The Rare Earth Elements and Clean-Energy Technologies Project

R&D Gaps Analysis

Prepared by

CANMET-Mining and Mineral Sciences Laboratories and Minerals, Metals and Materials Knowledge Branch

Minerals and Metals Sector

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Summary

In October 2011 the Office of Energy Research and Development (OERD, Energy Sector) provided the Minerals and Metals Sector (MMS) with $870k funding a over a three year period (from 2011-12 to 2013-14). The purpose of the funding is to support MMS work regarding Rare Earth Elements (REE), which are essential in the manufacture of clean-energy technologies.

An important component of the work to be completed is an analysis of research and development gaps in Canada's REE sector. The REE Project Gaps Analysis will serve as the basis for the R&D to be conducted with the OERD funding.

The primary finding of the gaps analysis is that Canadian exploration companies need help with the metallurgy regarding the extraction of REE from the hard rock deposits that have been found in Canada to date. Some research is underway but there is no national coordination of these efforts. To expand and deepen our collective knowledge of REE will require collaboration amongst all stakeholders: some consideration might be given towards the development of a domestic consortium to continue the R&D that has been initiated with the OERD funding as well as the science that is being conducted in labs and in the field across the country. The recovery of REE in an environmentally sound manner will have economic benefits for Canada over many decades to come.

Background

Information regarding the special nature of REE, its many high and clean technology applications, its current and projected production activities and the various political and market forces at play are covered in the Critical Non-Fuel Minerals & Metals, Policy Framework paper (still in progress as of March 14).

Nevertheless, it is worth reiterating that the demand for critical metals, including REE and other strategic metals are expected to exceed supply within 10-15 years; in particular, there will not be enough neodymium, europium, terbium, dysprosium and yttrium to meet global market demand.

Canada is bestowed with mineral resources that contain highly desirable REE but no deposits are currently being exploited. The knowledge and facility to research and design economically and environmentally more acceptable processes are generally lacking in Canada. Since the natural scarcity of rich deposits and the potential of the new geopolitical challenges in the maintenance of a steady supply of RE metals is now a reality, there is a compelling need to encourage and support the development of promising domestic ore deposits.

Objective and Approach

The objective of the gaps analysis paper is to investigate the lack of knowledge within the Canadian rare earth industry and to subsequently identify the potential areas best served by research and technology development.

To assess Canada's state of knowledge and capacity regarding REE, several tasks were undertaken including a literature review and consultations with industry, research institutes and academia. The gaps analysis process adopted a two-prong approach: (1) data from the literature including scientific journals through to popular media and (2) consultations with industry stakeholders.

In the case of the latter, consultation targets included leading Canadian exploration companies, universities, research institutions, the provinces and territories, other federal departments and international partners (i.e. those in the inter-governmental consortium). In fact, consultation with the consortium will be undertaken at its March meeting in Japan during which the proposed R&D and the Government of Canada's short list of projects will be presented and feedback received.

Findings: Literature Review

The Canadian REE Picture

Canadian geology, exploration know-how, mining experience, regulatory infrastructure and investment climate all strongly support a potentially prosperous REE industry in Canada; however, some issues could impact its success. In particular, there is a dearth of qualified personnel and laboratories especially in the areas of mineralogy, chemistry, and metallurgy. Insufficient skills and facilities could result in metallurgical testing delays that could ultimately delay production schedules.

Additional challenges for Canadian resource companies are the infrastructure, climate, the profile of REE in the investment community, and barriers with Asia (geographical, language barriers).

Unlike the metal mining industry where companies want to be 'first to be second', in the Canadian REE industry there is a clear a flat our sprint to be first. The three most important factors in this race are REE tonnage/grade, mineralogy and metallurgy (physical and chemical processing).

Technological Challenges

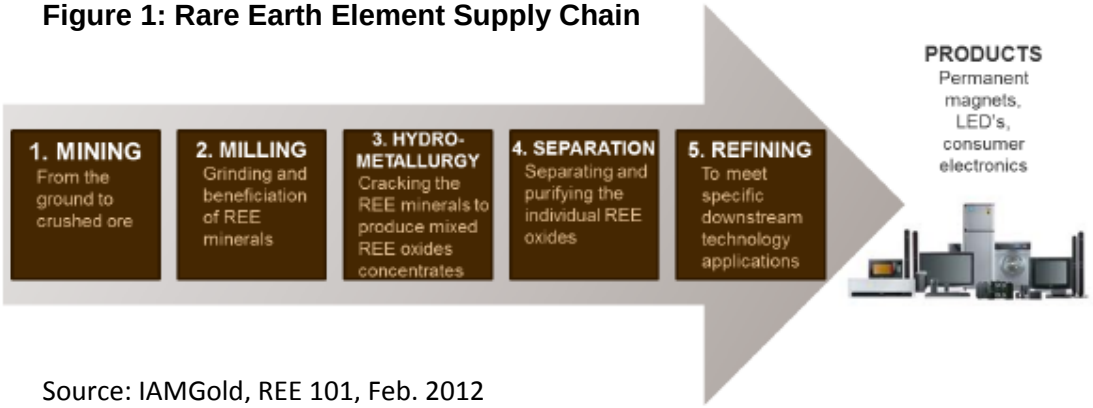
The geochemical properties of REE result in their geological dispersion; in other words, they are not found in a concentrated and economically exploitable form. While REE are relatively abundant in the earth's crust, minable deposits are less abundant relative to other minable deposits.

The greatest challenge facing the Canadian, and international, rare earth industry is the processing of rare earth ores. The multistep process to extract REE from an ore body is illustrated in Figure 1.

Missing from the figure is the initial exploration stage during which REE bearing minerals are identified and assessed. Step 3, hydrometallurgy, involves various leaching operations. Throughout all steps, the need for effective environmental controls is of paramount importance.

In each of these process steps, there is profound knowledge and technological gaps as discussed in following sub-sections on mineralogy, mineral processing and hydrometallurgy.

Figure 1: Rare Earth Element Supply Chain



Source: IAMGold, REE 101, Feb. 2012

Mineralogy

Considering the structural, morphological and compositional diversity of the various REE minerals and the complexity of natural (e.g. weathering) and engineered (e.g. concentration, leaching) REE fractionation/enrichment processes, mineralogical characterization is a key component at all steps ranging from exploration to production. To stimulate and support REE development efforts in Canada, extensive and useful innovation is crucial. Three main areas of investigation involving mineralogy have been identified and are listed as follows: Further details of each are provided in Appendix A: Mineralogical Characterization.

- Characterization of REE accessory minerals
- Characterization of reactive processes associated with leaching
- Distribution and nature of REE carriers in ion-adsorption REE deposits

Mineral processing

The separation of REE-bearing minerals requires complex unit operations, often consisting of crushing, grinding (without creating too much fines but just sufficient to liberate the minerals), classification, gravity separation and/or magnetic separation, before or after bulk or selective flotation of value minerals.

Review of the available literature shows the need for innovative approaches to close or at least narrow the key technological gaps related to physical separation (gravity and magnetic) followed by flotation. The main approaches for closing these gaps include but are not limited to opportunities for innovations as outlined below (with more details in Appendix B: Mineral processing):

- The development of generic grinding schemes that allow the liberation of individual RE minerals at coarse grind, thereby reducing the amount of hard-to-float ultrafine RE mineral particles.

- Rejection of sterile host rocks after crushing with emerging ore-sorting technologies that are gaining greater acceptance will allow a more efficient processing of ores containing one or multiple RE minerals.
- Development of a collector mixing strategy to maximize RE minerals recovery by flotation.
- Appropriate testing of RE minerals flotation is essential for development of the most efficient flowsheet.

Hydrometallurgy

By far the most challenging processing step is that of REE hydrometallurgy. According to the literature, specific research needs are as follows:

- Process fundamentals
- Leaching of REE from ores or concentrates
- REE elements recovery, separation and purification
- Hydrometallurgy process simulation and optimization, process control and automation
- Environmental control through reagent recycling and green processing

A much more detailed discussion of each of these research needs is contained in Appendix C: Hydrometallurgy.

Other potential R&D areas

The literature identifies several other areas where more work is needed to help establish a sustainable REE industry in Canada.

- Reference materials: The availability of credible rare earth element reference materials has been identified as a potential area for further work. Development of these reference materials would provide industry with a standard reference for reporting and analytical purposes.
- Radioactivity/thorium issue: The management of radioactive thorium from REE processing is less of a technical issue and more of a process issue both from the regulatory standpoint and that of social responsibility. All REE companies have concerns regarding the radioactivity/thorium issue. Market-ready REE concentrate must be uranium and thorium free. Companies that use REE powders to make magnets do not want to manage the radioactivity issue.
- Recycling: The recovery of REE from end-of-life high-tech products is a priority in countries such as Japan and Europe that have no or limited primary REE resources. The development of recycling options is constrained by a lack of efficient collection systems, the challenge of effective and safe disassembly and treatment [see Appendix D: Feedback from industry on REE Recycling and the results of the consultation process].
- Toxicity of REE: Some work on the toxicity of REE has been undertaken in the US although a comprehensive review of it and associated environmental impacts does not appear to have been undertaken.

Findings: Consultations

Industry

Consultations with Canadian rare earth industry have provided great insight regarding the gaps in knowledge and the opportunities for research and development in this area. In general, industry consultations validated the need for R&D in processing of rare earths particularly the concentration and separations steps. Table 1 summarizes these consultations. Details of these consultations are provided in Appendix E: Consultations at Technology Metals Summit, Toronto, Feb. 1-2, 2012.

Table 1: Results from industry consultations

Company	R&D gaps/issues	Other issues
Avalon Rare Metals Inc.	Separation step and certification of reference materials	HQPs, whether to process in Canada or the US; calling for greater collaboration among CDN REE companies.
Matamec Explorations Inc.	Interested in discussing R&D gaps	
Medallion Resources	Well advanced in metallurgy but interested in participating in NRCan project on separation	Installation of a processing plant in N.B.; facility permitting issues re radioactive wastes
Quest Rare Minerals Ltd.	Mineralization characterization and particle liberation, processing and optimizing recovery of the REE	REE processing facility
Pele Mountain	Using acid-baking process, piloting next year, welcomes CANMET involvement	Need for a Canadian refinery, radioactivity
Hudson Resources (foreign deposit)	Have conducted gravity separation, magnetic and heavy media separation only	Willing to provide samples
Ucore (foreign deposit)	Using ore sorting to recover 97% of the contained REE into 46% of the mass. Leach recovery of 90% of the rare earth elements plus Yttrium.	Willing to provide samples
IAMGold	Hosted in carbonatite rock, has a grade of 1.65% total rare-earth oxides, with light rare earths making up over 95% of that.	
GéoMéga	Optimization of the separation process; increase efficiencies, reduce the amount of reagents and acids required. Physical separation of REE	Willing to provide samples
Non mining/exploration companies		
Netchem Inc. (REE broker)	Certified reference materials	Must assay all REE materials imported to Canada to ensure quality
Dacha (REE broker)	Canada currently does not possess the technical know-how to concentrate and separate REE	

The Provinces and Territories

A quick scan of the provinces and territories was undertaken to determine whether they have engaged in any R&D activities where REE are concerned. Some of these consultations were conducted by telephone and some were conducted face-to-face at the PDAC conference in Toronto (March 5-7, 2012).

A detailed summary of these discussions is provided in Appendix F: Summary of Provincial and Territorial consultations. Collectively the following points of interest were gathered:

- With the exception of Saskatchewan, no province or territory appears to be directly funding or undertaking research where REE are concerned — while most of the work done by the Saskatchewan Research Council is client driven, some funding from the province may be supporting some R&D.
- It was observed that there are knowledge gaps in the REE sector.
- Some provinces have assigned staff members the responsibility of following the REE file.
- There is lots of interest in following any developments concerning REE that MMS may decide to pursue (including this Gaps Analysis).

There appears to be good potential to assemble a group of provincial/territorial representatives to peer review any work reports generated by the REE project.

Other Federal Government Departments

Only two other Government of Canada departments were consulted to see if they have any R&D activities aimed at REE: Environment Canada and the National Research Council. Appendix G: Summary of consultations with other Federal Government departments contains more details of those investigations. In brief, Environment Canada has a small contract underway entitled "Review of the Rare Earth Elements and Lithium Mining Sector". This project should be complete by March 31, 2012. The focus of this work is "substances of concern" (i.e. wastes and effluents) resulting from the mining and processing stages associated with REE and lithium. The results of this work will be used to inform Environment Canada's evaluation of its Metal Mining Effluent Regulations.

Academia

Canadian universities are home to a great deal of innovation and research in all scientific fields. Since there are nearly 100 universities and colleges in Canada, MMSL staff identified the ones that were likely to be involved in mining, geology, materials engineering and metallurgy (etc.) and these ones were contacted to find out if any R&D work into REE was being conducted. The institutes contacted were, from west to east: University of British Columbia (UBC), University of Alberta, University of Saskatchewan (U. of S.), Laurentian University, University of Toronto (U. of T.), Queens University, University of Waterloo, McGill University, Laval University, Ecole-Polytechnique, Dalhousie University and Memorial University. A review of grants and awards at Natural Sciences and Engineering Research Council of Canada (NSERC) for the years 2009, 2010 and 2011 was also reviewed to see if any REE projects had been supported.

The information assembled from these schools is attached in Appendix H: Summary of investigations regarding academic research activities. In brief, the following observations of note can be made about current research activities in Canadian at the institutes identified in the previous paragraph:

- Avalon Rare Metals Inc. has been very active supporting research into REE at a number of Canadian universities because of the widespread understanding that knowledge in this sector in Developed Countries is extremely low when compared to China. Avalon representatives have delivered lectures and have organized student led project work on specific REE mining or metallurgical issues (UBC, University of Toronto, Waterloo and Schulich School of Management).

- Professor Grosvenor at U. of S. is studying how structural and compositional changes affect the electronic structure of rare-earth (and transition-metal) oxides, silicates, and pnictides using X-ray spectroscopy. Of interest, which materials are capable of sequestering uranium? In his group, various materials are synthesized and their electronic structure and surface reactivity to different oxidizing environments are investigated by X-ray photoelectron spectroscopy and X-ray absorption spectroscopy, using the Canadian Light Source (CLS) and the Advanced Photon Source (APS). Several projects are underway and their summaries are provided in Appendix H.

- Professor Papangelakis at U. of T. is working on RE metal extraction by atmospheric leaching from clay materials. A published article is anticipated shortly in the journal Hydrometallurgy.

- Professor Waters at McGill is looking at understanding the physico-chemical properties of minerals associated with REE deposits in order to improve the development of processing flowsheets.

- The *Département des génies civil, géologique et des mines* at Ecole-Polytechnique is involved in areas of research involving neutron activation analysis that can be used in a geochemical manner to identify rare earth elements and platinum group metals in rocks formations and mineral deposits.

- Professor Kipouros at Dalhousie appears to have had private sector experience in the past with the development of the rare earth magnet technology that was eventually transferred to Magnequench when it was based in Indiana, US. At Dalhousie he maintains a small REE group but it has little funding. Professor Kipouros has been working on the extraction of rare earths and the preparation of anhydrous rare earth halides and on this subject he will shortly be making several conference presentations.

- Professor Piercy at Memorial is not directly involved in REE research but he has identified various colleagues with the following skills and interests: timing of REE mineralization using geochronology; mineralogy, isotopic tracing, geochemistry and REE genesis; and isotope systematics of REE mineralization (see Appendix H for more details).

- The only NSERC project recently funded was undertaken by Raman Kashyap at the École Polytechnique. The project, entitled “Solid state optical cooling with rare earth and

quantum doT doped glasses and crystals in semiconductors," evidently focuses much further along the life cycle of REE.

Other countries

As indicated previously, consultation with our partners in the inter-governmental consortium will occur at the end of March 2012 at its next meeting in Japan. The nature of this consultation is still being developed but is likely to involve all of the projects that have been proposed thus far (attached in Appendix H). If Canada is in a position to identify its preferred projects by that time, that information will also be presented for consortium feedback.

In January a CANMET-MMSL representative (Tesfaye Negeri) attended a meeting in Washington DC to hear a presentation by David Sandalow (US Department of Energy) on REE and to meet with Dr. Diana Bauer (also DoE), the US representative on the consortium. A summary from these meetings follows:

- Japan's research is overwhelmingly focussed on technology related to the production of permanent magnets, the recycling of REE from end-of-life products, and the search for REE substitutes for permanent magnets.

- The US research initiatives, interests and strategies are aligned with those of Japan. The two countries have had extensive dialogue although there are no exchange agreements in place yet. According to the "Clean Energy Cooperation communiqué" (US-Japan Clean Energy Cooperation), there is no mention of resource diversification (i.e. mining and processing), which is one of Canada's main interests. This is another indication of the gap that exists in terms of separation/processing. Although there has been a huge investment made by both governments related to REE substitution research, no breakthroughs have yet been reported. Both governments are particularly interested in the production of permanent magnets with reduced or no REE components. There is intent to bring together researchers from both countries to explore collaborations, but there is no firm mechanism in place yet.

- Notwithstanding the observation above, the US recognizes the importance of research into primary resources and it is anticipated that a good portion of the new $30 million budget being allocated to REE research will go towards the development of environmentally sound separation and processing.

- The European Union has shown more interest in recycling of specially phosphors, 30% of which is currently recycled. They support a policy framework in which the global supply of REE is diversified and freely accessible so as to reduce the monopoly presently enjoyed by China. It is also believed that they are promoting exploration and research on materials efficiency and substitute materials.

- Australia is more interested in the production of REE from primary resources. Efforts to determine their specific REE research activities have been fruitless to date but this intelligence can be gathered at the consortium meeting at the end of March.

Recent discussions with Germany, Finland and Japan (JOGMEC) indicate a high degree of interest in bi-/multi-lateral cooperation on the REE file.

The 2nd Trilateral EU-Japan-U.S. Conference on Critical Materials (Inter-governmental consortium), March 27-28, 2012

A representative from NRCan attended the consortium meeting in Japan and presented an update on Canada's plans to undertake research and development regarding heavy rare earth elements. The actual presentation is attached in Appendix G of the April 2012 Quarterly Report. In summary, Canada's focus on the mining and metallurgical end of the REE value chain was widely supported to the extent that some collaboration with our consortium partners may be possible (this will be pursued more vigorously once selected project details are ironed out and funding gaps understood).

It should also be noted in this section that several countries that have national laboratories provide substantial technical support for their domestic companies. It is however uncertain to what degree these labs embark on innovative R&D for the benefit of the entire REE sector. Some of the better known laboratories are as follows:

Ames Laboratory is a US government-owned, contractor-operated research facility linked to the Department of Energy and operated by Iowa State University. From their web site:

> *With a history spanning more than 60 years of pioneering work in rare-earth research, the Ames Laboratory and its team of internationally recognized rare-earth experts is uniquely positioned to provide the knowledge, expertise and training necessary to help ensure a global leadership position for the United States in rare-earth research, development and applications.* (http://www.ameslab.gov/rare-earth-metals)

ANSTO Minerals (Process Development Research, Australian Nuclear Science and Technology Organisation). From the ANSTO web site:

> *ANSTO Minerals has been working in the rare earth processing area for the since 1990 and we have been involved in process development for major projects like Lynas, Arafura and Alkane. Our main activities are commercially funded and we have R&D programmes spanning bench scale studies to pilot plants and demonstration plants. We also carry our own independent research, albeit at a fairly modest scale. We specialise in hydrometallurgical flowsheets but and have a strong background in acid baking, caustic cracking and solvent extraction processes relating to rare earths. (*www.ansto.gov.au)

Stans Energy Corporation is a Canadian company with metal interests in areas of the former Soviet Union and they have engaged the services of **Russian Research Institute of Chemical Technology**. From the Stans web site:

> *The Russian Research Institute of Chemical Technology (VNIIHT) was founded in April 1951. VNIIHT's objective was to focus on the exploration and development of technologies and raw materials for use in the Soviet nuclear energy sector. VNIIHT technologies were, and continue to be implemented during the main stages of the nuclear fuel cycle. This includes the processing of Uranium and Rare Metal Ores through to the generation of nuclear-pure materials. VNIIHT's sixty years of chemical technology*

experience combined with their capabilities of executing the complete cycle of rare earths research, development, and production[1] *…* enables it to provide extensive technical support to its customers.

Private engineering firms

There are a number of engineering firms in Canada that provide consulting services directly to mining, mineral processing and metallurgical industries. It is generally understood that these firms provide laboratory, analytical and technology support on a full cash recovery basis and therefore their work is completely client driven.

In Canada the engineering firms working on rare earth element projects are COREM, ORTECH, SNC-Lavalin and SGS Lakefield. Some Canadian exploration companies are using American firms as well such as Hazen Research Inc.

Next steps

Two papers have been simultaneously prepared: the Gaps Analysis and the Policy Framework paper. Both of these are being circulated for review and comment to the Working (Advisory) Group and possibly other stakeholders. Following this process, these papers will be finalized.

Parts of the Gaps Analysis were presented at the inter-government consortium meeting at the end of March in Japan for the purposes of eliciting feedback as discussed previously.

Meanwhile 7-8 project concepts were developed and circulated to the Working Group for review. These projects have been informed by the review of existing REE literature as well as the consultation process summarized in this document. It was intended that the Working Group identify preferred R&D projects to be undertaken over the next two years but that assessment was inclusive so project proponents were asked to develop Statements of Work outlining in more details, tasks, timelines, deliverables and a budget.

Finally, based on the consultations, it is apparent that many companies and consortium partners are very interested in the R&D plans that MMS staff members have been consulting on. In that regard, a peer review group may be established, drawing from industry, academia and the provinces and territories, to make sure that the work going forward is relevant and beneficial for both Canada and the world. Over the next two years MMS may also decide to establish a domestic consortium of sorts for the purposes of assembling financial and technical resources to continue the science and the R&D work into critical and rare earth metals that is being initiated with this OERD supported project as well as other private and public sector work.

[1] http://www.stansenergy.com/press-releases/stans-energy-appoints-vniiht-to-oversee-design-build-process-at-kutesay-ii/

Appendix A: REE Mineral Characterization

Characterization of REE accessory minerals

Each deposit has typically a variety of REE carriers. It is critical to measure the distribution of the different REE between those various phases in order to evaluate the most efficient concentration and extraction processes. Although conventional image analysis and X-ray microanalysis tools are now able to efficiently characterize the nature, morphology and compositions of micrometer-sized grains with complex REE chemistry, they are typically inadequate for the significant proportion of REE often concentrated in small interstitial fractures and at grain boundaries. The recent introduction of the field-emission electron probe X-ray microanalyzer (FE-EPMA) capable of sub-micrometer analytical spatial resolution may become a very important tool to properly characterize the chemistry of grain boundary segregation but it will require some development in the spectral analysis and quantification of low-energy characteristic X-ray lines. Additionally, state-of-the-art micro X-ray diffraction techniques could be adapted to provide structural information of these fine REE-bearing phases.

Characterization of reactive processes associated with leaching

To support the research efforts on the optimization of innovative leaching techniques during REE production, it is critical to have the ability to properly characterize the surface evolution during the reactive process. Expertise and innovation in state-of-the-art surface analyses, such as X-ray photoelectron spectroscopy (XPS) and secondary ion mass spectrometry (SIMS), will therefore be important to understand the composition and speciation of surface reaction products.

Distribution and nature of REE carriers in ion-adsorption REE deposits

Occurrences of potential ion adsorption REE mineralization outside China are now documented and it is believed that more deposits showing similar characteristics will be discovered. These deposit types are the result of complex weathering processes that redistribute and also fractionate the various REE which are eventually adsorbed on high-surface area phases such as clay. Consequently, the REE are not concentrated in discrete phases but finely dispersed in the weathered material. In order to evaluate the potential of such deposits, it is critical to understand the distribution of the different REE and evaluate the proportion in ion-exchangeable form. The detailed mineralogical characterization of this type of mineralization represents a significant challenge.

- First it is important to have the ability to determine the distribution of elements finely dispersed in minor to trace abundances. For this purpose, a microanalytical scanning technique with very high sensitivity for the REE is needed. In this context, when excited by energetic electrons, electronic transitions between the partially filled 4f orbital of REE give rise to sharp element-specific visible and near-infrared (NIR) luminescence peaks. Taking advantage of this property, monochromatic cathodoluminescence imaging using a field-emission scanning electron microscope (SEM) could provide the required sensitivity at optimal spatial resolution (submicrometer).

- Second, an evaluation of the local molecular structure of the REE using synchrotron-based extended X-ray absorption fine structure (EXAFS) spectroscopy may be essential to define the proportion and nature of the sorbed REE species, such information being important in the development of leaching processes that will optimize recovery.

Appendix B: Mineral processing

The separation of REE-bearing minerals requires complex unit operations; often consisting of crushing, grinding (without creating too much fines but just sufficient to liberate the minerals), classification, gravity separation and/or magnetic separation, before or after bulk or selective flotation of value minerals. De-sliming of flotation feed appears to be a requirement for efficient flotation. In many instances, the flotation of these minerals requires heating the flotation pulp to a boiling point, whereas in a few instances heating the pulp to about 45oC is sufficient. Such complex unit operations naturally require the development of physical separation flowsheet unique to individual operation.

Literature survey also shows the non-existent of generic/conceptual flowsheet for the separation of RE minerals from the gangue by flotation. In comparison, such generic flowsheets exist for the downstream extraction processes. In general, there have been no breakthroughs in the development of uniquely suited collectors for efficient flotation of major RE minerals, namely bastnaesite, monazite and xenotime, although extensive testing of various combinations of chemicals was made by the Chinese to activate the rare earth metal bearing minerals while depressing the accompanying rock forming minerals of lesser values.

As a result of the flowsheet complexity and the non-specificity of flotation reagents the current applicable mineral processing techniques appear to be inefficient in terms of concentrate grade, metal recovery, energy consumption and environmental performances. The overall recoveries of RE minerals in comparison to other industrial minerals and base metal minerals are relatively low; 60-70% at 50-60% total rare earth oxide (TREO) in the concentrate. The Chinese report an estimated recovery of as low as 10% of RE minerals from the Baiyun Obo iron production operation, where 90% of the contained thorium (Th) is rejected to the tailings, raising not only the environment related concerns but also the loss of this valuable resource.

Improving the recovery of RE minerals translates in to (a) maximizing the utilization of non-renewable and rare resources, a challenge that requires further refinement of existing technologies and the development of new ones (b) maximizing the removal of thorium and uranium (U)-bearing minerals (which almost always coexist with REE minerals) from the tailings, thereby improving the environmental performance of the operations. This equally requires very innovative approach to processing specifically by flotation, where the desirable final concentrate grade is higher than 60% TREO to render the downstream hydrometallurgical treatment flowsheet less complex, more economic, and more environmentally efficient. If the concentrate is not free of some of the gangue minerals, subsequent roasting with sulphuric acid will generate harmful gases such as hydrofluoric acid, sulphur dioxide, etc. and voluminous slag, a slag that is sometimes radioactive.

Review of the available literature shows the need for innovative approaches to close or at least narrow the key technological gaps related to physical separation (gravity and magnetic) followed by flotation. The main approaches to closing the gap includes but not limited to opportunities for innovations as outlined below:

- The development of generic grinding schemes that allow the liberation of individual RE minerals at coarse grind, thereby reducing the amount of hard-to-float ultrafine RE mineral particles. One innovative approach that has not yet been tried is size-by-size flotation. In flotation, the physical, chemical and hydrodynamic conditions that favour maximum recovery of coarse mineral particles are always at odds with conditions that favour fine particles. It is assumed that this is one of the areas where significant advancement can be made. The experience we gained from the fine particles recovery project we conducted over an extended period of times will come handy. Developments of efficient processes that do not require high temperature flotation are in high demand.

- Rejection of sterile host rocks after crushing using the emerging ore-sorting technologies which are gaining greater acceptance will allow a more efficient processing of ores containing one or multiple REE minerals. This will result in the processing of only 60 to 70 percent of the ore mined; savings in energy, water and reagent costs, improved concentrate grade, mineral recovery and scaled down processing, extraction and waste disposal facilities (capital investment and operating expenses).

- Development of collector mixing strategy to maximize REE minerals recovery by flotation. Currently there are no specific collectors suitable for the RE minerals recovery unlike in the case of base metals and industrial minerals flotation for which numerous families of commercially available reagents which have been synthesised based on decades of research. The processing of rare earth minerals has not captured the attention of process chemical industries hence the non availability of specific reagents. Only in China some work has been done to identify potentially useful collectors. The lack of systematic research in the area of rare earth minerals flotation is the main reason why the recovery is relatively low by the mineral industry standards. Currently a cocktail of collectors of varying chemical structures are used in almost all the cases. None of the published information shows how the mixing ratio may be determined. Our own experience with base metal minerals flotation efficiency improvement research has convinced us that mixing collectors can result in better grade and recovery of minerals. In that respect, we have developed statistical design based procedure of formulating collectors for specific applications, a knowledge that has been successfully transferred to the industry. We intend to employ this procedure in determining the best suite of collectors for substantially increased rare earth minerals recovery.

- Appropriate testing of REE minerals flotation is essential for development of the most efficient flowsheet. There are indications that the REE minerals are sensitive to moisture and air (just like base metal minerals) and should be processed by flotation immediately after crushing and grinding. In many of the test work reviewed, this has not been recognized, and no such precautions have been taken. This needs to be confirmed through further research, because it is often believed that only sulphide minerals are inclined to oxidation resulting in poor flotation.

Appendix C: Hydrometallurgy

By far the most challenging processing step is that of REE hydrometallurgy. Specific research needs are as follows:

Process fundamentals

- Studies on rare earth complexation chemistry in both aqueous and organic phases. This effort will allow for the invention of new chemicals, complexing agents for dissolving the REE elements from ores and will also lead to innovations in high efficient solvent extraction (separation) systems.

Leaching of REE from ores or concentrates

Leaching is an unavoidable step for the production of REE. The practice and research in REE leaching are primarily focused on acid leach.

- Although roasting is not a hydrometallurgy process, it has been an important step in the overall hydrometallurgy process for destructing REE-bearing ores. At least four major processes that have been active in REE production in China are using roasting as the pretreatment step before leach. To catch up this development, Canada needs to study these four processes and evaluate application to Canadian ores. Three processes are:
    - Concentrated Sulfuric Acid Roasting (high temperature or low temperature roasting)
    - Intensified Concentrated Sulfuric Acid Roasting (high temperature roasting)
    - CaO-NaCl Roasting
    - Na_2CO3 Roasting

- Alkaline leaching has become the major process in China for processing rock type REE ores. This process, however, has not yet been thoroughly investigated or applied in North America.

- Other processes include:

    - Alkaline high-pressure autoclave process
    - Mineral destruction in ultrafine grinding mill is an innovative technology (still developing) that can avoid the use of high concentrations of acid or alkali.
    - Ionic REE deposits heap leaching or in situ leaching.

REE elements recovery, separation and purification

This step typically uses precipitation, or solvent extraction technologies to separate REE elements from solution and then each REE element from others.

- Among the many topics in this area, the separation of U and Th (radioactive elements) from REE is of special importance in Canada.
- Liquid membrane permeation (LMP) has been an efficient technology in recovering REE from the leaching solutions. Such technology is not new in hydrometallurgy world, but still need to be thoroughly studied for REE productions.
- Cascade countercurrent solvent extraction is widely used in Chinese REE production. The principle of this technology is not entirely new but the application is much more complicated are valuable for Canadian producers.
- In the past 2-3 decades, Chinese scientists have invented and perfected several solvents that play an important role in their current flowsheet. These solvents must be imported and carefully studied for Canadian production need.
- Innovative solvent and organic metal ligands can help to maximize the production rate and reduce the environmental pressure.
- In the production of high purity product, the extraction chromatography technology appeared to be a new and effective method. This method has been applied by some Chinese producers and shall be studied for Canadian producers if we are to produce higher purity matters.
- Development in solvent extraction field can be used in REE production and will largely increase the economics and environmental rating of the process: microwave intensified SX, ultrasound intensified SX, magnetic intensified SX, froth flotation SX and certainly the very attractive centrifuge SX technologies.

Hydrometallurgy process simulation and optimization, process control and automation

This development is essential for the industry players to conduct their production in an efficient way. With the application of various new technologies in the production of rare earth nowadays, the process become more and more complicated, this is especially true for the precipitation and solvent extraction step. These complicated processes exist because they largely enhance the production rate, reduce the use of chemicals and minimize the environmental problems.

- Cascade counter current solvent extraction is a difficult process in operation. Expert system and automatic control are needed for a stable production rate and product quality.
- Multiple inlet and multiple outlet solvent extraction production flowsheet is widely used in separation and purification of REE. The flowsheet design, monitor and automation are critical to the success of such a complicated process.
- Online element analysis technologies, such as XRF energy emission online monitor are used in production for providing accurate and real-time data. Such a technology is a must-have for REE producers nowadays.

Environmental control through reagent recycling and green

- Saponification is a step for treating organic solvent. Such an operation generated significant amount of waste water containing NH3/NH4. New technologies that minimize the N pollution or even completely remove N from the flowsheet are under development.
- The use of large amount of acid or alkali eventually will generate large amount of discharge of salts. Technologies that reduce the dosage of these chemicals are therefore very important for Canadian producers.

Appendix D: Feedback from industry on REE Recycling

Consultation with REE companies was carried out at the Technology Metals Summit held in Toronto Feb. 4-5, 2012 to identify the economic and technical feasibility of REE recycling from end-of-life products. Some of the summit's presentations and panels discussed REE recycling and related issues. A brief summary of the consultations and comments follows.

- In general, not much interest was expressed at the summit in recycling end-of-life products containing REE. However, many companies are already involved in internal/in-house recycling of their process by-products.
- End-of-life products contain only very small amounts of REE, making the recycling process extremely difficult and un-economical.
- The recycling infrastructure for collection, dismantling and separation of REE from end-of-life products has not yet been developed. The recyclability of REE is currently limited to internal/in-house recycling by a lack of commercially proven technical and economical capabilities to effectively separate, identify, and sort materials and components from end-of-life products.
- It will take some time and investment before recycling increases for end-of-life products and the high price of REE will drive this recycling.

Notes on REE Recycling (from REE World's Technology Metals Summit)

- Constantine Karayannopoulos, NEO Material Technologies Inc.: Magnet scrap and Nd sludge has been recycled in sintered magnet production. Gallium and Indium are recycled. When prices of REE increase, more recycling make sense. Spending a lot of money on recycling technology for certain REE whose prices may fall in the next few years is not worth the effort. End-of-life product recycling is difficult and is not going to increase soon.
- Scott Moore, DACHA Strategic Metals Inc.: It will take a long time before recycling increases for end-of-life products but the high price of REE will be the key driver.
- Pierre Neatby, Avalon Rare Metals Inc.: High investment is required for end-of-life product recycling. Presently, there is no interest in end-of-life product recycling.
- Gary L. Billingsley Great Western Minerals Group Ltd.: A number of companies are trying to reduce the use of REE or find a substitute such as replacing Nd-B-Fe magnets with Sm-Co magnets.

- Daniel J. Cordier, National Minerals Information Center U.S. Geological Survey: The USGS is not involved with REE recycling but he could provide REE data from end-of-life products containing REE such as hard disk drives, cell phones, etc.
- Peter J. Cashin, Quest Rare Minerals Ltd.: Only internal/in-house recycling of process by-products and no future plans for end-of-life products recycling.
- Dr. Steven J. Duclos, General Electric Global Research Center: Recycling and material substitution should be a main part of any REE strategy. However, only internal recycling is being done and not the end-of-life products, which are very important.

Appendix E: Consultations at Technology Metals Summit, Toronto, Feb. 1-2, 2012

For the purposes of developing an R&D work plan for rare earth elements, to be implemented over the next few years, and to make sure such work is relevant and cross-cutting, MMS staff members consulted with Canadian companies and experts directly and currently involved in the rare earth elements sector at REE World's Technology Metals Summit. A summary of those discussions follows:

Consultation with Avalon Rare Metals (Ian M. London)

What significant knowledge/technology gaps currently exist in the Canadian REE sector?

There are not enough educated, qualified people in Canada to support the growth of this sector. As a result, Avalon is actively involved in supporting R&D at CDN universities. In this regard and in others, more collaboration is needed between industry and governments.

What are your priority R&D issues? (e.g. environment, energy efficiency, processing?)

To process REE in Canada or not, that is the question. For the separation stage, need power and chemicals. This has prompted Avalon to consider Southern Ontario or the US south. So Avalon's focus these days is determining how far along the supply chain they can go.

How are you addressing these issues?

Avalon is helping to organize the first ever Rare Earths Symposium at the 51st Annual Conference of Metallurgists (COM 2012). It will take place in Niagara Falls, Ontario, September 30 to October 3, 2012. They have invited NRCan to submit a paper: they need some Canadian content.

Do you have sufficient in-house R&D capacity or is this something you are contracting out?

We didn't get a chance to discuss this.

Consultation with Dacha Strategic Metals Inc. (Alistair Neill)

What significant knowledge/technology gaps currently exist in the Canadian REE sector?

The mineralogical characterization for REE is very complex and so it is very difficult to liberate the target material from the rock structure. In Canada, the knowledge and technology for separating REE efficiently does not seem to exist.

What are your priority R&D issues? (e.g. environment, energy efficiency, processing?)

As per note at bottom, Dacha is a REE broker/consultant that ware-houses supply.

How are you addressing these issues? *n/a*

Do you have sufficient in-house R&D capacity or is this something you are contracting out?

From http://www.dachametals.com, the corporate overview:

The Corporation's primary objective is to achieve, through its wholly-owned subsidiaries, long-term capital appreciation through the buying, holding and selling of Strategic Minerals, particularly, Rare Earth Elements, which are predominantly supplied by China. The Corporation seeks to achieve this objective by investing in difficult to access markets by establishing trading relationships and purchasing stockpiles of Strategic Minerals. An investment in the Corporation provides an investment alternative for investors interested in gaining exposure to Strategic Minerals without the risks inherent to mining companies.

The Corporation intends that the majority of the funds it raises from time to time will be invested by the Operator to purchase and store inventories of Strategic Minerals in warehouses around the world which have been approved by the London Metals Exchange or the Minor Metals Trade Association. Most of the Strategic Minerals purchased by the Operator are held, following delivery, at licensed warehouse facilities outside of China. The Corporation generates value by (i) assembling a portfolio of Strategic Minerals that it believes has the greatest potential for capital appreciation and thereafter employing a "buy and hold" investment strategy; and (ii) opportunistically trading from time to time to realize gains to meet its investment objectives.

Consultation with GéoMégA (Simon Britt)

What significant knowledge/technology gaps currently exist in the Canadian REE sector?

They have no problems with the concentration stage but the next stage, separation, is the big challenge. China is using Molycorp technology from 30 years ago: that process requires lots of chemicals and acids.

What are your priority R&D issues? (e.g. environment, energy efficiency, processing?)

He would like to optimize the separation process; increase efficiencies, reduce the amount of reagents and acids required. Is there some physical way to separate the REE?

How are you addressing these issues?

They are working with Quebec universities such as Laval and Polytechniques. They would be willing to send a sample of their ore to CANMET for analysis.

Do you have sufficient in-house R&D capacity or is this something you are contracting out?

See above.

Consultation with Matamec (André Gauthier)

What significant knowledge/technology gaps currently exist in the Canadian REE sector?

Matamec is very interested in talking about their R&D issues and needs however there was not enough time to pursue these discussions at the Summit. Fortunately, André plans to pass through Ottawa the week of Feb-13. I told him I would coordinate a meeting with CANMET-MMSL at a time convenient for him.

What are your priority R&D issues? (e.g. environment, energy efficiency, processing?)

Not discussed.

How are you addressing these issues? (March 2012 announcement)

Mr. Paul Blatter has been appointed Director of Metallurgy for Matamec Explorations Inc. Mr. Blatter holds a B.Sc. in Metallurgical Engineering (1999) from McGill University in Montreal, Canada, and he is a member of l'Ordre des Ingénieurs du Québec.

He joins Matamec to lead the mill process design team during the feasibility study, construction phase, and, subsequently, the mill commissioning, start-up, and operation. The Company will use his strong ore processing background, his experience in R&D, and his improvement skills to maximise the value from a new and challenging ore. He will also take on new challenges associated with REE ore valuation.

Do you have sufficient in-house R&D capacity or is this something you are contracting out?

Not discussed but are working with Laval and Polytechniques in Quebec.

From http://www.matamec.com, the corporate overview:
Matamec Explorations Inc is a junior mining exploration company whose main focus is in developing the Kipawa deposit. It is also exploring more than 35km of strike length in the Kipawa Alkalic Complex for rare earths-yttrium-zirconium-niobium-tantalum mineralization on the surrounding Zeus property. A timely, high value and low cost mine is projected for early 2016.

Consultation with Medallion (Bill Bird and Don Lay)

What significant knowledge/technology gaps currently exist in the Canadian REE sector?

Medallion is looking for a good location in Canada to build a REE separation plant. They've recently shifted their focus from Nova Scotia to New Brunswick mostly because of the radioactive waste issue. NB has a nuclear reactor so it's familiar with the issue. A deep water port would allow them to import all of the feedstock they'd need to separate REE. Their focus is monazite because the technology for processing that is well known and already used.

What are your priority R&D issues? (e.g. environment, energy efficiency, processing?)

Their first priority is to get a permit to manage radioactive waste. Can we help them with that? http://www.nuclearsafety.gc.ca/eng/about/regulated/minesmills/index.cfm

How are you addressing these issues?

They can handle all of the metallurgy (it's appears to be off-the-shelf technology). However, if the Federal Government is undertaking some R&D into REE separation, they would be willing to participate.

Do you have sufficient in-house R&D capacity or is this something you are contracting out?

See response above.

Consultation with Netchem Inc. (Anil Choudhary)

What significant knowledge/technology gaps currently exist in the Canadian REE sector?

This company purchases and imports REO for re-export. However, he cannot be sure of the quality of material that he buys so all product is sampled and analysed before the purchase is completed. Then the shipment can be moved out of China.

What are your priority R&D issues? (e.g. environment, energy efficiency, processing?)

For his purposes, a certified reference material would be invaluable.

How are you addressing these issues?

He contracts his own assays and lab analyses.

Do you have sufficient in-house R&D capacity or is this something you are contracting out?

Not applicable.

Consultation with Pele Mountain (Al Shefsky and Roger Payne)

What significant knowledge/technology gaps currently exist in the Canadian REE sector?

Al Shefsky believes that the industry should focus on establishing HREE refining capacity in Canada. Pele itself has enough local HREE resources to justify such a facility (their deep water port, etc. will help for the delivery of re-agents). Turn key REE plants and equipment are available from a Chinese/CDN vendor.

What are your priority R&D issues? (e.g. environment, energy efficiency, processing?)

Pele believes that their acid-baking process boosts REE recovery yields: improved efficiencies are always desired. Radioactive wastes are an ongoing issue. This deposit is monazite so the technology is well-understood whereas the Avalon and Quest mineralogy is different. The CDN Nuclear Assoc. will issue the facility permit because of the uranium part of the project. The province is involved but Al is not sure if they are investing in R&D.

How are you addressing these issues?

Pele stores their radioactive wastes underground. Al did not elaborate on what Pele is doing to encourage industry collaboration but he thought that a CDN REE separation facility was in the "national interest". A pilot processing plant is planned for next quarter and CANMET is welcome to play a role.

Do you have sufficient in-house R&D capacity or is this something you are contracting out?

SNC Lavalin is supervising work being undertaken at the Saskatchewan Research Council (Jack Zhang, 306-964-2008), Laurentian University (MIRARCO, talk to Roger Payne about their work with a PhD student on mine closure issues) and another company called Activation Laboratories Ltd. Senes and Golder are providing environment/waste management services.

Consultation with Quest Rare Minerals Ltd. (Peter Cashin, Reno Pressacco and Mehdi Azodi)

What significant knowledge/technology gaps currently exist in the Canadian REE sector?

Mineralization characterization and particle liberation were mentioned. Peter Cashin says more value is added downstream than at the mine site (this is probably subject to debate).

What are your priority R&D issues? (e.g. environment, energy efficiency, processing?)

Processing and optimizing recovery of the REE.

How are you addressing these issues?

Quest is talking to the Quebec govt. about the possibility of their support for a REE processing facility in that province. A REE facility would need abundant cheap power so presumably Quest is looking for an agreement with Quebec like the one the aluminum industry was able to establish.

Do you have sufficient in-house R&D capacity or is this something you are contracting out?

In addition to internal staff, Quest is using Hazen Research Inc. (http://www.hazenusa.com/) for some of their lab work. They are very interested in CANMET capabilities so MMSL will follow up with Peter Cashin.

Appendix F: Summary of Provincial and Territorial consultations

British Columbia (Energy & Mines)

- From the BC perspective, there is a need to FILL IN KNOWLEDGE GAPS, closely linking geology and metallurgy (much more than usual), as any extraction will likely be site specific.
- There are apparently significant differences between metallurgical approaches for different sites.
- Concentrate shipping may not get you much value as "general purpose" rare earth separation processes may not exist.
- All companies are pushing integrated approaches as they won't make money shipping concentrates (sounds like comments from Dean MacNeil of NRC-ICPET in Ottawa, but in a different Rare Earth context).
- An industry perspective is that prices may justify some deposits, but some may want to wait until the situation stabilizes in order to justify the risks of development.

Bill Howell spoke with George Simandl, Specialty Metals & Industrial Minerals, Victoria, BC george.simandl@gov.bc.ca, 250-952-0413

- Has a background in metallurgical (or mining) engineering and geology, and therefore has a crucial understanding of the importance of considering both for site-specific [mine, process, product, environment, market] development, including the strategic importance of vertical development.
- George has been following very closely geology and project intentions across Canada, and has been actively visiting properties.

Saskatchewan Government / Saskatchewan Research Council

- Janice Zinck spoke with Ranga Ranganathan Small team at SRC on REE led by Jack Zhang
- Doing mainly work for specific clients
- Not doing R&D per se
- Welcomed opportunity to collaborate
- Pilot scale facilities
- Site visit opportunity

- The Saskatchewan Geological Survey includes a geologist dedicated to Rare Earths. There has been significant REE exploration in SK, but there is no provincial special strategy or focus. While there is no SK strategy specific to Rare Earths (unlike potash and uranium), REE will be considered next year from a tax point of view.

Manitoba

- Janice Zinck spoke with Ernie Armitt and Ric Syme at PDAC
- They have no advanced REE projects
- They are not doing any R&D
- Have been involved in Targeted Geoscience Initiative
- Keep in the loop

Ontario

- Janice Zinck spoke with Dr. Michael Easton at PDAC
- They are not doing any R&D
- They have provided information to the Targeted Geoscience Initiative,
- have had some dealings with Pele Mountain
- Feel mineralogical work would be worthwhile
- From Bill Howell, Pam Sangster is the rare earths contact for Ontario, in terms of geology as well as commodities. Rare earths are at the top of a list of provincial mineral priorities.

Québec

- Bill Howell spoke with Denis Raymond. He is more involved with technology and science than policy. Another Quebec government contact is Charles Maurice.
- They do not yet have an "official" strategy or policy for Rare Earths, but they have certainly been looking at the exploration, exploitation, and environmental issues,
- interested in discussing R&D issues further and interested in a "gaps analysis" as well

Northwest Territories

- Bill Howell identified three key contacts in this region. John Ketchum and Luc Ootes are with the NWT government, and Scott Cairns is with INAC. Scott Cairns is involved in the development of an NWT Minerals Strategy, so any discussions and networking on Rare Earths may help that component of their strategy. John and Scott would be the primary NWT contacts, with Luc as a back-up. Luc explained the dominance of the Thor Lake deposit from a NWT perspective and as an important project for Canada.
- Reference was made to a student project on pegmatite (near Great Bear Lake?) plus an inquiry into the environmental nature of leachate from tailings (including aquatic toxicology), in collaboration with Heather Jamieson of Queen's University.

Nunavut

- Janice Zinck spoke with representative from Nunavut who identified David Mate (Chief Geologist at Nunavut Geoscience) as the key contact
- There are few small deposits in Nunavut
- No R&D indicated

Newfoundland & Labrador, Department of Natural Resources

- Bill Howell spoke with Bernadine Lawlor.
- She has been designated to follow Rare Earths and is interested in being in the loop on NRCan gap analysis and other REE activities.
- No official strategy, but there has been significant Rare Earths exploration in the last 2-3 years.
- There are several programs within the Mineral Development Division to encourage exploration including the Mineral Incentive program. Some of the assistance offered is financial support for programs undertaken by a specific company on its active mineral

claim. It also offers help to prospectors exploring a specific claim or Crown Land. A prospectors training course is also offered by the Division. Some of the companies applying for assistance may or may not be exploring for REE deposits.

http://www.nr.gov.nl.ca/nr/mines/exploration/mip/index.html

This Division also enforces *the Mining Act* when a company wants to forward into the development phase. This includes the Acceptance of a development plan, rehabilitation and closure plan and financial security. Prior to application to develop all companies must go through the Environmental Assessment Process; it is here that they will first outline the undertaking and its development.

Selected provincial & territorial rare earth contacts:

Québec	
Renée Garon. Exécutive Director, Dev industrie minerale. Ressources naturelles et faune. Québec <Renee.Garon@mrnf.gouv.qc.ca>	(418) 627-6292 x5600
Denis Raymond. Direction générale du développement de l'industrie minérale. Quebec <denis.raymond@mrnf.gouv.qc.ca>	(418) 627-6292 x5616
Ontario	
Pam Sangster. Geologist. Geological Survey. Tweed Office. Ontario <pam.sangster@ontario.ca>	(613) 478-5238
Saskatchewan	
Cory Hughes. Dir Mineral Policy. Energy & Resources. Saskatchewan <cory.hughes@gov.sk.ca>	(306) 787-3628
Jason Berenyi. Manager & Industrial Minerals Geologist. Geological Survey. Saskatchewan <jason.berenyi@gov.sk.ca>	(306) 787-2579
Newfoundland	
Alex Smith. Director. Mineral Development. Natural Resources. Newfoundland <asmith@gov.nl.ca>	(709) 729- 6379
Bernadine Lawlor. Analyst & Geologist. Mineral Development incl Rare Earths. Natural Resources. Newfoundland <bernadine.lawlor@gov.nl.ca>	(709) 729-6940
North-West Territories	
John Ketchum. Mgr Sr Geologist. NWT Geosciences Office. Yellowknife. NWT <John_Ketchum@gov.nt.ca>	(867) 669-2498
Hendrik Falck. District Geologist. NWT Geosciences Office. Yellowknife. NWT <hendrik_falck@gov.nt.ca>	(867) 669-2481
Luke Ootes. Metallogenist. NWT Geoscience Office. Yellowknife. NWT <Luke_Ootes@gov.nt.ca>	(867) 669-2641
Scott Cairns. Manager. INAC Geosciences Office. Yellowknife. NWT <Scott_Cairns@gov.nt.ca>	(867) 669-2479
British Columbia	
George Simandl. Specialty Metals & Ind Minerals. Energy & Mines. Victoria. BC <george.simandl@gov.bc.ca>	(250) 952-0413

The Research & Development Corporation (RDC), Newfoundland and Labrador

http://www.researchnl.com/index.htm GeoEXPLORE (2011-2013), currently funded projects:

- **Mineralogy, age and origin of rare metals at the Fox Harbour property, Port Hope Simpson, south eastern Labrador; $50,000**
  This project will enhance an understanding of the rare earth element (REE) potential for south eastern Labrador. Field mapping and analysis of samples will provide data on mineral compositions, age of the minerals, and the spatial distribution and origin of the REE mineralization, thereby assisting in the determination of the most prospective rock units for exploration. RDC's support will also help a full-time M.Sc. student expand his field experience and develop his analytical skills. RDC's investment is $50,000 of a total project cost of $108,216. The research team includes: Dr. Paul Sylvester (Memorial University); James Haley (M.Sc. student, Memorial University); Dr. Randy Miller (Search Minerals Inc.); and Dr. Charles Gower (Geological Survey of Newfoundland and Labrador).

- **The mineralogy and form of rare-metal mineralization in the Red Wine District, central Labrador; $53,200**
  This project seeks to provide a better understanding of the rare earth element (REE) mineralization in the Red Wine Mountains area of central Labrador. Several new prospects will be sampled and analyzed to identify the various mineral phases and their REE concentrations. This may lead to the recognition of a favourable mineralogy for REE mineralization as a guide to exploration, as well as understanding how REEs are disposed in the host minerals, an important consideration for potential mining and refining processes. RDC's investment is $53,200 of a total project cost of $91,950. The research team includes: Dr. Derek Wilton (Memorial University); Wayne Reid (Rare Earth Metals Inc.); and an undergraduate-level student.

- **Alteration and mineralization of the Pope's Hill rare earth element deposit, Labrador; $73,830**
  This project will research rare earth element (REE) mineralization in the Pope's Hill area, on the Trans Labrador Highway, to the west of Happy Valley-Goose Bay in south-central Labrador. Geological mapping will be carried out with mineralized samples taken for analysis. This will identify the REE-containing mineral phases and help define their relationship to the host-rock formations, all significant guides for further exploration. Important information will also be gathered on where, how and when the REEs originated and were emplaced with potential implications for the rest of Labrador. RDC's investment is $73,830 of a total project cost of $154,230. This includes support for a full-time M.Sc. student, both field and laboratory work and a part-time PhD student applying his expertise in isotope geochemistry to REE mineralization. The research team includes: Dr. John M. Hanchar (Memorial University); Peter Dimmell and other field personnel (Silver Spruce Resources Inc.); Alex N. Chafe (M.Sc. student, Memorial University); Christopher M. Fisher (PhD student, Memorial University), and Karalee McAskill (B.Sc. Honours student, Memorial University).

Appendix G: Summary of consultations with other Federal Government departments

Environment Canada

An Environment Canada project called "Review of the Rare Earth Elements and Lithium Mining Sector" (valued at $18,000 max.) was awarded October 2011. It is expected to be completed by March 31, 2012.

REQUIREMENT STATEMENT

Environment Canada (EC) has a requirement for consulting and professional services. The objective of this project is to develop a background information document on the rare earth elements and lithium mining sub-sectors with particular emphasis on the effective management of their environmental aspects. The report will consider these sub-sectors within Canada and internationally and will address their current state and the potential for future development in a Canadian context. The results of the study will inform Environment Canada's planned evaluation of the Metal Mining Effluent Regulations (MMER) as current regulatory standards with the intention of identifying any unique environmental aspects that must be considered in the context of these sub-sectors.

Under the guidance of the Departmental Representative, the contractor is required to produce a report containing:

- a discussion of the current and emerging markets for rare earth elements and lithium and what impacts these markets may have from a Canadian mining perspective;
- a discussion of the current rare earth elements and lithium mining activities in Canada and internationally and the potential for their future development;
- a discussion of the mining and processing methods that are currently applied to the extraction and processing of rare earth elements and lithium in China and internationally, coupled with the identification of the relative pros and cons of each methodology employed;
- a discussion of substances of concern in the solid waste and associated effluents, that are produced and must be effectively managed during the mining and processing of rare earth elements and lithium; and
- a discussion of and approaches to minimize the entry of substances of concern into site effluents.

BACKGROUND INFORMATION

This study is being undertaken in response to the global expanding market demand for rare earth elements and for lithium and the potential for associated impacts on the existing Canadian mining sector. While Environment Canada has considerable experience with the management of the environmental aspects of a broad range of metal mines, there are currently no lithium or rare earth elements mines operating in Canada. This drives the need to ensure that the current requirements of the MMER are adequate for these sub-sectors.

TASKS:

- Kick-off meeting;
- Information gathering;

- Discussion of the state of global markets for rare earth elements and lithium;
- Discussion of the state of rare earth elements and lithium mining in Canada and internationally;
- Discussion of the mining extraction and processing methods used for rare earth elements and lithium in China and internationally;
- Discussion of substances of concern that may be present in rare earth elements and lithium mining solid wastes and effluents; and
- Report Preparation.

The project contact is Sarah Bennett, Senior Program Engineer, Environment Canada Mining and Processing, 819-956-9279, Sarah.Bennett@ec.gc.ca

National Research Council

- Jean Bussière is heading up the rare earth activity in the NRC's new Energy, Mining and Environment Portfolio. His expertise in rare earths is presently unknown;
- Institute for Chemical Process and Environmental Technology (ICPET) & the Industrial Materials Institute (IMI) have been planning an initiative in this area (downstream, including recycling) for some time. Once the program is up and running there may be an activity in recycling batteries for rare earth recovery (but program direction is completely uncertain at this time).

Jean Bussière. Rare Earths. Energy-Mining-Environment. NRC of Canada, Bouchervile. Québec <Jean.Bussiere@imi.cnrc-nrc.gc.ca> 1-450-641-5252
Dean MacNeil. Research Officer - Recycle. NRC of Canada, Ottawa <Dean.MacNeil@nrc-cnrc.gc.ca> 1-613-990-1769

Geological Survey of Canada, ESS, NRCan

Mike Villeneuve (GSC TGI-4) has a background in REE deposits. Comments from Mike Villeneuve, GSC's Program Manager for TGI-4 are as follows:

- Rather than "Rare Earths", a better phrasing is "Critical Metals, as [Nb, Ta, Li] are often grouped with REE.
- Rare earths (which occur as surface manifestations) are a poor fit with TGI-4 (deep exploration program).
- While most of the provincial activity that I ran into with my survey was geology-oriented, the key issue for Mike is BENEFICIATION, and not exploration, as we already have a very good idea of multiple deposits for REE.
- Rare Earths are a difficult subject for geologists to resist because they are so complex, so different, and so interesting.

Bruce Kjarsgaard. ResSci - Rare earth & diamond exploration. NRCan-ESS-GSC-CC. Ottawa <bkjarsga@nrcan-rncan.gc.ca> (613) 995-5705
Mike Villeneuve. Geologist - Program Manager, TGI-4. NRCan-ESS-GSC-CC. Ottawa <mvillene@nrcan-rncan.gc.ca> (613) 995-4018

CANMET-MMSL, NRCan

There is a shortage of Rare Earth standards and while George Simandl (B.C.) has had discussions over the past 1.5 years with Maureen Leaver (CANMET-MMSL), The Canadian Certified Reference material Project (CCRMP) resources are limited and there is a backlog of other material to get out the door. George Simandl says that some companies are offering/sharing rocks from deposits as at least some basis for comparison. Perhaps more than many other areas of the standards, rare earth standards have a key strategic role well beyond the analytical and exploration quality issue. Maureen Leaver has indicated that a new CCRMP standard (or batch?) coming out at the end of March will have Rare Earths at ~50 ppm, and another standard in the summer will have 200 ppm. She also knows of several other rare earth standards from other sources, but does not have all of the details on them.

Appendix H: Summary of investigations regarding academic research activities

Institute	Details	Response
University of British Columbia http://www.mining.ubc.ca/ http://www.mining.ubc.ca/ResearchProjects.html	No graduate research currently focusing on REE. Note sent to Prof. Malcolm Scoble. Invited by Professor Robert Hall, Avalon's Mining Engineer, Stanley Chan, delivered a presentation to UBC Engineering students on design criteria for mine ventilation and occupational health and safety. The assignment to the class of 25 students was to determine the total ventilation system head loss and fan power requirements for Avalon's Nechalacho rare earth mine. The students were also introduced to the rare earth elements and their use in a variety of clean technology and more traditional applications. http://avalonraremetals.com/news_media/industry_info/index.php?&content_id=327	My note forwarded to Bern Klein (CRA: Comparison of Fine Grinding Technologies: Interactions with Downstream Processing): "I am wondering if you can help Robert ... see below ... I am not in tune with any REE activity. I know that we contributed a lot of info to MineCan but it never really took off ... Louise Laverdure was a pioneer as I remember. There is still no useful repository of Canadian university-based research."
University of Alberta http://www.civil.engineering.ualberta.ca/Research/ResearchAreas/Mining.aspx http://www.cme.engineering.ualberta.ca/Research.aspx	Note sent to Prof. Clayton Deutsch and Dr. Zhenghe Xu (two different faculties)	No response as of March 14.
University of Saskatchewan http://www.usask.ca/chemistry/groups/grosvenor/	See below.	See below.
Laurentian University http://www.merc.laurentian.ca/L	Note sent to Dr. Francois Caron (Director of School of Mines) and Dr. Harold Gibson (Director, Mineral	No response as of March 14.

aurentian/Home/Departments/MERC/SGRG.htm?Laurentian_Lang=en-CA	Exploration Research Centre) and Sherry Greasley, VP Administration of MIRARCO but should have sent note to Dr. Fidelis Suorineni Senior Research Engineer - Geomechanics Research Centre, Grad Studies Co-ordinator - MIRARCO: fsuorineni@mirarco.org	
Queens University http://www.mine.queensu.ca/	Note sent to James Archibald Grad Chair/Professor (613) 533-2198, Goodwin 337 jamie.archibald@mine.queensu.ca	No response as of March 14.
University of Waterloo	See below.	See below.
University of Toronto	See below. And note sent to D. W. Kirk B.A.Sc., M.A.Sc., Ph.D., P.Eng. Tel.: 416-978-7406 don.kirk@utoronto.ca www.chem-eng.utoronto.ca/~kirk	"Professor Don Kirk forwarded your request to me as there is REE research going on in our Department. We re working on RE metal extraction by atmospheric leaching from clay materials. A publication in the journal Hydrometallurgy that provides details is imminent. Feel free to contact me if you have any questions." Regards, Vlad Papangelakis vladimiros.papangelakis@utoronto.ca
McGill University	Note sent to: James Finch Wong Building, Rm 2600 3610 rue University, Montreal H3A 0C5 Quebec H3A 0C5 514.398.1452 [Office] 514.398.4492 [Fax]	"Would it be OK to send you a quick synopsis early next week? I am currently out of the country and return on Sunday. I could send you something this week if required, however I will be without a lot of information on my office desktop. In very brief, we are looking at understanding the physico-chemical properties of minerals associated with REE deposits in order to improve the development of processing flowsheets." Regards, Kristian

		Assistant Professor McGill University Department of Mining and Materials Engineering, Kristian Edmund Waters, Prof kristian.waters@mcgill.ca
Laval University (Mineral, Metallurgical, and Materials Engineering) http://www.gmn.ulaval.ca/en/research/projects/	Jacek (Jack) Paraszczak, Eng., Ph.D. Professor and Head Department of Mining, Metallurgy and Materials Engineering, Université Laval 1065 Ave. de la Médecine Quebec City, PQ, G1V 0A6 418-656-5103 jacek.paraszczak@gmn.ulaval.ca	"Your conclusion is correct: at this moment we do not do any research touching rare earth elements (REE). We have been thinking about "attacking" processing of REE, but this would require an additional position, which we will probably do not get in the near future."
Ecole-Polytechnique, Département des génies civil, géologique et des mines AND	See below. Doesn't appear to be any REE research. Note sent to brcdt@polymtl.ca and cgm@polymtl.ca . Note re-sent to Professors Robert P. Chapuis and Michel Aubertin in the Laboratoire d'hydrogéologie et environnement minier www.polymtl.ca/enviro-geremi	« Je ne fais pas de travaux sur les terres rares. Salutations." Michel Aubertin, ing. Ph.D., Prof. Chaire industrielle CRSNG Polytechnique-UQAT Industrial NSERC Polytechnique-UQAT Chair Ecole Polytechnique, Université de Montréal CP 6079, Sccl Centre-Ville, Montréal, Qc, H3C 3A7 514-340-4711 #4046, michel.aubertin@polymtl.ca « Je confirme que je n'ai pas d'acitivité de recherche en relation avec les terres rares. Cordialement, » Robert Chapuis
Dalhousie University http://gr.cal.dal.ca/PROCENG.htm#10 (Materials Engineering Program, formerly Metallurgical)	Note sent to: Georges J Kipouros, Ph.D., P. Eng. Professor of Materials Engineering Director of Minerals Engineering Centre Faculty of Engineering, Dalhousie University Halifax, Nova Scotia, B3J 2X4 Tel: (902) 494-6100	"As Director of the Minerals Engineering Centre we do work with an increasing number of clients who are investigating the content of rare earths in minerals that they explore. Due to confidentiality we cannot reveal the name of the companies or the nature of the work we perform for them.

	Fax: (902) 494-3506 Email: georges.kipouros@dal.ca	As a researcher on rare earths I worked at the General Motors Research for five years during which we developed a process to produce neodymium metal and alloys for the strongest ever magnets today NdFeB. After we transfer[red] the technology to the Magnequench SBU in Anderson, Indiana I returned to academia. I do maintain a small program in rare earths due to lack of research of funding in this area. My present work to be presented in three conferences this year (24th CMSC, International Conference on Chemical Thermodynamics (ICCT 2012), and possibly COM 2012) is in the area of extraction of rare earths and the preparation of anhydrous rare earth halides. I attach the abstract of the rare earth presentation." [attached] Regards, GJK
Memorial University http://www.esd.mun.ca/~spiercey/Piercey_Research_Site/Home.html	Note sent to Steve Piercey, Ph.D., P.Geo. Associate Professor and NSERC-Altius Research Chair in Mineral Deposits	"At the present time I'm not really working in REE as this is not really my area of expertise. I find the topic interesting, but at the present time my time is already spread pretty thin working on base metals, U, Fe, and Au projects. I'm always interested in new things, but at the present time I am not working too much on this. That being stated there are numerous projects here at MUN on REE, particularly projects in Labrador, across a variety of disciplines, including mineralogy and geochemistry of REE, REE grades and distributions, timing of REE mineralization, and so-on. My colleagues that are working on this include, in alphabetical order: 1) Greg Dunning - timing of REE mineralization using geochronology (gdunning@mun.ca); 2) John Hanchar - mineralogy, isotopic tracing, and REE genesis (jhanchar@mun.ca);

		3) Graham Layne - mineralogy and isotope systematics of REE mineralization (gdlayne@mun.ca); 4) Paul Sylvester - geochemistry, mineralogy, and geochronology of REE mineralization (psylvester@mun.ca); and 5) Derek Wilton - field, mineralogy, and geochemistry of REE mineralization (dwilton@mun.ca)."

Natural Sciences and Engineering Research Council of Canada (NSERC)

From NSERC, there appears to be only one REE research project granted funds in 2011 and it is not related to mineralogy or metallurgy in any way. No other projects were found for 2010 or 2009.

http://www.nserc-crsng.gc.ca/NSERC-CRSNG/FundingDecisions-DecisionsFinancement/ResearchGrants-SubventionsDeRecherche/ResultsGSCDetail-ResultatsCSSDetails_eng.asp?Year=2011&GSC=1505&Field=Physics

Kashyap, Raman R Department Génie physique	École Polytechnique	SOCRATES; Solid state optical cooling with rare earth and quantum doT dopEd glasses and crystals and in semiconductors	$48,000.00

University of Saskatchewan

Andrew Grosvenor
B.Sc., M.Sc., Ph.D.
Assistant Professor
Office: Thorvaldson 356
Phone: (306) 966-4660
Email: andrew.grosvenor@usask.ca
Website: http://www.usask.ca/chemistry/groups/grosvenor/

Research

My research focuses on studying how structural and compositional changes affect the electronic structure of rare-earth (and transition-metal) oxides, silicates, and pnictides using X-ray spectroscopy. In particular, I am interested in developing materials capable of sequestering uranium. In my group, various materials are synthesized and their electronic structure and surface reactivity to different oxidizing environments are investigated by X-ray photoelectron spectroscopy and X-ray absorption spectroscopy, using the Canadian Light Source (CLS) and the Advanced Photon Source (APS). Please feel free to contact me if you have questions about my research or available graduate and undergraduate student positions.

From http://www.usask.ca/chemistry/groups/grosvenor/research.html

Oxidation behaviour of rare-earth filled and unfilled skutterudites (REM4Pn12, CoPn3): Transition-metal (M) and rare-earth (RE) containing pnictides (REM4Pn12), having the skutterudite structure have been studied in the past as potential thermoelectric materials which can be used for power generation and refrigeration applications [12,13]. The crystal structure consists of a network of corner-sharing metal centred octahedra, which are tilted to form Pn4 squares creating large voids in the form of dodecahedral cages of Pn atoms [12,13]. Within these voids, RE atoms can be present and actinide (U, Th)-containing analogues are known. It is because of these Pn cages that these materials may be useful for waste sequestration. However, it is unknown how the RE, Pn, and M atoms will be effected when these materials are exposed to reactive gases. In this investigation, students are studying the surface and bulk oxidation of RE containing skutterudites, REM4Pn12 (RE = La, Ce, Eu, Gd; M=Fe, Ru, Os; Pn = P, As, Sb), by XPS and XAS after exposure to various gases.

Electronic structure and Oxidation behaviour of Pyrochlores and Zirconolites: Of the systems being examined for use in nuclear waste sequestration applications, the pyrochlore and zirconlolite phases have been studied the most [14-16]. Materials adopting either the zirconlite (A2B2O7; A = Ca, V, Zr, Ti; B = Ti, Nb, Ta, Zr, Hf; X/X' = O, F, OH) or pyrochlore (A2B2X6X'; A = Ca, Mn, Fe, rare-earths (RE), Gd; B = Ti, Nb, Ta, Zr, Hf; X/X' = O, F, OH) structure can have a variety of chemical compositions [14,15]. Along with being able to incorporate actinides and being examined for possible sequestration applications, these materials have also been studied for their catalytic and magnetic properties [14]. The focus of these studies is the investigation of Hf, Zr, and Ti containing systems by XAS and XPS owing to their suitability for sequestration applications (e.g., Yb2Ti2-yFeyO7-x, RE2ZryTi2-yO7) [14,17]. As metals having vastly different electronegativity values can be substituted into these compounds, it is expected that next-nearest neighbour effects will shift the XPS binding energies, providing another opportunity to examine how and why this effect occurs.

Waterloo Institute of Nanotechnology

With the inspiration and leadership of Professor Frank Gu, as part of the first-year Introduction to Nanotechnology course requirement, Avalon sponsored the "Grand Rare Earth-Nanotechnology Challenge", where teams of three or four students were asked to identify future applications that would utilize a rare earth element expected to be in surplus, or a solution to reduce the demand for a specific rare earth that may be in short supply. Given eight-weeks, the teams were asked to address the underlying science, environmental issues and anticipated commercial opportunities. In addition to the technical papers to be submitted, each team will be 'pitching' their ideas and taking questions before the full class, thereby also providing the opportunity to hone their presentation and communication skills.

In support of the project, Avalon also delivered a one-hour lecture on the chemistry and physics of rare earth elements to the freshman class of 110 students enrolled in Waterloo's highly competitive Nanotechnology Engineering undergraduate program.
http://avalonraremetals.com/news_media/industry_info/index.php?&content_id=327

University of Toronto – Chemical Engineering

Under the leadership of Professor Don Kirk, three teams, each comprised of six fourth-year students, designed different variations of Avalon's hydrometallurgy process for the recovery of rare earths as their graduating year Plant Design Project. Over the course of 12 weeks, the teams researched technical data, designed and costed alternative process and plant schemes, complete with project economic and environmental assessments. Avalon provided the overall project objectives, preliminary design considerations and regular oversight. The teams presented their final projects to Avalon and the Chemical Engineering faculty on December 1, 2011.

With the cooperation of Professor Charles Jia, Avalon also delivered a two-hour guest lecture to the second year Applied Chemistry I – Inorganic Chemistry class, attended by approximately 100 students. Under the banner "What are the Rare Earths and How Chemistry Brings them to Life'", the students were introduced to the rare earth elements, their current applications, the chemistry that underlies their unique properties, and processing parameters. The discussion also touched on developing the downstream infrastructure to support rare earth processing and materials manufacturing within Canada, and related environmental and human resource needs. In addition to the science behind magnetism and luminescence, the students were also interested in rare earth recycling, environmental regulations, and the utilization of rare earths in automotive and medical applications.
http://avalonraremetals.com/news_media/industry_info/index.php?&content_id=327

Ecole-Polytechnique

Programme de recherche http://www.polymtl.ca/nucleaire/LTN/SLP.php

1. Analyse par activation neutronique (AAN)
Le Laboratoire est surtout utilisé pour l'analyse par activation neutronique, une méthode d'analyse chimique qui permet de mesurer, de façon instrumentale, les concentrations des éléments dans les substances solides et liquides. Il s'agit de bombarder la substance par des neutrons pour la rendre radioactive et ensuite de détecter les rayons gamma émis par les différents éléments.

Bien que l'AAN soit une technique bien établie, le personnel du Laboratoire cherche toujours à l'améliorer. Nous travaillons sur une nouvelle méthode de standardisation qui devrait permettre des analyses plus exactes et nous développons des logiciels de spectrométrie gamma afin d'améliorer la sensibilité et la précision.

Les utilisateurs du Laboratoire viennent de l'École Polytechnique, de l'Université de Montréal et de six autres universités au Québec. Les exemples suivants illustrent les nombreux domaines de recherche impliquant l'analyse par activation neutronique:

Géochimie, pour la détermination des éléments terres-rares et du groupe du platine qui sont d'importants outils d'étude de la formation des roches et des dépôts de minéraux.
Science des matériaux, pour la vérification de la composition des matériaux nouveaux.
Archéologie, la composition chimique d'objets céramiques, métalliques et lithiques anciens sert à déterminer leur provenance.

Médecine, études sur la toxicité des métaux.
Environnement, études sur la pollution de l'air et de l'eau par les métaux lourds, émissions de métaux à partir de la combustion des produits pétroliers. Les résultats de notre étude sur les émissions atmosphériques à partir de la combustion de l'essence dans les automobiles a contribué à convaincre le gouvernement d'approuver un nouvel additif, moins polluant que les précédents, ce qui améliora de façon significative la qualité de l'air de nos villes.

2. Traceurs radioactifs
Une collaboration étroite a été établie entre le Laboratoire et le département de génie chimique pour la production et l'utilisation des traceurs radioactifs pour l'étude de la dynamique des écoulements dans les réacteurs chimiques multiphasiques. Pour la mesure des temps de séjour dans les réacteurs chimiques, des solides et des gaz sont activés dans le SLOWPOKE et injectés dans le système sous étude. Leur mouvement est suivi par plusieurs détecteurs NaI.

Plusieurs autres collaborations sont en cours en médecine et en pharmacie où les traceurs radioactifs sont utilisés pour l'étude du taux de dissolution des médicaments dans le système digestif et leur répartition dans les organes chez l'animal et l'humain.

3. Radioactivité environnementale
La spectrométrie gamma servent à mesurer les radioisotopes dans le sol, dans l'eau, dans les matériaux de construction et dans la nourriture.

Dalhousie

PREDICTION AND ESTIMATION OF THERMODYNAMIC QUANTITIES IN RARE EARTH CHLORIDE HYDRATES (MCl_x*nH_2O)

William Judge and Georges J. Kipouros*, Materials Engineering Program
Department of Process Engineering and Applied Science, Dalhousie University
1360 Barrington Street, Halifax, NS, Canada B3H 4R2
(*corresponding author, Email: georges.kipouros@dal.ca)

Abstract

The prevalent metal extraction processes for most reactive metals are fused salt electrolysis and metallothermic reduction. The feed material for both of these processes is the anhydrous chloride of the metal under consideration. Impurities in the feed material contaminate the final product and lower efficiencies. Dehydration of the feed material is then a critical step in the production of reactive metals and requires rigorous thermodynamic analysis. Thermodynamic data for most of the reactive metal chloride hydrates have not been reported. Improper dehydration of the metal chloride may lead to the formation of a prohibitive amount of oxide and hydroxychloride. To avoid hydrolysis a certain pressure of hydrogen chloride is required. An estimation and prediction model is presented for the vapour pressures of reactive metal chloride hydrates in an attempt to deduce the conditions necessary for dehydration without hydrolysis. Thermodynamic data including heat capacities, standard entropies, and standard enthalpies were estimated/predicted for all conceivable intermediate compounds. Estimations were based on published data as well as trends proven in similar systems. The thermodynamic estimations and predictions for the neodymium, praseodymium and dysprosium trichloride hydrates are presented.