing actuator malfunctions 4. Actuator hydraulic system malfunctions	4	4
Winch system	Move carriage linearly	Winch system gets stuck	1. Winch system replacement required 2. Movement correction required 3. Recovery operation required	3	1. Winch gets stuck 2. Pulley gets stuck 3. Winch motor malfunctions 4. Movement controller malfunctions 5. User makes mistake	4	12
		Winch system moves carriage slower	1. Program reset, or movement correction required 2. Carriage system replacement required 3. If also location information lost then extra location measurement required	2	1. Too much friction in winch 2. Too much friction in pulley 3. Winch motor malfunctions 4. Movement controller malfunctions 5. User makes mistake	4	8
		Winch system moves carriage too fast	1. If no collision occurs: a. Movement correction required b. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment replacement and/or cassette required b. Vacuum vessel repair required c. Recovery operation required	5	1. Winch motor malfunctions 2. Movement controller malfunctions 3. User makes mistake	3	15

		Winch system moves carriage wrong direction	1. If no collision occurs: a. Movement correction required b. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment replacement and/or cassette required b. Vacuum vessel repair required c. Recovery operation required	7	1. Steel wire breaks 1. Winch motor malfunctions 2. Movement controller malfunctions 3. User makes mistake	3	21
	Support carriage	Carriage moves to wrong direction	1. Maintenance equipment replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	6	1. Steel wire stretches 2. Winch malfunctions 3. Winch motor malfunctions	2	12
		Carriage gets loose	Collision occurs almost certainly between cassette and surrounding parts 1. Recovery operation required 2. Cassette, maintenance equipment, vacuum vessel, maintenance port or another part replacement required 3. Leakage mitigation for radioactive dust required, if transport cask seal breaks	9	1. Steel wire breaks 2. Winch breaks 3. Winch motor breaks 4. Pulley breaks	1	9

Rail system	Support carriage and cassette	Cassette drops down from the rails	1. Recovery operation required 2. Maintenance equipment, transport cask and/or cassette replacement required 3. Vacuum vessel and/or maintenance port repair required 4. Leakage mitigation for radioactive dust required, if transport cask seal breaks	9	1. Sliding support or toroidal rail breaks 2. Lower port rail breaks 3. Dummy rail breaks 4. Dummy rail detaches	1	9
		Cassette moves to wrong direction	1. Rail replacement required 2. If collision occurs: a. Maintenance equipment, transport cask and/or cassette replacement required b. Vacuum vessel and/or maintenance port repair required c. Recovery operation required	6	1. Sliding support or toroidal rail bends 2. Lower port rail bends 3. Dummy rail bends	1	6
	Allow toroidal movement of the cassette	Cassette gets stuck to rails	1. Recovery operation required 2. Rail or transport cask replacement required	4	1. Sliding support or toroidal rail move, bends or breaks 3. Dummy rail moves, bends or breaks	1	4
		Cassette moves slower	1. Movement correction required 2. Rail replacement required	3	1. Sliding support or toroidal rail bends or gets dirty	1	3
	Allow linear movement of the carriage	Carriage moves slower	1. Movement correction required 2. Rail replacement required	2	1. Lower port rail bends or gets dirty	1	2

		Carriage gets stuck	1. Recovery operation required 2. Rail or transport cask replacement required	4	1. Lower port rail moves, bends or breaks	1	4