Status of Materials Handbook for Target and Target-Interfacing Systems at European Spallation Source

Yongjoong Lee

Target Division, European Spallation Source ERIC, Odarslösvägen 113, 224 84 Lund, Sweden

E-mail: yongjoong.lee@esss.se

(Received May 14, 2019)

For a systematic management of the materials data to support the design of the components in target environment at European Spallation Source (ESS), a Materials Handbook has been under active development since 2015. The ESS Materials Handbook mainly consists of three parts on Top Level Materials Selection Criteria, Materials Scope and Components Lifetimes, and Materials Properties Database. This paper reports the development status of the ESS Materials Handbook, which is presently under work for Revision 6.

KEYWORDS: European Spallation Source, Materials Handbook, Target

1. Introduction

The European Spallation Source (ESS) is currently under construction in Lund in southern Sweden, with an ambition to become the brightest neutron source for materials research, upon its completion in mid-2020s. The linac system will deliver 2 GeV protons to the rotating tungsten target, at an unprecedented beam power of 5 MW. In steady operation, 5,400 hours of beam time per year on the target is planned. At 5 MW beam power and 2.5 mA time averaged beam current, the accumulated beam energy and beam current will reach 27 GWh and 13.5 Ah per year, respectively. The intensive primary protons, secondary neutrons from meV to GeV energy range and decay gammas induce thermo-mechanical loads and radiation damages in the materials in target environment, limiting the functionality, reliability and lifetime of the systems exposed to particle radiations.

With the progress of the construction of the European Spallation Source (ESS), a need to systematically manage the materials information has risen, to support the design of the components that are exposed to radiation fields in target environment. To serve this purpose, the ESS Materials Handbook has been under active development since 2015. With time, the scope of the Handbook evolved beyond that of the target. As a result, the most recently released Revision 5 of the Handbook provides materials information and guidelines to the ongoing projects for the target-interfacing systems as well, which include the systems in proton beam drift room and neutron beam extraction area.

The objective of the Handbook is threefold. Firstly, it compiles the data on radiation induced damages in the materials that are to be applied in target environment. The compiled data are used to set guides for materials selection and dose-limited lifetime determination for the systems exposed to intense proton, neutron, and gamma radiation fields created by particle-matter interactions. The Handbook also records the decisions on materials selections. The selected material for each component is compiled in the Handbook, together with the reasonings and justifications behind the decision. Secondly, it provides reference materials data for finite element and finite volume simulations. This enables consistency in obtained numerical data from computational simulations for systems design, as all the simulations performed are to be based on a single set of physical, mechanical, and thermal materials data. Thirdly, the Handbook provides reference elemental composition of materials
for shielding, activation and nuclear inventory calculations. This particularly ensures a credibility of radiation safety analyses.

The ESS Materials Handbook has been evolved on the basis of requirements provided by the designers of target and target-interfacing systems. Required materials data are compiled from a broad range of knowledge sources, which include published articles, existing handbooks such as AFCI Materials Handbook [1], ITER Material Properties Handbook [2] and ASM Handbook [3], technical reports, design rules such as RCC-MRx [4], and advices of leading experts from other accelerator and target facilities. For critical materials in target environment with scarce literature sources, dedicated research program has been set up and the obtained materials data are compiled in the Handbook. Extensive studies of project critical materials have been conducted in collaboration with other leading institutions, which include tungsten as spallation material [5–11], liquid hydrogen as moderator material [12], beryllium as reflector material, and greases as lubricating material [13, 14]. This paper presents an overview of the ESS Materials Handbook and its development status as of May 2019.

2. Contents of the ESS Materials Handbook

The ESS Materials Handbook consists of three parts on Top Level Materials Selection Criteria, Materials Scope and Components Lifetimes, and Materials Properties Database.

2.1 Top Level Materials Selection Criteria

Different severity levels of radiation damage determines the design specifications and service lifetime of each component. In this part of the Handbook, the severity levels of radiation damage are categorised into three classes, depending on its impacts on design and component lifetime. The three radiation damage classes are presented in Table I.

| Damage class   | Description                                                                 |
|----------------|-----------------------------------------------------------------------------|
| Negligible     | The level of radiation damage is so low that it does not affect the design of the component. |
| Non-negligible | The radiation damage should be taken into account in design, but the component has a lifetime of the facility. |
| Significant    | The radiation damage should be taken into account in design, and the component has a limited lifetime shorter than facility lifetime, requiring periodic replacement. |

The components in target environment are exposed to different radiation damage sources. The radiation damage types which are identified to be relevant in determining lifetimes of the components are listed in Table II. For each radiation type, the radiation damage class following Table I is defined in this part of the Handbook.

As the cobalt impurity level affects the residual activation of the components after being in the radiation field, the requirement on the cobalt impurity level must be defined before the procurement of the material. This part of the Handbook also sets the guideline in selecting the cobalt impurity level of the materials applied in target environment. The required cobalt impurity limit depends on the need of water cooling of the nuclear heat deposition, the need of remote handling during facility lifetime and the radiation damage class. For the classification of the cobalt impurity, the convention of RCC-MRx [4] is adopted.
Table II. Different radiation damage types identified to be relevant in determining lifetimes of the components in target environment.

| Damage type               | Description                                                                 | Materials affected |
|---------------------------|-----------------------------------------------------------------------------|--------------------|
| Neutron damage            | Material properties degradation correlated with displacement damage caused by neutrons | Stainless steel, tungsten, Al-alloys, Cu-alloys, invar |
| Proton damage             | Material properties degradation correlated with displacement damage caused by protons | Stainless steel, tungsten, Al-alloys, Cu-alloys |
| Thermal neutron capture   | Material properties degradation correlated with thermal neutron capture        | Al-alloys, tungsten |
| Fast neutron fluence      | Material functionality degradation correlated with fast neutron fluence        | Neodymium magnet, image sensors, concrete |
| He-embrittlement/swelling | Material embrittlement and swelling due to hadron irradiation induced helium production | Stainless steel, beryllium, aluminium alloys |
| Radiation dose            | Change in material properties correlated with radiation dose                  | Polymers, concrete, oils, lubricants, paintings |

2.2 Materials Scope and Components Lifetimes

This part of the Handbook compiles the selected materials for the components in target environment. This serves as a materials selection baseline for the target project. The reasonings and justifications of the decisions made on the materials selections are described. In case a system is subject to a non-negligible or a significant radiation damage, the service lifetime is defined based on the characteristics of radiation induced degradation of the material of which the system is made. The materials selection baseline could change with the progress of the project, as more materials knowledge and market information are becoming available. The revision of this part of the Handbook continues until the related system design passes the critical design review after which the design is frozen.

Table III summarises the materials scope and radiation damage limited lifetimes of critical structural components in target environment at ESS, as of May 2019.

Table III. Materials scope and radiation damage limited lifetimes of critical structural components in target environment.

| Component            | Material       | Lifetime criteria | Lifetime limit | Lifetime at 5 MW |
|----------------------|----------------|-------------------|----------------|-------------------|
| Target vessel        | SS 316L        | Proton-DPA        | 8.0 DPA        | 5 Years           |
| Target drive rotor   | Neodymium      | Neutron fluence   | 1.0-10^13 p>0.1 MeV cm^-2 | 5 Years |
| Moderator vessel     | Al 6061-T651   | Neutron fluence   | 1.8-10^22 p<0.625 eV cm^-2 | 1 Year |
| Proton beam window   | Al 6061-T651   | Proton fluence    | 5.0-10^22 p cm^-2 | 0.5 Year |
| Monolith vessel      | SS 316L        | Neutron-DPA       | 2.75 DPA       | 40 Years          |

2.3 Materials Properties Database

This part of the Handbook compiles material properties data for numerical simulations and hazard analyses. The numerical analyses covers the finite element and finite volume simulations of coupled flow, thermal, mechanical, and electrical problems for systems design, and particle transport Monte-Carlo (MC) simulations for heat deposition, shielding, activation and nuclear inventory calculations. This enables consistency in obtained numerical data from computational simulations for systems design and hazard analyses for facility licensing.
2.3.1 Material Properties Database: Solids

The materials properties data of solids for beam stopping, structural pressure confinement, shielding, leak-tight sealing, magnetic, and neutron reflections applications are compiled. Provided are thermal, physical and chemical properties of the materials used in target environment. In particular, the reference chemical elemental data are presented to serve for particle transport MC analyses. As containment of minute impurity of certain isotopes such as cobalt could largely affect the activation level of the irradiated component, care has been taken to include small fraction of impurities in the elemental data compiled. The data of irradiated materials are compiled as well, which are used to set application area and component lifetime criteria. In this part of the Handbook, materials informations listed in Table IV are presented.

Table IV. Materials data compiled in the part ”Material Properties Database: Solids.”

| Material                        | Functional Applications | Available Materials Data |
|---------------------------------|-------------------------|--------------------------|
| Tungsten                        | Beam Stopping           | Y                        |
| Carbon Steel EN-1.0345/1.0425/1.0481 | Shielding/Structural    | Y                        |
| Structural Steel EN-1.0025      | Shielding/Structural    | Y                        |
| Grey Cast Iron                  | Shielding               | Y                        |
| Austenitic Steel EN-1.4306/1.4307 | Structural/Shielding    | Y                        |
| Austenitic Steel EN-1.4404/1.4432/1.4435 | Structural/Shielding | Y                        |
| Austenitic Steel EN-1.4429     | Structural              | Y                        |
| Martensitic Steel EN-1.4903    | Structural              | Y                        |
| Alloy 718                       | Structural              | –                        |
| Aluminium Alloy 6061-T6        | Structural              | Y                        |
| Beryllium                       | Neutron Reflection      | Y                        |
| Invar                           | Cryogenic               | Y                        |
| Copper                          | Beam Stopping           | Y                        |
| Copper-Chromium-Zirconium       | Beam Stopping           | Y                        |
| Graphite                        | Beam Stopping           | Y                        |
| Elastomers                      | Sealing                 | –                        |
| Neodymium Magnet                | Magnetic                | –                        |
| SmCo Magnet                     | Magnetic                | –                        |

2.3.2 Material Properties Database: Fluids

The materials properties data of fluids for computational fluid dynamics (CFD) calculations are compiled. Specifically, the flow properties of helium, water and hydrogen in liquid and gas phases are compiled. As a functional fluid, the properties of ferrofluid are compiled as well, which is used as a sealant of helium coolant of the rotating spallation target. Since it is exposed to the neutron streaming through the gaps in the target shaft, the radiation induced changes of viscosity and magnetism are of particular concern.

2.3.3 Material Properties Database: Building Materials

The properties of clay, stones, and concrete that are used for the civil construction of ESS are compiled in this part of the Handbook. The data sets a reference for the shielding and activation calculations for ensuring the radiation safety of the facility. The mechanical data compiled serves for the structural analyses of the building structure.
2.3.4 Material Properties Database: Electronic Component

Currently, the radiation damage behaviours of CMOS and CCD image sensors are compiled. The radiation dose based lifetime limits of different electronic components in target environments will be added with the progress of the project.

3. Conclusion

The ESS Materials Handbook has been under active development since 2015, providing materials information and guidelines to the ongoing projects for target and target-interfacing systems. As of May 2019, it is presently under work for Revision 6. After each sub-project passes the Critical Design Review (CDR), dedicated editing efforts will be given to this document. Each section will then go through a rigorous review process towards the final release. With the final release, the Handbook will serve as a project completion report of the Target Materials subproject and the document will be shared with spallation community. The final release of the ESS Materials Handbook is planned in December 2020.

References

[1] P. L. Rittenhouse and S. A. Maloy and M. W. Cappiello, AFCI Materials Handbook: Materials Data for Particle Accelerator Applications, Los Alamos National Laboratory, LA-CP-06-0904 – Revision 5 (2006)
[2] ITER EDA, ITER Material Properties Handbook, ITER, ITER Document No. S 74 MA 2 (1998)
[3] ASM Handbook, ASM International, ISBN: 978-1-62708-026-2
[4] RCC-MRx: DESIGN AND CONSTRUCTION RULES FOR MECHANICAL COMPONENTS OF NUCLEAR INSTALLATIONS, 2012 Edition, ISBN 2-913638-40-6, AFCEN (2012).
[5] J. Habainy, Y. Lee, K. B. Surreddi, A. Prosvetov, P. Simon, S. Iyengar, Y. Dai and M. Tomut, A study of heavy ion beam induced damage in tungsten for high power target applications, Nucl. Instr. Meth. Phys. Res. B, Vol. 439, pp. 7–16 (2019).
[6] J. Habainy, Y. Dai, Y. Lee and S. Iyengar, Mechanical properties of tungsten irradiated with high energy protons and spallation neutrons, J. Nucl. Mater., Vol. 514, pp. 189–195 (2019).
[7] J. Habainy, Y. Dai, Y. Lee and S. Iyengar, Thermal diffusivity of tungsten irradiated with protons up to 5.8 dpa, J. Nucl. Mater., Vol. 509, pp. 152–157 (2018).
[8] J. Habainy, S. Iyengar, K. B. Surreddi, Y. Lee and Y. Dai, Formation of oxide layers on tungsten at low oxygen partial pressures, J. Nucl. Mater., Vol. 506, pp. 26–34 (2018).
[9] J. Habainy, A. Lövberg, S. Iyengar, Y. Lee and Y. Dai, Fatigue properties of tungsten from two different processing routes, J. Nucl. Mater., Vol. 506, pp. 83–91 (2018).
[10] J. Habainy, S. Iyengar, Y. Lee and Y. Dai, Fatigue behaviour of rolled and forged tungsten at 25°, 280° and 480 °C, J. Nucl. Mater., Vol. 465, pp. 438–447 (2015).
[11] T. Shen, Y. Dai and Y. Lee, Microstructure and tensile properties of tungsten at elevated temperatures, J. Nucl. Mater., Vol. 468, pp. 348–354 (2015).
[12] M. Hartl, R. C. Gillis, L. Daemen, D. P. Olds, K. Page, S. Carlson, Y. Cheng, T. Hügle, E. B. Iverson, A. J. Ramirez-Cuesta, Y. Lee and G. Muhrer, Hydrogen adsorption on two catalysts for the ortho- to parahydrogen conversion: Cr-doped silica and ferric oxide gel, Phys. Chem. Chem. Phys., Vol. 18 (26), pp. 17281–17293 (2017).
[13] M. Ferrari, A. Zenoni, M. Hartl, Y. Lee, A. Andrighetto, A. Monetti, A. Salvini and F. Zelaschi, Experimental study of consistency degradation of different greases in mixed neutron and gamma radiation, Heliyon, submitted (2019).
[14] M. Ferrari et. al., An Irradiation Campaign of Lubricants at TRIGA Mark II Nuclear Reactor for the European Spallation Source (ESS) and the Selective Production of Exotic Species (SPES) facilities, Proc. of 26th Nuclear Energy for New Europe - NENE 2017 (2017).