Rare Earth Permanent Magnet Value Chain

Lifelong Learning Course

The course development is supported by EIT Raw Materials. Project No 21104**,** **ExpSkills-REM**, Expanding Knowledge and Skills in Rare Earth Permanent Magnets Value Chain.

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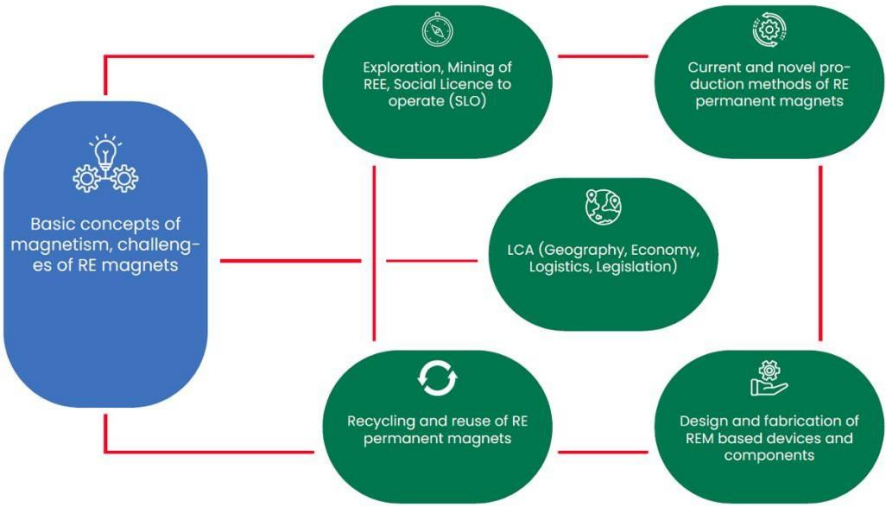
Course structure: The course has a modular structure. Each Module represents a critical link in **REE magnets value chain**: **M1** Exploration and Mining; **M2** Magnet production; **M3** Magnet-based devices; **M4** REE Magnet recycling; **M5** Life Cycle Assessement. **M0** Basic Concepts of magnetism is included in the content of other modules.



Educators' team: Our expert team possess knowledge and experience that enable us to provide training on important aspects of the critical links in the Rare Earth permanent magnet value chain. We are researchers, engineers, teachers and business partners from Spain, Greece and Sweden. The activity is coordinated by KTH Royal Institute of Technology.

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Rare Earth Permanent Magnet Value Chain: General Description

Customer design: The customer can choose its own course design, depending on the company profile. Thus, for ***mining companies*** M1, M4 and M5, are strongly recommended, while M2 and M3 could be optional. For ***companies producing electrical motors and vehicles***, M2, M3 and M4 are very useful. For ***companies producing magnets***, the knowledge obtained from all 5 Modules could be of help.

Teaching format: On-site and On-line

Timeline and plan of the day: The course is designed for 5 days of training and has a modular structure. The content of one Module is designed for about 6-8 hours of teaching and learning activities, (1 working day) including breaks for coffee and lunch.

One lecture duration is 45 minutes, followed by a 15-minute break. There are also two 30-minute coffee breaks, and one hour lunch breaks. Theoretical material, lectures, are mainly given during the first half of the day. Practical activities start mainly after lunch. By agreement, a guided tour to the plant's facilities can be included. At the end of the day, wrap-ups, tests and conclusions will be given.

Certificates will be issued based on Modules attended and test results.

Website: *https://expskills-rem.eu/*

Contacts: For more information, please, contact us: Dr. Inna Soroka (*soroka@kth.se).* Prof. Dr. Pavel Korzhavy: (*pavelk@kth.se)*

Module 0: Basic concepts of magnetism. Challenges of Rare Earth magnets

Origin of magnetism.
Magnetic moments of atoms and their units. Electronic structure of atoms.

The Periodic Table: *3d* and *4f* elements
Types of magnetic materials: Behaviour of materials in magnetic field. Paramagnets, diamagnets, ferromagnets.
Hysteresis loops: How to characterize magnetic materials. Saturation, remanence magnetisation, energy product (BH_{max}). Units.
Magnetic anisotropy: Shape and magneto-crystalline
Permanent magnets. Characteristics of REE permanent magnets

Module 0 consists of 2 × 45 min lectures and is given at the beginning of the course.

In addition, 6 weeks digital course "Basic concepts of magnetism. Challenges of Rare Earth magnets" available for the user at the FutureLearn platform:
https://www.futurelearn.com/courses/introduction-to-magnetism-the-challenges-of-rare-earth-magnets?utm_campaign=eitr_bau&utm_medium=referral&utm_source=eitr

Module 1: Rare-Earth Elements containing ores in Mining

REE Exploration

The main aspects of REE ores exploration are introduced, along with cases of study from both inside and outside the EU

- Basic concepts in REE mineral resources
- Exploration and prospecting techniques
- Mineral characterization of REE samples
- Mineral deposit models – cases of study

Rare Earth Element Mining (Part I)

A review of mining and metallurgical aspects of REE ores is presented, with a special focus on the best available technologies (BAT).

- Economic aspects in REE Mining
- Underground mining techniques
- Open pit mining techniques

Rare Earth Element Mining (Part II)

- Mineral Processing Techniques
- Extractive Metallurgy Techniques

Safety and Environmental Aspects of REE Mining

Quick review of S&E issues in REE ores mining and metallurgy, dealing specifically with the content presented during the morning sessions.

Social Licence to Operate in mining of Rare Earth elements

A practical activity focused on the SLO issues found in REE mining projects at the EU, including a self-critical-analysis exercise.

- The social paradox of REE mining activities
- Case of study: Matamulas Project

Socio-technical toolbox

A practical and ludic activity designed to suggest responsible actions with the aim to change how mining projects are approached, including socio-technical aspects.

Module 2: Current and Novel production methods of Rare-Earths Permanent Magnets (REPM)

Advanced REPM production techniques. (Part I)

This activity will cover novel fabrication techniques, mainly focused on metal injection molding (MIM) and additive manufacturing technologies. These fabrication technologies allow for the production of magnets with complex shapes and minimal waste of material.

- Metal Injection Molding (MIM)

Advanced REPM production techniques (Part II)

- Advanced manufacturing of permanent magnets (3D and 4D printing)
- Summary and open discussion

Fully dense REPM production techniques (Part I)

Main aspects of the production chain and characteristics of fully dense magnets obtained through sintering routes. These types of magnets can achieve the highest maximum energy product and they are used in high-performance applications such as EVs motors and wind turbine generators, among others.

- Production of sintered Nd-Fe-B magnets

Fully dense REPM production techniques (Part II)

- Production of sintered Nd-Fe-B magnets
- Production of hot-formed Nd-Fe-B magnets

Fully dense REPM production techniques (Part III)

- Production of Sm-Co magnets: Sintering
- Summary and open discussion

Permanent magnets coating: Corrosion protection of Rare Earth magnets

Bonded REPM production techniques (L: AM-C)

Here, we will show the production line and characteristics of bonded magnets. These types of magnets possess a lower energy product than fully dense magnets. On the other hand, they show other advantages such as good mechanical properties and higher electrical resistivity.

- Compression bonded magnets
- Injection molded magnets
- Flexible magnets: extrusion and calendaring
- Bonded Sm-Fe-N magnets
- Summary and open discussion

Module 3: Design and fabrication of magnet-based devices and components

Introduction of electrical machines

- Key components and magnetic material property
- Application of electrical machines
- Types of electrical machines
- Working principle of a DC machine

Fundamental theory for electrical machines

- Electromagnetism (Maxwell equations)
- Electromagnetic model of electrical machines
- Typical magnetic materials for electrical machines

Analysis of permanent magnet -based machine performance

- Modelling of permanent magnet-based machines
- Influence of defects in magnets on the electrical machine performance
- Flux weakening
- Different topology of permanent magnet-based machines

Demonstration (videos) of the process of manufacturing magnets and assembling permanent magnet-based machines

The videos include:

- Production of permanent magnets (PM)
- Production of stators and rotors from iron
- Winding techniques and assembly of electrical machines

Finite Element Method (FEM) for modelling of permanent magnet-based machine

- Demonstration of PM-based motor assembly using FEM software
- Demonstration of how the choice of magnetic materials influence the performance of permanent magnet-based machines.

- Optimization of permanent magnet-based machines performance considering materials properties.

Analysis of demagnetization problems in permanent magnet-based machines

- Demonstration of the demagnetization problem using FEM
- Effect of demagnetization on the performance of permanent magnet-based machines
- Discussion on the choice of permanent magnet for electrical machines

Module 4: Rare-Earth Permanent Magnets Recycling and REE extraction technologies

Introduction to Rare Earth permanent magnets (Part I)

- Rare-earth Elements, REEs: An introduction to REEs, their properties and how they are produced.
- Why are REEs defined as Critical Raw Materials? We analyze the importance of REEs and the problems around their supply from primary sources.

Introduction to Rare Earth permanent magnets (Part II)

Main applications of REEs: In this chapter we dive into the many applications of REEs in modern society.

- Permanent Magnets: Discussion of the types and properties of permanent magnets.
- Why are permanent magnets important: An economic analysis of the market share of permanent magnets in various fields of their applications.

Recycling of REE's from permanent magnets (Part I)

Why is recycling important: An economic and technical analysis of the sustainability of permanent magnet recycling.

- State-of-the-art of the REE Recovery Methods: This is an introduction to the methods used to date for the recycling of permanent magnets.
- Pyrometallurgy: Here we explain pyrometallurgical methods used to recycle REEs from permanent magnets.

Recycling of REE's from permanent magnets (Part II)

Hydrometallurgy: In this chapter we elucidate hydrometallurgical methods used to recycle REEs from permanent magnets.

- Challenges: In this chapter we analyze the problems associated with the recycling of permanent magnets.

Pre-processing methods for REEs recovery from permanent magnets (AM onsite)

- Challenges in the pre-processing of REEs permanent magnets: Here we explain the difficulties in the preparation of permanent magnets for the recycling process.
- Hydrogen treatment of permanent magnets: Method of preprocessing of magnet scrap with hydrogen.
- Demagnetization of permanent magnets: Methods of achieving zero magnetization in permanent magnets.
- Milling process: This chapter analyzes the grinding processes that are used for reduction of the particle size of permanent magnets.

Metallurgy Techniques for extraction of REEs from ores and tailings

- Pyro-metallurgy
- Hydro-metallurgy
- Electro-metallurgy

Hydrometallurgical recovery of REEs from permanent magnets based on MONOLITHOS' recycling method

MONOLITHOS hydrometallurgical Recycling of REEs from permanent magnets: In this chapter we describe the state-of-the-art method developed by MONOLITHOS to recover REEs from permanent magnets.

- Potential benefits for Environment: A discussion of how the MONOLITHOS method provides a greener alternative to existing recovery processes.
- Future Perspectives: Here we describe the various ways in which MONOLITHOS will attempt to improve and upscale its REE recycling technology.

Module 5: Life-Cycle Assessment (LCA) of Magnets and environmental impact

Introduction to LCA

The key aspects related to LCA will be introduced, together with research cases from both inside and outside the EU.

- General aspects of the LCA approach
- What is Life-Cycle Assessment (LCA)?
- LCA Stages & phases
- Using LCA to meet Sustainability Goals

Types and Benefits of LCA

A review of the types, benefits, challenges and limitations that LCA professionals face in integrating it into sustainable decision-making, and practices for addressing them. Special attention will be paid on the benefits of LCA.

- Types of LCA
- Benefits of LCA
- Support Product Design & Marketing
- Challenges and Considerations

Sustainable Magnets Recycling: Insights from LCA Case Studies

In this activity, Case studies showcasing how LCA can be applied to ensure sustainable decision-making in the context of magnet recycling, will be presented.

- Case Study 1: "LCA of Neodymium Magnets: Virgin Production vs. Magnet-to-Magnet Recycling".
- Case Study 1: "LCA of REE Recovery and Recycling for Permanent Magnets: A Comparative Analysis of Three Processes".
- Benefits of permanent magnet Recycling

Life Cycle Assessment of Magnets and Environmental Impacts

The Life Cycle Assessment of Magnets and Environmental impacts will be presented in this activity.

- Environmental Improvement Strategies
- Environment, Health and Safety (EHS) Assessment
- REEs as key CRMs for the future of renewable energy and smart mobility in the EU
- Future Trends and Innovations