Development of Radiometric Methods for Exploration and Process Optimization in Mining and Mineral Industries

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Summary Report

Consultants’ Meeting on

Development of Radiometric Methods for Exploration and Process Optimization in Mining and Mineral Industries

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Abstract

A consultants’ meeting on ‘’Development of Radiometric Methods for Exploration and Process Optimization in Mining and Mineral Industries’ held at IAEA Headquarters, Vienna, Austria aimed to provide practical information and guidelines for the use of radiation technologies in exploration, mining, mineral, and metallurgical industries, as well as define the scope of future Coordinated Research Project (CRP) on the subject and propose corresponding work program. The most critical technical and research areas/directions for the future of mining, minerals, and metallurgical industries are identified. Finally, strategies for the future development of radiation technologies in mining, mineral, and metallurgical industries were discussed and recommendations reported here.
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1. INTRODUCTION

1.1. Background

Exploration, mining, mineral, and metallurgical (E3M) industries are invaluable to the progress of modern society. Metals and other raw materials have played and continue to play the key role through human history. According to British Geological Survey (World Mineral Statistics) the world mineral production, including the most critical metal ores, phosphate ore, and gypsum, was more than 2.7 billion tonnes/year averaged over the 2006-2009 period. Additional 6.4 billion tonnes of coal is mined and processed yearly worldwide. The mining and mineral industry value-added contribution to the economy of many developing and developed countries is significant, with approximately 50% contribution in Chile, 40% in Australia, 25% in Morocco, 20% in Canada, and 15% in USA.

According to U.S. Energy Information Agency projections, the mining and minerals industry sector will continue to grow over the next decade in most countries around the world. In the U.S. alone, every woman, man and child consumes in average about 23 tons of natural resources and raw materials each year. In other words, to sustain the current living standard average person in developed countries consumes about 60% of his body weight in minerals and metals every day! With a steady and rapid increase in the world population followed by the constant demand for better living standards, especially in developing countries, more and more raw materials are going to be required. Per capita steel consumption reported in relation with per capita GDP, for selected developed and developing countries from 1960 to 2020 (projected), is given in the Figure 1.

![Figure 1. Steel consumption per capita reported in relation with GDP per capita for several developed and developing countries from 1960 to 2020 (projected)](image)

The management and conservation of natural resources are the key fundamental social, economic, and political challenges to implementing sustainable development. Economic growth in the 21st century will require safe and sustainable resources to support the increasing needs of society. It is, therefore, vital that the novel solutions and technologies are developed, which have the potential to use much more complex ore deposits, including non-renewable resources (minerals and coal) and renewable resources (solid waste) as well.

In order to increase production rates, exploitation has become more intensive over the years, which was followed by a range of environmental and social consequences in many parts of the world. Increase in mine operation size has lead toward the increase in mine waste production, water pollution, as well as energy intensity of mining and extraction operations. Easily accessible, high-grade ore deposits are becoming less and less available over time. In
many cases, high quality ores have largely been exploited, and ores that require more complex processing remain. As a consequence, mining operation has to be directed toward lower grade, deeper and/or more complex ores, which are considerably more difficult and expensive to extract. Grades of typical copper, gold, nickel, lead, silver and zinc ores in Australia and worldwide (shown for gold only) in the period from 1844 to 2010 is shown in Figure 2.

**Figure 2.** Decline in gold ore grade in Australia, Brazil, Canada, South Africa, and USA from 1844 to 2010

As the world consumption of metals increases and larger lower-grade deposits are mined to meet demand, sustainable and economic mineral processing will require technological innovation. The development and implementation of novel instruments to facilitate real-time monitoring of mining and mineral processing plants for improved control has the potential to support recovery improvements of the order of 5% across a wide range of commodities. A wide-spread roll-out of these technologies has the potential to deliver a global economic benefit of $19Billion annually.

Nucleonic analysis and control systems, radiotracing technologies, and other relevant nuclear technologies are well suited to the optimization of E3M industries, will remain important in achieving economic and technical benefit in the future.

The main field of application of nuclear techniques include the following:

1. **exploration**
   - delineation of the deposit
   - elemental analysis
   - deposit value evaluation

2. **mining**
   - subsidence in mines assessment
   - slope stability and caving process assessment
   - gas leakage monitoring
   - water penetration monitoring
   - in-situ leaching process monitoring
3. **mineral processing** (or mineral beneficiation)
   - unit operation efficiency evaluation
   - mass balancing
   - ore sorting
   - grade determination
   - process dynamics monitoring

4. **chemical extraction** (including hydrometallurgy, pyrometallurgy, and electrometallurgy)
   - monitoring of high temperature, high pressure processes
   - unit operation efficiency evaluation
   - monitoring of highly corrosive processes

5. **environmental**
   - mining waste management
   - water management
   - energy management
   - monitoring of contaminant transport through ground water, underground water, and soil
   - leakage detection and evaluation

The foremost objective of the consultant meeting was to prepare a technical document which will provide practical information and guidelines for the use of radiation technologies in E3M industries.

1.2. **Consultants’ Meeting Goals**

The participants of the CM discussed and evaluated the following issues:

1. The state-of-the-art for nuclear techniques application with particular focus on:
   - Main fields of applications: mineral exploration (logging), mining operation, and process optimization and troubleshooting
   - Actual technical limitations of available technologies,

2. Future potential for the development of nuclear based technologies as applied to developing countries with emphasis on:
   - Identification of new applications,
   - Identification of the major trends of technique development,
   - Cost considerations,
   - Advices on possible future activities of the Agency.

Six consultants attended the meeting., Nick Cutmore (CSIRO, Australia) was elected Chairman of the meeting, and Sanja Miskovic (University of Utah, USA) agreed to serve as a meeting reporter. The approved Agenda is attached (Annex A), as well as a list of participants and their affiliations (Annex B). Other consultants’ attending the meeting were Jamal Chaouki (École Polytechnique de Montréal, Canada), Jacek Charbucinski (JC Consulting, Poland), Rachad Alami (CNESTEN, Morocco), Francisco Javier Diaz Vargas (Trazado Nuclear e Ingenaria, Chile), and Jovan Thereska (Albania). The scientific secretary was Patrick BRISSET from Nuclear Sciences and Applications Department.
2. NUCLEAR TECHNOLOGIES IN E3M

Experimental methods based on the use of nuclear properties of various kinds offer unique solutions to scientific and industrial monitoring challenges. Many of the potential methods are non-destructive in nature, and may be applied without disturbing the system of investigation so-called non-destructive investigation (NDI). The experimental methods are combined with modelling efforts to enable the conversion of measured data into information. Overview of nuclear methods and tools utilized in E3M industries is given in Table 1.

In this particular context, three intrinsically different methods may be mentioned here:

1. The use of nuclear analytical methods for measurement of elemental concentrations based on the interaction of nuclear radiation with matter. Examples are neutron activation analysis with neutrons of different energy (NAA), charged particle activation analysis (CPAA), prompt gamma neutron activation analysis (PGNAA), gamma-gamma backscattering, gamma-induced x-ray fluorescence (GIXRF) and others.

2. Application of nuclear radiation for detection of physical properties of the matter. This includes gamma transmission and backscattering (including gamma tomography) to measure density profiles and distributions, neutron moderation, transmission and back-scattering (back-diffusion) to measure contents of elements with low atomic number in bulk volumes, beta (and alpha) transmission and backscattering for measurements of elemental concentration and thickness of surface-covering films and others.

3. The use of radioactive tracers to measure flow and distribution of certain components in a dynamic system. This includes single-phase or multiphase flow of gaseous, liquid or solid components in tubes, pipelines and process equipment’s (flow rates, chemical reaction rates, separation efficiency, leakages etc.), in the geosphere including oil and gas reservoirs, in geothermal reservoirs, in water reservoirs (groundwater, surface waters), and many others.

A brief technical overview of the most critical nuclear methods and tools as applied to E3M industries is given in the following section.

2.1. Natural Radiation Based Analysis

The applications of natural gamma ray method to on-line, off-belt and in situ analysis are based on the correlation between natural gamma ray intensity measured in one or more pre-selected energy windows and the concentration of particular elements (e.g. U, Th, K) or the value of a given parameter of interest (e.g. ash in coal). Natural gamma-ray logging has been applied as a geochemical tool for more than sixty years. Although the method was originally applied to uranium mining, it was soon extended to evaluate zone thickness and ore grade in deposits of other chemical elements which either emit gamma-rays directly or are associated with gamma-ray emitting elements.

Nuclear geophysical techniques are also useful for the supply of parameters that are related to particular physical and chemical properties without giving the absolute values of the chemical and physical properties of the matrix. For example, seam correlation for coal lithology can be obtained from the spectrometric analysis of recorded natural-gamma logging. Also, delineation of various ore bodies can be successfully practised without provision of quantitative information on ore grade.
2.1.1. Determination of $K$, $U$ and $Th$ contents

There are three families of natural radio-nuclides that are common in mineral products: the uranium chain, the thorium chain and potassium. In the case of uranium, two isotopes, $^{238}U$ and $^{235}U$, are present in significant amounts, with $^{238}U$ making up 99.3% of the total. Each isotope of uranium decays by α-emission to an isotope of thorium. The half-lives vary widely. In the cases of uranium and thorium particular parent radioisotopes – $^{238}U$, $^{235}U$ and $^{232}Th$ undergo radioactive decay and generate ‘daughter’ radioisotopes. The daughters are the radioisotopes which emit the gamma-rays producing the measurable radiation fields. The half-life of $^{238}U$ is orders of magnitude longer than that of any of its radioactive daughters, so in undisturbed ore/rock there is secular equilibrium.

Thorium also is radioactive, as are its daughters, and so decay chain characteristic of the parent isotope is produced. Again, many daughters are gamma-emitters.

The naturally radioactive isotope of potassium, $^{40}K$ has a very low abundance of 0.011%. $^{40}K$ decays to $^{40}Ca$ and emits a very strong line at 1.46 MeV. Because many rock-forming minerals (such as potassium feldspars, biotite, orthoclase and several clay minerals) contain potassium, it is the commonest natural gamma ray encountered in borehole logging applications, outside uranium ore logging. Natural gamma-ray logging is the simplest method for the determination of K-grade in potassium deposits. Due to a high count-rate obtainable from $^{40}K$ the logging can be performed with a relatively high speed.

Natural radioactivity is a property of the nucleus and is therefore not affected by the chemical form in which a radioactive element occurs. The geophysical search for radioactive elements is primarily a search for locations with abnormal gamma-radiation. However, not all radioactive elements emit gamma rays and their deposits cannot then be located unless a daughter element present in the deposit emits these rays. For borehole measurements of uranium through natural gamma ray logging, secular equilibrium is essential if the practical basis for the measurement will be scintillation spectroscopy.

The spectrometric gamma-ray probes used for uranium exploration require calibration in special test pits of known concentration of potassium, uranium and thorium. Two of the three natural radioactive sources, uranium and thorium, produce counts not only in the window corresponding to that source but also in the two windows corresponding to the other sources. These effects must be dealt with in calibration. A spectral stripping method is applied to spectra measured in the test pits for the determination of constants to be used for quantitative interpretation of KUT logging data. The expense of construction of model facilities requires that centralized facilities be provided for calibration of logging probes. Two well-known facilities are located in Grand Junction, Colorado and in Adelaide, South Australia.

2.1.2. Delineation of coal seams and ore-zones

Since all rocks, igneous as well as sedimentary, contain traces of radioactive elements, the logging can also be used for lithological profiling provided different rocks with strata and stratigraphic units have significantly different level of natural radioactivity (either total or spectral). A typical example of the application of this method of logging is delineation of coal seams in coal deposits intersected by exploration or production holes.

2.1.3. Determination of ash content in coal

An inverse correlation between measured count-rate of natural gamma-ray radiation and ash content of coal has been found to be useful for the determination of coal quality in on-line applications. The correlation between the ash content and natural gamma-radioactivity of coal holds good for bituminous, sub-bituminous and lignite coals, as well as raw and washed
products. However, different coals require separate calibrations. This is due to the fact that the amount of natural radioactivity present in lithological strata (or in a mineral product transported on a conveyor belt) is dependent on their mineral composition. The same amount of ash will produce more natural radiation if associated with shale in coal, than when mineral matter in coal is mostly sandstone.

The Off-Belt Analyser of the Beijing RTDC with the neutron source removed can also be used for the natural gamma-ray method for the determination of ash content of bulk samples of coal.

2.1.4. Coal seam correlation

An interesting application of the natural gamma-ray logging has been for the correlation of coal seams through identification of the ‘spectral prints’ of the inter-sediments present in a given coal deposit. The spectral prints are either count-rates or ratios of count-rates measured in U, Th and K related spectral windows during natural gamma-ray borehole logging. The spectrometric method is useful for identifying strata because the sedimentary beds laid down at different geological periods frequently vary with regard to the K, U and Th concentration ratios. It is particularly important in planning the development of open-cut coal mines to identify the various plies of the coal seam in different regions of the mine, often affected by faults.

2.2. Nucleonic gauges

There are several hundred thousands nucleonic gauges or Nucleonic Control Systems (NCS) installed in many plants all over the world. They have been widely used by various industries to improve the quality of product, optimize processes, and save energy and materials. The economic benefits of this technology have been amply demonstrated and recognized by industry. Looking at trends in the industrialization process of developing countries, there is evidence that NCS technology will continue to play an important role in industry for many years to come.

Nucleonic control systems (NCS) are defined here as: “Control by instrumental measurement and analysis as based on the interaction between ionizing radiation and matter”. There are several ways of applying the NCS, among them:

1. On-line (process),
2. Off-line (process),
3. In-situ (well logging),
4. Used in laboratory (on samples), and
5. Portable, for site measurements

Simple nucleonic gauges first began to be used in industry over forty years ago. Since then, there has been a continuous expansion in their usage. The competition from alternative methods shows that NCS have survived and prospered in the past because of their superiority in certain areas to conventional methods. The success of NCS is due primarily to the ability, conferred by their unique properties, to collect data, which cannot be obtained by other investigative techniques.

Promotion of new applications and techniques in NCS design, calibration, quality control and operation is going on. There is need to stimulate, build and maintain consulting capability in interested developing Member States (MS).

The other most important change is the introduction of neutron generators replacing isotopic sources.
2.3. Gamma Based Analysis

Gamma based techniques fall into two categories, gamma transmission for densitometry in industrial flows and gamma activation based elemental analysis using high energy photon sources.

Gamma based densitometry is widely accepted in the mineral industry for decades and numerous commercial suppliers have addressed this need. Gamma transmission and backscattering (including gamma tomography) is used to measure density profiles and distributions. There are few opportunities for further developments other than those impacting the cost of technology.

Gamma transmission is widely applied in laboratory and pilot scale tomography to gain dynamic information on the operating conditions with closed or not easily accessible unit processes. Commercial technologies developed for other industry sectors (security) are available for application in E3M industries, although currently, this is only an emerging application.

While the technique of gamma activation analysis has been known for decades, achieving the necessary sensitivity and accuracy for industrial scale material analysis is a major challenge. Recent developments by CSIRO have demonstrated a novel method for stabilising the measurement process, significantly improving measurement accuracy and the method is being assessed for routine automated analysis of precious metals in mining and processing.

2.4. Neutron Based Analysis

Neutron based analysis is highly suited to the analysis of bulk mineral ores due to the highly penetrating nature of the interrogating radiation. The most significant development supporting the wider application of neutron-based analysis is the increasing availability of compact, long tube life neutron generators. There are thousands of long-lived radioisotope sources (252Cf, 137Cs, and Am-Be) used throughout the world in mining and mineral industries with varying degrees of security that could be replaced by accelerator sources.

Significant developments of the past 20 years have seen large numbers of neutron based systems installed for on-conveyor elemental analysis in the minerals and cement industries. There are several current commercial suppliers of such systems that employ either radioisotope or neutron generator based sources. The basis of analysis with these systems involves neutron inelastic scattering, prompt gamma activation analysis in combination with gamma spectrometry. The current research focus is centred on improving analysis accuracy through improvements in detector resolution, spectral analysis and calibration approaches.

More recently, neutron techniques have been applied to the in-situ characterization of mineral resource during mining via borehole logging. Drilling accounts for 5-10% of mine production costs and rapid elemental analysis contributes significant economic benefits in the effective planning of drilling programs and the optimisation of the mining operation. Recent developments by CSIRO and Sodern have employed compact long life switchable neutron generator in a logging probe suited to provide continuous, elemental determinations within PQ (core drill), and RC (Reverse Circulation) sized, drill holes in near real-time. The neutron activation analysis method provides a volume-based elemental concentration, which overcomes sampling issues that concern other analytical methods.

Neutron based analysis also provides an opportunity for compact, well controlled and relatively low cost systems for the off-line analysis of bulk ore samples. Such systems help fill a market need where rapid elemental analysis is required but the cost of larger online systems is difficult to justify.
2.5. X-ray Based Analysis

X-ray analysis (using X-ray fluorescence) is at the foundation of current nucleonic analysis and control in a large proportion of mineral processing plants. Introduced in the 1970’s, the past 40 years has seen significant improvements in X-ray source and detector performance, however the same fundamental design of such systems has prevailed where probes are immersed in mineral slurry analysis zones that involve substantial sampling of mineral flows throughout the plant unit processes.

The most recent developments in compact and low cost X-ray sources and solid state detectors do offer an opportunity to break from the traditional approach and implement small relatively low cost analysis systems at multiple points in a mineral plant and thereby avoiding costly and sometimes unreliable sampling of mineral streams. In addition, X-ray analysis (using energy dispersive X-ray diffraction) is now being extended to in-stream mineralogical analysis, providing key information for optimisation of grinding and flotation and potentially improved recoveries.

Effort is currently dedicated to widening the application of in-line X-ray analysers to other points in the mining chain to provide real time information. For example, analysis of sampled ore flows during drilling and mining can provide key elemental and mineralogical information to direct a drilling program or optimise a mining process, with significant economic benefits.

X-ray analysis (using fluorescence and diffraction principles) is also the basis of the majority of laboratory based characterisation of mineral samples. This is a highly commercial activity with numerous suppliers continuously advancing the accuracy, cost and automation of the analysis process.

2.6. Radiotracing

Radiotracers applications have been widely used in various industries to optimise and monitor processes, save energy and materials and reduce environmental impact. Their technical, economic and environmental benefits have been demonstrated and recognised in many industrial sectors. The major radiotracer techniques have been transferred to many developing MS through IAEA TC projects.

The usefulness of radiotracers in evaluation or trouble-shooting industrial processes has been proven beyond doubt. There are many instances, where nuclear techniques based on open sources have been used on laboratory and industrial scales to provide solutions to problems which otherwise would have been insoluble.

The radiotracer technology developed at earlier stages is now being applied by developed countries as routine procedures. However, their results are not often reported in literature. Many developing countries have also gathered a considerable technical knowledge and experience to apply this useful technology to the benefit of local industry. International Atomic Energy Agency has played an important and leading role in transfer of the technical knowledge and the technology itself from developed to developing member states through its Technical Cooperation Programme.

Recently, several advanced nuclear techniques have been developed, validated and used in laboratory experimentations in the developed countries such as multi-radiotracers phase velocity measurement, Single Photon Emission Computed Tomography (SPECT), radioactive particle tracking (CARPT), among others. These techniques are in very early stage in most of the developing countries. Even the basic radiotracer techniques are still underutilized due to various problems faced by developing countries. These are lack of technical knowledge and experience, limitations due to lack of equipment, non-availability of radioisotopes, strict regulations not technically related with real radiological safety impact, and many others. The
society for radiotracer and sealed source is requested to solve the problems through various cooperative activities.

2.6.1. Residence Time Distribution Measurement

Residence time can be described as the time taken by particles to move from inlet to outlet in continuous processes. Since not all particles spend the same amount of time in the process, residence time information thus obtained is usually in a form of distribution, which is called the residence time distribution (RTD). An important consequence of RTD is the calculation of mean residence time. Furthermore, the width and shape of obtained RTD curves are general measures of process imperfections, such as short-circuiting, stagnant regions, and fluid channeling. Therefore, the information obtained from the RTD can be used to assess and improve the overall performance of the monitored system by identifying dead zones, particle circulation regions, effective reactor volumes, and average particle sojourn times.

Information about the RTD of any small element of monitored multiphase system provides valuable information about the process dynamics and is obtained by “particle tracking”, which involves tagging of either natural or artificial particles and studying the transport of these particles within the monitored system.

One of the most commonly used methods for measuring RTD of various systems is impulse response method (or radioactive particle tracing). In general, the RTD method consists of selection of an appropriate tracer, its injection in the feed stream, measurement of the response signal at the outlet, and data analysis. Radionuclide RTD method is the most favoured of all other RTD methods since it is more robust, accurate, less prone to operator and experimental errors, allows on-line RTD data acquisition, and has been successfully used for RTD measurements of lab- to large-scale systems by many research groups in the past. Also, due to typically extremely high dilution rate after tracer injection, there is practically no danger of exposure to radioactive material within the process.

Since the procedures for the radionuclide generation are well established and standardized by the International Atomic Energy Agency (IAEA), radiotracer RTD measurement of solid, liquid, and gas phases can be performed easily and potentially simultaneously.

From the literature review it is clear that the main focus of radionuclide RTD studies over the past ten years have been directed toward small- and large-scale RTD measurements by using standard scintillator detectors. Also, some progress should be noted in the field of data filtering/conditioning and interpretation. However, little or no effort has been invested on the improvement of radiation detection equipment and systems, utilization of alternative low energy, short-lived radionuclides, and alternative radiation generator sources and radiotracer generation procedures.

The feasibility of industrial radiotracer technique strongly depends on the availability of short-lived radionuclides (half-life less than 120 days), which enables the reduction of health and environmental risks at the measurement site. On the other hand, the availability of short-lived radionuclides at remote industrial sites remains a major challenge, since majority of current radiotracer preparation and RTD usage practices require access and proximity to reactor or cyclotron facilities. Due to their short life, rapid and frequent transportation of radiated material to the application site is one of the main logistical challenges that are encountered, which limits the use of radionuclides to sites in “close” proximity to their generation facilities. As a consequence, this routine of material management comes with significant costs associated with multiple shipments to distant site. To ensure onsite availability of larger amounts of short-lived radiotracers, utilization of portable compact radionuclide generator systems is of great importance for the future of this technology.
2.6.2. Radioactive Particle Tracking

Multiphase flows and processes – with at least two phases – are widely used for the production of energy fuels, chemicals and biotechnological products, as well as in E3M industries. In the mining industries, the compositions of feedstock are changing rapidly due to the shortage of conventional resources. The development of new mines is typical for many upcoming and future applications. The intrinsic variability of these new feedstocks combined with stringent environmental constraints make the processes much more difficult to design and operate. The use of high temperature and/or high pressure during the conversion and handling of high viscosity materials and/or viscosity ratios yield to extreme processing conditions for which multiphase process hydrodynamics is completely unknown.

Reliable measurement of the flow dynamics in various systems is essential. To do so, sophisticated measuring techniques have been developed and improved by advances in computer control and nuclear technology including radioactive techniques such as radioactive particle tracking (RPT) and positron emission particle tracking (PEPT).

PEPT uses two positron-sensitive detectors mounted on the opposite sides of a system to detect pairs of exactly back to back gamma rays resulting from the annihilation of a positron. This technique is able to detect a tracer when this tracer is within the volume covered by the detectors.

RPT employs an array of several compact Sodium Iodide (NaI-Tl) detectors, which can be flexibly arranged around the system. Since RPT and PEPT use different detectors and rely on different algorithms to reconstruct tracer trajectories, they have their own advantages and drawbacks. For instance, RPT setups are compact, flexible and cheap compared to those of PEPT.

2.7. Densitometry

The densitometry refers to measurement of the density of a system (homogeneous or heterogeneous) by determining the degree to which that system attenuates any kind of radiations. The measured electromagnetic radiation can originate from an x-ray or gamma ray sources. The system to be study is placed between a photon source and a photon detector. The response from a detector is a linear integration through the X-ray or Gamma ray trajectory. If the source and the detector are moving together linearly then a 2D image of the heterogeneous system can be obtained.

2.8. Tomography

Tomography refers to imaging by sections, or sectioning, through the use of any kind of penetrating wave, specially X-ray or gamma rays. The basic setup of a tomography system consists of an X-ray or Gamma ray source for beam generation, a manipulator to position the object to be inspected, a detector to capture the radiosopic image and a computer unit for image generation (reconstruction), image depiction and analysis. Those images are subsequently computed to create a three-dimensional image. The manipulation system must therefore make sure that either the inspected object or the X-ray tube or gamma ray source/detector unit can rotate around a 180° axis as well as be vertically adjustable. A high degree of precision and stability is necessary hereby in order to obtain reproducible images.

3. STATE-OF-THE-ART IN NUCLEAR TECHNOLOGIES

An overview of nuclear technologies for advanced analysis, troubleshooting, optimization, and control of systems and processes in E3M industries is given in Tables 1(a)-
1(c). Information about advantages, limitation, information type obtained, and opportunities for further development of each presented technology is also presented.
Table 1(a). An overview of nuclear technologies for analysis, troubleshooting, optimization, and control of systems and processes in E3M industries

<table>
<thead>
<tr>
<th>E3M PROCESS TYPE</th>
<th>EMPLOYED NUCLEAR TECHNOLOGIES</th>
<th>ADVANTAGES</th>
<th>LIMITATIONS</th>
<th>INFORMATION OBTAINED</th>
<th>OPPORTUNITIES FOR FURTHER DEVELOPMENT</th>
</tr>
</thead>
</table>
| EXPLORATION      | Borehole logging              | • Fast elemental analysis using portable easily deployable probes  
                   |                   | • In-situ analysis  
                   |                   | • Detection of some elements only (over 30 elements)  
                   |                   | • Not suitable for measurement of low concentrations (ppm level)  
                   |                   | • Various sensitivity and accuracy depending on local geological conditions  
                   |                   | • Delineation of the ore body and coal seams  
                   |                   | • Elemental analysis within the ore body and coal seams  
                   |                   | • Improved neutron generators  
                   |                   | • Implementation of cheap and high-resolution detectors  |
| MINING           |                                |            |             |                      |                                       |
| MINERAL PROCESSING | Bulk ore elemental analysis  | • More penetrating than X-ray techniques and suited to large sample analysis (tens of kg to tons)  
|                   | (gamma and neutron techniques) | • Of-line and on-line applications are widely applied  
                   |                   | • More limited elemental analysis than X-ray  
                   |                   | • Large radiation sources and required larger shielding  
                   |                   | • Higher cost (>$300K)  
                   |                   | • Bulky units  
                   |                   | • Additional license requirements  
                   |                   | • Elemental analysis of a large ore sample or conveyed mineral ores  
                   |                   | • Use of neutron generators and linear accelerators to replace radioisotope resources  
                   |                   | • Improved accuracy  
                   |                   | • Wider elemental capability  |
| MINERAL PROCESSING | Ore elemental analysis       | • Fast and accurate multielement mineralogical analysis  
|                   | (XRD, XRF)                   | • Suitable for on-line use  
                   |                   | • Portable and compact  
                   |                   | • Widely applied for both on-line and lab analysis  
                   |                   | • Low comparative cost  
                   |                   | • Mature technology  
                   |                   | • Widely commercially available for more than 30 years  
                   |                   | • Results interpretation might be challenging  
                   |                   | • Sample presentation is important because of limited penetration depth of radiation  
                   |                   | • Accuracy influenced by ore/rock matrix  
                   |                   | • Sampling for representative analysis is always a challenge  
                   |                   | • Elemental analysis of an ore sample or a mineral stream  
                   |                   | • Development of lower cost, more compact systems with high accuracy  
                   |                   | • Applications for low concentrations  |
Table 1(b). An overview of nuclear technologies for analysis, troubleshooting, optimization, and control of systems and processes in E3M industries

<table>
<thead>
<tr>
<th>E3M PROCESS TYPE</th>
<th>EMPLOYED NUCLEAR TECHNOLOGIES</th>
<th>ADVANTAGES</th>
<th>LIMITATIONS</th>
<th>INFORMATION OBTAINED</th>
<th>OPPORTUNITIES FOR FURTHER DEVELOPMENT</th>
</tr>
</thead>
</table>
| EXPLORATION      | Radiotracing (RTD, on-off analysis) | - Non-invasive
- Easy to deploy
- Results are accurate and highly reproducible
- Detection limit is very low
- Unique information obtained
- Can be deployed in all conditions
- Online detections of gamma radiotracers
- Small mass of radiotracer required
- Can be used to track solid, liquid, and gas phases
- Facilitates reactor compartment modeling | - Global/volumetric information
- Perceived liability at many sites around the world
- Different regulatory environment affect the application range
- Results interpretation can be challenging
- Low availability of radiotracers
- Radiotracer transport from the generation site to the plant | - Residence time curve
- Mean residence time of tracked phases
- Process troubleshooting
- Flow meter calibration
- Leakage detection
- Mass balancing of units, systems, circuits | - Portable radionuclide generators
- Improved availability of radiotracers
- Spectroscopic monitoring of multiple radiotracers
- Cheap detectors
- High resolution detectors |
| MINING           | Radioactive particle tracking (RPT) and Positron emission radioactive particle tracking (PEPT) | - Individual (pseudo) particle tracking
- Offers unique hydrodynamic information about the system
- Non-intrusive methods
- Applicable in many conditions (complex multiphase flows)
- Multi tracer mapping | - Medium to high cost
- Limited to small-to-medium systems
- Results interpretation might be challenging
- Research method | - Particle trajectories
- 3D flow field mapping
- Mean sojourn time
- Tomographic information
- Particle rotation information
- Process troubleshooting
- CFD, DEM, PBM model validation | - Portable radionuclide generators
- Improved availability of radiotracers
- Spectroscopic monitoring of multiple radiotracers
- Cheap detectors
- High resolution detectors |
| MINERAL PROCESSING | Chemical extraction | - | - | - | - |
| ENVIRONMENTAL | - | - | - | - | - |


Table 1(c). An overview of nuclear technologies for analysis, troubleshooting, optimization, and control of systems and processes in E3M industries

<table>
<thead>
<tr>
<th>E3M PROCESS TYPE</th>
<th>EMPLOYED NUCLEAR TECHNOLOGIES</th>
<th>ADVANTAGES</th>
<th>LIMITATIONS</th>
<th>INFORMATION OBTAINED</th>
<th>OPPORTUNITIES FOR FURTHER DEVELOPMENT</th>
</tr>
</thead>
</table>
| EXPLORATION      | Densitometry                  | • Simple density mapping of small to medium size systems  
| MINING           |                               | • Simple method and setup  
| MINERAL PROCESSING |                               | • Easy to use  
| CHEMICAL EXTRACTION |                               | • Widely accepted method  
| ENVIRONMENTAL    |                               | • Commercial units are widely available  
|                  |                               | • On-line information  | • Global measurement  
|                  |                               | • Results interpretation might be challenging  
|                  |                               | • Unit calibration might be challenging  | • 2D density map of the measured system  
|                  |                               |                               | • Process troubleshooting  | • Cheap detectors  
|                  |                               |                               |                               | • High resolution detectors  
|                  |                               |                               |                               | • Availability of sources  |
| EXPLORATION      | 3D information of various systems (from micro to m scale)  
| MINING           |                               | • Applicable to both static and dynamic systems  
| MINERAL PROCESSING |                               | • Unique information  
| CHEMICAL EXTRACTION |                               | • Can be used to monitor complex dynamic systems  | • High cost  
| ENVIRONMENTAL    | X-ray and gamma tomography (CT) |                               | • Limited to small-to-medium sized systems  
|                  |                               |                               | • Complex system  
|                  |                               |                               | • Interpretation of the results is challenging  | • Tomographic map of the system  
|                  |                               |                               |                               | • 3D mineralogical information from small ore samples  
|                  |                               |                               |                               | • 3D process information from process units  
|                  |                               |                               |                               | • Process troubleshooting  
|                  |                               |                               |                               | • Hydrodynamic information  | • Application to medium to large processing units  
|                  |                               |                               |                               | • Application to nanoscale systems  
|                  |                               |                               |                               | • Low cost gamma tomography systems  
|                  |                               |                               |                               | • Robust reconstruction  |
4. ABSTRACTS OF CONSULTANTS’ PRESENTATIONS

4.1. “Nuclear Technologies in Mining and Mineral Processing”

Nick Cutmore, CSIRO Mineral Resources National Research Flagship, Australia

Abstract:

The mining and mineral processing industry is a major component of the Australian economy. The substantial mining boom of the first decade of the 21st century led the industry to focus on throughput and production volume. Pressures resulting from levelling or decreasing commodity prices, falling ore grades, the strong Australian dollar and rapidly climbing input costs are shifting this focus back to improving efficiency and productivity. Technologies targeting mining automation, the selective processing of mined ore and improving recovery and productivity in mineral processing, have the potential to generate substantial economic returns and to yield commensurate reductions in energy and water usage.

In-situ and on-line analysis of key elemental, mineralogical and physical information about ores at all stages of mining and processing will directly support efficient exploitation of increasingly lower grade deposits via selective processing and improved recovery.

Nuclear techniques of analysis play a key role in these current research developments and include neutron based borehole logging technologies; in-situ ore characterisation using x-ray, gamma activation and neutron techniques; the on-line determination of elemental and mineralogical information using x-rays; and bulk ore sorting using gamma activation techniques.

Picture Abstract:

4.2. “Residence Time Distribution & Radioactive Particle Tracking: Applications in Mining Industries”

Jamal Chaouki, Chemical Engineering Department, École Polytechnique de Montréal, Canada

Abstract:

Multiphase flow technology is utilized extensively in many industries from fuel and chemicals processing to the production of feed, food, pharmaceuticals and specialty materials. Applications of systems involving two phases or more are countless and ubiquitous in
industrial practice. Despite such wide usage, the state-of-the-art design technology for multiphase reactors is still at a rudimentary stage. The reasons for this shortcoming are that the local structure of multiphase flows is extremely complex and the link between the macroscale and the microscale is only poorly understood. Lack of detailed structural and dynamic information at the microscale, and mathematical difficulties caused by the randomness of the multiphase media make the application of first principles very difficult. Hence, experimental techniques capable of probing non-invasively the whole multiphase flow field are valuable tools in understanding and modelling transport phenomena in multiphase reactors.

The radioactive particle tracking technique in its two versions (Radioactive Particle Tracking and Positron Emission Particle Tracking) aims to follow a single labelled tracer particle which represents one of the phases of interest. Using external radiation measurements, the location of the tracer with time (Lagrangian trajectory) can be determined. With further data processing, detailed information about the flow pattern of the selected phase is obtained. The measurement is non-invasive and can be performed in opaque multiphase systems with large volume fractions of dispersed phases.

In this presentation, the current status and the development made on RPT and PEPT are outlined.

In-situ and on-line analysis of key elemental, mineralogical and physical information about ores at all stages of mining and processing will directly support efficient exploitation of increasingly lower grade deposits via selective processing and improved recovery.

Nuclear techniques of analysis play a key role in these current research developments and include neutron based borehole logging technologies; in-situ ore characterisation using x-ray, gamma activation and neutron techniques; the on-line determination of elemental and mineralogical information using x-rays; and bulk ore sorting using gamma activation techniques.

**Picture Abstract:**

4.3. “Metallurgical & Mining Processes: What is the Future?”

*Jamal Chaouki,* Chemical Engineering Department, École Polytechnique de Montréal, Canada
Abstract:

In the currently prevailing industrial and economic practices, only 25% of natural resource feedstocks are converted to goods and services; the remaining 75% is converted to wastes, the vast majority of which is discarded in landfills. The tendency is also towards increasing generation of wastes. According to OECD, for the period ranging from 1980 to 2005, the amount of solids municipal waste (MSW) generated per capita increased by 129%, 154%, and 134% in North America, European OECD countries, and in all OECD countries, respectively. On an absolute basis, the total amount of municipal waste generated increased during the same period due to the increase in population by 173%, 170%, and 167% in North America, European OECD countries, and in all OECD countries, respectively. Over the past few decades, a significant effort was invested in the development of recycling schemes for easily divertible materials, such as paper, cardboard, glass, and metals. These schemes involve the development of multiple collection strategies and the systematic sorting of waste. As a result of this effort, recycling rates of paper and cardboard currently reaches 46% to 50% in North America and 64% in European OECD countries. Furthermore, the recycling rate of glass currently reaches 13% to 22% in North America and 65% in average in European OECD countries. Many programs were also implemented for the recycling of construction materials. Waste valorization through recycling is, however, not always possible due to waste cross contamination since residential, institutional and commercial waste contains organic materials (food, leaves and grass, trimmings, etc): cross contamination is therefore likely as potentially divertible material (paper and plastics) will absorb some organic load. Moreover, the organic fraction usually contains high levels of water, carbohydrates, greases and proteins. Organic materials are subject to decomposition and often yield odours, which makes sorting difficult and sometimes impossible. Furthermore, recycling is sometimes not economically possible due to the high cost of existing processes (polystyrene recycling, for example). As a result, despite a waste valorization effort through recycling and reusing, there are still important waste streams that are disposed.

In 2008, Canadians generated 25 million tons of waste, of which only 25% was diverted. The remaining 17 million tons was either incinerated or buried in landfills. Today, most research on new processes to transform these waste is performed at atmospheric pressure and at temperatures in the range of 400°C to 1600°C. However, there is a lack of experimental research at high pressure and high temperature (HP-HT) and it remains a relatively unexplored area of research. The potential advantages of these operating conditions (HP-HT) include the reduction of the fixed capital cost for bio-refinery plant, reduction of the size of reactors and piping, elimination of downstream equipment such as compressors, increase in the reaction rate and efficiency. This is where Radiometric Methods would help to develop these new processes.

Picture Abstract:
Abstract:

From the first days of their discovery, radionuclides have been successfully used to monitor or trace various physical, chemical, and biological processes which occur instantaneously or over period of time. Radiotracers are selected based on the type of radiation emitted, half-life of the radionuclide, energy of emitted radiation, and its physical and chemical properties. Compared to other tracer technologies, radiotracers are superior due to their significant resistance to extreme process/system conditions, very low injection amounts, extremely high detection sensitivity, feasibility of accurate on-line and in-situ measurement and diagnostic, and possibility of simultaneous multi-tracer detection. For all these reasons, radiotracing techniques have been extensively used worldwide for over three decades to monitor and evaluate the efficiency of numerous dynamic and multiphase industrial processes aiding their performance and design optimization.

According to fundamental chemical reactor theory, the residence time distribution (RTD) is defined as the probability distribution of the time that particular finite element of a mixture (solid, liquid, or gas) stay inside of monitored part of the process (i.e. unit/reactor or series of units/reactors) in a continuous flow system. The RTD approach has been widely used to understand, monitor, and model the material flow profile and material transport phenomena inside of various industrial continuous flow systems. By RTD measurement, potential system problems such as channelling, bypassing, short-circuiting, and existence of dead volumes within the reactor, could be determined. The RTD measurement is performed by the injection of a suitable tracer into the inlet of the system followed by measurement of the tracer concentration at the outlet or other region of interest at regular time intervals. Due to their great physico-chemical compatibility and high detection sensitivity, radioisotopes and radiation detectors can be used successfully to reliably troubleshoot industrial processes via RTD method. When obtained experimentally, radiotracer RTD information generally suffers from substantial noise as a result of background radiation, radioisotope decay, and signal fluctuations, among others. Standard signal processing steps, such as background correction, radioactive decay correction, starting point correction, and signal extrapolation, are some of the well-established methods for raw signal conditioning.

This presentation aims to provide an overview of radiotracing technology as applied to RTD measurements with a brief background on the physical properties of radioactive decay, main concepts related to the production and preparation of radionuclides, and fundamentals of radiotracer detection. Furthermore, main characteristics of typical industrial radiotracers and strategies for their selection will be given. Finally, most commonly used RTD modelling strategies, including the CSTR and PFR series model, axial dispersion model, stochastic model, and RTD prediction by means of computational fluid dynamics (CFD) simulation, will be reviewed.
4.5. “Nuclear Borehole Logging for In-Situ Analysis in Coal and Metalliferous Mining Industries”

Jacek Charbucinski, JC Consulting, Poland

Abstract:

The presentation includes review of nuclear methods and instrumentation applied in exploration and mining of coal and mineral deposits for both borehole logging and bulk analysis. The methods reviewed were: natural-gamma logging, gamma-gamma logging, PGNAA logging and DGNAA logging. The examples of calibration and interpretation of logging data are given. Also, summary of CSIRO collaboration with IAEA under RCA regional projects is included.

Picture Abstract:

4.6. “Hydrodynamic Characterization of Industrial Flotation Machines Using Radiotracers”

Francisco Javier Diaz Vargas, Trazado Nuclear e Ingenaria, Chile
Abstract:

- Use of radiotracers in mineral processing applications, mainly flotation machines, starts 30 years ago.
- Collaboration between: CCHEN and UTFSM.
- Flotation circuit at San Francisco mill, Disputada de las Condes, 1981 (mechanical cells).
- Investigated units:
  - Columns: 0.1, 0.5, 1.0 m diameter up to 7.8-16 m²
  - Mechanical Cells: 5, 10, 20, 30, 45, 85, 100, 130, 160, 200, 250, 300 m³
- Industrial flotation machines need to accomplish several functions such as:
  - Gas dispersion (small bubbles: 1-2 mm)
  - Solid suspension (particle size: 10-300 microns)
  - Provide the best conditions for bubble-particle collision, aggregate formation and froth transport
- Flotation cells characteristics:
  - Agitation system: generate well mixed conditions for the pulp and air bubbles.
  - Troubles: Short circuit (by-pass flow)
  - Arrangement: Cells in series (banks)

Picture Abstract:

4.7. “New Challenges for Radioisotope technology as applied to phosphate industry”

Rachad Alami, CNESTEN, Morocco

Abstract:

Moroccan reserves of phosphates are the largest ones in the world. They are estimated to more than 85 billion m³. The drainage of the phosphate rock from the mines site to the chemical sites, which is currently done by train, requires dry phosphate to lower the humidity from 12% to 2% in order to carry it cheaply. However the chemical processing of raw phosphates, to get the final products (phosphoric acid, fertilizers) requires large amounts of water to be added back (up to 60%).

For the transport of phosphate extracted from Khouribga mines to Jorf Lasfar chemical units, OCP has decided to build a pipeline that represents a real technological leap in the context of the group's industrial strategy. The pipeline between Khouribga to Jorf Lasfar is a
flagship project for convergence between cost reduction and rationalization of water and energy consumption. The goals with this project are the increase in production capacity to 38 million tons/year and also a significant reduction in transport costs as well as valuable water and energy savings.

In the “Slurry pipe”, which is now completed and currently being tested the pulp of phosphate will increase from 12% humidity to 40% in the pipeline and finally to 60% at the stage of recovery.

This new mining facilities are raising new challenges for radioisotope technology as applied to phosphate industry. Indeed, it is the first time such a material is transported by pipe over such long distances and the risk of blockages cannot be neglected. Determination of physical parameters, such as concentration, viscosity, flow rate, etc… of the material inside the pipe becomes a key issue for handling and maintaining the whole system. Developing new specific nucleonic control systems or new radiotracer methodologies to obtain such information could be a challenging project within the frame of the foreseen CRP.

**Picture Abstract:**

4.8. **“Radioisotope Techniques in Mining and Mineral Processing”**

*Jovan Thereska*, Consultant for IAEA, Austria

**Abstract:**

Radiotracer residence time distribution (RTD) is an important tool for the analysis of processing units in mineral processing industry. Some typical examples chosen to cover a wide range of industrial processes are given illustrate how information obtained by radiotracers was successfully used in real conditions to analyze the operation of industrial units, to eliminate troubles and to improve the economic performance of processes.

The determination of crack zones above the galleries roof of an underground coal mine using the radiotracer single well dilution technique was described as well. The radiotracer single well dilution technique provided the preferential movement of underground water, the vertical displacement and time characteristics of fractured zones produced during exploitation of subaquatic underground coal mining.
Picture Abstract:
5. PROPOSAL FOR A CO-ORDINATED RESEARCH PROJECT

Title of the CRP:

“Advancement of the application of nuclear technologies in Exploration, Mining, Mineral, and Metallurgical Industries”

5.1. Rationale/Problem Definition

Exploration, mining, mineral, and metallurgical industries are invaluable to the progress of modern society. Metals and other raw materials have played and continue to play the key role through human history. According to British Geological Survey (World Mineral Statistics) the world mineral production, including the most critical metal ores, phosphate ore, and gypsum, was more than 2.7 billion tonnes/year averaged over the 2006-2009 period. Additional 6.4 billion tonnes of coal is mined and processed yearly worldwide. The mining and mineral industry value-added contribution to the economy of many developing and developed countries is significant, with approximately 50% contribution in Chile, 40% in Australia, 25% in Morocco, 20% in Canada, and 15% in USA.

As the world consumption of metals increases and larger lower-grade deposits are mined to meet demand, sustainable and economic mineral processing will require technological innovation. The development and implementation of novel instruments to facilitate real-time monitoring of mining and mineral processing plants for improved control has the potential to support recovery improvements of the order of 5% across a wide range of commodities. A wide-spread roll-out of these technologies has the potential to deliver a global economic benefit of $19 billion annually.

Nucleonic analysis and control systems, radiotracing technologies, and other relevant nuclear technologies are well suited to the optimization of E3M industries, will remain important in achieving economic and technical benefit in the future.

5.2. Overall CRP Objective

The overall objective of the CRP is to facilitate further advancement and implementation of nuclear technologies in exploration, mining, mineral, and metallurgical industries. Specifically, targets to be addressed will include safety, cost, and availability of nuclear technologies, as well as knowledge transfer with a particular focus on developing Member States.

5.3. Specific CRP Objectives

The specific objectives of this CRP should be:

1. to facilitate further development of techniques based on neutron generator technologies for use in E3M
2. to encourage development of new nucleonic control systems to address new raising needs in E3M
3. to facilitate further development and implementation of radiotracing techniques with a specific targets on improved methodologies to improve accuracy, efficiency, and safety
4. to facilitate development of new compact and low cost X-ray techniques for improved monitoring of complex multiphase/multicomponent systems in nano, micro, and macro scale
5. to provide a platform for efficient and transparent knowledge transfer among the Member States

5.4. **Expected Research Outcomes:**

1. Demonstration of nuclear technologies application in E3M fields
2. Expansion of the application range of nuclear technologies in E3M fields

5.5. **Potential Member States participation list:**

Morocco, South Africa, Niger, Peru, Chile, Argentina, Brazil, India, Pakistan, China, Turkey, Russia, Malaysia, Indonesia, Vietnam, Finland, Sweden, Poland, Serbia, Australia, Canada, USA and other Member States as nominated by IAEA.
ANNEX A

Consultants’ Meeting on

“Development of Radiometric Methods for Exploration and Process Optimization in Mining and Mineral Industries”

IAEA Headquarters, Vienna, Austria
1-5 September 2014
Room MOE61

AGENDA

Monday, 1 September
09:30 - 10:00 OPENING
• Opening remarks
  \textit{Mr. Patrick BRISSET – IAEA-NAPC}
• Election of the chairman and reporter
• Adoption of the agenda
• Scope and objectives of the CM
  \textit{Mr. Patrick Brisset (Scientific Secretary, IAEA)}
• Administrative arrangements

10:00 - 10:30 Coffee break
10:30 - 12:00 SESSION I: Participants’ presentations (1)
12:00 – 14:00 Lunch
14:00 – 15:30 SESSION I: Participants’ presentations (2)
15:30 – 16:00 Coffee break
16:30 - 17:30 SESSION I: Participants’ presentations (3)

Monday, 2 September
09:30 - 10:00 SESSION II: Technical discussions (1)
• Discussions on the presentations
• Strategy for the efficient meeting organization
• Identification of future CRP main topics
• Strategy and organization of the future CRP

14:00 – 17:30 Lunch
10:30 - 12:00 SESSION II: Technical discussions (2)

Monday, 3 September
09:30 - 10:00 SESSION III: Technical discussions (1)
14:00 – 17:30 Lunch
10:30 - 12:00 SESSION III: Technical discussions (2)
Monday, 4 September
09:30 - 10:00 SESSION IV: Preparation of Draft Meeting Report (CRP)
14:00 – 17:30 Lunch
10:30 - 12:00 SESSION IV: Preparation of Draft Meeting Report (CRP)

Monday, 5 September
09:30 - 10:00 SESSION V: Discussion on Meeting Report
• Finalization of the meeting report
14:00 – 17:30 Lunch
10:30 - 12:00 SESSION VI: Approval and Closing
• Approval of the meeting report
• Closing of the Meeting
ANNEX B

“Development of Radiometric Methods for Exploration and Process Optimization in Mining and Mineral Industries”

IAEA Headquarters, Vienna, Austria
1 - 5 September 2014

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ANNEX C

Consultants’ Meeting Participants:

From left: Patrick Brisset (IAEA, Austria), Francisco Javier Diaz Vargas (Trazado Nuclear, Chile), Jamal Chaouki (Ecole Polytechnique de Montreal, Canada), Jacek Charbucinski (Poland), Nick Cutmore (CSIRO, Australia), Sanja Miskovic (University of Utah, USA), Rachad Alami (CNESTEN, Morocco), Jovan Thereska (Austria)