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Canadian Chromite R&D Initiative

Chapter 1.1

Chromite R&D Initiative – Background, Objectives, Approach and Summary of Accomplishments

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January 2022

CanmetMINING

Canada

This work was completed through funding provided by Natural Resources Canada as part of the Canadian Rare Earth Element and Chromite R&D Initiative.

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ABSTRACT

Ring of Fire chromite deposits in northern Ontario are considered world-class offering significant economic development potential over many decades. As the largest known undeveloped chromite resource in the world and forming the sole source of chromite in North America, the deposits represent an opportunity for Canada to supply world markets with value-added and essential ingredients of stainless steel and advanced alloys. However, the remoteness of the area and the sensitivities related to social and environmental issues require special considerations for the development of the resources in a responsible and sustainable manner. This requirement and the fact that Canadian value and benefits are maximized necessitates careful planning and research. Sustainability drivers for the development of the resources can be summarized under three main themes: (1) improved resource utilization, (2) competitiveness of the Canadian mining industry and the need for value-added products, and (3) reduced environmental liability and health concerns. These sustainability drivers and associated challenges were addressed by undertaking research to improve and optimize the critical unit processes, develop clean technologies in value-added products, and evaluate the long-term environmental stability of mine and metallurgical wastes. The initiative resulted in a number of major accomplishments that can be outlined as (1) improvement and development of new knowledge on conventional processing technologies, (2) identification of waste minimization and footprint reduction options, (3) defining conditions influencing the formation of hexavalent chromium during smelting, (4) discovery and early-stage development of a novel chromite reduction process, and (5) development of new and improved methodologies and techniques. In addition, the research program facilitated the development of capacity and expertise by the private sector through issuing 30 external contracts with a total funding of $2.5 million. Furthermore, the program achieved training of 9 postdoctoral fellows, 2 masters students, 2 technologists and 18 CO-OP students as highly qualified personnel. The R&D results and new knowledge generated were disseminated in the form of 2 patents, 10 journal publications, 2 proceedings publications and over 50 presentations made at conferences, workshops and seminars. Outreach activities of the program involved technical and steering committee meetings, meetings with government organizations like NDMNRF and MOECP, foreign research organizations and industry such as Mintek, North-West University, Outokumpu and Glencore.

INTRODUCTION

Background and objectives

The Ring of Fire chromite deposits discovered in 2007 are considered world-class with NI-43-101 compliant measured and indicated resources of more than 200 Mt grading approximately 33 wt% Cr_2O_3. Other deposits in the area and conversion of inferred resources through additional drilling can add to this resource tonnage. The deposits are located in northern Ontario in the James Bay lowlands, approximately 280 km north of the town Nakina and 530 km northeast of Thunder Bay. The region, covering about 5,000 square km, offers significant potential for economic development and technological innovations for many decades to come, if not for a century. With a value exceeding $120 billion, it has been described by the Ontario Chamber of Commerce as the most promising mineral development opportunity for Ontario since the discovery of the Sudbury basin in 1883 and the Timmins gold camp in 1909 (McGuinty 2015). There are, however, important challenges to the exploitation of these world-class resources both in terms of their processing and environmental footprints. In addition, the remoteness, pristine and fragile nature of the area and ecosystem in a wetland and bog environment present further challenges to economic developments in the area. These challenges are compounded by the lack of Canadian experience in mining and processing of chromite and production of ferrochrome.

The enormous size and longevity of the undeveloped chromite resources in the Ring of Fire area provide an opportunity for developing holistic plans, clean processes for mining and metals extraction, and for environmental protection. In response to Budget 2015, named "*Mines to Market*" for responsible development of REE and chromite deposits to maximize Canadian value and benefits from the deposits, CanmetMINING was tasked to carry out R&D studies with a budget of $8.3 million over 6 years. The primary objectives of the Chromite R&D program were to (1) develop new methodologies and technologies to overcome processing and smelting challenges for chromite from the Ring of Fire in northern Ontario, (2) improve industrial capacity to produce chromite concentrates and mitigate environmental and health and safety impacts, and (3) to provide skills development and training to scientific staff, who could apply these skills to sustain the continued growth of the chromite industry in Canada. These objectives fed into broader goals, which were (1) to ensure that the Ring of Fire resources are developed responsibly, (2) to enable project proponents (i.e. the industry) to choose the best available technologies, (3) to support innovation and the use of clean and low-carbon technologies, (4) to ensure that Canadian value and benefits from the resources are maximized, and (5) to reduce environmental impacts and liabilities arising from mining and processing. The initiative was meant to serve the NRCan minister in terms of helping to get our natural resources to market through sustainable practices and low-carbon processes, and to ensure that decisions are based on science, facts and evidence and serve the public's interest.

Approach

Exploitation of the chromite resources with value-added products will involve three major steps: mining, mineral processing and extractive metallurgy. Following mining, chromite ore is processed by crushing and grinding to liberate chromite ore mineral particles from the unwanted minerals in lower-grade ores, and concentration of liberated chromite. Concentration typically involves gravity and/or magnetic techniques depending upon the characteristics of the chromite ore. Mineral processing operations that culminate with a concentrate are typically followed by smelting the ore in electric arc furnaces to produce ferrochrome through carbothermic reduction reactions. Unlocking the development potential of the Ring of Fire chromite resources and their sustainable development while maximizing Canadian value and benefits would require the development of clean technologies with lower energy demands, value-added products, increased mineral and metal recoveries, and reduced CO_2 emissions. Considering that ferrochrome production from chromite requires the use of carbon as a reductant, greenhouse gas emissions (GHG) can be profoundly important as Canada transitions to a low-carbon economy.

In addressing the stated objectives above and to provide a context to R&D program activities, it is essential to discuss the drivers of sustainability for the development of Ring of Fire chromite resources. With the premise that the natural resources sector is fundamental to the strength of Canada's economy and the quality of life of Canadians as stated by the Energy and Mines Ministers conference in 2013 (EMMC 2013), sustainability drivers for responsible development of the Ring of Fire chromite resources can be outlined under 3 main themes (Table 1). It should be noted that the nickel and other resources in the Ring of Fire area are not considered in this study.

Table 1. Sustainability drivers for the development of Ring of Fire chromite resources and the means of addressing them

Sustainability Driver	Task
Improved resource utilization	Make processing of lower grade ores viable Increase mineral recoveries Recover chromite fines
Competitiveness and the need for value-added products	Identify clean and technologically most advanced ferrochrome flow sheets Develop a fundamental-level understanding of carbothermic reactions Develop energy efficient ferrochrome processes
Reduced environmental liability and health concerns	Make slag inert Minimize carbon and mining footprints Assess Cr(VI) generation during processing

The first theme is on improved resource utilization. Considering that chromite resources with much lower grades elsewhere are being economically exploited, it was essential that the options for the processing of lower grade Ring of Fire chromite resources were identified. This would also ensure that the value from the deposits are maximized while the burden on the environment is minimized. This was considered essential for sustainability of the Ring of Fire chromite resources.

The second sustainability driver was about the competitiveness of the Canadian mining industry and the need for value-added products. These were necessitated by the fact that Canada is falling behind its competitors, which calls into question the long-term sustainability of Canada's mining industry as per the Energy and Mines ministers' conference in 2018 (EMMC 2018). In addition, Canada despite being a world leader in R&D, is lagging behind in innovation performance. Furthermore, between 2006 and 2015, the mineral sector's real GDP declined 5.8%, driven by the downstream manufacturing industries. In contrast, value added in the upstream mineral extraction industry grew 10% (EMMC 2016). This important factual information needed to be addressed in relation to value-added products and the focus on innovation.

The third main driver for sustainability was about reduced environmental liability and health concerns. This is critical to protecting the environment and remaining responsive to societal expectations, both of which are priorities for the Canadian government. In addition, GHG emissions and their impacts on climate change are important issues in a low-carbon economy.

These sustainability drivers were addressed by the main accomplishments listed in the following section and in reference to the work plan, designed to address the processing and environmental challenges in a holistic way. The processing challenges included improved recovery dealing with both the chromite and ferrochrome, and reducing energy requirements, whereas the environmental challenges included assessing environmental impacts, waste minimization and contaminant reduction at source.

SUMMARY OF MAIN ACCOMPLISHMENTS

Research and development

The current state of knowledge on chromite processing and ferrochrome production was reviewed in an R&D gaps analysis study commissioned to Hatch (Hatch 2016a,b,c,d). The Hatch study documented the global best practices and lessons learned, and collated the R&D needs specific for responsible development of the Ring of Fire chromite resources. The study highlighted the importance of selecting appropriate technologies to minimize energy and transportation costs due to the remoteness and location of the deposits in a low lying waterlogged area. The study recommendations related to R&D needs in the Canadian context included developing an understanding of the potential for the generation and control of hexavalent Cr, flow sheet development and optimization, KWG technology advancement, establishment of a Chromite Center of Excellence, and by-product development like re-utilization of slag and CO in offgas (Hatch 2016b).

Main accomplishments of the chromite R&D initiative are summarized in reference to the sustainability drivers discussed earlier and Hatch recommendations related to R&D needs.

Improved resource utilization

The first driver on improved resource utilization relates to maximizing value from the resources through the exploitation of the lower grade deposits and increasing recoveries during mineral processing. Considering that chromite resources with much lower grades are being exploited elsewhere, it is conceivable that exploitation of the low-grade chromite resources in the Ring of Fire area can be economically viable. Furthermore, improved resource utilization can be addressed through the recovery of chromite in the fines fraction (Paktunc 2021a). This would not only add value to the operations but would also reduce chromite losses to mine tailings and minimize chromium loadings in the mine environment. This would be an essential criterion for sustainability, resulting in reduced mining footprints addressing not only the techno-economic goals, but also the environmental goals of the sustainability hierarchy of Petrie at al. (2007). Accordingly, this sustainability driver was addressed by evaluating the comminution and beneficiation options of the lower grade ores, and the recovery of chromite fines. The study findings indicated that chromite particles in both the coarse and fine size fractions could be recovered through a process flowsheet consisting of milling and classification, jig or spiral concentration, regrinding and sizing followed by gravity concentration using a shaking table, and wet high-intensity magnetic concentration or Kelsey jig separation of the fines fraction (Paktunc et al. 2021). This would result in concentrate grades of 40-43% Cr_2O_3, and the value that would have otherwise reported to the tailings would be reclaimed, lessening the burden on tailings impoundments.

Competitiveness and the need for value-added products

The second sustainability driver on the competitiveness and the need for value-added products was addressed by identifying clean and technologically most advanced flow sheets. As a new entrant to the metallurgical processing of chromite, development of a fundamental-level understanding of carbothermic reactions was a necessity for ensuring Canada's competitiveness in the long term. Moreover, developing energy-efficient processes was a must for competitiveness.

Ferrochrome is typically produced by smelting of chromite ore in electric arc furnaces. Conventional smelting processes are energy intensive with variable energy consumptions from about 3 MWh per ton ferrochrome produced to about 7 MWh/t (International Chromium Development Association 2011). On average, the energy requirements are greater than 4 MWh/t (Riekkola-Vanhanen 1999; Naiker and Riley 2006; Beukes et al. 2015). In addition, the GHG emissions can be significant, exceeding 10.5 t CO_2 per ton Cr in ferrochrome produced (International Chromium Development Association 2016). These are two of the most important metallurgical processing challenges for the development of the Ring of Fire chromite resources.

These challenges were addressed by identifying and evaluating the most technologically advanced ferrochrome production flow sheets through a quantitative review and assessment of smelting technologies that can be used as benchmarks for the Ring of Fire chromite ores. The study commissioned to Kingston Process Metallurgy (Kingston Process Metallurgy 2017) identified that the closed submerged arc furnace with oxidized pellet feed, DC-arc with pre-heated feed and Premus smelting technologies were the most advanced flow sheets that were viable options for the development of the Ring of Fire chromite resources. The closed submerged arc furnace with oxidized pellet feed technology involves pre-treatment steps like pelletizing, oxidative sintering and pre-heating followed by smelting in a submerged closed electric arc furnace. The DC-arc furnace technology involves an open bath that allows greater flexibility in the use of lumpy ore, chromite fines and lower quality reductants. The open bath design also allows more process controls enabling improved separation of molten ferrochrome from slag. The Premus technology employs a pre-reduction step whereby the pellets are partially reduced in a rotary kiln before they are fed to a submerged electric arc furnace for smelting. This process, designed to optimize the energy input, typically has a high Cr recovery with the lowest energy requirement at about 2.4 MWh/t (Naiker and Riley 2006) and lower reductant consumption in comparison to the other smelting technologies. For each technology option, process flow diagrams, heat and mass balance models, capital and operating costs, and risk analyses were prepared using a common set of assumptions and design criteria. For plants processing 450 kt/a Ring of Fire chromite concentrate and producing 192-203 kt/a ferrochrome, electricity consumptions would be variable from 2.5 to 3.8 MWh per ton ferrochrome produced. These were comparable to the 3.3 MWh/t figure for a DC-arc furnace made by a previous feasibility study on the Ring of Fire ore. In terms of the electricity consumption, the selected smelting technologies would be considered competitive in comparison to the figures indicated earlier (i.e. >4 MWh/t). Given these assumptions, this preliminary study estimated that the total installed costs of the three technology options were between $463 and $515 M USD, and that their operating costs would be between $122 and $138 M USD per annum. Considering the uncertainties in the cost estimates, there are no discernable differences in the financial performances of the three technologies.

In addition, developing new or improved energy efficient and clean processes was essential for this sustainability driver which required a fundamental level understanding of the carbothermic reactions during chromite reduction. Our studies on developing an understanding of the evolution of Cr and Fe species during reduction demonstrated that several fluxes can play significant roles in terms of achieving high degrees of metallization at temperatures much lower than required by smelting in electric arc furnaces (Paktunc 2021b). The fluxes include $CaCl_2$ (Yu and Paktunc, 2018a,b,c), NaOH (Paktunc et al. 2018; Sokhanvaran et al. 2018), cryolite (Sokhanvaran and Paktunc 2019) and aluminum spent pot lining (Yu and Paktunc 2019). The flux-assisted reduction rates in direct reduction of chromite are 2.3-2.7 times higher than the rates with no-flux (Paktunc et al. 2018; Yu and Paktunc 2018c).

In the case of $CaCl_2$-assisted direct reduction (Yu and Paktunc 2018a,b,c), the feed composed of 66% chromite ore, 20% $CaCl_2$ flux and 14% carbon reductant is agglomerated and dried at 300 °C to remove the moisture and reduced at 1300 °C for 2 hours. Particle sizes of chromite and reductant, and pellet properties are criticial for product quality. Pellets behave like mini reactors during carbothermic reactions. Pellet properties help maintain CO partial pressure within the pellet and limit ingress of oxidizing gasses (KPM 2021; Carter et al. 2021; Coumans et al. 2022). Pellets that are coated with fine chromite ore or ferrochrome provide similar results. The DRC process produces liberated ferrochrome and slag particles measuring about 200 µm. The product is water leached to separate the solids and remove $CaCl_2$. Liberated ferrochrome particles are readily recovered through simple gravity or magnetic separation techniques. In addition to ferrochrome, the slag, which is largely a refractory spinel compound (i.e. $MgAl_2O_4$), could be considered as a by-product with a value. The leachate from the water leaching is evaporated to recover $CaCl_2$ which is then recirculated for reuse as a flux. Preliminary indications are such that recovery of more than 70% $CaCl_2$ is possible (Yu and Paktunc 2018; Kemetco 2021). Thus, the $CaCl_2$-assisted direct reduction process is highly efficient and promising in terms of its cost and environmental performance with very little waste produced.

The results paved the way towards the development of a novel made-in-Canada ferrochrome process through scaling-up and modelling studies as summarized in Chapter 3.2.9 (Kingston Process Metallurgy, 2018a,b, 2019, 2020a,b, 2021; ExMente 2019). A critical review of the furnace technologies developed for direct reduction of iron has resulted in the identification of rotary kiln and rotary hearth reactors as potential furnaces for the direct reduction process for chromite. The review considered reactor sizes, unit capacity, throughput, material handling, heat sources, furnace liner, types of reductants, material types and sizes, material flow and metal-slag segregations with respect to their relevancy and applicability to direct reduction of chromite, and their potential limitations for metal recoveries (Kingston Process Metallurgy 2018). Computational fluid dynamics modelling determined the applicability of the two furnace types for the $CaCl_2$-assisted direct reduction process (M4Dynamics 2018; Watson et al. 2018). Numerical modeling of the 80 m long kiln in terms of heat transfer, mass transfer, reaction kinetics, equilibrium thermodynamics, fluid flow and granular flow models indicated that the high degrees of metallization (i.e. 90% Cr) was achieved after 2.4 h of reduction. Simulation of a rotating hearth furnace that is 60 m in diameter, 7.6 m wide and 2.44 m high with a feed rate of 40 t/h indicated that the furnace is fully capable of reducing the ore (XPS 2022).

Preliminary technoeconomic analysis indicated that the total production cost of the new direct reduction process was about 30% lower than that of the Premus technology (Kingston Process Metallurgy 2018). The Technology Readiness Level (TRL) of this new process is TRL4 which is the demonstration level, confirming that the direct reduction process has successfully matured and it is ready for pre-pilot studies followed by pilot testing of the technology (Paktunc 2021b). If proven and adopted, this potentially disruptive technology could provide the Canadian industry a competitive advantage as a new entrant to the established world markets, while addressing the very difficult and essential challenge of developing an energy efficient process.

Reduced environmental liability and health concerns

The third main driver for sustainability on reduced environmental liability and health concerns was addressed by assessing the potentials of hexavalent chromium formation during smelting and mineral processing operations, making slag inert and minimizing carbon and mining footprints (Fig. 1), consistent with Canada's societal expectations and regulations. Environmental challenges related to milling and metallurgical processing of the Ring of Fire chromite ores include potential Cr metal(loid) releases from mine tailings and slag, formation of hexavalent Cr during processing, and management and liability associated with wastes such as the tailings and slag piles. Furthermore, environmental objectives include minimizing carbon and mining footprints.

In addition, GHG emissions and their impacts on climate change are crucial issues for the government, industry, and public in a low-carbon economy. An assessment leading to minimizing carbon and mining footprints from the development of the Ring of Fire chromite resources was done with the help of Hatch, through a life cycle inventory and carbon footprint study (Hatch 2017). The results indicated that total GHG emissions would be 421, 383 and 472 kt CO_2 for producing 192, 203 and 198 kt ferrochrome per year using Closed SAF, DC-arc and Premus technologies, respectively (Table 1). Total GHG emissions including those related to combustion of fuels and use of reductants during smelting and indirect emissions resulting from upstream power generation and other processes would be 3.9 and 4.7 t CO_2 for the production of 1 t Cr in ferrochrome using the DC arc and closed SAF technologies in a Canadian context. These numbers are significantly lower in comparison to the global average, estimated to be 10.5 t CO_2 per t Cr in ferrochrome (International Chromium Development Association 2012). This difference is largely resulting from the fact that Ontario's electricity generation is essentially from very-low GHG emission sources, whereas 93% of the energy sources in the global study (International Chromium Development Association 2013) originate from predominantly coal-based power grids. Another contributing factor is that the global average (International Chromium Development Association 2012) includes older open furnace technologies that are far less efficient than the modern technology options identified for the Ring of Fire case. The results are critical for supporting the industry, and informing the regulators and public about the GHG emissions and carbon footprints of the selected smelting and other processing technologies for the Ring of Fire case while providing improvements in environmental performance in comparison to current global ferrochrome production cases.

Assessments of potential Cr releases from mine tailings and the formation of Cr(VI) were made through in-house studies as they were highly specialized requiring synchrotron research and expertise. One source of Cr in mine tailings would be chromite fines. Other sources include gangue minerals like clinochlore, phlogopite and amphibole, present in the Ring of Fire ores (Paktunc 2021). Clinochlore can contain up to about 10% Cr_2O_3 whereas phlogopite and amphibole group minerals can have Cr_2O_3 concentrations reaching 3.9 and 6.1 wt%, respectively (Paktunc 2021a). Orthopyroxene, olivine, serpentine and carbonates can also carry trace to minor amounts of Cr. Accordingly, in addition to chromite, these gangue minerals would constitute potential sources of Cr in mine tailings. Leaching studies suggest that both chromite and clinochlore will be important sources of Cr in future mine tailings from processing of the Ring of Fire chromite ores. Total Cr releases would be low, at levels comparable to that of the drinking water guideline which is set at 50 µg/L for total Cr (Health Canada 2016). Our exploratory leaching tests indicated that only in the presence of a strong oxidant like birnessite, Cr would be released as Cr(VI) from the tailings. 2021). Magnitudes of such releases will be controlled primarily by the tailings mineralogy (i.e. the presence of Cr-bearing silicate minerals) and particle size. Preliminary indications based on our mineralogical characterization results on various chromite ores from the Ring of Fire area are that birnessite is not present in appreciable quantities; therefore, the potential for Cr(VI) formation from mine tailings should be considered low.

Hexavalent chromium can form in small quantities during metallurgical processes at high temperatures such as ferrochromium and stainless steel production (ICDA 2012; Hatch 2016c), especially during smelting in open and semi-closed electric arc furnaces (Beukes et al. 2010, 2015, 2017; Du Preez et al. 2017). Hexavalent chromium compounds are found in the highly oxidizing fumes from the melting/smelting processes, particularly the tapping process (Beukes et al. 2017). This is essentially influenced by temperature and oxygen partial pressure but other factors such as particle size, fluxes or catalysts can contribute to the formation of Cr(VI). As discussed by Beukes et al. (2017), industrial practices employed to prevent and/or significantly reduce the formation of Cr(VI) during smelting can include (1) operation of a closed submerged arc furnace with an acidic slag, (2) screening the smelter feed to reject the fine particles that are less than 4 mm, (3) utilization of wet scrubbers and sintered plate filters to remove fine particles that are less than 1 µm from off-gas formed during smelter operations, and (4) granulation of slag to prevent/minimize the contact of molten slag with oxygen.

With the ultimate purposes of determining the sources and conditions promoting the formation of Cr(VI) during smelting, pilot scale smelting tests were commissioned to Expert Process Solutions (XPS) to capture dusts and fumes representing various unit operations and DC electric arc furnace conditions (XPS 2018; 2019). The dust samples subjected to selective extraction tests using the protocol of Du Preez et al. (2017) indicated that the cyclone, baghouse and drop out box dust samples had variable concentrations of Cr(VI) in leachates (i.e. 250 to 2930 mg/L). In addition, dust samples collected from the freeboard and downstream offgas were studied by the most advanced and state-of-the-art materials characterization techniques such as those available at synchrotron facilities (Berryman and Paktunc 2022; Berryman et al.

2022). Chromite is the major source and host of Cr in the DC arc smelter dusts. Spherules, especially the Si-Ca-Mg-rich glassy micro-spherules are the dominant Cr(VI)-bearing phase in the off-gas dust. Overall, fine-grained dusts captured by the baghouse host the highest proportion of Cr(VI). Oxidized iron species like FeOOH are present in the furnace freeboard dust and Cr(VI) forms up to about one-third of the Cr species present on particle surfaces. These results demonstrated that there was sufficient oxygen ingress and sufficiently high temperatures in the closed DC furnace for Cr(VI) to be generated in the freeboard off-gas dusts. This is in essence influenced by the open-bath nature of the DC furnace and the presence of chromite fines and Ca-rich flux in the feed. Cr(VI) forms in the furnace when the fine dust particles are exposed to the high temperatures in the off-gas. Smelting conditions that would minimize the presence of chromite fines and Ca flux in the off-gas dusts above the open bath could prevent the formation of Cr(VI) during smelting. The results form the first unequivocal indication of the formation of Cr(VI) in a DC arc furnace providing insight into the generation of Cr(VI) and conditions influencing the formation of Cr(VI). These findings will help the operations to optimize unit processes so that the formation of Cr(VI) is controlled and prevented or to enable capture of particles with Cr(VI).

Significant quantities of slag are generated during ferrochrome production. About one half of the feed to smelting furnaces becomes slag. For instance, the Tornio smelter (Finland) generates about 700,000 t ferrochrome slag per annum (Ylimaunu, 2017) which is slightly greater than the 600,000 t ferrochrome produced. Overall, the ferrochrome industry generates about 13.2 Mt of slag annually (International Chromium Development Association 2017). Ferrochrome slag is used as a construction material in some countries while it is classified as a waste in others (International Chromium Development Association 2017). As a waste material, the slag needs to be kept in secure sites and managed to perpetuity; therefore, slag piles constitute an important liability for the industry both in terms of cost and potential risk to the environment. Accordingly, it was prudent that the slag from smelting of the Ring of Fire chromite ores be evaluated for its potential use as a by-product such as by determining and engineering the conditions for the formation of a slag that is inert and unreactive under environmental conditions in Ontario. Making slag inert so that it can be considered as a by-product rather than waste would result in reduced costs and liabilities associated with large slag piles. We therefore commissioned several studies, including pilot scale smelting of the Ring of Fire chromite ore followed by geotechnical and geochemical assessment of the quality of slag formed under different conditions such as air cooled and granulated (XPS 2020, 2021) to determine the required conditions for making slag unreactive and inert. Findings indicate that there are ferrochrome particles in the slag, some of which are spherical measuring several hundred microns across. The presence of ferrochrome particles would influence slag stability and requires that considerations must be given to carefully adjust parameters like tapping intervals, residence times and slag viscosity so that immiscible ferrochrome droplets can settle through the slag under the influence of gravity. In addition, findings are such that there are compositional differences between the slag formed under slow cooling and water granulation and the deportment of Cr among various phases making up the slags. The slags are predominantly made of spinel ($MgAl_2O_4$), forsterite (Mg_2SiO_4) and quartz (SiO_2). In addition, periclase (MgO) is present in the granulated slags and a Ca-Mg silicate ($CaMgSiO_4$) occurs in the air-cooled slag. The slags consist primarily of a Ca-Al-Mg silicate glass matrix with forsterite and a Ca-Mg silicate occurring as fine needle-shaped prismatic grains. A Ca-Al-Mg silicate glass and spinel ($MgAl_2O_4$ or $MgCr_2O_4$) are the carriers of Cr in the slag. In the air-cooled slag, Cr occurs as spinel where it is evenly distributed between the Ca-Mg slag matrix and spinel in the granulated slag. It is unclear if the noted chemical and mineralogical differences between the air-cooled and granulated slags are significant enough to influence their leaching behaviour. The slag quality and the potential for its re-use will therefore have to take into consideration the different Cr carriers in the slag. In addressing this need, a study was commissioned to determine the nature and quantitative distribution of the Cr-bearing phases in the slag. The study results indicated that the entrained ferrochrome alloy particles in slag formed a small percentage of the slag (i.e. < 1%). These potentially leachable ferrochrome particles can be removed by dry magnetic separation to yield a clean slag potentially suitable for aggregate applications (Kemetco 2021).

In support of the sustainability driver on reduced environmental liability and health concerns and acknowledging the lack of Canadian experience with chromite mining and ferrochrome processing, a benchmark study was commissioned. The study reviewed Finnish and European Union regulations, current environmental practices employed at the Kemi mine and Tornio smelter complex, and assessed the effectiveness of mitigation strategies. Finland was chosen as the benchmark for regulatory compliance in Canada because Finland has strict environmental regulations similar to Canada, and has differentiated itself globally by establishing environmentally conscious best practices in ferrochrome smelting. Finland, additionally, has a similar climate and physiographic conditions to those of northern Ontario. According to the findings of the study which are presented in Golder Associates Ltd (2021a,b,c), the Finnish regulation regime has been successful in managing the environmental impacts from ferrochrome production. This is in essence due to the choice of the furnace technology by the operator as the best available technology. The study identified some gaps in the Canadian/Ontario acts and regulatory framework and recommended that the approach and the lessons learned at the Finnish operations should form a baseline of control required for the Canadian chromite/ferrochrome facilities.

A literature review study was additionally undertaken on peat in the ecologically-sensitive and globally significant James Bay lowlands to assess knowledge gaps related to the interactions of mine dust carrying heavy metals from chromite mining activities with peatlands. The review identified a number of knowledge gaps including the species of microorganisms, soil conditions, and sediment mineralogy in the peatlands environments that may influence Cr accumulation and its potential for oxidation (Woloszyn and Berryman 2021).

Capacity building

The R&D initiative facilitated the development of capacity and expertise in the private sector through issuing 30 external technical contracts and providing total funding of about $2.5 million (Table 2). These contract projects enabled the private R&D service providers such as XPS, KPM, Hatch and Kemetco to not only learn and understand the issues and challenges related to chromite and ferrochrome processing but also develop capacity and utilize expertise.

Table 2. List of external contracts issued

Title	Contractor	FiscalYear
Chromite and ferrochrome market survey	Hatch	2015-16
R&D gaps analysis	Hatch	2015-16
Reduction tests	XPS	2015-16
Lifecycle and carbon footprint	Hatch	2016-17
Quantitative assessment of ferrochrome technologies	KPM	2016-17
Reduction tests	Uni. of Toronto	2016-17
Reduction tests	Uni. of Toronto	2016-17
TGA tests	XPS	2016-17
Smelting testwork and sampling of dust, fumes and slag	XPS	2017-18
Scaling-up processes and CFD modelling	KPM	2017-18
Reduction tests	Uni. of Toronto	2017-18
Reduction tests	Uni. of Toronto	2017-18
Grindability testing	SGS	2017-18
Mineral processing test	Downer	2017-18
Smelting testwork and sampling of dust, fumes and slag	XPS	2018-19
Smelting testwork and sampling of dust, fumes and slag	XPS	2018-19
Microtomography	Carleton Uni.	2018-19
Reduction tests	Uni. of Toronto	2018-19
X-ray photoelectron spectroscopy	NRC	2018-19
Scaling up DRC Phase II	KPM	2018-19
Scaling up DRC Phase III	KPM	2019-20
Scaling up DRC Phase III	KPM	2019-20
Ferrochrome slag quality and byproduct potential	XPS	2019-20
Ferrochrome slag quality and byproduct potential	XPS	2019-20
Reduction tests	Uni. of Toronto	2019-20
Computational Fluid Dynamics simulations	XPS	2020-21
Large-scale TGA tests	XPS	2020-21
Environmental benchmark review	Golder	2020-21
Recovering ferrochrome from slag and DRC products	Kemetco	2020-21
Optimization of DRC process	KPM	2020-21
Characterization and geotechnical testing of smelter slag	XPS	2020-21

The R&D initiative enabled hiring and training of 9 postdoctoral fellows (Table 3). These HQPs are now well aware of the issues and as experts on chromite and ferrochrome processing along with environmental issues, they are ready to tackle with new research questions in helping the public, the regulators and emerging Canadian industry. In addition, 2 MSc research projects were supported through the Research Assistance Program (RAP). This first project was on designing a graphene-based electrochemical sensor to detect Cr(VI) in mine leachate, drinking water and digestive fluids, and estimating the amount of Cr(VI) that solubilizes in simulated gastrointestinal fluids corresponding to site-specific conditions in the Ring of Fire. This project was awarded to Sammi Cheng at Chemical Engineering, Queen's University under the supervision of Drs. Louise Maunier and Dominik Barz, but was not completed due to a change in career direction by the student. The other MSc project funded under the Research Assistance Program was on the stabilization of chromium in ferrochrome slag for its utilization as aggregate material. This thesis project was carried out by Tahmeed Tasnim under the supervision of Dr. Leili Tafaghodi at the Materials

Engineering department of University of British Columbia. Training also involved 2 technologists: Kevin Ferris with a BSc degree from Carleton University and Jeff Scott with an MSc degree from Carleton University. Furthermore, training involved 18 CO-OP students from the University of Waterloo and University of Ottawa, mostly chemical engineering and earth science students but also from the nano-technology engineering department of Waterloo. They were Adam Wojtczak, Alexis McMorran, Connor Keilty, Dana Li, Ekaterina Komarova, Elizabeth Houghton, Firas Elchamaa, Joey Laird, We-Cheng Chen, Khushmeet Gill, Natasha Bell, Susan O'Brien, Victoria Corbasson, Richard Kashmirian, Sherina Jeyachandran, Joanne Woloszyn, Laura Dickson and Tanya Li. With hands-on experience on chromite and ferrochrome research, these students will be available as engineers and scientists to fulfill the needs of the industry, academia and research organizations.

Table 3. List of postdoctoral fellows as HQPs

Name	Original affiliation
Dr. Aimee Williamson	Laurentian University, Environmental Sciences
Dr. Dawei Yu	University of Toronto, Materials Science and Engineering
Dr. Samira Sokhanvaran	Massachusetts Institute of Technology, Materials Science and Engineering, Postdoctoral Research Associate
Dr. Erika Revesz	University of Ottawa, Earth and Environmental Sciences
Dr. Nasseh Khodaie	University of Alberta, Metallurgy
Dr. Nail Zagrtdenov	Géosciences Environnement Toulouse, Observatoire Midi-Pyrénées, Toulouse, France
Dr. Eleanor Berryman	Princeton University, Postdoctoral Research Associate
Dr. David Carter	University of Ottawa, Chemical Engineering
Dr. Jason Coumans	Durham University, Postdoctoral Research Associate

Accomplishments in capacity building included re-establishment of the pyrometallurgy lab at CanmetMINING. After more than about 15 years of hiatus, CanmetMINING now has a fully functioning lab with high-temperature furnaces equipped with gas analysers, a thermogravimetry and differential scanning calorimetry analyser, and other pyrometallurgy lab equipment. In addition, mineral processing facilities needed for chromite and ferrochrome research were upgraded including high-intensity wet and dry magnetic separators, elutriation tube, drum pelletizer, lab-scale SAG mill and SelFrag equipment. In short, CanmetMINING is now well positioned to address the industry needs on chromite and ferrochrome processing.

Dissemination of results and outreach activities

The R&D results were disseminated through patenting 2 inventions, 11 journal publications and 2 proceedings publications. There are additional journal publications in various stages of completion. Dissemination of developments and new knowledge was also made in the form of presentations during conferences, workshops and seminars (more than 50). The final report consisting of 44 reports or publications made during the 6-year period of R&D activities which are grouped under 3 main chapters: (1) introduction, (2) chromite ore and (3) ferrochrome production (Table 4).

Table 4. List of publications as part of the final report

1. Introduction
1.1. Chromite R&D Initiative Paktunc (2021)
1.2. R&D gaps analysis
1.2.1. Hatch (2016a)
1.2.2. Hatch (2016b)
1.2.3. Hatch (2016c)
1.2.4. Hatch (2016d)
1.2.5. Beukes et al. (2017)
1.3. Review of Environmental Practices
1.3.1. Golder Associates Ltd (2021a)
1.3.2. Golder Associates Ltd (2021b)
1.3.3. Golder Associates Ltd (2021c)
2. Chromite ore:
2.1. Paktunc (2021)
2.2. Paktunc et al. (2021)
2.3. Woloszyn & Berryman (2021)
3. Ferrochrome production
3.1. Smelting
3.1.1. Kingston Process Metallurgy (2017)
3.1.2. Hatch (2017)
3.1.3. Pilot Smelting Campaign
3.1.3.1. XPS Expert Process Solutions (2018)
3.1.3.2. XPS Expert Process Solutions (2019)
3.1.4. Smelter dust
3.1.4.1. Berryman et al. (2020)
3.1.4.2. Berryman & Paktunc (2022)
3.1.4.3. Berryman et al. (2022)
3.1.5. Smelter slag
3.1.5.1. XPS Expert Process Solutions (2020)
3.1.5.2. XPS Expert Process Solutions (2021)
3.1.5.3. Kemetco (2021)
3.1.5.4. Tasnim (2021)
3.2. Direct reduction of chromite
3.2.1. Paktunc (2021)
3.2.2. Alkali-assisted DRC
3.2.2.1. Sokhanvaran & Paktunc (2017)
3.2.2.2. Sokhanvaran et al. (2018)
3.2.2.3. Paktunc et al. (2018)
3.2.3. Cryolite-assisted DRC Sokhanvaran & Paktunc (2019)
3.2.4. Aluminum smelter waste as flux Yu & Paktunc (2019)

3.2.5.Nickel additive Yu & Paktunc (2018d)	
3.2.6.CaCl2-assisted DRC	
3.2.6.1.	Yu & Paktunc (2018a)
3.2.6.2.	Yu & Paktunc (2018b)
3.2.6.3.	Yu & Paktunc D (2018c)
3.2.6.4.	Kingston Process Metallurgy (2018a)
3.2.6.5.	Kingston Process Metallurgy (2018b)
3.2.6.6.	M4Dynamics (2018)
3.2.6.7.	Kingston Process Metallurgy (2019)
3.2.6.8.	Exmente (2019)
3.2.6.9.	Kingston Process Metallurgy (2020a)
3.2.6.10.	Kingston Process Metallurgy (2020b)
3.2.6.11.	Carter et al. (2021)
3.2.6.12.	Coumans et al. (2022)
3.2.6.13.	Kingston Process Metallurgy (2021)
3.2.6.14.	XPS Expert Process Solutions (2022)

Outreach activities during the 6-year period involved attending committee meetings, providing briefings to government organizations such as the Ontario Ministry of Northern Devleopment, Mines, Natural Resources and Forestry (MNDMNRF) and the Ontario Ministry of Environment, Conservation and Parks (MECP), discussions and collaborative research efforts with experts at Mintek and North-west University in South Africa, GTK of Finland, and site visits to Outokumpu and Glencore operations.

SUMMARY

Improved resource utilization, competitiveness and the need for value-added products, and reduced environmental liability and health concerns were considered to be the sustainability drivers under this program, for the development of the Ring of Fire chromite resources.

The driver on improved resource utilization was tackled by undertaking research on the development potential of the lower grade ores and the recovery of chromite fines since they would result in recovering the value which would normally be lost to the tailings and in reduced mining footprints which would significantly lessen the burden on the environment.

For addressing the sustainability driver on competitiveness and the need for value-added products, our R&D efforts have resulted in the identification of the most technologically advanced and clean flow sheets involving closed submerged arc furnace with oxidized pellet feed, DC-arc with pre-heated feed and Premus smelting furnace technologies. Our studies indicated that GHG emissions would be 3.9 and 4.7 t CO_2 for the production of 1 t Cr in ferrochrome using DC arc and closed SAF technologies. These are significantly less than the global average value of 10.5 t CO_2 per t Cr in ferrochrome.

In addition, our studies aimed at improving our understanding of the fundamentals of carbothermic reactions have resulted in a new direct reduction process whereby ferrochrome is produced at much lower temperatures than those of the conventional smelting technologies utilizing electric arc furnaces. The new direct reduction process has the potential to become an emerging new technology.

For reducing the environmental liability and health concerns, our studies focussed on identifying the potential sources and determining the conditions influencing the generation of hexavalent Cr during smelting, making slag inert or unreactive and reducing GHG emissions. Advanced characterization and speciation studies also identified critical information regarding where and how Cr(VI) is generated during smelting. The results will help in making process improvements for controlling the formation of Cr(VI) during smelting and developing regulations for environmental protection and preventing workers' exposure to Cr(VI) containing dust and fumes. An outcome of our attempt to make slag inert or unreactive would be the designation of the slag as a by-product rather than waste, which would result in reduced operational costs and liabilities associated with long-term storage of large slag piles. This is considering that slag comprises about one-half of the smelting products, and that ferrochrome slag is effectively utilized as a by-product in Finland.

Our main achievements include: (1) development of processing flow sheets for increased mineral recoveries including recovery of chromite fines, (2) development of a novel and energy-efficient pre-commercialization ferrochrome process/technology (Direct reduction of Chromite – Made-in Canada), (3) identification of clean and technologically most advanced ferrochrome flow sheets, (4) assessing re-use potential of the Ring of Fire smelter slag and identification of options for minimizing carbon and mining footprints, (5) determining conditions promoting the formation of Cr(VI) during processing, (6) facilitating the development of capacity and expertise by private sector, (7) training of highly qualified personnel on chromite/ferrochrome processing and related environmental issues, and (8) development of facilities suitable for continuing chromite and ferrochrome research.

ACKNOWLEDGEMENT

The study has benefited from contributions and discussions with Drs. Dawei Yu, Samira Sokhanvaran, Erika Revesz, Eleanor Berryman, Nail Zagrtdenov, Nasseh Khodaie, David Carter and Jason Coumans at CanmetMINING, and Drs. John Peacey, Kevin Watson and Boyd Davis at Kingston Process Metallurgy, Dr. Tanai Marin of XPS, and Dr. Paul Beukes of North-West University (South Africa). Management support of Janice Zinck and Bryan Tisch, generous support provided by Frank Smeenk of KWG Resources and for program direction by Noront, Matawa and other members of the steering committee are acknowledged. The program was funded by Natural Resources Canada's REE and Chromite Initiative.

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