INTRODUCTION
The transition toward resource efficient, low-carbon closed-loop economies is an urgent necessity as our world is facing unstable but rising fossil energy prices, resource shortages, and unprecedented environmental challenges. In the E.U. in particular the prospect of insufficient and often critical raw materials (metals and minerals) will hamper further economic development. For example, the attempts to increase the share of wind energy, solar power, and electric transportation will face a shortage of critical metals for the production of batteries, PV-panels, and strong magnets. New technologies are required to better separate metals and minerals from leaner ores and secondary materials.

The advanced treatment of secondary raw materials is part of Belgium’s strength in recycling and contributes to the vision of closed loop processes. Companies and policymakers are starting to incite universities and research institutes to increase their efforts in this field as they recognize the urgency of the transition to Sustainable Materials Management (SMM). Katholieke Universiteit Leuven (K.U.Leuven) and its researchers are acting to take the lead in this development and to create the scientific insights to support technological innovations for the transition to SMM. This article will discuss the sustainable inorganic materials management program at K.U.Leuven and its relationship with the Center for Materials Resource Recovery and Recycling (CR³).

INTERDISCIPLINARY COLLABORATION INITIATIVES
K.U.Leuven research groups have been investigating the recovery and recycling of inorganic materials, more specifically metals and minerals, for some time now. Recently there have been several successful developments that have increased the focus on inorganic resource recovery and recycling, both by a more structural collaboration between the different research groups already working in this domain and by the additional interaction with research groups previously less active in the domain. These developments have propelled Sustainable Inorganic Materials Management (SIM²) to a flagship topic for the involved research groups (Metallurgy, Geology, Chemical Engineering, Building Materials, Chemistry, Economics, Process Psychology, Law, etc.) and for the K.U.Leuven as a whole. The philosophy of the SIM²@K.U.Leuven Consortium has been to work on various types of projects, ranging from fundamental science to precompetitive projects to fully competitive, industry-driven projects. The various K.U.Leuven Consortia—under the umbrella of the K.U.Leuven Materials Research Centre—have developed a diversified research portfolio with a total budget of more than 11.5 M€ ($15.84 million). The research approach operates in two directions: fundamental science and precompetitive projects generate new ideas for breakthroughs in applied research, whereas the applied research generates new fundamental science questions. The research domains covered by SIM²@K.U.Leuven are depicted in Figure 1, based on Fiksel’s classification of SMM. Among the recent developments are:

- The Center for High Temperature Processes and Sustainable Materials Management (CHTP), supported by its member companies, is a flywheel for large (competitive) research projects in the areas of vessel integrity for high temperature processes, slag valorization, and metal quality. CHTP was also the driving force behind the successful International Slag Valorisation Symposia in 2009 and 2011.
- The K.U.Leuven Industrial Research Fund Knowledge Platform on Sustainable Materialization of Residues from Thermal Processes into Products (IRF-KPSMaRT-Pro², since 2009) brings together academics from five research fields (chemical engineering and technology, metallurgical and materials engineering, building materials and technology, geology and applied mineralogy, economy and psychology law) and three research institutions (K.U.Leuven, Hogeschool Universiteit Brussel (HUB), and Catholic University College of Bruges-Ostend (KHBO). HUB and KHBO are University Colleges in Flanders focusing on developing directly applicable solutions for industry. Working closely with industry, government, and civil society, the generic goal is to strengthen knowledge on valorization of inorganic industrial by-products and provide a formal platform that can enhance the closing of industrial material cycles in Flanders and abroad.
- In 2010 the Flemish Funding Institute for Applied Science (IW) granted a 6 M€ ($8.6 million) Enhanced Landfill Mining (ELFM) O&O research project to Group Machiels, and an academic consortium coordinated by K.U.Leuven (CHTP and SMaRT-Pro²). Enhanced Landfill Mining targets the integrated valorization of the contents of historic, present,
and future landfills as both materials (WtM) and energy (WtE), using the most advanced technologies, while respecting the most stringent ecological and social criteria. In the ELFM vision, a landfill is no longer considered a final solution but rather a temporary storage place, awaiting future valorization.

K.U.Leuven was approached to take part in CR³, the Center for Resource Recovery and Recycling, which is a U.S. National Science Foundation Industry/University Cooperative Research Center (I/UCRC). K.U.Leuven is the first non-U.S. university that has been invited to join an I/UCRC. As CR³ will expand and partner with other universities to meet the societal challenges we face for a sustainable future, K.U.Leuven will be the coordinator of the European branch. Global sustainable thinking and action requires local engagement, as the solutions need to be local. As it has been said: “Think Global, but Act Locally.”

RESEARCH SCOPE OF SIM²@K.U.LEUVEN

The scope is to develop intensified separation technologies in integrated flow sheets for the recovery of resource elements and minerals from solid and liquid media. The new techniques will be applicable to the treatment of ores and secondary materials such as electronic scrap and residues from industrial activities, thereby incorporating (enhanced) landfill mining, urban mining, and direct recycling (see Figure 2). The following disciplines are at the core of the scope, all related to inorganic materials: Physico-chemistry, Electrochemistry, Hydrometallurgy, and Pyrometallurgy. Technologies developed in these disciplines can take advantage of process intensification and flow sheet integration, as well as from detailed material characterization.

Based on the expertise in K.U.Leuven and the current issues in industry, the following research lines in particular are currently explored:

- Immobilization of inorganic pollutants (solidification/stabilization, carbonation, sorption)
- Recycling of residues as construction materials (cement, aggregate, concrete blocks, alkali-activated or carbonated products)
- New sources for metal recovery and recycling, with a focus on the short term focus on fayalite slag, residues from Zn and Fe production, Li batteries
- Critical materials for clean energy technology, with a focus on rare-earth elements
- Direct reduction for the production of elements, with a focus on electrowinning of metals
- Membrane processes for the recycling of valuable minerals, with a focus on phosphates
- Process intensification of separation technology, with a focus on ultrasound fields, electrical fields, magnetic fields, centrifugal fields

**References**
1. E.g. European Commission, “Critical Raw Materials for the EU” (June 2010).

**Relevant Websites**
a. SMaRT-Pro²: www.smartpro2.eu.

P.T. Jones, T. Van Gerven, K. Van Acker, D. Geyser, K. Binnemans, J. Fransaer, B. Blanpain (Professor & Center Co-Director of CR³) are at KU Leuven, B. Mishra is a Professor and the Center Co-Director of CR3 at the Colorado School of Mines; and D. Apelian is a Professor and Center Director of CR3 at the Worcester Polytechnic Institute, Worcester, “A. Dr. Apelian can be reached at dapel@wpi.edu.